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MEPC 58/INF.6
1 September 2008
ENGLISH ONLY

PREVENTION OF AIR POLLUTION FROM SHIPS

Updated 2000 Study on Greenhouse Gas Emissions from Ships

Phase 1 Report

Note by the Secretariat

SUMMARY

Executive summary:	The annex to this document provides the full report of Phase 1 on the updated 2000 study on greenhouse gas emissions from ships
Strategic direction:	7.1
High-level action:	7.1.1
Planned output:	7.3.1.3
Action to be taken:	Paragraph 2
Related documents:	MEPC 45/8, MEPC 55/23, MEPC 56/23, MEPC 57/4/18 and Add.1, MEPC 57/21, MEPC 58/4/2 and MEPC 58/4/4

Background

1 The full report of Phase 1, covering CO_2 emission inventories from international shipping and future emission scenarios, is set out at annex to this document. The executive summary can be found in document MEPC 58/4/4.

Action requested of the Committee

2 The Committee is invited to note the attached full report of Phase 1 as a basis for further consideration on the issue of greenhouse gas emissions from ships and take action as appropriate.

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ANNEX

Updated Study on

Greenhouse Gas Emissions from Ships

Phase 1 Report

1st September 2008

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Preface

This report constitutes Phase 1 of a study on greenhouse gas emissions from ships. This is an update of a study done for IMO in 2000. As in the 2000 report, a main objective of the update is to establish emission inventories and reduction potentials for greenhouse gas emissions from international shipping; however the scope of the updated study is broader and puts more emphasis on the trends and impacts of future emissions. As was also the case in the original study, the updated study is delivered to the International Maritime Organization by the consortium run by MARINTEK. This updated study benefits from a larger and more global team of expert contributors and the work is done in partnership with the following institutions:

CE Delft, Dalian Maritime University, Deutsches Zentrum für Luft- und Raumfahrt e.V., DNV, Energy and Environmental Research Associates (EERA), Lloyd's Register-Fairplay, Mokpo National Maritime University (MNMU), National Maritime Research Institute (Japan), Ocean Policy Research Foundation (OPRF).

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In the course of this work, the research team has gratefully received input and comments from the International Energy Agency (IEA), the Baltic and International Maritime Council (BIMCO) and the International Association of Independent Tanker Owners (INTERTANKO)

The objectives of Phase 1 of the study have been as follows: (1) to undertake an assessment of present day CO_2 emissions from international shipping; (2) to estimate future CO_2 emissions from international shipping emissions towards 2050; (3) to compare CO_2 emissions from shipping with other modes of transport; and (4) to assess the impact of CO_2 emissions from shipping on the climate. This report will be followed by a Phase 2 report which will address other greenhouse gases than CO_2 and the possibilities and mechanisms for reductions in GHG emissions.

Recommended Citation: Buhaug, Ø.; Corbett, J. J.; Endresen, Ø.; Eyring, V.; Faber, J.; Hanayama, S.; Lee, D. S.; Lee, D.; Lindstad, H.; Mjelde, A.; Pålsson, C.; Wanquing, W.; Winebrake, J. J.; Yoshida, K. *Updated Study on Greenhouse Gas Emissions from Ships: Phase I Report*; International Maritime Organization (IMO) London, UK, 1 September, 2008;

List of abbreviations

AIS	Automatic Identification System
CO_2	Carbon dioxide
EIA	United States Energy Information Administration
FAME	Fatty Acid Methyl Ester (a type of bio diesel)
FTD	Fischer Tropsh Diesel (a type of synthetic diesel)
GDP	Gross domestic product
GHG	Greenhouse gas
GT	Gross Tonnage
HFO	Heavy fuel oil
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LNG	Liquefied Natural Gas
MDO	Marine diesel oil
OECD	Organisation for Economic Co-operation and Development
OPRF	Ocean Policy Research Foundation
PM	Particulate Matter
RF	Radiative Forcing
SRES	IPCC Special report on emissions scenarios
UNCTAD	United Nations Conference on Trade and Development
UNFCCC	United Nations Framework Convention on Climate Change

Definitions

International shipping	Shipping between ports of different countries as opposed to *domestic shipping*. International shipping excludes military and fishing vessels. By this definition, the same ship may frequently be engaged in both international and domestic shipping. This is consistent with IPCC 2006 Guidelines.
Domestic shipping	Shipping between ports of the same country as opposed to *international shipping*. Domestic shipping excludes military and fishing vessels. By this definition, the same ship may frequently be engaged in both international and domestic shipping This definition is consistent with IPCC 2006 Guidelines
Coastwise shipping	Coastwise shipping is freight movements and other shipping activities that are predominantly along coast lines or regionally bound (e.g. passenger vessels, ferries, offshore vessels) as opposed to ocean-going shipping. The distinction between is made for the purpose of scenario modelling and is based on ship types, i.e. a ship is either Coastwise or an ocean-going ship
Ocean-going shipping	Ocean-going shipping is a term used for scenario modelling. It refers shipping refers to large cargo carrying ships engaged in ocean crossing trade.

CONTENTS

1. Executive Summary

1.1 Introduction

This report has been prepared by an international consortium as set out in the preface to this report. The report covers Phase 1 of a study that will be conducted in two phases. Phase 1 concentrates on CO_2 emissions only. The report covers four main elements:

1. An inventory of current emissions of CO_2 from international shipping.
2. Estimates of future emissions of CO_2 from international shipping.
3. A comparison of CO_2 emissions from various types of ships with CO_2 emissions from other sources in the transport sector.
4. An analysis of the impact of CO_2 emissions from international shipping on climate change.

1.2 Main Conclusions

The Intergovernmental Panel on Climate Change (IPCC) developed guidelines for national greenhouse gas emissions inventories. These guidelines divide emissions from water borne navigation into two primary categories: domestic and international. International waterborne navigation is defined as navigation between ports of different countries. As set out in the terms of reference, this study provides estimates of present and future CO_2 emissions from international shipping. International shipping has been defined in accordance with the IPCC Guidelines. Total estimates that include domestic shipping emissions and emissions from fishing are also included in this report.

CO_2 emissions from international shipping have been estimated both from activity data and from international fuel statistics. Following discussion and analysis it is concluded that the activity-based estimates with use of detail activity data (for different ship sizes and types) give a better prediction of global fuel consumption and CO_2 emissions from international shipping than fuel statistics due to apparent under-reporting of marine bunker sales.

Previous activity-based estimates have relied on different sources of activity data resulting in differences in estimated emissions. The research team behind this study, whose members include lead authors and main contributors from all peer reviewed scientific studies on this topic and a participant from the IMO Informal Cross Government/Industry Scientific Group of Experts agreed to a consensus estimate for CO_2 emissions in 2007. This estimate is based both on analysis of new activity data that is unique to this study in addition to data from previous studies.

The activity based model developed cannot differentiate between international and domestic emissions. In order to provide an estimate for emissions from international shipping by use of on the activity based model, domestic emissions as reported in bunker statistics have been subtracted from the total shipping emissions.

Table 1. Consensus estimate 2007 CO_2 emissions [million tonnes CO_2]

	Low bound	Consensus estimate	High bound	Consensus estimate % Global CO_2 emissions
Total ship emissions[1]	854	**1019**	1224	3.3
International shipping[2]	685	**843**	1039	2.7

[1]Activity based estimate including domestic shipping and fishing, but excluding military vessels
[2]Calculated by subtracting domestic emissions estimated from fuel statistics from the activity based total excluding fishing vessels

IPCC has developed scenarios for future global development. Future emissions from international shipping have been estimated in this report based on global developments outlined by IPCC. Assuming that there are no explicit regulations on CO_2 emissions from ships, CO_2 emissions are predicted in the base scenarios to increase by a factor of 2.4 to 3.0 by 2050. For 2020, the base scenario predicts increases ranging from 1.1 – 1.3. These predictions take into account significant efficiency improvements resulting from expected long-term increases in energy prices.

Climate stabilization will require significant reductions of CO_2 emissions by 2050. To reduce CO_2 emissions from international shipping, it appears necessary to either modify the current path of continued growth in seaborne transport, since the efficiency gains expected cannot deliver net reductions in the face of such growth; and / or develop mechanisms that will result in the introduction of technologies with significantly lower emissions than what is anticipated in these scenarios.

1.3 Current CO_2 emissions from international shipping

This study estimates international marine bunker fuel consumption and CO_2 emissions based on activity data and compares these with statistical data for global fuel sales to establish a consensus estimate for 2007 CO_2 emissions from international shipping.

1.3.1 CO_2 estimate based on fuel statistics (top-down estimate)

A global inventory was established based on statistical data for fuel use, derived from IEA summaries of marine fuel sales. The methodology used for the fuel-based estimate conforms to the methodology used and reported in the 2000 IMO Study of Greenhouse Gases. This approach is limited by the quality of the statistical data, and the way in which fuel sales volumes are assigned as either international or domestic.

Annual fuel consumption data were obtained from the IEA database for all reporting years from 1971 to 2005, the most recent data available. CO_2 emissions were calculated using the emission factors for marine fuels established by the IMO Informal Cross Government/Industry Scientific Group of Experts. CO_2 emissions for 2005 and an estimate for 2007 are shown in Table 2.

Table 2. CO_2 Emissions from shipping based on IEA data [million tonnes CO_2]

Year	2005	2007 est.
International shipping	531	582
Domestic shipping	101	111
Fishing	18	20
Total	651	713

As discussed in the main section of the report, issues such as the classification of fuel sales and the availability of statistical data from various countries result in a risk of under-reporting global total fuel sales. This also applies to other global data sets of marine fuel consumption or emissions such as data from EIA which largely rely on the same data as IEA. Therefore, as called for in the terms of reference an activity-based estimate was also made for the purpose of comparison.

1.3.2 Activity-based estimate (bottom-up estimate)

A global inventory was established for all ships greater than 100 GT based on data from the Lloyds Register Fairplay database for the year 2007, and using the best available data on vessel activity, engine and fuel characteristics, and carbon dioxide emission rates. The methodology used for the activity-based estimate has been applied in a number of scientific studies of this topic. This approach was also used in the work of the Informal Cross Government/Industry Scientific Group of Experts established by the IMO Secretary General.

The input data must be estimated for each ship category based on available background data. Although there is uncertainty in all of these figures, some of them can be estimated with high accuracy (number of ships, average power of main and auxiliary engines, specific fuel oil consumption, and fuel carbon content), and emission rates based upon fuel and combustion conditions can be described within well-understood ranges that give a satisfactory level of confidence. Other activity inputs vary by vessel service and voyage conditions and these are more difficult to assess. Comparisons with estimates for different periods would result in expected differences (e.g., from year to year, among vessel types, among routes, and even voyage to voyage) as they depend on the transport demand and the fleet size. In this study, an extensive set of AIS data collected from a global network has been used to assist the assessment of ship activity; AIS information and information on engine operating hours, fleet operating practices, etc., provide us with the ability to produce a consensus estimate inventory for shipping that is bounded by the range of reasonable estimates largely driven by activity-based inputs.

Since the estimate is based on all ships greater than 100 GT, the inventory includes domestic shipping and fishing vessels. In order to explore the uncertainty in the estimate, low and high bounds estimates were made. These bounding estimates represent feasible results but are less likely than the consensus estimate.

Table 3. Activity-based 2007 estimate of CO_2 emissions [million tonnes CO_2]

	Low bound	Consensus estimate	High bound
Total ship emissions[1]	854	1019	1224
- Oceangoing	474	593	681
- Coastwise	240	275	357
- Other	140	150	186

[1] All non-military ships greater than 100 GT

1.3.3 Comparison of fuel consumption estimates

Previous activity-based estimates have been reported for different years (2000, 2001, and 2007). In order to be able to compare them with the results from this study (2007), backcasts and forecasts for these point estimates are calculated from the time evolution of freight tonne-miles from Fearnleys (2007). The result is shown in Figure 1 which also presents international bunker sales statistics and the historical estimates from Eyring et al. (2005a) and Endresen et al. (2003) from 1950 to 2007. Since some of these studies included emissions from military vessels, auxiliary engines and boilers while others did not, corrections have been applied to allow comparison as detailed in the main report. Also, these studies typically estimate totals for the fleet of ships listed in national ship registries, as summarized in the Lloyds ship registry data; therefore, they represent what has been termed the World Fleet within which international shipping as defined by IPCC would be a subset.

The activity-based estimate from the present study is shown as a blue dot in Figure 1. Light blue whisker lines extend from this point to indicate the range of uncertainty given by the high and low bound estimates. The activity-based estimate from the present study is lower than the estimate from the IMO expert group and forecasts based on Eyring et al. (2005a); however it agrees well with the result of Corbett and Kohler (2003) when military vessels are removed from their original figures. The 2007 estimate of this study is higher than that of Endresen et al. (2007), and higher than fuel statistics.

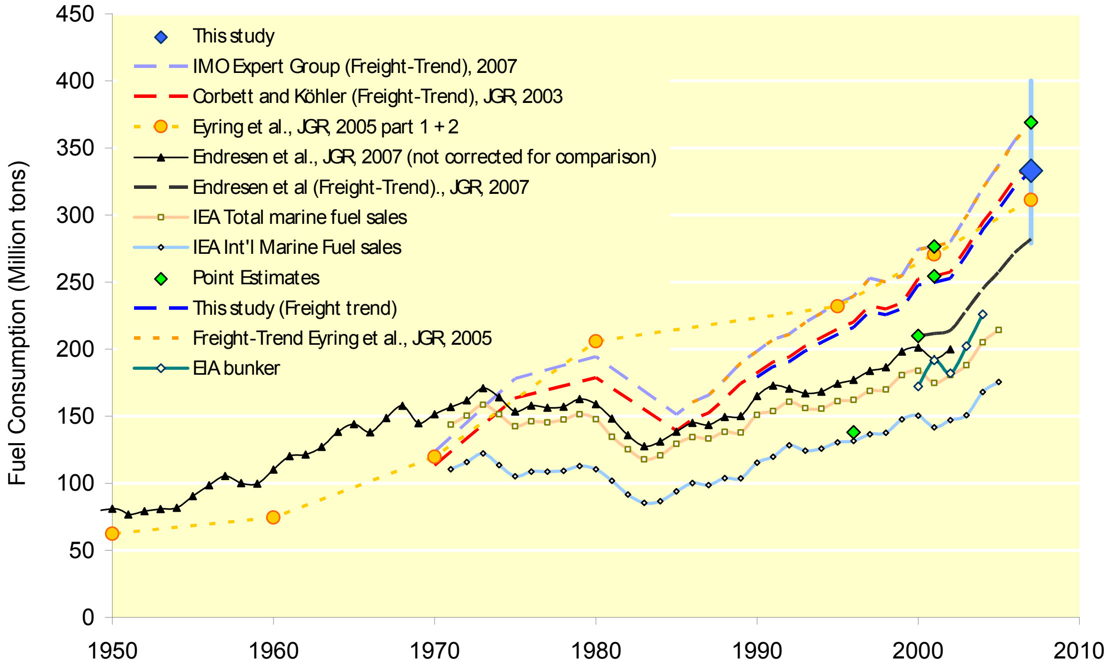


Figure 1. World fleet fuel consumption (except military vessels) from different activity based estimates and fuel statistics. The blue square shows the consensus estimate from this study and the whiskers the high and low bound estimates

1.3.4 Consensus estimate 2007 CO_2 emissions from International Shipping

Activity-based estimates consistently predict fuel consumption values that are higher than what is indicated in fuel statistics. While these activity-based estimates share many common inputs and assumptions and as such are not fully independent, statistical data on the other hand show some inconsistencies and could be expected to under-report consumption. Vessels can be categorized by activity as shown in Table 3, although this grouping does not explicitly match IPCC delineation of international and national shipping; for example, the sum of coastwise and other vessel activity categories exceeds the IEA statistics for domestic and fishing by more than three times, which indicates that significant coastwise and other shipping activity would likely be international.

Following the discussions detailed in Section 2.5 of this report, the international team of scientists behind this study concluded that the activity-based estimate is a more correct representation of the total emissions from the world fleet including in national ship registries than what is obtained from fuel statistics. Our team agreed that the activity-based estimate (Table 4) should be used as the consensus estimate from this study. Since the activity based model cannot separate domestic shipping from international shipping, domestic shipping emissions figures from bunker statistics have been used to calculate international shipping. Upper and lower bound estimates are about 20% higher and lower than the consensus figure.

Table 4. Consensus estimate 2007 CO_2 emission for international shipping [million tonnes CO_2]

	Low bound	Consensus	High bound
Total shipping emissions[1] (activity based)	854	1019	1224
Total less fishing (activity based)	796	954	1150
IEA domestic shipping (statistical data)	111	111	111
International shipping (hybrid estimate)	685	**843**	1039

[1] All non-military ships greater than 100 GT

1.4 Future CO_2 emissions from international shipping

Future CO_2 emissions from international shipping were estimated on basis of a relatively simple model developed in accordance with well-established scenario practice and methodology. The model incorporates a limited number of key driving parameters as shown in Table 5. These driving factors affect the various categories of ships in different ways. Therefore, the international shipping fleet was separated into three primary categories to allow differentiation of the overall effects of the above factors. These categories are:

- Coastwise shipping- Smaller ships used in coastal operations;
- Ocean-going shipping - Larger ships used long distance /intercontinental trade; and,
- Container ships (all sizes).

Table 5. Driving variables used for scenario analysis

Category	Variable	Related Elements
Economy	Shipping transport demand (tonne*miles/year)	Population, global and regional economic growth, modal shifts, sectoral demand shifts.
Transport efficiency	Transport efficiency (MJ/tonne*mile) – depends on fleet composition, ship technology and operation;	Ship design, propulsion advancements, vessel speed, regulation aimed at achieving other objectives but that have a GHG emissions consequence
Energy	Shipping fuel carbon fraction (gC/MJ fuel energy)	Cost and availability of fuels (e.g., use of residual fuel, distillates, biofuels, or other fuels)

Scenarios are based on the framework for global development and storylines developed by the Intergovernmental Panel on Climate Change (IPCC) in the special report on emission scenarios (SRES).

- Storyline A1: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.
    - A1 is modeled in three variations: A1FI – emphasis on fossil fuels, A1T emphasis on technology and A1B, balanced emphasis

- Storyline A2: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.

- Storyline B1: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

- Storyline B2: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

1.4.1 Economy and future shipping transport demand

Transport demand governs the size and activity level of the world fleet and is the most important driver for emissions from ships. The number of tonnes to be transported will depend on developments in trade, locations of factories, consumption of raw materials and other factors, while the distance will be affected by issues such as changing trade patters or possible new sea routes.

When determining future tonne-mile projections, GDP projections in the SRES scenarios have been the primary consideration. A hybrid approach considering both historic correlations between economic growth and trade as well as detailed analysis considering regional shifts in trade, increased recycling, new transport corridors, inter alia has been employed to derive the projections for future trade.

1.4.2 Future transport efficiency

Changes in the fleet composition can feasibly improve efficiency since larger ships are potentially more energy efficient. The effect of using larger ships has been modelled by predicting a change in the world fleet based on current trends towards 2020 as estimated by Lloyds Register Fairplay Research. Due to the uncertainties in predicting a 2050 fleet composition, no structural change is explicitly modelled from 2020 to 2050.

Economical optimal speed may decrease since fuel costs are expected to increase relative to other costs; hence market-driven speed changes are modelled.

Improvements can be made to new and existing ships to increase their energy efficiency. A detailed review of this topic will be made for Phase 2 of this study; however a preliminary assessment has been made to facilitate the scenario modelling. Since there are no regulations regarding fuel consumption, the change in the technology factor reflects improvements that are cost effective in the various scenarios rather than the technological potential. In addition to technological improvements, regulatory developments to improve other aspects of shipping may have impacts on the energy efficiency of ships. These factors are discussed and their impacts considered when determining scenario values for technological improvements.

1.4.3 Developments in marine fuels

The amount of CO_2 emitted from ships depends on the fuel type. For instance, certain fuels may contain more carbon per energy output than other fuels, and hence may produce more CO_2 emissions per unit work done. To capture this effect, future scenarios contain assumptions about future fuel use. When considering the market penetration of new fuels for the various scenarios it is noted that:

- Oil is a significant primary energy source in 2020 and 2050 in all scenario families (16-28% of world primary energy in 2050)
- In 2050, fossil fuels contribute from 57-82% of all primary energy in the SRES scenarios
- Previous estimates based on SRES scenarios range fuel consumption for shipping in 2050 from 400-810 million tonnes. This corresponds to 15-32 EJ or 10-15% of the global primary oil energy as specified for 2050 in the SRES scenarios.

It is thus considered that the SRES scenarios permit the continued use of oil-based fuels, although the cost would be expected to be higher. Therefore, in these non-GHG regulation scenarios, the move from oil-derived fuels would have to be motivated by economic factors. Since there are already binding emission targets for GHG reductions on land it is assumed that biofuels would fetch a better price there and would not be used by ships. The same situation would apply for the use of non-emitting or renewable energy from land.

1.4.4 Emission predictions

Key results from the scenario model are shown in Figure 2. Significant increases of CO_2 emissions are predicted. The emission increase is driven by the expected growth in seaborne transport. The scenarios with the lowest emissions deliver small reductions in 2050 compared to current emissions.

Our highest CO_2 emissions are essentially based on extrapolations of business as usual and minimum levels of efficiency improvements. Sustained low energy prices towards 2050 are a prerequisite for these scenarios. Therefore, the highest CO_2 emission scenarios do not appear likely. None of the scenarios show significant reductions in 2050 emissions. Such reductions would require radical changes compared to the assumptions in our model. Examples include:

- Abrupt decoupling between seaborne trade and global economic growth. In our model, the growth in transport demand is already lower than the correlation with GDP suggests, hence such decoupling must be rapid and very significant.
- Global economic growth rates significantly lower than the B2 scenario.
- Extreme fossil energy shortages compared to the SRES scenarios. According to SRES scenarios, by 2050, total primary energy consumption ranges from 160-284% of 2010 values and fossil fuels cover from 57-82% of global primary energy demand.
- Introduction of unexpected technologies

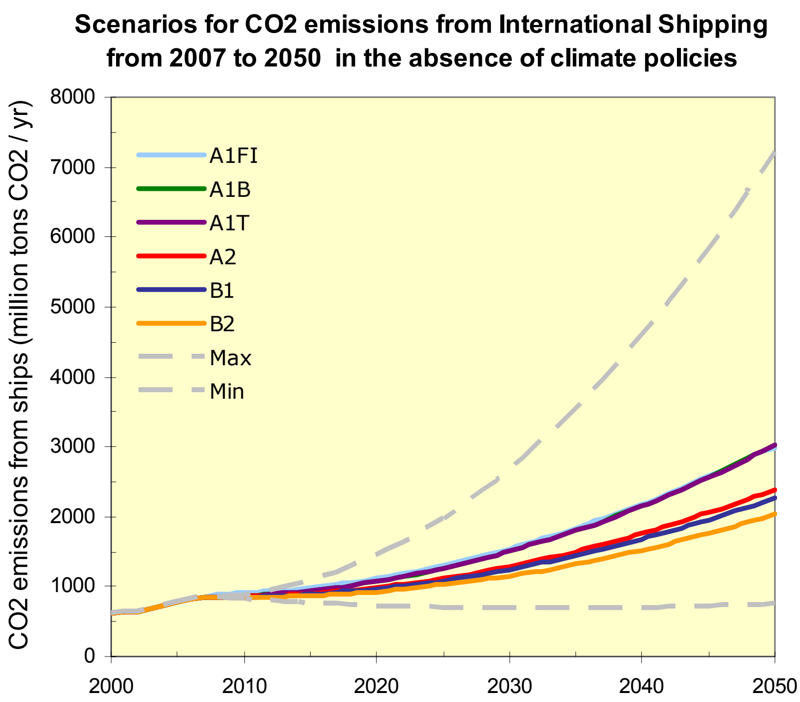


Figure 2. Emission trajectories for different scenarios. Legend refers to IPCC SRES The scenario terminology is explained in Section 1.4 of this summary

1.5 Comparison of CO_2 emissions from ships with emissions from other modes of transport

Efficiency ranges of various forms of transport was estimated using actual operating data, transport statistics and other information. The efficiency of ships is compared with that of other modes of transport in Figure 3. Efficiency is expressed as mass CO_2 / tonne-kilometre where the CO_2 expresses the total emissions from the activity and tonne-kilometre expresses the total transport work done. Total CO_2 emissions from ships have been compared to other transport modes based on fuel consumption data reported for other sectors in IEA statistics. This is shown in Figure 4. In this figure, the term 'Road diesel' refers to the total amount of diesel sold for road use, including cargo freight, passenger transport and diesel cars.

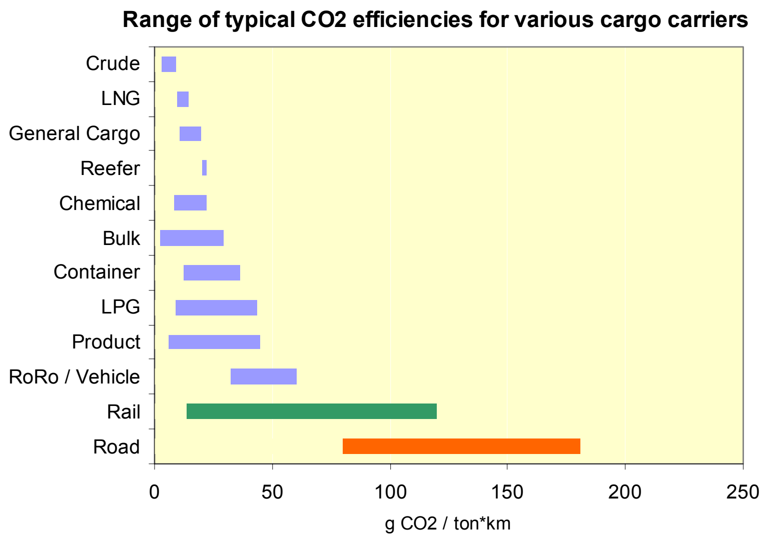


Figure 3. Typical ranges of ship CO_2 efficiencies compared to rail and road

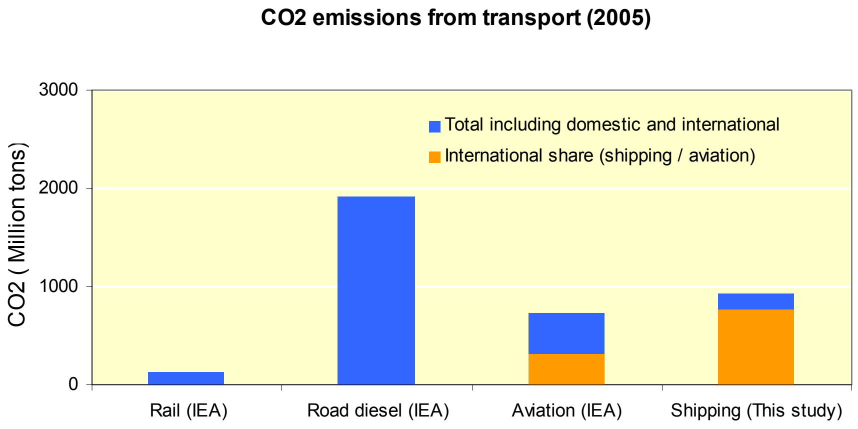


Figure 4. 2005 CO_2 emissions from shipping compared to other modes of transport

1.6 Radiative forcing impacts of CO_2 emissions from shipping

Increases in well-mixed greenhouse-gases such as carbon dioxide lead to positive radiative forcing (RF) and to global warming. Other radiative effects from shipping emissions will be considered in Phase 2.

CO_2 remains in the atmosphere for a long time and will continue to have a warming effect long after its emission. Therefore, emissions data from ships starting as early as 1870 has been used when calculating the RF of shipping CO_2 emissions. Since the historic data does not distinguish between international and domestic shipping, RF calculations are based on total shipping emissions rather than international shipping only.

In order to calculate the RF from shipping we use a linear climate response model to calculate the contribution of CO_2 emissions to marginal CO_2 concentrations and the consequential radiative forcing. This model takes emission rates, calculates the resultant atmospheric concentrations of CO_2 and then the RF which arises from changes in CO_2 concentration.

The RF from shipping CO_2 for 2005 was calculated to be 46 mW m^{-2}, contributing approximately 2.8% to the total anthropogenic CO_2 RF. For comparison, aviation has a similar – if slightly smaller – present day annual emission rate (733 Tg CO_2, 2005) but the RF is only 28 mW m^{-2}. The somewhat larger forcing from shipping in this comparison may be easily explained by both the residence time of CO_2 in the atmosphere and the time period of the activity.

Stabilization of atmospheric CO_2 concentrations by the end of the 21st century will require significant reductions in future global CO_2 emissions. The resultant temperature from stabilizing CO_2 concentrations at various levels (450 ppm, 550 ppm etc.) depends on climate sensitivity. Climate sensitivity is common test of climate models to the global mean surface temperature arising from a doubling of the CO_2 concentration. This is usually estimated to be between 2 and 4.5°C. A recent assessment of climate stabilization concluded that at 550 ppm, a target of 2°C would be exceeded, and 450 ppm would result in a 50% likelihood of achieving this target. To achieve this goal, total global CO_2 emissions must be limited to the values shown in WRE450 in Figure 5 below. For comparison, the WRE550 emission trajectory is also shown.

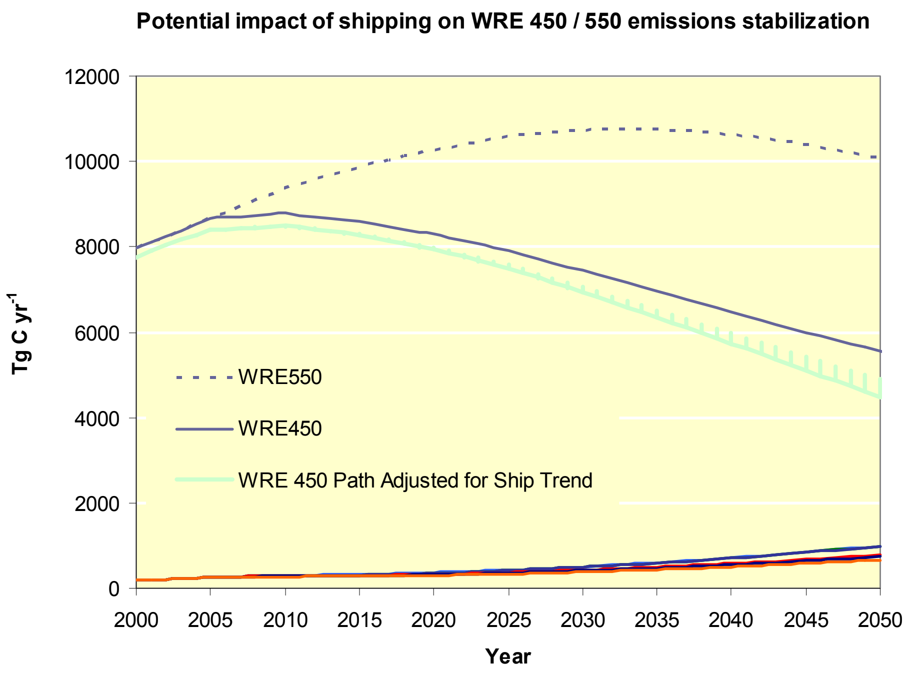


Figure 5. Comparison of modelled shipping emissions, lines for WRE 450 and WRE 550, and WRE 450 adjusted for ship emissions (Global total less shipping emissions). To achieve stabilization of atmospheric CO_2 at 450 ppm, global CO_2 emissions must follow the WRE 450 line

2. Present day CO_2 emissions from international shipping

2.1 Introduction

In this chapter, fuel consumption and CO_2 emissions from ships are estimated for the year 2007 from 1: activity data and 2: based on global fuel statistics. Results are compared and discussed to identify a consensus estimate for present day (2007) emissions of CO_2 from international shipping and shipping as a whole. Based on the consensus estimate, CO_2 emission series are generated from the years 1990 to 2007.

2.2 Estimate of CO_2 emissions from ships based on activity data

2.2.1 Methodology

The amount of CO_2 emitted from ships is a function of the amount of fuel that is combusted in the world fleet and the carbon content of the fuel. The carbon content of present day marine fuels can be estimated with high accuracy. However, the estimation of fuel consumption entails a significant degree of uncertainty as evidenced by the differences observed in previous estimates (Corbett et al., 1999 [15]; Corbett and Köhler, 2003 [1]; Endresen et al., 2003, 2007 [5] [6]; Eyring et al., 2005a [3]; Olivier et al., 2001 [11]; Skjølsvik et al., 2000 [12], Gunner, 2007 [8]).

Fuel consumption for the world fleet is estimated in an ‘activity-based bottom-up’ approach where the fuel consumption is estimated for individual ship categories. The fuel consumption estimates are then added together to find the global total. Ship categories for use in this inventory have been chosen so that they represent distinct ship types in terms of not only size but also typical operational patterns, which is beneficial to identify and assess activity data.

The Main Engine (ME) fuel consumption of a ship category is estimated by multiplying the number of ships in each category with the average ME power to find the installed power [kW] by category. The annual power outtake [kWh] is then estimated by multiplying the installed power with a category specific estimate of the main engine operating hours and the average engine load factor. Finally, the fuel consumption is estimated by multiplying the power outtake with the specific fuel oil consumption value applicable to the engines of the given category [g/kWh]. The process of estimating the fuel consumption of a ship category is illustrated in Figure 6. The same principle is applied to estimate auxiliary engine fuel consumption.

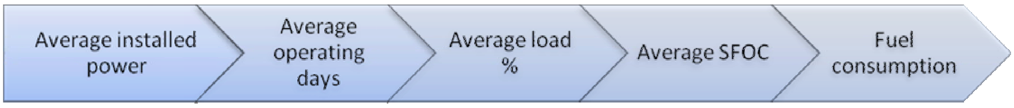


Figure 6. Calculation of fuel consumption

2.2.2 Model input data

The emission inventory requires data for each ship category on

- number of ships
- average power of main and auxiliary engines [kW]
- average age of main engines (used to improve fuel consumption estimates) [years]
- average design speed of ships (used when processing AIS data and estimating load) [knot]
- average specific fuel oil consumption of main and auxiliary engines [g/kWh]
- average running hours for the main and auxiliary engines [days]
- average load on main and auxiliary engines [% MCR]
- average steam boiler fuel consumption [tonnes/year]
- average boiler consumption [tonnes/year]
- average fuel carbon content [gram carbon / gram fuel]

2.2.2.1 Ship count and technical data

Statistical information on the world fleet was obtained from the Lloyds Register Fairplay database for the year 2007. This database contains information of all ships larger than 100 GT. An extended version of the Lloyds Register Fairplay database which contains additional technical information such as auxiliary engine power and vessel design speed was used [16]. There may be some missing raw data in the extended Lloyds Register Fairplay database concerning certain specific technical data. Therefore, for these special fields and for specific uses, Lloyds Register Fairplay has a database version where fields have been populated with estimated values using statistical relationships. This means that the precision of additional data such as vessel design speed and auxiliary engine power may be lower than that of the core data such as ship numbers, tonnage and main engine power. The key data used in this report are shown in Table 14**.**

2.2.2.2 Average specific fuel oil consumption of main and auxiliary engines

Specific fuel oil consumption (SFOC) denotes fuel consumption in relation to work done and is commonly expressed in g/kWh. The specific fuel oil consumption depends on a range of parameters including engine size, age and fuel energy density. Data on fuel consumption can be obtained from test bed results, from sea trial measurements and also to a certain extent eluded from daily fuel consumption figures given in charter contracts and listed in ship databases. SFOC may also be calculated based on thermodynamic first principles and engine characteristics. Typical best specific fuel oil consumption (BSFOC) values are given in Table 6. These figures have been established by reviewing various CIMAC [25] papers, manufacturer catalogues and Diesel and Gas Turbine Worldwide [18]. The figures indicate a difference of about 10% depending on age category and 20% depending on size.

Table 6. Typical best specific fuel oil consumption values [g/kWh] [17]

Engine year	2 stroke low speed	4 stroke medium / high speed (> 5000 kW)	4 stroke medium / high speed (1000- 5000 kW)	4 stroke medium / high speed (< 1000 kW)
1970-1983	180-200	190-210	200-230	210-250
1984-2000	170-180	180-195	180-200	200-240
2001-present	165-175	175-185	180-200	190-230

Specific fuel oil consumption data are measured in an engine test bed except for very large (two stroke) engines that are simply too large to fit in a test bed. The fuel consumption is determined and given in accordance to standard ISO procedure and reference conditions (ISO 3046-1) and corrected to standard fuel energy and standard ambient conditions. The best specific fuel oil consumption value corresponds to a single operating point.

The fuel consumption in actual operation is expected to be higher than when measured in test bed conditions. The reasons for this include:

- The engine is not always operating optimally at its best operating point
- The energy content of the fuel may be lower than that of the test bed fuel (for engines using residual fuels this typically amounts to about 5%)
- Best SFOC values are given with 5% tolerance
- Engine wear, ageing and maintenance (fuel injector and injection pump wear, improper settings, turbocharger fouling, increased filter resistance, heat exchanger fouling and more).

Considering the differences between the SFOC of new and old engines and the differences in average engine age, the values given in Table 2 have been used in the inventory model. Further refinements such as differentiation by power/ cylinder or distinction of slow and medium speed engines could not be done since the ship database does not contain engine cylinder number or stroke number.

Steam turbines used in Liquefied Natural Gas (LNG) tankers are assumed to consume 275 g/kWh on a heavy fuel oil (HFO) basis. This figure has been derived by considering fuel consumption figures for a turbine-driven LNG ship in operation. When considering the SFOC of auxiliary engines, consideration was given to the fact that auxiliary engines are expected to operate extensively on part load. The values used in the model are given in Table 8

Table 7. Main engine specific fuel consumption values [g/kWh] used in the inventory model

Engine age	**Above 15000 kW**	**15000- 5000 kW**	**Below 5000 kW**
< 1983	205	215	225
1984-2000	185	195	205
2001-present	175	185	195

Table 8. Auxiliary engine fuel consumption values [g/kWh] used in the inventory model

Engine age	**Above 800 kW**	**Below 800 kW**
Any	220	230

2.2.2.3 Average fuel carbon content

A CO_2 emission factor is needed to calculate the CO_2 emissions resulting from the combustion of the fuel in question. Various types or grades of fuel oil are used on ships. The combustion and handling properties of these fuels as well as the need for pre-treatment can be very different. These differences relate primarily to molecular structures and certain non-hydrocarbon impurities such as sulphur and water, however the CO_2 emission factor varies little as shown below. Therefore, there is no need to distinguish between many fuel grades for the analysis of CO_2 emissions. In this assessment, we use only marine diesel oil (MDO) representing all distillate types of fuel (free of residual blending components) and heavy fuel oil (HFO) representing all fuels containing residual components)

In order to calculate our CO_2 emission factor, we start with the determination of the carbon content (by mass) of the *hydrocarbon component* of each fuel type based on molar mass fractions – we call this our *C:HC mass ratio*. We then adjust this value to a carbon content of *fuel* by removing the mass percentage of the fuel occupied by impurities and multiplying by the *C:HC mass ratio*. We then convert carbon to CO_2 using molar mass ratios. For example, for HFO, we assume the hydrocarbon of the fuel to be $C_{30}H_{62}$. This is the same assumption as that of the IMO expert group [4]. Given the atomic mass of carbon (12 g/amu) and hydrogen (1 g/amu), we can determine that the *C:HC mass ratio* of HFO is equivalent to (12x30)/[(12*30 + 1x62)], or 85.3%. Again based on the IMO expert group [4] we also assume for HFO that there exists 3.50% impurities (see Table 9). Thus, if 3.50% of the fuel is due to impurities, then we apply the 85.3% carbon mass fraction is applied to the hydrocarbon mass of the fuel (100%-3.5% = 96.5%). In the case of HFO, we obtain an "adjusted carbon fraction" of 85.3% x 96.5% = 82.3% (carbon to fuel mass ratio). Furthermore, assuming that all carbon is converted to CO_2, we can convert this carbon to CO_2 by applying the molar mass ratio of CO_2:C (44/12). This type of calculation is shown in the equation below, where *I* represents impurity (%), *n* represents the number of atoms in the hydrocarbon molecule, and *C* and *H* represent the atomic mass of carbon and hydrogen, respectively.

The carbon content of Diesel / Gasoil and Heavy fuel oil is based in the work of the IMO expert group [4] while the carbon content for LNG is based on pure liquid methane.

$$\frac{kg\ CO_2}{kg\ \ fuel} = \left[\frac{C_n}{C_n H_{n+2}} \times (1 - I)\right] \times \frac{44}{12}$$

Table 9. Average carbon content in fuels and emission factors

Type of fuel	Hydrocarbon carbon content m/m	Impurities	Net carbon content m/m	kg CO_2 / tonne Fuel
Marine Diesel Oils (MDO)	0.850	1.0%	0.842	3.09
Heavy Fuel Oils (HFO)	0.853	3.5%	0.825	3.02
LNG	0.750-	0	-	2.75 (kg / tonne LNG)

In the inventory, it is assumed that all ships categorized as Ocean-going use heavy fuel oil (HFO) while ships categorized as Coastwise use either marine distillate fuel oil (MDO) or Heavy Fuel oil. The fraction of coastwise ships using MDO has been selected so that the total global ratio of HFO/MDO is the same in our mode as in the IEA statistics. The fuel assumption for each ship category is shown in Table 14.

The use of the emission factors in the IPCC guidelines was also considered. These factors are based on fuels with less impurity than typical marine fuels. If these factors had been used, this would result in more CO_2 emitted for each kg fuel burned. On the other hand, fewer impurities would cause IPCC fuels to have higher energy content than typical marine fuels. This would then affect the SFOC assumptions; hence the net effect on CO_2 would be marginal.

LNG Carriers

The average carbon content of LNG carriers depends on the amount of energy that is in the form of LNG. This ratio depends on the boil-off gas (BOG) rate and the fuel consumption. A modern 135 000 m^3 LNG vessel with a BOG rate of 0.15% is calculated to achieve an LNG energy substitution rate of 75% at 19-20 knots. In ballast, the LNG carrier is assumed to have no LNG available. Therefore, the LNG is estimated to contribute only 45% of the total energy. Older LNG tankers will have higher BOG rates and higher fuel consumption and it is assumed that the same ratio would apply to these ships.

On an equal energy basis, the CO_2 emissions from LNG combustion are about 76% of that of HFO. On a fuel oil equivalent basis, the CO_2 emission factor for the LNG tanker is 2.69 kg CO_2 / tonne heavy fuel oil equivalent.

2.2.2.4 Activity input Data

The emission model requires certain input which describes the activity of the ships. These are

- Average running hours for the main and auxiliary engines
- Average load on main and auxiliary engines
- Average steam boiler fuel consumption

Estimation of activity is particularly challenging because activities vary to a certain degree from one year to the next, depending on factors such as transport demand in relation to the size of the fleet in any given segment. Previous research has estimated activity from the service record of engine running hours, by interviews, using Lloyds Marine Intelligence Unit, ship movement data and more. For this study, data from Automatic Identification Systems (AIS) from the AIS live network were used as a new and independent source of activity information.

2.2.2.4.1 AIS Data

The Automatic Identification System (AIS) is a safety device that automatically transmits information - including the ship's identity, type, position, course, speed, navigational status (e.g. “at anchor” or “moving with engines running”) and other safety-related information to appropriately equipped shore stations, other ships and aircraft.

The International Convention for the Safety of Life at Sea (SOLAS) [28] requires an AIS transponder to be fitted aboard all ships of 300 gross tonnage (GT) and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size. The requirement became effective for all ships as of 31 December 2004. Ships fitted with AIS are to maintain AIS in operation at all times except where international agreements, rules or standards provide for the protection of navigational information.

AIS Live is a network of shore-based AIS receivers covering more than 2000 locations in 100 countries. This network collects and processes AIS data and makes the information available for various analytical purposes on a commercial basis. For this project, a database containing all AIS observations logged each hour for the year 2007 was used. The location of these receivers is indicated in Figure 7. In this figure, green dots signal the position of AIS base stations in the network. Orange and yellow and red signal a higher density of receivers.

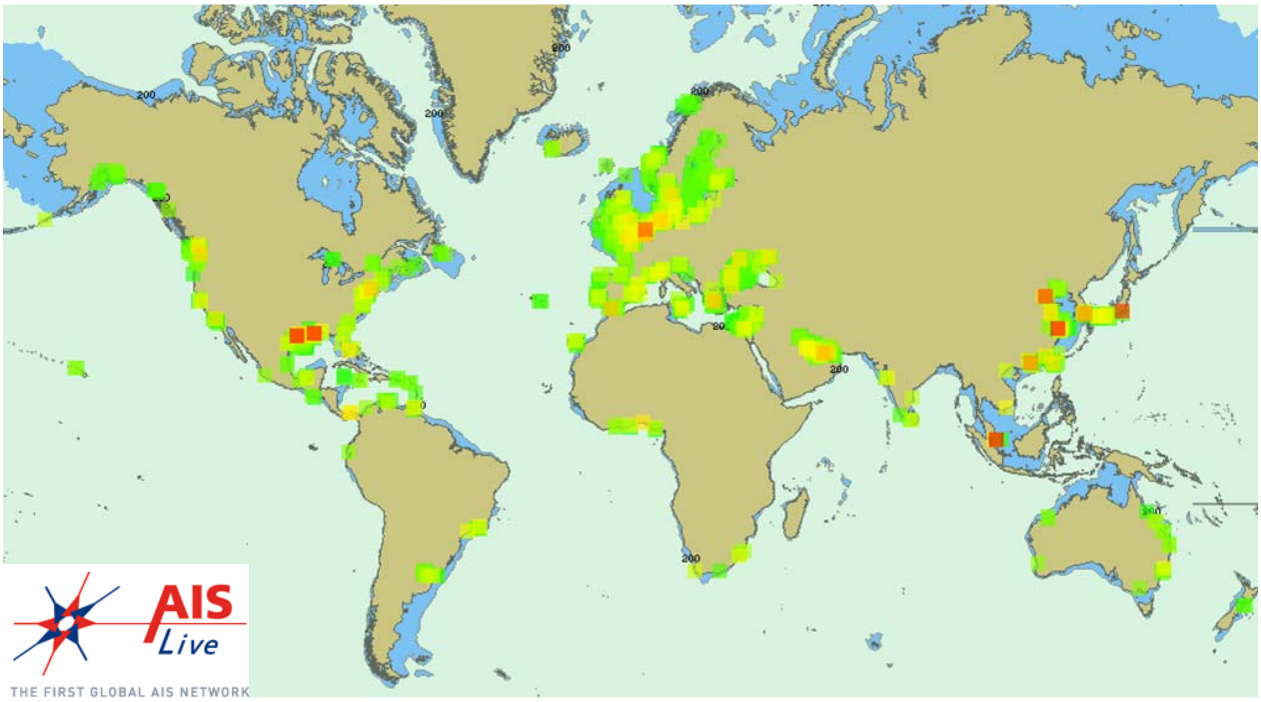


Figure 7. Shore-based receivers in the AIS live network (Lloyds Register Fairplay)

AIS shore stations are able to continuously detect the presence of ships in the vicinity of the shore station. Ship movement and speed are also detected; however the range is limited (Typically to somewhere around 100 km, depending on the height of antenna, atmospheric conditions, and more). Therefore, the AIS network cannot track ships between ports. However, since the identity of a ship is broadcasted it is possible to record the time between when a ship disappears from one port within the AIS network and appears in another. Assuming that the ship travels directly between these ports, these data would provide the time at sea and average speed. Unfortunately, it is not possible to determine if the ship has detoured and / or called on other ports that are not part of the AIS network.

Data from the AIS network were prepared by counting for the year 2007 the number of hours each ship detected by network spent either:

- Within AIS network coverage, in port, status
- Within AIS network coverage, not in port, status “at anchor”
- Within AIS network coverage, moving
- Outside AIS network coverage

Whenever a ship left AIS network coverage, the time until it reappeared was used to calculate its average speed assuming the ship had followed the shortest route between the observations. This calculation does not take into account the presence of land masses which could cause significant error on certain distances. However, since ships will be detected not only by the ports of departure and arrival but also when passing other ports as well as other strategic waypoints with AIS coverage (e.g. Suez, Panama, Gibraltar, Strait of Malacca, Alaska

Peninsula, South of Sri Lanka), the error of making this direct route assumption will be reduced.

Voyages where the calculated average speed is above 80% of the service speed for the particular ship (as given in the extended Fairplay database) were categorized as ‘normal’ while voyages where the average speed is less than 80% were categorized as ‘slow’. By this procedure, the ship activity could be grouped in four categories, see Table 10.

Table 10. Definition of data categories

Category	**Description**
Port	Hours within range of AIS network with navigation status “moored”
Anchor	Hours within range of AIS network, with navigation status “at Anchor”
Slow	Hours within and outside AIS network, calculated average speed < 80% of service speed.
Normal	Hours within and outside AIS network, calc. average speed > 80% of service speed.

The input summary table (Table 14**)** shows the number of vessels (unique counts) detected by the global AIS live network in 2007. The table also shows the number of ships in the database in April 2008 and the percentage of the ships in the database that have been observed at least once within the AIS network. In general, the indicated coverage is high for large cargo carrying ships, however for smaller ships and particularity fishing vessels the coverage is low. This is believed to be a result of smaller ships calling more frequently at smaller ports and operating in areas which are less likely to be part of the AIS live network

In some instances, more vessels are detected by the AIS system than are recorded in the statistics. This may be caused by a reduction in fleet size or a delay in the updating of the statistics or other errors.

2.2.2.4.2 Days at sea and average power estimates

The inventory model requires an estimate of the average number of days ships within each category spend moving at sea. In order to use the AIS data to estimate days at sea, it is first necessary to interpret the data. An example of the AIS data is shown below in Table 11.

Table 11. Example AIS data (accumulated hours by ship category)

Type	Size	Port (h)	Anchor (h)	Slow (h)	Normal (h)	Total (h)
Bulker	100 000 -199.999 dwt	225 065	348 160	728 101	2 860 034	**4 161 360**

Type	Size	Service speed (knot)	Cut-off speed slow (knot)	Average speed slow (knot)	Average speed Normal (knot)
Bulker	100 000 -199.999 dwt	14.1	11.3	7.6	12.8

Hours spent in port and at anchor are not spent at sea. Time allocated in the 'slow category' is likely to include both some time moving but also some port time to justify a detour which could explain the unusually low average speed. Another reason for slow voyages would be detouring around land not anticipated in the AIS distance calculation. Time in the normal category could in theory contain some port time and detouring also, however the difference between average observed speed and service speed could also be caused by temporary speed reductions in congested waters, detours caused by weather and other natural causes. For the purpose of this study it was assumed that hours recorded in the normal speed category are all at sea. What remains is interpreting the hours logged by Lloyds AIS analysis as 'slow'.

If it is assumed that "slow" voyages are a result of stops in port that are on the route between the two ports where AIS is used, and also assuming that the speed in sea is the same as the average speed observed in "normal voyages" then the time at sea can be calculated as:

$$Total\_at\_sea = Time\_normal + Time\_slow * \frac{Average\_speed\_slow}{Average\_speed\_normal}$$

The assumption that additional ports are on route is not unreasonable since a significant share of shipping follows coastlines where stops without a significant detour could be possible. However, if ships do detour significantly and the additional ports are not generally on the route between them the above calculation would be in error and underestimate time at sea. Naturally, the accuracy of the time at sea estimate depends not only on the validity of the assumptions but also on how representative the data are for the ship category as a whole.

The AIS data can also be used to estimate average engine load. This is done by comparing the average speed observed at sea with vessel service speed while assuming a third power relationship between power and speed and a sea margin of 10% for all vessels as illustrated in Table 12. This table shows that with a 10% service margin[1], the maximum speed obtained with a clean hull and calm weather at full design draft (i.e. 100% speed) corresponds to 90% MCR. When the speed is reduced, the propeller load and engine load are reduced correspondingly. The average load can then be indicated by comparing the speed observed by

[1] A service margin is used to prevent engine overloading in the event of extreme hull fouling and or weather

AIS with the maximum speed of the ship. This estimate will only be indicative since it does not include a number of significant parameters including the effect on average load of speed variations en route, wind, waves, hull degradation or the draft of the ship.

Table 12. Typical engine and propeller load corresponding to ship speed in clean-hull calm sea conditions at design draft

Ship speed	50 %	75 %	80 %	90 %	95 %	100 %
Propeller load [% kW]	13 %	42 %	51 %	73 %	86 %	100 %
Engine MCR [% MCR]	11 %	38 %	46 %	66 %	77 %	90 %

Following the above approach, AIS data and fleet statistics were used to estimate days at sea and the main engine load for all ship categories in the inventory. The resulting days at sea estimates were subsequently reviewed in light of other data such as activity data from previous studies and logistic analysis. Thereafter, the average main engine load was assessed considering other data sources and the effect of ballast and low load runs which would not be accurately predicted using this methodology. Several changes were made both with regard to days at sea and load. In particular, changes were made to all categories of small ships where AIS coverage is low and where the AIS days at sea was significantly higher than could be expected from other data. The resultant input data are shown in Table 14.

2.2.2.5 Average auxiliary engine load and operating hours

The average auxiliary engine load and operating hours are needed to calculate auxiliary engine fuel consumption. The load and operating hours vary greatly between ship types. Typically, and according to Lloyds data, ships will normally have at least three generators where one is operational, one is on standby and the third is available for maintenance. Normally, generators will be operated on a rota basis to distribute running hours. The standby generator(s) will be used in periods with high load or risk of high load peaks such as when thrusters are used for manoeuvring or when large pumps, winches or cranes will be operated. This typically occurs at arrival in port. Certain ships will also need electricity for cargo care purposes such as ventilation and refrigeration. Other ships may use a shaft generator. In this case, auxiliary engines would not normally be operated at sea. Following this discussion, the research team made assumptions for annual AUX running hours and load factors. In doing this, the relative consumption between main and auxiliary engines was considered and compared with typical operating data for certain ship segments.

2.2.2.6 Average steam boiler fuel consumption

All ships using residual fuel oil will need to heat this fuel to maintain it as a liquid. When the ship is at sea, this heat will normally be taken for the exhaust waste by way of a steam boiler, hence no additional fuel is consumed. In port, however, the main engine is not running and the ship may therefore need to generate steam using an auxiliary oil fuelled boiler. In the total picture, the amount of fuel used to heat fuel is considered to be insignificant. For tank ships, where steam is required for cargo heating and / or pumping work, the boiler fuel consumption is no longer insignificant. The fuel oil boiler consumption for these ships is estimated on the basis of the work of the IMO Expert group (BLG 12/Inf.10).

- **VLCC Tankers**

  It is assumed that Very Large Crude Carrier (VLCC, DWT 200 000+) oil tankers undertake 10 voyages per annum of which 5 are loaded, thus 5 discharges are made each year. For each discharge a VLCC (DWT 200 000+) uses 250 tonnes of boiler fuel oil to power the main cargo pumps.

- **Suez Max Tankers**

  It is assumed that Suez Max (120 000-200 000 DWT) crude oil tankers undertake 12 voyages per annum of which 6 are loaded, thus 6 discharges are made each year. For each loaded voyage a VLCC (DWT 200 000+) is estimated to use 150 tonnes of boiler fuel oil to power the cargo pumps and also to heat certain cargoes

- **Aframax Tankers**

  It is assumed that the Aframax (80 000-120 000 DWT) crude oil tankers carry heated cargo 50 days per year. Heating requires 60 tonnes of boiler fuel oil per day.

- **Small Crude Tankers**

  The smaller Crude Tankers (60 000-79 999 dwt, 10 000-59 999 dwt, and < 9999 dwt) are assumed to carry heated cargoes 100 days per year. The boiler consumption per day for cargo heating is 30, 15 and 5 tonnes respectively.

- **Product tankers**

  For Product tankers the assumptions are:
  - 40% of all product tankers carry heated cargoes;
  - These cargoes are carried 150 days per annum; and
  - The boiler consumption per day is 5, 15, 30, 50 and 60 tonnes for each size category respectively.

- **LNG tankers**

  For consistency and to ease future scenario modelling, the boiler consumption is modelled as ME consumption taking into account the lower efficiency of steam boilers and the change in fuel carbon fraction to account for the LNG boil-off fraction in the fuel

2.2.3 Confidence and uncertainty

The activity-based estimate of marine bunker consumption is based on a series of inputs. An uncertainty is associated with each and all of these inputs. A list of these inputs and a qualitative description of the confidence of the inputs and uncertainty is given in Table 15 and Table 16.

Previous research has shown that the input variables causing the greatest uncertainties in this type of bottom-up activity model is the engine load factor estimate (duty cycle) and days at sea (engine running hours) [1]. The present study uses extensive global AIS data to assist the assessment of both these inputs. Even so, the uncertainty in an inventory of this type remains significant. This is apparent when comparing key inputs used in previous research. Estimates of key parameters and data sources for other estimates are given below in Table 13. As seen in Table 13, various data sources and assessments result in differences for model inputs which again result in different estimates. The figures cited are indicative of typical inputs; however they are not fully comparable due to differences in categorization and also definition of inputs.

In order to get a better grip of the uncertainties, two alternate sets of model input data were developed to generate alternative high and low fuel consumption estimates. In doing this, only the days at sea and the average load factor were manipulated. For each category, combinations of days at sea and load which would result in respectively high and low fuel consumption were identified. These combinations were considered to be feasible, but significantly less likely than our consensus estimate. The high and low bounds generated are not absolute limits.

Table 13. Comparison of activity-based bunker fuel inventories (Comparison of Results: see Table 25)

	Primary source of activity data	Ship category average main engine operating [days / year]	Average main engine SFOC [g/kwh]	Average main engine [% MCR]
Corbett et al., 2003 [1]	Engine running hours and operating data provided by a major diesel engine manufacturer	Cargo ships 229-292 Average 271	Cargo ships average 206 (range 185-225)	Cargo ships 65-70% average load based on rated power 55-80% max All types weighted average 63%
Eyring et al., 2005 [3]	Engine running hours and operating data provided by a major diesel engine manufacturer	Cargo ships 225-275	Cargo ships average 210	Cargo ships average 70-80%
IMO expert group, 2007 [4]	Questionnaires to 20 selected major ship owners	All types 175-310, weighted average 226	Weighted average 185	All types 62-90%, weighted average 80%
Endresen et al., 2007 [5]	Published data on seaborne trade length of haul, laid up tonnage, cargo capacity utilization and operational speed	Cargo ship average 181	Cargo ship average 221	Average 70%
This study, consensus estimate	AIS data combined with fleet statistic and results from previous work. Contributors to studies listed above have been represented in the team behind this update	All types 100 -285, weighted average 240	Weighted average 196	Cargo ships 65-80% weighted average 70 All types 16- 80%, weighted average 64%

Table 14. Summary Table – Input data used in the inventory

Category	Size / Type	No ships (2007)	Ave. GT	Ave. ME kW	Ave. per engine Aux kW	AIS Unique Counts (4)	AIS Cover-age (5)*	Days at sea (1) Modelled	Avg. ME load Modelled	Avg. AUX running days (2)	Avg. AUX load Modelled	Fuel type(3)
Crude oil tanker	200,000+ dwt	494	155 685	24 610	1 034	514	99 %	274	73 %	450	50 %	HFO
Crude oil tanker	120 -199,999 dwt	353	80 711	17 075	1 232	368	100 %	271	80 %	450	50 %	HFO
Crude oil tanker	80 -119,999 dwt	651	56 921	12 726	769	685	101 %	254	80 %	450	50 %	HFO
Crude oil tanker	60 -79,999 dwt	180	39 498	10 529	731	190	101 %	238	70 %	400	50 %	HFO
Crude oil tanker	10 -59,999 dwt	245	24 290	7 889	729	229	91 %	238	70 %	400	50 %	HFO
Crude oil tanker	-9,999 dwt	114	2 085	1 865	222	49	41 %	180	65 %	400	50 %	MDO/HFO
Products tanker	60,000+ dwt	198	46 775	12 644	780	215	99 %	171	80 %	450	50 %	HFO
Products tanker	20 -59,999 dwt	456	24 262	8 482	736	455	96 %	171	66 %	450	50 %	HFO
Products tanker	10 -19,999 dwt	193	9 723	4 640	535	147	75 %	183	70 %	400	50 %	HFO
Products tanker	5 -9,999 dwt	466	4 264	2 691	291	306	63 %	177	75 %	400	50 %	MDO/HFO
Products tanker	-4,999 dwt	3.959	1 056	1 032	123	909	23 %	175	65 %	400	50 %	MDO/HFO
Chemical tanker	20,000+ dwt	1.010	24 917	9 027	837	1059	100 %	251	80 %	450	50 %	HFO
Chemical tanker	10 -19,999 dwt	584	9 357	5 161	623	621	95 %	246	80 %	400	50 %	HFO
Chemical tanker	5 -9,999 dwt	642	4 651	3 252	416	615	92 %	246	76 %	400	50 %	MDO/HFO
Chemical tanker	-4,999 dwt	1.659	1 331	1 257	216	668	40 %	180	65 %	400	50 %	MDO/HFO
LPG tanker	50,000+ cbm	138	43 784	13 494	1 004	147	103 %	273	70 %	450	50 %	HFO
LPG tanker	-49,999 cbm	943	4 834	3 225	436	697	72 %	180	65 %	400	50 %	MDO/HFO
LNG tanker	200,000+ cbm	4	135 846	37 322	3 210	8	100 %	260	70 %	450	50 %	HFO
LNG tanker	-199,999 cbm	239	90 933	24 592	2 610	251	98 %	274	70 %	400	50 %	HFO
Other tanker	Other	402	2 030	1 522	210	163	41 %	180	65 %	400	50 %	MDO/HFO
Bulk	200,000+ dwt	119	114 519	17 224	794	101	97 %	281	71 %	450	60 %	HFO
Bulk	100 -199,999 dwt	686	83 619	15 108	697	695	99 %	279	70 %	450	60 %	HFO
Bulk	60 -99,999 dwt	1.513	39 568	9 912	549	1509	98 %	271	70 %	450	60 %	HFO
Bulk	35 -59,999 dwt	1.864	27 596	8 209	533	1859	96 %	262	70 %	425	60 %	HFO
Bulk	10 -34,999 dwt	2.090	15 351	6 436	458	1915	90 %	258	70 %	400	70 %	HFO
Bulk	-9,999 dwt	1.120	1 942	1 532	237	382	34 %	180	65 %	400	60 %	MDO/HFO
General cargo	10,000+ dwt	674	11 382	5 914	414	491	71 %	260	80 %	410	60 %	HFO
General cargo	5,000-9,999 dwt	1.528	4 704	2 939	235	1171	76 %	272	80 %	410	60 %	MDO/HFO
General cargo	-4,999 dwt	11.006	1 061	868	90	3553	32 %	180	65 %	380	50 %	MDO/HFO

Category	Size / Type	No ships (2007)	Ave. GT	Ave. ME kW	Ave. per engine Aux kW	AIS Unique Counts (4)	AIS Cover-age (5)*	Days at sea (1) Modelled	Avg. ME load Modelled	Avg. AUX running days (2)	Avg. AUX load Modelled	Fuel type(3)
General cargo	10,000+ dwt, 100+ TEU	1.225	15 641	7 882	628	1160	94 %	240	65 %	410	50 %	HFO
General cargo	5--9,999 dwt, 100+ TEU	1.089	5 294	3 720	401	969	88 %	180	65 %	380	50 %	MDO/HFO
General cargo	-4,999 dwt, 100+ TEU	1.486	2 724	1 860	249	1321	88 %	180	65 %	380	70 %	MDO/HFO
Other dry	Reefer	1.239	4 998	4 941	551	930	75 %	256	69 %	360	60 %	MDO/HFO
Other dry	Special	228	12 201	5 787	511	174	78 %	235	65 %	360	60 %	MDO/HFO
Container	8,000+ teu	118	100 082	68 477	3 081	145	94 %	241	67 %	600	60 %	HFO
Container	5 -7,999 teu	417	70 290	55 681	2 433	438	97 %	247	65 %	600	60 %	HFO
Container	3 -4,999 teu	711	45 317	34 934	1 782	732	99 %	250	65 %	500	60 %	HFO
Container	2 -2,999 teu	667	29 363	21 462	1 359	695	99 %	251	65 %	500	60 %	HFO
Container	1 -1,999 teu	1.115	16 438	12 364	985	1157	98 %	259	65 %	450	60 %	HFO
Container	-999 teu	1.110	6 967	5 703	600	1025	90 %	180	65 %	400	60 %	MDO/HFO
Vehicle	4,000+ ceu	398	51 549	13 137	1 034	419	97 %	284	76 %	300	70 %	HFO
Vehicle	-3,999 ceu	337	20 561	7 971	671	289	86 %	271	73 %	300	60 %	HFO
Roro	2,000+ lm	194	25 725	15 736	1 293	186	96 %	219	65 %	360	50 %	HFO
Roro	-1,999 lm	1.517	3 557	2 934	381	602	40 %	180	65 %	360	50 %	MDO/HFO
Ferry	Pax Only, 25kn+	984	302	3 113	60	244	25 %	262	65 %	360	60 %	MDO/HFO
Ferry	Pax Only, <25kn	2.108	392	1 213	79	215	10 %	258	80 %	360	60 %	MDO/HFO
Ferry	RoPax, 25kn+	177	12 119	27 395	785	125	71 %	232	65 %	360	70 %	MDO/HFO
Ferry	RoPax, <25kn	3.144	4 723	4 891	469	1054	34 %	254	74 %	360	70 %	MDO/HFO
Cruise	100,000+ gt	24	119 041	66 523	1 500	16	67 %	262	65 %	360	70 %	HFO
Cruise	60-99,999 gt	69	79 541	49 779	3 269	46	67 %	227	65 %	360	70 %	HFO
Cruise	10-59,999 gt	130	29 559	19 048	1 780	87	67 %	227	65 %	360	70 %	HFO
Cruise	2-9,999 gt	74	4 851	4 026	702	47	64 %	227	65 %	360	70 %	HFO
Cruise	-1,999 gt	202	664	945	143	129	64 %	180	65 %	360	70 %	MDO
Yacht	Yacht	1.051	560	2 285	141	467	44 %	100	50 %	360	70 %	MDO/HFO
Offshore	Crew/Supply Vessel	607	246	2 546	69	187	30 %	232	25 %	360	60 %	MDO/HFO
Offshore	Platform Supply	1.733	1 127	2 527	316	956	54 %	191	30 %	360	60 %	MDO/HFO
Offshore	Tug/Supply Ship	550	905	3 218	253	285	52 %	205	16 %	360	60 %	MDO/HFO
Offshore	Anchor Handling T/S	1.190	1 545	5 266	574	810	66 %	210	31 %	360	50 %	MDO/HFO
Offshore	Support/safety	487	1 486	2 504	291	265	54 %	194	34 %	360	70 %	MDO/HFO
Offshore	Pipe (various)	246	6 657	6 195	667	115	47 %	233	16 %	360	70 %	MDO/HFO

Category	Size / Type	No ships (2007)	Ave. GT	Ave. ME kW	Ave. per engine Aux kW	AIS Unique Counts (4)	AIS Cover-age (5)*	Days at sea (1) Modelled	Avg. ME load Modelled	Avg. AUX running days (2)	Avg. AUX load Modelled	Fuel type(3)
Service	Research	895	1 641	2 386	367	372	41 %	187	49 %	360	60 %	MDO/HFO
Service	Tug	12.330	281	1 903	96	2186	18 %	215	40 %	360	50 %	MDO/HFO
Service	Dredging	1.206	2 191	2 614	516	374	31 %	175	43 %	360	50 %	MDO/HFO
Service	SAR & Patrol	992	523	2 597	145	171	17 %	180	28 %	360	70 %	MDO/HFO
Service	Workboats	1.067	1 559	2 077	174	266	25 %	161	25 %	360	60 %	MDO/HFO
Service	Other	813	1 360	2 613	194	201	25 %	156	51 %	360	60 %	MDO/HFO
Misc	Fishing	12.849	313	687	164	484	4 %	285	26 %	360	70 %	MDO/HFO
Misc	Trawlers	9.709	601	956	319	776	8 %	261	58 %	360	70 %	MDO/HFO
Misc	Other fishing	1.291	1 296	1 388	236	322	25 %	249	77 %	360	70 %	MDO/HFO
Misc	Other	667	11 497	9 000	647	168	25 %	153	65 %	360	70 %	MDO/HFO

Note 1: Days at sea express total accumulated time at sea. Number of days when the ship has been at sea part of the time will be higher. This distinction is primarily of interest for small vessels on short routes, ferries etc.

Note 2: Average AUX running days is the sum of several engines, resulting in a more than 356 running days / year.

Note 3: Fuel type denotes typical fuel type for main and auxiliary engines. Multiple fuel types indicate either frequent difference between main and auxiliary engines or that a fraction of the ships in this category is expected to use either fuel type.

Note 4: Unique AIS counts indicates the number of different vessels detected.

Note 5: AIS coverage denotes the ratio of ships detected at least once during the year to the number of ships in the database used.

Table 15. Confidence and uncertainty of main engine fuel consumption calculation

Input	Source	Confidence	Comment
No. ships by category	Fairplay database	Very high, well known	High accuracy of registered ships. Uncertainty regarding whether all ships are actively trading or if some ships in some categories are laid up etc
Average main engine size	Fairplay database	Very high, well known	High accuracy expected
Average main engine operating days	Calculated from AIS data except for ship types with low AIS coverage	Moderate, but dominates uncertainty	Accuracy depend on accuracy of AIS collection system, how representative ships moving between ports with AIS network coverage are, assumptions made for ship movement , cut-off and filtration of data, Assumed average Off hire / Lay-up, Port-to-port distance calculations, Vessel design speed
Average main engine load	Default values calculated from AIS average speed and Fairplay design speed. Defaults replaced where other data or special conditions suggested this to be appropriate	Moderate, second influence on uncertainty	Calculations are sensitive to vessel design speed data from the extended Lloyds database and errors in estimating AIS at sea speed. Also, load will be overestimated when ship is in ballast or lightly loaded. Where other data suggest that the results are unreasonable, calculated values are substituted by expert judgement.
Average Offhire / Lay-up	Assumed	Moderate, influences main engine op. days	It is assumed for all ships that the effective calendar is 355 days (On average 10 days is spent out of active trade)
AIS observation to observation distance calculations	Calculations based on AIS coordinates	Moderate	Used for AIS average speed calculations. Accuracy will be affected when there is land mass between the shortest route between AIS receivers Where other data suggest that the results are unreasonable, calculated values are substituted by expert judgement.
Vessel design speed	Extended Fairplay database	Moderate	Used to determine cut-off between ‘normal’ and ‘slow’ (abnormal) voyages. Also used to estimate power factor at sea. Moderate accuracy
Average main engine SFOC	Estimated from a vide range of test bed and other measurement data	High, well known from	While there is some variation from engine to engine the average figure is expected to have comparatively high accuracy

Table 16. Confidence and uncertainties of auxiliary engine fuel consumption calculation

Input	Source	Confidence	Comment
No. ships by category	Fairplay database	Very high, well known	As above
Average aux engine size	Extended Fairplay database	High but with data gaps	Accuracy somewhat lower that main engine data, however relatively high accuracy is expected
Average aux engine operating days	Expert Judgement and consultations with operators	Moderate, dependent upon vessel operating days, and auxiliary demand	Assessment is challenging du to variability in ship power demands and operating practices. While confidence is moderate, the impact on total inventory is small
Average aux engine load	Expert Judgement and consultations with operators	Moderate, dependent on vessel operating conditions and demand	Assessment is challenging due to variability in ship power demands and operating practices
Average aux engine SFOC	Estimated from a wide range of test bed and other measurement data	High, well known from operators and manufacturers	While there is some variation from engine to engine the average figure is expected to have comparatively high accuracy

The confidence of the estimated steam boiler consumption must be categorized moderate, however it has little impact on the overall inventory.

2.2.4 International bunker consumption and CO_2 emissions estimate based on the activity-based model

The activity based model used in this project cannot differentiate between international and domestic emissions. In order to provide an estimate for emissions from international shipping by use of on the activity based model, fishing emissions must been removed from the inventory and domestic emissions as reported in bunker statistics must been subtracted from the shipping emissions.

Using the activity-based model and inputs as described in Table 14, the global emissions from all non-military shipping activities in 2007 are estimated as follows:

Table 17. Total fuel consumption and CO_2 (million tonnes) emissions from non-military shipping (2007)

2007	Low bound	Best	High bound
Total fuel consumption	279	333	400
Total CO_2	854	1019	1224

Low and high bounds represent feasible extremes that are considered significantly less likely than the consensus estimate. The above figure is total for all non-military shipping. Fixed offshore installations such as production vessels and rigs are also excluded. These figures include the fuel consumption and emissions that are already registered as domestic shipping and fishing.

The 2005 figures for domestic fuel consumption recorded by the IEA is shown in Table 18 along with an estimated total fuel consumption scaled forward to 2007 using Fearnleys data for global seaborne trade as explained in Section 2.4

Table 18. Domestic consumption figures from IEA [26] and CO_2 emissions (million tonnes)

	2005		2007 est.	
	Fuel	CO_2	Fuel	CO_2
HFO	13.3	40.2	14.6	44.0
MDO	19.7	61.0	21.6	66.7
Total	33.1	101.2	36.2	110.8

Fishing emissions can be subtracted from the inventory as shown in Table 19

Table 19. Estimated 2007 CO_2 emissions (million tonnes) for total fleet and fishing

	Low	Consensus	High
Total fleet inventory	854	1.019	1.224
Activity based fishing estimate	57	65	74
Total less activity based fishing emissions	796	954	1.150

An estimate of the 2007 fuel consumption and emissions for international shipping – i.e. all non-military, non fishing fuel consumption that is not accounted for as domestic or – is then calculated as shown in Table 20.

Table 20. 2007 CO_2 emissions (2007) from international shipping* (million tonnes)

	Low bound	Consensus	High bound
Inventory total less fishing	796	954	1.150
IEA domestic shipping	111	111	111
International shipping	**685**	**843**	**1039**

*Total not accounted for in statistics as domestic and fishing

2.3 Estimate of CO_2 emissions from ships based on bunker fuel statistics

2.3.1 Introduction

The 2000 Study of GHGs from ships estimated the emissions using a fuel-based inventory approach. This approach makes an implicit assumption that world-wide sales of bunker fuel represent total fuel consumption. The 2000 study of greenhouse gas emissions from ships reviewed different data sources for global bunker consumption by ships including IEA and United States Energy Information Administration (EIA). A number of inconsistiencies were identified at that time.

International Bunker fuel sales figures require summing a combination of marine fuels reported by countries under different categories (e.g. national or international bunker fuel). This can be challenging on a global scale because most energy inventories follow accounting methodologies intended to conform to the International Energy Agency's energy allocation criteria [13] while some statistical sources for marine fuels do not define international marine fuels in the same way [10]. In this section, we summarize the current statistical fuel data and in Section 2.5 we present a fuel-based inventory for comparison with our more explicit activity-based inventory in Section 2.2.

2.3.2 IEA statistics and reporting practices

The International Energy Agency (IEA) maintains an energy database containing global record of fuel use by ships. The IEA was established by the Organisation for Economic Co-operation and Development (OECD). IEA member governments are committed to taking joint measures to meet oil supply emergencies. They also have agreed to share energy information, to coordinate their energy policies and to cooperate in the development of rational energy programmes that ensure energy security, encourage economic growth and protect the environment. These provisions are embodied in the Agreement on an International Energy Programme, the treaty pursuant to which the Agency was established in 1974. The IEA database contains records of demand for (sales of) heavy fuel oil (HFO) and marine distillate fuel oil (MDO) for three categories

- International marine bunkers
- Domestic navigation
- Fishing

These terms have been defined by the IEA as follows:

International marine bunkers
Covers those quantities delivered to ships of all flags that are engaged in international navigation. The international navigation may take place at sea, on inland lakes and waterways, and in coastal waters. Consumption by ships engaged in domestic navigation is excluded. The domestic/ international split is determined on the basis of port of departure and port of arrival, and not by the flag or nationality of the ship. Consumption by fishing vessels and by military forces is excluded.

Domestic Navigation
Includes fuels delivered to vessels of all flags not engaged in international navigation. The domestic/international split should be determined on the basis of port of departure and port of arrival and not by the flag or nationality of the ship. Fuel used for ocean, coastal and inland fishing and military consumption is excluded;

Fishing
Includes fuel used for inland, coastal and deep-sea fishing. Fishing covers fuel delivered to ships of all flags that have refuelled in the country (including international fishing) as well as energy used in the fishing industry.

Heavy fuel oil (HFO)
Heavy fuel oil (HFO) defines oils that make up the distillation residue. It comprises all residual fuel oils, including those obtained by blending. Its kinematic viscosity is above 10 cSt at 80°C. The flash point is always above 50°C and the density is always higher than 0.90 kg/l.

Marine distillate oil (MDO)

Marine distillate oil (MDO) comprises gas oils and diesel oils sold to ships. Gas/diesel oil includes heavy gas oils. Several grades are available depending on uses: diesel oil for diesel compression ignition (cars, trucks, marine, etc.), light heating oil for industrial and commercial uses, and other gas oil.

In practical terms, the split between domestic and international fuel consumption means that whenever a ship bunkers fuel, if the next port is in the same country, the complete amount of fuel is likely to be registered as domestic. Otherwise, the fuel is likely to be recorded as international.

2.3.3 Analysis of IEA statistical data

The IEA maintains statistics for member and non-member countries; hence the IEA can provide global energy data. However, since non-member countries are not obliged by the IEA treaty to publish data according to the specific methodologies and standards, data collected by the IEA for the non-member countries could be less accurate.

In order to get an idea of the data quality of the IEA bunker statistics, the data entries International Marine Bunkers and Domestic Marine Bunkers were assessed for all countries in the IEA statistics. The changes from one year to the next could occasionally be very significant. The same number could occasionally also be reported year by year. While this could be valid and reflect actual use in some cases, a high frequency of these occurrences could indicate errors and inaccuracies in the reporting of fuel consumption. Typically, the number of these occurrences is higher for countries delivering less fuel. A summary is shown below.

Table 21 IEA International Marine Bunkers Reporting 1971-2005

	No. of countries reporting change in yearly volume > 25% at least once*	**No. of changes > 25%**	**No. of countries reporting identical non-zero figures in sequence**
10 largest supplier countries (61% of the reported total)	9 (90%)	63 (18%)	1 (10%)
Next 20 countries (29% of reported total)	17 (85%)	121 (17%)	8 (40%)
Next 44 countries (6% of reported total)	40 (100%)	485 (31%)	27 (59%)

*These typically do not occur in the same year

Table 22 IEA Domestic Marine Bunkers Reporting 1971-2005

	No. of countries reporting change in yearly volume > 25% at least once*	**No. of changes > 25%**	**No. of countries reporting identical non-zero figures in sequence**
10 largest supplier countries (53% of the reported total)	7 (70%)	46 (13%)	2 (20%)
Next 20 countries (25% of reported total)	10 (50%)	107 (15%)	6 (30%)
Next 44 countries (10% of reported total)	21 (48%)	146 (9%)	16 (36%)

*These typically do not occur in the same year

Variations from one year to the next could be caused by abrupt changes in demand, but may also be the result of changes to definitions and practice in national accounting. Also, to avoid double counting, fuel sales should only be reported once. Therefore, if fuel is sold for use on land but subsequently sold for use by ships, this fuel could avoid registration in the bunker sales statistics. Also, registration could fail if a fuel is exported and subsequently sold offshore.

In 2005, the IEA data show that 55% of world ship fuel sales occur in the OECD countries. The OECD share of world ship fuel sales has declined since 1991 when this share peaked at 65%. The OECD countries report 99% of fuels for fishing. This could indicate that fuel sales to fishing in non-OECD countries are either reported in one of the other ship fuel categories or not reported. It is also possible that fuel consumption for fishing is included in a non-shipping category such as “forest and agriculture”. The latter was previously the practice in the OECD countries.

2.3.4 Fuel consumption according to IEA statistical data

Annual fuel consumption data were obtained from the IEA database for all reporting years from 1971 to 2005, the most recent data available [26]. Data from the various categories fuel for all countries were combined to produce the following figure.

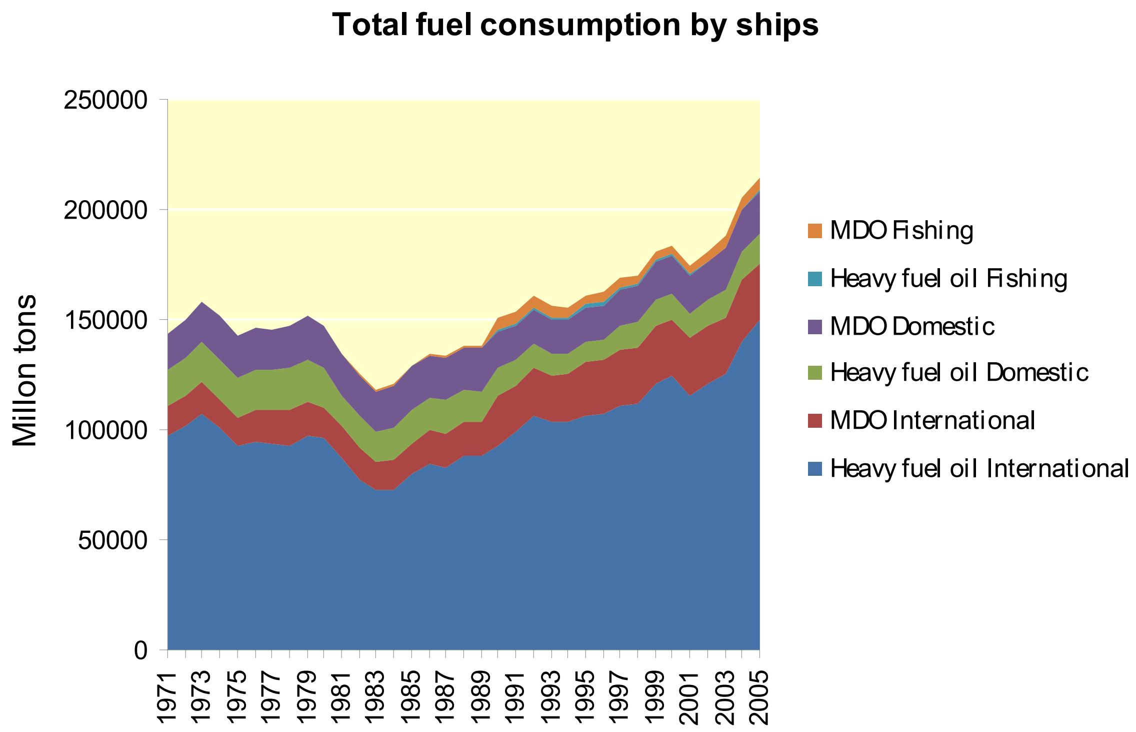


Figure 8. Total fuel consumption by ships (Figure based on IEA data)

The total HFO and MDO fuel consumption for 2005 and corresponding estimate for 2007 (based on tonne-miles transported) is shown below together with CO_2 emissions calculated using the same carbon fraction figures as for the activity-based inventory.

Table 23. IEA Ship fuel consumption data [26] and calculated corresponding CO_2 (million tonnes)

		2005		2007 est.	
		Fuel	CO_2	Fuel	CO_2
International	HFO	150	452	159	495
	MDO	26	79	27	87
Domestic	HFO	13	40	14	44
	MDO	20	61	21	67
Fishing	HFO	0	1	1	2
	MDO	5	16	6	18
Total		**214**	**651**	**234**	**713**

2.3.5 Fuel consumption according to EIA statistical data

EIA provides global statistics for bunkers. Bunkers include fuel supplied to ships and aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft. [27] The 2000 IMO Study of greenhouse gas emissions from ships concluded that IEA and EIA data were close for OECD countries and that the amount of international jet fuel in the EIA data at that time was limited. Later research has concluded that IEA and EIA data mainly overlap but differences in estimates for a limited number of countries are significant. [29] A comparison of recent IEA and EIA data is shown in Table 24. IEA data includes domestic and fishing. EIA data is bunkers as per Energy Information Annual [27]. Table 24 shows that EIA and IEA data is not very different in magnitude. In these five years EIA figures are consistently higher on distillate fuels and have the higher total in 4 out of 5 years.

Table 24. Comparison of IEA [26] and EIA [27] fuel data [Million tonnes]

	Residual		Distillate		Total	
	IEA	EIA	IEA	EIA	IEA	EIA
2000	136	120	48	52	184	172
2001	127	129	47	63	175	192
2002	133	126	48	56	181	182
2003	138	129	50	74	188	202
2004	154	144	51	82	205	226

2.4 Backcasting and forecasting fuel consumption estimates

In order to compare fuel consumption estimates from different years it is necessary to adjust the figures to account for developments in world trade and transport efficiency.

Over the last 30 years a clear and well understood correspondence is observed between fuel consumption and seaborne trade in tonne-miles, because the work done in global trade is proportional to the energy required (Skjølsvik et al., 2000[12]; Corbett et al.,2007[2]; Endresen et al., 2007 [5]). Recent annual growth rates in total seaborne trade in tonne-miles have been 5.2% on average from 2002 to 2007, a lot higher than in past decades (Fearnleys, 2007[7]). Accordingly, the fuel consumption from 2001 to 2006 has increased significantly as the total installed power increased by about 25% (Lloyd's Register Fairplay, 2006[9]).

Developments in transport efficiency are discussed in Section 4.4. As shown there, the efficiency of new build ships improves over time. This improvement shows typical steps resulting from developments in technology and market conditions. Between 1985 and 1995, the average efficiency of new build bulk ships and tankers increased while the average efficiency of new build general cargo ships and container ships decreased slightly. The fleet average efficiency has not been calculated, however the net change is expected to be fairly low in comparison with trade volumes measured as tonne-miles which doubled in the same time span.

Therefore, in order to be able to compare fuel consumption estimates from different years and also to calculate the emissions series from 1990 to the present from this study (2007), backcasts and forecasts of point estimates are calculated based on the annual growth in seaborne trade expressed by annual total freight in tonne-miles from Fearnleys [7].

2.5 Comparison of bunker consumption estimates

The 2000 IMO study on GHG emissions from ships used global bunker fuel sales statistics. Other studies such as that of Corbett et al., [1]; Eyring et al. [3] The IMO expert group [4], and Endresen et al. [5] have been based on ship activity estimates.

Fuel consumption and emission estimates in the above studies are given for different years. (2000, 2001, and 2007). In order to be able to compare them with the results from this study (2007), backcasts and forecasts for these point estimates are needed. As outlined in Section 2.4, backcasts and forecasts for these point estimates are calculated from the time evolution of freight tonne-miles from Fearnleys [7]. The result is presented in Figure 9 which also shows international bunker sales statistics [26] and the historical estimates from Eyring et al. (2005a) and Endresen et al. [5] from 1950 to 2007. Since some of these studies included emissions from military vessels, the emissions from such vessels have been removed. Also, estimated boiler consumption and auxiliary engine consumption are added where appropriate to allow just comparison as shown in Table 25.

The activity-based consensus estimate from the present study is shown as a blue dot in Figure 9. Light blue whisker lines extend from this point to indicate the range of uncertainty given by the high and low bound estimates. As can be seen in this figure, the consensus estimate from the present study is:

- lower than the estimate from the IMO expert group [4], but
- higher than the estimate based linear interpolating 2020 emissions from Eyring et al. (2005b) (Military vessels removed); however, the consensus estimate is
- lower than forecasts based on Eyring et al. (2005a) [3] using the freight trend method outlined in Section 2.4 above, ¨
- close to the result of Corbett et al. when military vessels are removed from the original figures, but
- higher than the forecast based on Endresen et al. (2007) [5]

In case of the Endresen et al. (2007) [5], backcast values of the consensus estimate would match around 1985 due to the difference in slope.

Table 25. Corrections applied to enable comparisons with previous inventories

	Base year	Total [Mt]	Military [Mt]	Auxiliary [Mt]	Boiler [Mt]	Adjusted total [Mt]	2007 est. [Mt]
Eyring et al., 2005 [3]	2001	280	- 9,4	Incl.	5,9 (1)	277	361
Corbett et al., 2003 [1];	2001	289	- 40,5	Incl.	5,9 (1)	254	339
Endresen et al., 2007 [5]	2000	195	Not incl.	14,9 (2)	5,9 (1)	210	282
IMO expert group [4]	2007	369	Not incl.	Incl.	Incl.	369	369
IEA total marine sales	2005	214	Not incl.	Incl.	Incl.	214	234
EIA bunker	2004	225	Not corr.	Incl.	Incl.	225	260

(1) Estimate based on present study. (2) Estimate based on Corbett et al., 2003 [1];

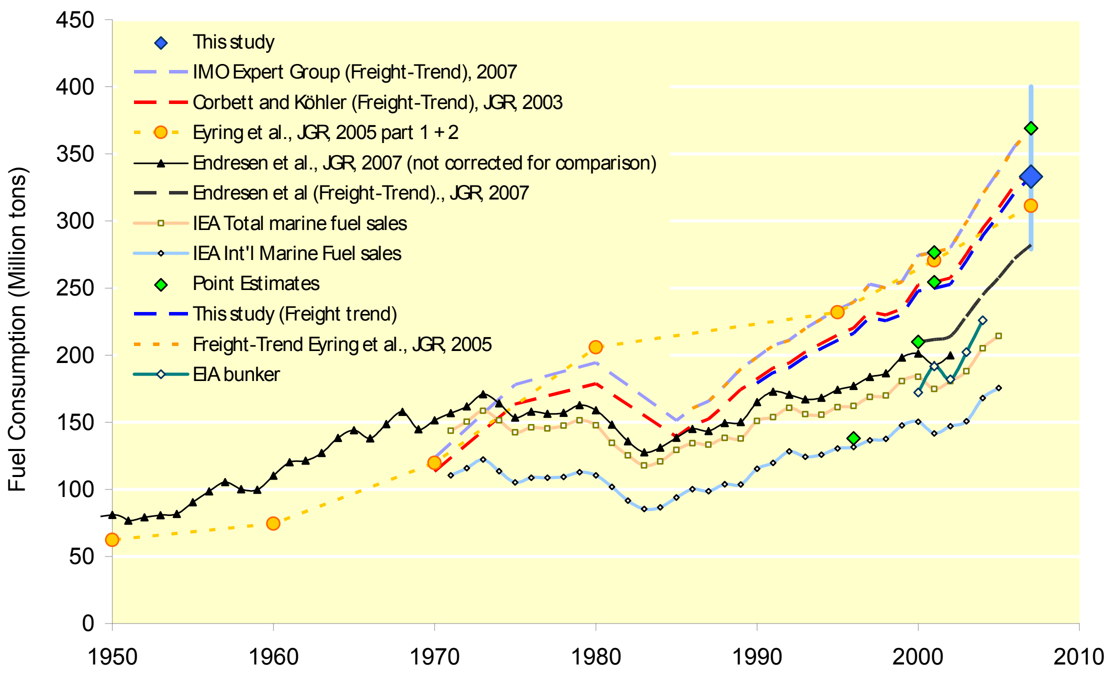


Figure 9. World fleet fuel consumption (except military vessels) from different activity based estimates and statistics. Symbols indicate the original estimates for individual years and the solid lines show the original trend estimates. Dashed lines show the backcast and forecast calculated from the time evolution of freight tonne-miles with the point estimates. The blue square shows the activity-based estimate from this study and the whiskers are the high and low bound estimates

2.5.1 Discussions

IEA and EIA data mainly overlap but differences in estimates for a limited number of countries are significant [29]. We reviewed the data entries International Marine Bunkers and Domestic Marine Bunkers for all countries in the IEA statistics. The compilation of bunker fuel statistics requires a combination of fuels reported under different categories (e.g. national or international bunker fuel). As mentioned in Section 2.3.1, this can be challenging on a global scale because most energy inventories follow accounting methodologies intended to conform to the International Energy Agency's energy allocation criteria [13] while some statistical sources for marine fuels do not define international marine fuels the same way [10]. Understanding what portion of ocean shipping energy is described by international marine sale statistics requires a historical review of energy cooperation and reporting among nations. This section reviews the relevant background based on the published history of the International Energy Agency (IEA) and current studies of past marine fuel demand.

The IEA was established in 1974 within the OECD framework, in part, to promote "co-operation with oil producing and other oil consuming countries with a view to developing a stable international energy trade as well as the rational management and use of world energy resources in the interest of all countries" [19]. The IEA Agreement on an International Energy Program (IEP) was designated to be the "focal point for the industrial countries' energy co-operation on such issues as: security of supply, long-term policy, information "transparency", energy and the environment, research and development and international energy relations" [19].

This required the development of energy statistics, particularly for oil supplies that were disrupted during the 1973 oil crisis. Motivated by energy security (including an oil sharing system), these statistics were to be the basis for emergency allocations among signing nations. According to the IEA agreement [19], fuels were to be included within a nation's "oil stocks" if, among other conditions, they were a) in barges; b) in intercoastal tankers; c) in oil tankers in port; or d) in inland ship bunkers. Fuels were to be excluded from domestic stocks if, among other conditions, they were a) in seagoing ships' bunkers; or b) in tankers at sea.

International marine fuels statistics were not intended to represent the total energy used by ships engaged in global commerce. Rather, these data were used to differentiate those fuels within a nation's domestic stock from those not eligible for emergency allocation calculations within the oil emergency sharing system. Specifically, the IEP agreement tasked the Standing Group on Emergency Questions to "consider common rules for the treatment of marine bunkers in an emergency, and of including marine bunkers in the consumption against which stocks are measured" [19]. Later, the IEA clarified that a nation's marine fuel stocks "may not be counted if they are held as international marine bunkers, since such bunkers are treated as exports under a 1976 Governing Board decision incorporated into the Emergency Management Manual (EMM)" [19].

Since then, IEA definitions have been reworded to be more consistent with reporting guidance under IPCC [22]. Currently, the IEA defines “international marine bunkers (fuel) [to] 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.” The IEA defines national navigation to be “internal and coastal navigation (including small craft and coastal vessels not purchasing their bunker requirements under international marine bunker contracts). Fuel used for ocean, coastal and inland fishing should be included in agriculture.”

Because of this terminology, the term “*international marine fuel*” introduces a classification problem for environmental assessments, because it does not conform to vessel activity data and also the quality of the data gathered for IEA reporting of ship fuel sales is inconsistent across nations and over time. For example, non-member countries are not obliged by the IEA treaty to publish data according to the specific methodologies and standards, data collected by IEA for the non-member countries could be less accurate. IEA data inconsistencies could be expected to under-report consumption. This is particularly the case with regard to the countries that are not part of the IEA and which do not have the same obligations to report fuel sales in the first place and need not use the same standards and definitions for reporting data.

It was observed that the changes from one year to the next occasionally could be very significant and also that the same number could be reported year by year. A high frequency of these occurrences could indicate errors and inaccuracies in the reporting of fuel consumption. The total energies represented as ship fuels in IEA statistics represent variable quality in reporting by nations, and the classification between international and domestic sales of marine fuels is not reliable.

Relying primarily on these classifications leads to a significant error in terms of estimating total energy used by the fleet when historical sales data are misinterpreted as complete energy consumption by ships engaged in international trade (i.e., the fleet of ships in international registries). For example, in work published in 1997 and 1999, Corbett and Fischbeck clearly assumed that international marine fuel sales represented consumption [23][15] The 2000 study of GHGs from ships also used these data in their fuel-based estimates of emissions. Later work produced activity-based methodologies and guidance that identified best practice for calculating updated global estimates [22][20][13][21].

In 2003 and 2004, Corbett and Koehler and Endresen et al. replaced these sales-based assumptions with activity-based estimates of ship energy requirements that exposed the bias of sales statistics and suggested the error could range between 25% for cargo ships and a factor of two for the world fleet [1]. Independent work largely confirms the validity of activity-based methodologies [4][5][6] (and supports the insight that world marine fleet energy demand is the sum of international fuel sales plus domestically assigned fuel sales [5][6]). Some debate continues about the estimates of global fuel usage within these bounds, but the methodological elements of activity-based inventories are widely accepted.

2.5.2 Consensus estimate of annual emissions data from 1990 to the present.

In light of the comparison of previous fuel consumption estimates and subsequent discussions the international team of scientists behind this study concluded that the activity-based estimate with use of detailed activity data is a more correct representation of the total emissions from ships than what is obtained from the available fuel statistics. Therefore, we agreed i) that the activity-based estimate should be used as the consensus estimate from this study; ii) that we could agree on a bounding range of fleet fuel consumption and emissions that considered the most likely input parameters for activity-based emissions calculations; and iii) that we could present a consensus number for use by IMO.

Since AIS data are not available for years other than 2007, separate inventories have not been set up for each year. Instead, the historic emission series has been constructed by back-casting as set out in Section 2.4. The consensus estimates from this study is given in Table 26 and Table 27 and Figure 10. Fuel consumption and CO_2 emissions split by ship categories with uncertainty bars are presented in Figure 11 and Figure 12. Fuel consumption and CO_2 emissions split by Coastwise / ocean-going type of operation and high level ship categories are given in Figure 13 and Figure 14 and Table 28 and Table 29

Table 26. Total shipping: consensus estimate 2007 fuel consumption and CO_2 emission (million tonnes)

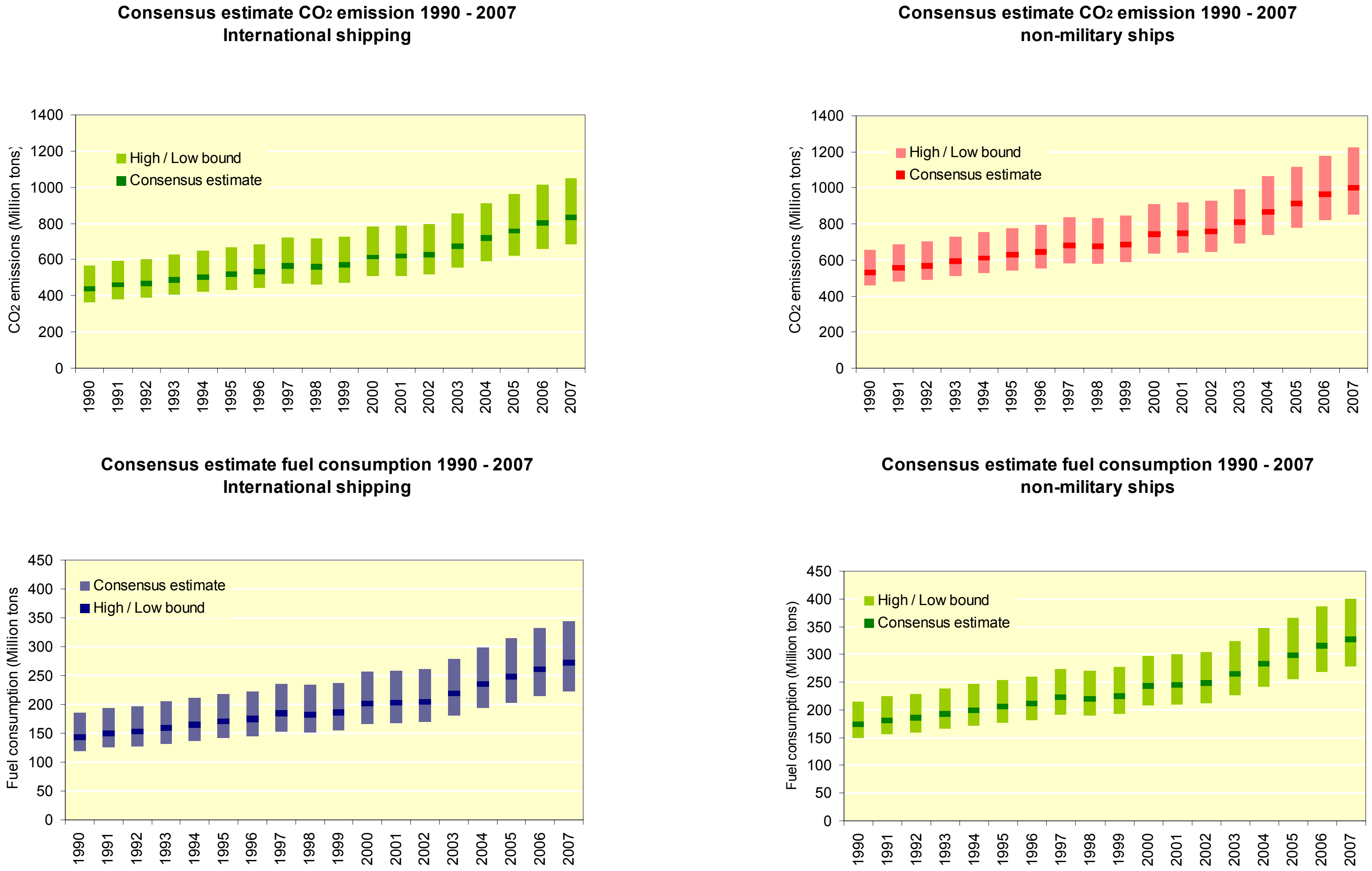
2007	Low bound	Best	High bound
Total fuel consumption	279	333	400
Total CO_2	854	1019	1224

Table 27. International shipping*: Consensus estimate 2007 fuel consumption and CO_2 emission (million tonnes)

	Low bound	Best	High bound
Total fuel consumption	223	277	344
Total CO_2	682	847	1052

*Total fuel consumption not accounted for in statistics as either domestic or fishing

Figure 10. Consensus estimates of fuel consumption and CO_2 emissions from 1990 to 2007



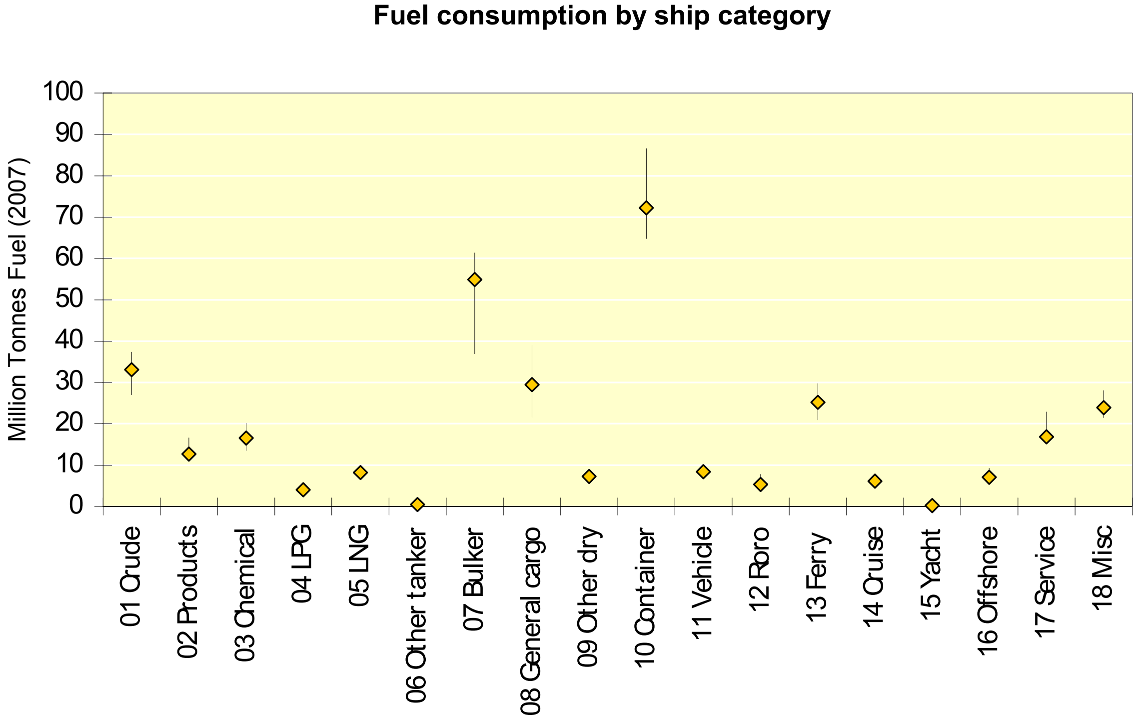


Figure 11. Estimated fuel consumption in 2007 by main ship categories with uncertainty bars

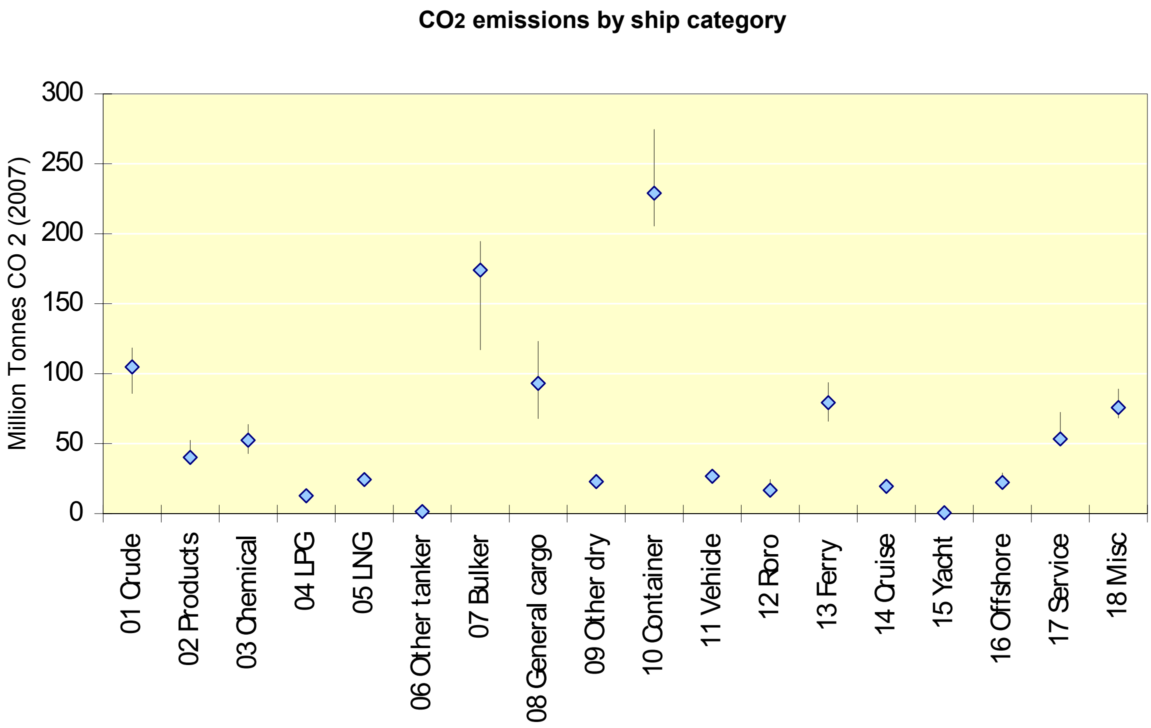


Figure 12. Estimated CO_2 emissions in 2007 by main ship categories with uncertainty bars

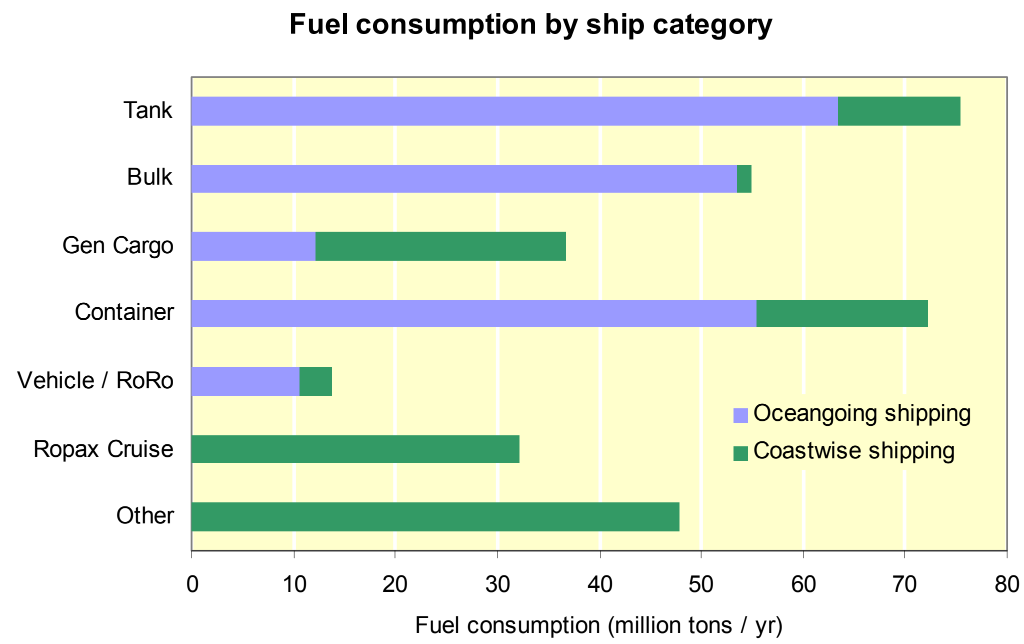


Figure 13. Fuel consumption divided by main ship categories and assumed typical type of operation (Coastwise shipping is mainly ships < 15000 dwt, RoPax, Cruise, Service and Fishing)

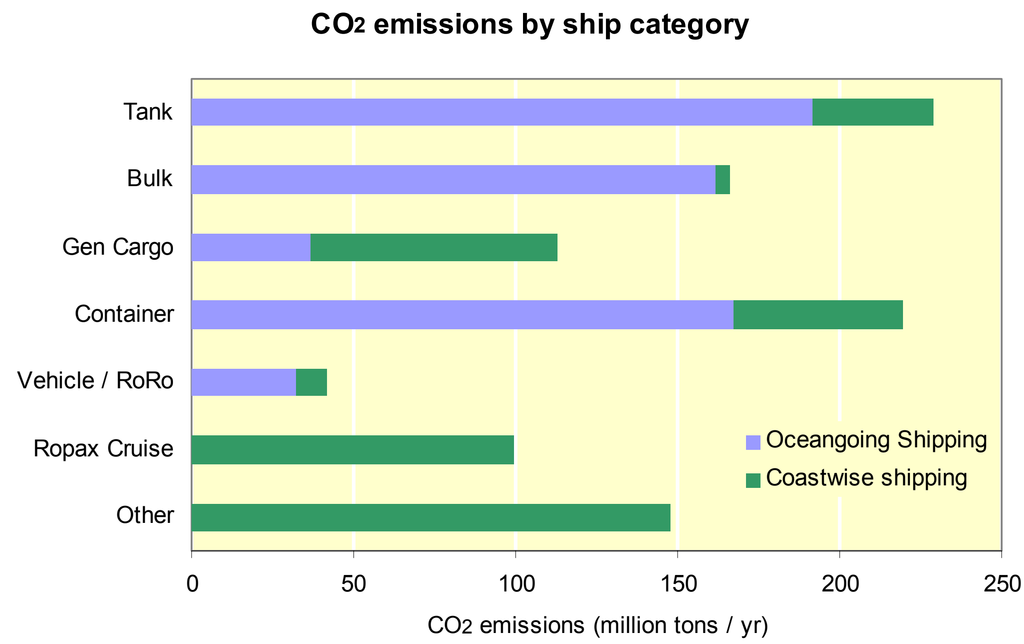


Figure 14. CO_2 emissions divided by main ship categories and assumed typical type of operation (Coastwise shipping is mainly ships < 15000 dwt, RoPax, Cruise, Service and Fishing)

Table 28 Activity-based 2007 fuel use estimate.

	Oceangoing	Coastwise	Other	Total
Bulk	54	1	0	55
Container	55	17	0	72
Gen Cargo	12	25	0	37
Other	0	0	48	48
Ropax Cruise	0	31	0	31
Tank	63	12	0	75
Vehicle / RoRo	11	3	0	14
Grand Total	195	89	48	332

Table 29 Activity-based 2007 CO_2 estimate.

	Oceangoing	Coastwise	Other	Total
Bulk	162	4	0	166
Container	171	52	0	223
Gen Cargo	37	76	0	113
Other	0	0	150	150
Ropax Cruise	0	96	0	96
Tank	192	37	0	229
Vehicle / RoRo	32	10	0	42
Grand Total	593	275	150	1019

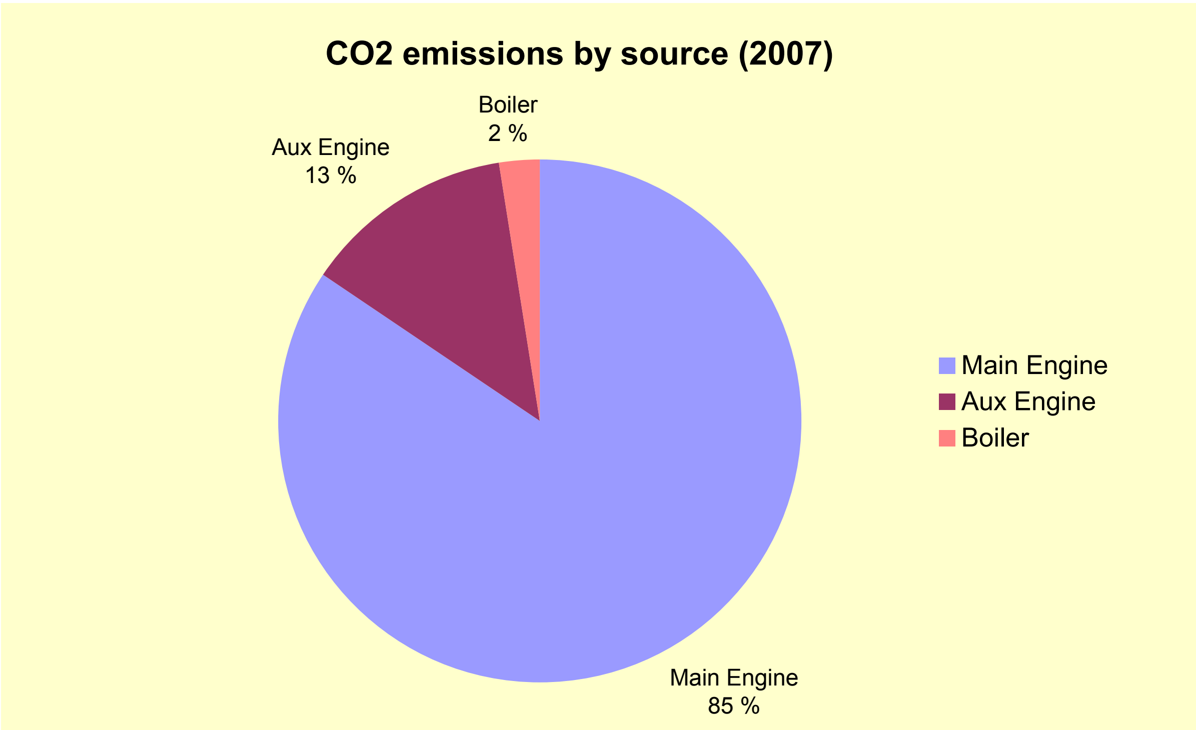


Figure 15. CO_2 emissions by source

Table 30. Summary of results from consensus estimate fuel oil consumption calculations [thousand tonnes]

Category	*Size / Type*	*	*Ship Average fuel oil consumption [thousand tonnes]*				*Category Total fuel oil consumption [thousand tonnes]*			
			Main Engine	*Aux Engine*	*Boiler*	*Total*	*Main Engine*	*Aux Engine*	*Boiler*	*Total*
Crude oil tanker	200,000+ dwt	O	21.8	1.2	1.3	24.3	10760.2	607.1	617.5	11984.8
Crude oil tanker	120 -199,999 dwt	O	16.5	1.5	0.9	*18.8*	5810.8	516.6	317.7	6645.1
Crude oil tanker	80 -119,999 dwt	O	12.2	1.0	3.0	*16.1*	7912.8	621.8	1953.0	10487.7
Crude oil tanker	60 -79,999 dwt	O	8.2	0.8	3.0	*12.0*	1480.2	145.3	540.0	2165.5
Crude oil tanker	10 -59,999 dwt	O	6.2	0.8	1.5	*8.5*	1506.4	196.8	366.8	2070.0
Crude oil tanker	-9,999 dwt	C	1.1	0.2	0.5	*1.8*	122.4	27.9	57.0	207.3
Products tanker	60,000+ dwt	O	7.7	1.0	3.6	*12.2*	1520.0	191.9	712.8	2424.8
Products tanker	20 -59,999 dwt	O	4.5	0.9	3.0	*8.4*	2050.2	416.6	1366.5	3833.3
Products tanker	10 -19,999 dwt	O	2.9	0.6	1.8	*5.3*	562.4	113.6	346.5	1022.5
Products tanker	5 -9,999 dwt	C	1.8	0.3	0.9	*3.0*	821.3	149.3	419.0	1389.5
Products tanker	-4,999 dwt	C	0.6	0.1	0.3	*1.0*	2288.2	536.3	1187.7	4012.2
Chemical tanker	20,000+ dwt	O	8.5	1.0	0.0	*9.5*	8574.1	1004.0	0.0	9578.1
Chemical tanker	10 -19,999 dwt	O	4.7	0.7	0.0	*5.4*	2771.6	401.7	0.0	3173.3
Chemical tanker	5 -9,999 dwt	C	3.0	0.5	0.0	*3.5*	1924.4	294.6	0.0	2219.0
Chemical tanker	-4,999 dwt	C	0.7	0.2	0.0	*1.0*	1199.7	395.1	0.0	1594.8
LPG tanker	50,000+ cbm	O	12.1	1.2	0.0	*13.3*	1666.3	164.7	0.0	1830.9
LPG tanker	-49,999 cbm	C	1.9	0.5	0.0	*2.3*	1749.7	453.6	0.0	2203.4
LNG tanker	200,000+ cbm	O	28.5	3.8	0.0	*32.4*	114.2	15.3	0.0	129.4
LNG tanker	-199,999 cbm	O	31.1	2.8	0.0	*33.8*	7411.6	657.3	0.0	8068.9
Other tanker	Other	C	0.9	0.2	0.0	*1.1*	351.8	93.1	0.0	445.0
Bulk	200,000+ dwt	O	15.2	1.2	0.0	*16.4*	1811.0	140.8	0.0	1951.8
Bulk	100 -199,999 dwt	O	13.1	1.0	0.0	*14.1*	8982.5	712.4	0.0	9694.9
Bulk	60 -99,999 dwt	O	8.8	0.8	0.0	*9.6*	13314.0	1237.4	0.0	14551.4
Bulk	35 -59,999 dwt	O	7.0	0.8	0.0	*7.8*	13122.5	1397.3	0.0	14519.8
Bulk	10 -34,999 dwt	O	5.4	0.7	0.0	*6.1*	11353.5	1479.7	0.0	12833.2
Bulk	-9,999 dwt	C	0.9	0.3	0.0	*1.2*	987.1	350.9	0.0	1338.0
General cargo	10,000+ dwt	O	5.8	0.6	0.0	*6.3*	3877.2	378.2	0.0	4255.5

Category	Size / Type	*	Ship Average fuel oil consumption [thousand tonnes]				Category Total fuel oil consumption [thousand tonnes]			
			Main Engine	Aux Engine	Boiler	Total	Main Engine	Aux Engine	Boiler	Total
General cargo	5,000-9,999 dwt	C	3.1	0.3	0.0	*3.5*	4801.9	487.0	0.0	5288.9
General cargo	-4,999 dwt	C	0.5	0.1	0.0	*0.6*	6036.4	1038.3	0.0	7074.7
General cargo	10,000+ dwt, 100+ TEU	O	5.8	0.7	0.0	*6.5*	7055.0	869.9	0.0	7925.0
General cargo	5--9,999 dwt, 100+ TEU	C	2.1	0.4	0.0	*2.6*	2332.0	458.1	0.0	2790.2
General cargo	-4,999 dwt, 100+ TEU	C	1.1	0.4	0.0	*1.4*	1590.5	542.5	0.0	2133.0
Other dry	Reefer	C	4.3	0.7	0.0	*5.0*	5348.9	813.0	0.0	6161.9
Other dry	Special	C	4.1	0.6	0.0	*4.8*	944.1	139.0	0.0	1083.0
Container	8,000+ teu	O	46.4	5.9	0.0	*52.3*	5457.1	688.1	0.0	6145.2
Container	5 -7,999 teu	O	37.5	4.6	0.0	*42.1*	15647.1	1928.8	0.0	17575.9
Container	3 -4,999 teu	O	25.2	2.8	0.0	*28.0*	17904.9	2006.5	0.0	19911.4
Container	2 -2,999 teu	O	15.6	2.2	0.0	*17.7*	10386.9	1436.3	0.0	11823.2
Container	1 -1,999 teu	C	9.7	1.4	0.0	*11.1*	10859.8	1565.3	0.0	12425.1
Container	-999 teu	C	3.1	0.8	0.0	*3.9*	3466.3	882.1	0.0	4348.3
Vehicle	4,000+ ceu	O	13.2	1.1	0.0	*14.4*	5263.2	456.1	0.0	5719.3
Vehicle	-3,999 ceu	O	7.3	0.7	0.0	*8.0*	2472.6	224.7	0.0	2697.3
Roro	2,000+ lm	O	10.0	1.2	0.0	*11.2*	1931.7	238.5	0.0	2170.1
Roro	-1,999 lm	C	1.7	0.4	0.0	*2.1*	2561.7	573.9	0.0	3135.6
Ferry	Pax Only, 25kn+	C	2.6	0.1	0.0	*2.7*	2566.5	70.0	0.0	2636.5
Ferry	Pax Only, <25kn	C	1.2	0.1	0.0	*1.3*	2592.7	199.8	0.0	2792.5
Ferry	RoPax, 25kn+	C	18.3	1.1	0.0	*19.4*	3241.4	193.3	0.0	3434.7
Ferry	RoPax, <25kn	C	4.5	0.7	0.0	*5.2*	14259.5	2053.2	0.0	16312.7
Cruise	100,000+ gt	C	47.5	2.0	0.0	*49.5*	1141.1	47.9	0.0	1189.0
Cruise	60-99,999 gt	C	32.6	4.3	0.0	*36.9*	2247.1	300.1	0.0	2547.2
Cruise	10-59,999 gt	C	12.5	2.4	0.0	*14.8*	1620.0	307.8	0.0	1927.9
Cruise	2-9,999 gt	C	3.2	1.0	0.0	*4.2*	237.0	72.3	0.0	309.3
Cruise	-1,999 gt	C	0.5	0.2	0.0	*0.7*	109.8	40.2	0.0	150.1
Yacht	Yacht	N	0.6	0.2	0.0	*0.8*	590.7	205.7	0.0	796.4
Offshore	Crew/Supply Vessel	N	0.7	0.1	0.0	*0.8*	445.3	57.9	0.0	503.2
Offshore	Platform Supply	N	0.7	0.4	0.0	*1.1*	1251.3	652.9	0.0	1904.2

Category	Size / Type	*	Ship Average fuel oil consumption [thousand tonnes]				Category Total fuel oil consumption [thousand tonnes]			
			Main Engine	Aux Engine	Boiler	Total	Main Engine	Aux Engine	Boiler	Total
Offshore	Tug/Supply Ship	N	0.5	0.3	0.0	*0.8*	290.0	165.9	0.0	455.9
Offshore	Anchor Handling T/S	N	1.6	0.7	0.0	*2.3*	1895.4	814.7	0.0	2710.1
Offshore	Support/safety	N	0.8	0.3	0.0	*1.1*	394.9	140.5	0.0	535.4
Offshore	Pipe (various)	N	1.2	0.9	0.0	*2.1*	287.8	228.1	0.0	515.8
Service	Research	N	1.1	0.4	0.0	*1.5*	954.9	391.3	0.0	1346.3
Service	Tug	N	0.8	0.1	0.0	*0.9*	9949.8	1170.2	0.0	11120.0
Service	Dredging	N	1.0	0.5	0.0	*1.5*	1172.1	617.5	0.0	1789.6
Service	SAR & Patrol	N	0.6	0.2	0.0	*0.8*	627.3	199.9	0.0	827.2
Service	Workboats	N	0.4	0.2	0.0	*0.6*	434.2	221.8	0.0	656.0
Service	Other	N	1.1	0.2	0.0	*1.3*	903.4	187.7	0.0	1091.1
Misc	Fishing	N	0.3	0.2	0.0	*0.5*	3599.5	2928.6	0.0	6528.1
Misc	Trawlers	N	0.8	0.4	0.0	*1.2*	7565.5	4303.7	0.0	11869.2
Misc	Other fishing	N	1.3	0.3	0.0	*1.6*	1685.8	422.8	0.0	2108.6
Misc	Other	N	4.2	0.9	0.0	*5.1*	2796.4	600.1	0.0	3396.5

* Ship size categories: O = Ocean-going shipping; C = Coastwise shipping ; N = Non-transport shipping (Modelled as coastwise). Note that all container ships of all sizes are modelled as ‘Container’ in the scenarios

Please note that the uncertainty of the estimate of individual ship categories is higher than the estimated total.

2.6 Geographic distribution of ship traffic and emissions

2.6.1 Introduction

Global inventory estimates for fuel use or emissions derived from activity-based bottom-up estimates or from fuel sale statistics are distributed according to a calculated ship traffic intensity proxy per grid cell referring to the relative ship reporting frequency or relative ship reporting frequency weighted by the ship size. The accuracy of the resulting totals is limited by uncertainty in global estimates as discussed above and the representative bias of spatial proxies limits the accuracy of emissions assignment (spatial precision).

2.6.2 Spatial proxies of global ship traffic

Corbett et al. (1999) produced one of the first global spatial representations of ship emissions using a shipping traffic intensity proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS), a data set of voluntarily reported ocean and atmospheric observations with ship locations which is freely available. Endresen et al. (2003) improved the global spatial representation of ship emissions by using ship size (gross tonnage) weighted reporting frequencies from the Automated Mutual-assistance Vessel Rescue system (AMVER) data set. AMVER, sponsored by the United States Coast Guard (USCG), holds detailed voyage information based on daily reports for different ship types. Participation in AMVER was, until very recently, limited to merchant ships over 1000 GT on a voyage for 24 or more hours and the data are strictly confidential. The participation in AMVER is 12 550 ships but only around 7100 ships have actually reported. Endresen et al. (2003) observed that COADS and AMVER lead to very different regional distributions. Wang et al. (2007) addressed the potential statistical and geographical sampling bias of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and AMVER data sets, the two most appropriate global ship traffic intensity proxies, and used ICOADS to demonstrate a method to improve global-proxy representativeness by trimming over-reporting vessels that mitigates the sampling bias, augments the sample data set, and accounts for ship heterogeneity.

In this first phase of the project, calculations are not affected by the geographic distribution of the emissions. However, as a reference, global ship traffic patterns is illustrated in Figure 16

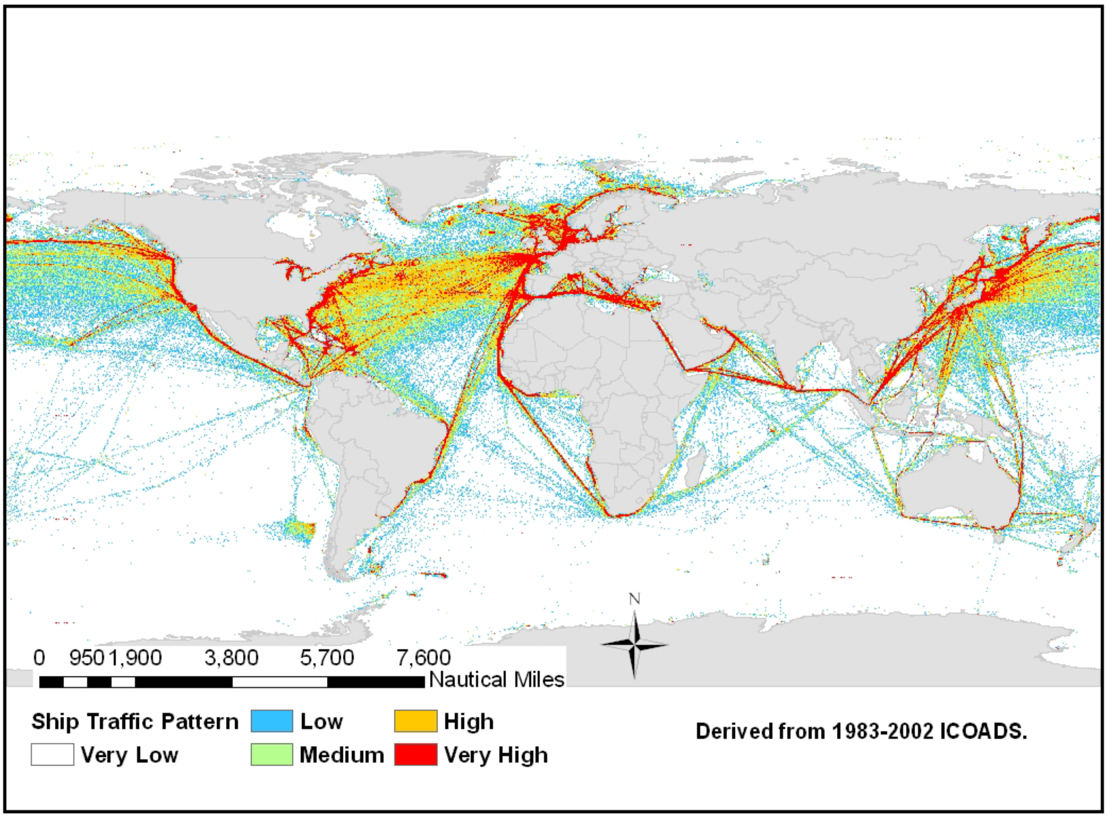


Figure 16. Ship traffic patterns based on ICOADS data

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3. Estimates of future CO_2 emissions from international shipping

3.1 Introduction

This chapter presents an analysis of a suite of future scenarios that affect CO_2 emissions from international shipping. The scenarios are primarily based on assumptions on global development in the Intergovernmental Panel on Climate Change (IPCC) SRES storylines (Nakicenovic et al., 2000 [6]). Principally, the scenarios developed within this project can be considered as a detailing of shipping and seaborne trade within possible futures outlined by IPCC SRES scenarios. In developing these scenarios, the research team interpreted the phrase 'different regulatory Scenarios' mentioned in 3.1 of the Terms of Reference as follows: For Phase 1, the scenarios assume that there are no *explicit* regulatory policy or mandates requiring the mitigation of CO_2 from shipping; as such the scenarios are used to help identify important economic, technological, and operational variables affecting future emissions. Naturally, differences in technology (ship efficiency and fuel type) can be seen as the effects of *implicit* policies.

The chapter identifies four key driving variables that will affect ship emissions up to the year 2050. These variables fall into the following categories: (1) economy; (2) transport efficiency; and (3) energy. The values for the key parameters in each of these four categories were generated using an "open Delphi process" based on expert opinion and analysis. Developed at Rand Corporation in the 1960s, this process allows for diverse expert groups to rely upon their best sources of information for each parameter without explicitly compromising or agreeing on their differences. [22] We then applied these values to a global fleet emissions inventory model that was calibrated to the inventory model discussed in the previous chapters. Altogether we modelled and analysed 324 scenarios (set of 162 for 2020 and a set of 162 for 2050). The results of this analysis provide a range of possible future GHG emissions from shipping up to the year 2050.

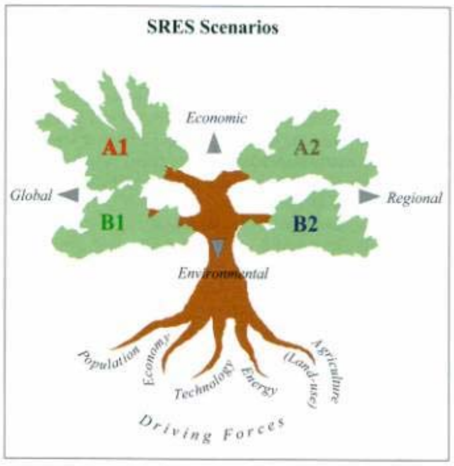
3.2 IPCC SRES Scenarios

Scenario planning is a common tool for researchers evaluating uncertain futures. Some of the definitions of scenario planning, include: [1]

- "[A]n internally consistent view of what the future might turn out to be—not a forecast, but one possible future outcome."[2]
- "[A] tool for ordering one's perceptions about alternative future environments in which one's decisions might be played out." [3]
- "[A] disciplined methodology for imagining possible futures in which organizational decisions may be played out." [4]

Scenarios help us envision a future in order to develop robust decisions and test how these decisions play out in possible future worlds [5]. In this chapter, scenarios are used to provide a range of possible GHG emissions futures in order to help decision makers strategically think about the options for reducing such emissions.

In 1992, the IPCC began to develop a set of emissions scenarios that would provide both a contextual setting and emissions data for their climate models. These scenarios build on a baseline emissions estimate and then explore different rates of technological change, economic growth, and demographic trends [6]. For the most part, these scenarios were updated in 2000 for the Third Assessment Report, and more recently in 2007 for the Fourth Assessment Report and the IPCC Special Report on Emissions Scenarios (SRES) [7]. The IPCC uses the following terminology for its scenarios [8]:



IPCC Storylines (IPCC)

> "Storyline: a narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces.
>
> Scenario: projections of a potential future, based on a clear logic and a quantified storyline.
>
> Scenario family: one or more scenarios that have the same demographic, politico-societal, economic and technological storyline." [8]:

Figure 1 shows the different storylines developed in the SRES. These are labelled A1, A2, B1 and B2. The driving forces are shown in this figure to include: *Population, Economy, Technology, Energy, Land-Use, and Agriculture*. These driving forces are evaluated against two major tendencies: (1) globalization v. regionalization; and (2) environmental values v. economic values. Below is a summary of each storyline, taken from IPCC documentation (noting that each storyline includes a variety of individual scenarios). [6, 7]

- Storyline A1: a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.

- Storyline A2: a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.

- Storyline B1: a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.

- Storyline B2: a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

The IPCC used these storylines to project values for the different driving factors, resulting in a set of 40 scenarios, developed by six modelling teams. The IPCC did not apply probabilities to these scenarios. Six groups of scenarios were taken from the four storylines: one group each in the A2, B1 and B2 families, and three groups in the A1 family. The three A1 scenarios were used to characterize future energy use as follows: A1FI (fossil intensive), A1T (technologically advanced and predominantly non-fossil) and A1B (balanced across energy sources).

The identification of key driving variables for the IPCC work relied on relationships best exhibited in the IPAT model of environmental impact and its related CO_2 emissions model, shown below:

$$\textit{Impact} = \textit{Population} \times \textit{Affluence} \times \textit{Technology}$$

$$CO_2\ \textit{Emissions} = \textit{Population} \times (\textit{GDP}/\textit{Population}) \times (\textit{Energy}/\textit{GDP}) \times (CO_2/\textit{Energy})$$

Although simple, the IPAT model demonstrates the important relationships of four of the key driving factors mentioned above: population, economics, technology, and energy. The final data tables for each of the 40 IPCC scenarios can be found at: http://sres.ciesin.org/final_data.html.

3.3 Methodology

This project takes a similar approach as the IPCC in developing scenarios for analysis. Using Schwartz's methodology for scenario construction [9], we identified key driving variables that would affect GHG emissions from ships into the future. These variables can be placed into three primary categories, as shown in Table 31. This table also shows some of the related elements that might affect the future value of each variable.

Table 31. Driving variables used for scenario analysis

Category	Variable	Related Elements
Economy	Shipping transport demand (tonne*miles/year)	Population, global and regional economic growth, modal shifts, sectoral demand shifts.
Transport efficiency	Transport efficiency (MJ/tonne*mile) – depends on fleet composition, ship technology and operation;	Ship design, propulsion advancements, vessel speed, regulation aimed at achieving other objectives but that have a GHG emissions consequence
Energy	Shipping fuel carbon fraction (gC/MJ fuel energy)	Cost and availability of fuels (e.g., use of residual fuel, distillates, biofuels, or other fuels)

These driving factors affect various categories of ships in different ways. Therefore, the international shipping fleet was separated into three primary categories to allow differentiation of the overall effects of the above factors. These categories are:

- Coastwise shipping - Ships used in regional (short sea) shipping; mostly small ships and RoPax vessels
- Ocean-going shipping - Larger ships suitable for intercontinental trade; and,
- Container ships (all sizes).

This categorization allows modelling of different growth rates, efficiencies and fuel use for the various scenarios. The split between large and small ships is generally set at about 15 000 dwt, hence the vast majority of the non-containerized fleet is considered to be Ocean-going shipping. Although small container feeder vessels could be considered to be short-sea vessels, the demand for container feeders is linked with the demand for container transport in general. Thus it was decided to include all pure container ships in a single category. The exact categorization is indicated in Table 30 presented in the previous chapter.

Based on this categorization, we estimated values for each variable with respect to each of the IPCC scenario families (i.e., A1FI, A1B, A1T, A2, B1, and B2). These values were generated using an “open Delphi approach,” which relies on shared expert opinion interspersed with “rounds” of reflection and discussion. In this case, the project team, made up of shipping experts from around the globe, met in Munich, Germany for a three-day workshop (5-7 March 2008) to discuss each variable, the elements that affect the value for each variable, and the role the variable would play in the overall scenario logics. During this workshop, the initial parametric values for each variable were generated through a process of discussion and debate. Following this workshop, further refinement of variable estimates and the scenario model design were made after the workshop through electronic means and via an electronic web-based project team meeting on 25 April 2008 and other conference calls throughout May 2008. Scenario parameterization was finalized in a team workshop held in London on 3-4 June 2008.

3.4 Input Values for Scenario Modelling

3.4.1 Economic growth and growth in seaborne transport

Transport demand governs the size and activity level of the world fleet and is the most important driver for emissions from ships. Future transport demand will depend on developments in trade, locations of factories, consumption of raw materials changing trade patters, possible new sea routes etc. Emissions from ships are also sensitive to the freight market in the sense that when demand for transport for a cargo type is low compared to the number for ships in this market, speed reductions will be encouraged and transport efficiency may increase. Conversely, when there is a relative shortage of ships, they will be operated at higher speeds resulting in lower efficiency and more emissions. This type of market instability is not modelled. Instead, the scenario model projects future transport demand based on expectations for economic growth also the future fleet is assumed to grow at an idealized rate in order to meet future transport demands.

Historically, there is a strong link between economic growth and an increase in shipping. This relationship has been used in previous studies to estimate future transport demand [11]. Given the complexity of the problem and the strong historical link between GDP and shipping, the use of the historic relationships is not an unreasonable approach. However, this approach cannot account for other trends that may be important. The Ocean Policy Research Foundation (OPRF) has recently reported the result on a fundamental study of future seaborne trade based on the IPCC A1B scenario [21]. A brief review and results of these two approaches is now given.

3.4.1.1 Transport demand estimates from historic GDP correlation

A historic correlation between global GDP and sea transport demand is given in [11]. Based on this correlation, estimates for future tonne-mile demand were made for each of the scenarios. Since our scenario model distinguishes between Ocean-going shipping, Coastwise shipping and Container shipping, the tonne-mile projections must be divided between the modes. This split has been made considering the regional emphasis of the various SRES scenarios and the strong growth in container traffic. During the past 20 years, container transport has grown nearly 10% annually [10]. This trend cannot be assumed to continue to 2050 since container transport would then in itself exceed the projected tonne-mile levels for world seaborne trade. Instead it is assumed that the average growth of containerized transport is 2% points higher than other cargo types. This results in 55% of the global tonne-miles being containers as opposed to 24% in 2007. Projections for 2020 were exponentially interpolated from the 2050 scenario. The resulting input values for the scenarios are given in Table 32 below. This table shows future tonne-miles on an index relative to 2007 for each scenario family. For instance, a figure of 320 for Ocean-going shipping in the 2050

A1B scenario family means that the total tonne-miles of work done by Ocean-going shipping in 2050 is 3.2 times larger than in 2007.

Table 32. Tonne-mile index for 2050 from correlation GDP (2007=100)

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	320	320	320	240	220	180
Coastwise shipping	320	320	320	270	220	220
Container	1230	1230	1230	960	850	690
Average all ships	540	540	540	421	372	302

3.4.1.2 Transport demand scenarios building on the OPRF A1B scenario

The OPRF in Japan is currently undertaking a major study where transport demand in tonne-miles is projected towards 2050 based on the IPCC A1B scenario. In this interesting and detailed scenario, the OPRF applies the correlation between GDP and tonne-miles to transport of containers only. For other cargo, such as dry bulk, crude oil, LNG and petroleum production, the OPRF uses different parameters, such as total population and primary energy use. These parameters are also estimated by the IPCC; however their rate of increase is lower than that of GDP. Therefore the resulting transport demand projection is lower than if GDP was used on all rates. Secondly, the OPRF also foresees changes in the average distance for transport due to changes in the transport patterns and modal shifts. Among the significant future developments anticipated by the OPRF are: New gas pipelines from Myanmar to China (2030s), from the Middle East to India (2030s), and from Russia to China (2010s). It is also anticipated that the pipeline from North Africa to Europe is expanded (2030s), and that the modernization of Siberian railroad is completed (2030s). This railroad will carry a share of the container traffic from East Asia to Europe. It is also anticipated that the Arctic sea route between East Asia and Europe will be commercially attractive (2040s). Moreover, increased recycling of scrap iron from 2020 to 2050 will be the equivalent of an approximately 5% reduction in iron ore production. All together, the eOPRF estimates a transport demand for A1B in 2050 that is about half of what is estimated by GDP trend analysis.

Transport demand is estimated for a broad range of ship types in the OPRF scenario. These ship types are aggregated into the relevant categories needed and the A1B tonne-mile projection was given for our A1B family. For our other scenario families, judgements were made regarding the relative developments in the scenarios with regards to regionalization, GDP growth and other scenario aspects compared with A1B to produce the scenarios below. It is stressed that while A1B is the product of a detail analysis, the others are not. Projections for 2020 were exponentially interpolated from the 2050 scenario. The resulting scenarios are given in Table 33 below.

Table 33. Tonne-miles building on OPRF detail A1B 2050 scenario (2007=100)

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	170	170	170	140	150	130
Coastwise shipping	170	170	170	160	150	150
Container	570	570	570	330	380	360
Average all ships	266	266	266	188	205	187

3.4.1.3 Tonne-mile projections used in this study

Acknowledging the uncertainties with each of the two above-mentioned approaches, it was agreed that the average of these two approaches should be used. This average would encapsulate both the historic relationship and aspects of an analysis of future trends including changes in trade patterns, the possible opening of Arctic sea routes etc. At the same time it was agreed to construct upper and lower bounds for the scenario that were wide enough to cover estimates from both approaches with a reasonable margin. The relationship between these figures is schematically shown in Figure 17. The resulting tonne-mile projections summarized in Table 34, Table 35, Table 36 were selected for use in this study.

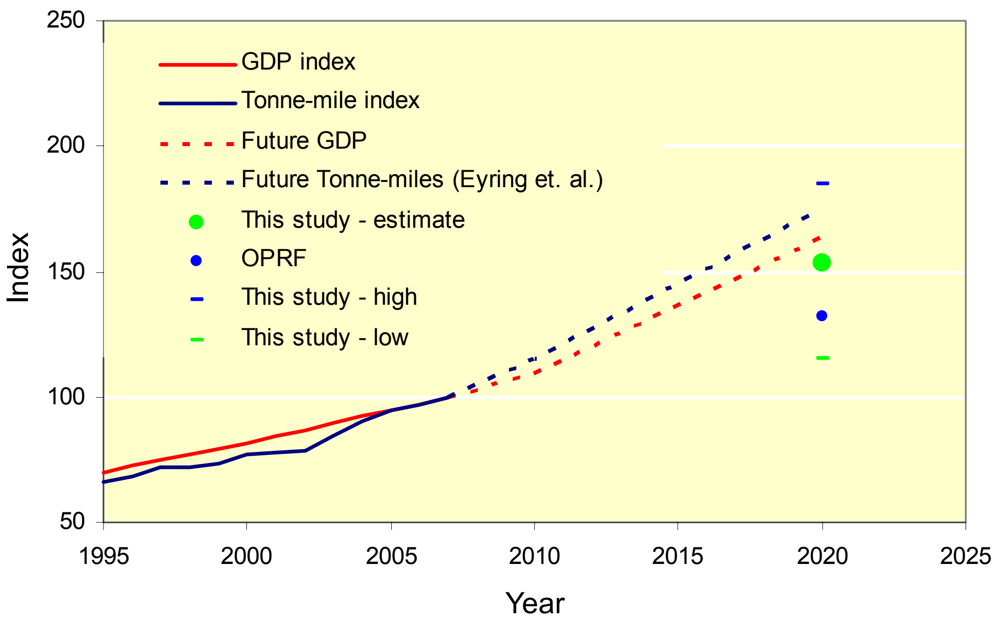


Figure 17. Principles for the estimation of transport demand. For each of the scenarios, transport demand was estimated from SRES GDP expectation and: 1) historic GDP correlation (blue dotted line), and 2) based on the OPRF forecast. The estimate used in this study is the average value illustrated by the green dot. High and low values were respectively higher and lower than the results from the two approaches

Table 34. Tonne-miles projections used in this study (2007=100)

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	245	245	245	190	185	155
Coastwise shipping	245	250	245	215	185	185
Container	900	875	905	645	615	525
Average all ships	402	397	403	302	288	247
2020	**A1B**	**A1F**	**A1T**	**A2**	**B1**	**B2**
Ocean-going shipping	131	131	131	121	120	114
Coastwise shipping	131	132	131	126	120	120
Container	194	193	195	176	173	165
Average all ships	146	146	146	135	133	127

Table 35. Upper bound for tonne-miles projections used in this study (2007=100)

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	383	383	383	262	252	193
Coastwise shipping	383	395	383	315	252	252
Container	2700	2588	2723	1638	1525	1203
Average all ships	939	913	945	597	558	441
2020	**A1B**	**A1F**	**A1T**	**A2**	**B1**	**B2**
Ocean-going shipping	150	150	150	134	132	122
Coastwise shipping	150	152	150	142	132	132
Container	271	267	272	233	228	212
Average all ships	179	178	179	159	155	145

Table 36. Lower bound for tonne-miles projections used in this study (2007=100)

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	157	157	157	138	136	124
Coastwise shipping	157	158	157	147	136	136
Container	300	296	301	254	248	229
Average all ships	191	190	192	167	163	150
2020	**A1B**	**A1F**	**A1T**	**A2**	**B1**	**B2**
Ocean-going shipping	115	115	115	110	110	107
Coastwise shipping	115	115	115	112	110	110
Container	139	139	140	133	132	128
Average all ships	121	121	121	116	115	112

Table 37. Scenario inputs summarized as annual growth rates

		A1B	A1F	A1T	A2	B1	B2
GDP (1)		3.9 %	4.0%	3.6 %	2.4 %	3.3 %	2.7 %
Total Transport Demand	Base	3.3 %	3.3 %	3.3 %	2.6 %	2.5 %	2.1 %
	High	5.3 %	5.3 %	5.4 %	4.2 %	4.1 %	3.5 %
	Low	1.5 %	1.5 %	1.5 %	1.2 %	1.1 %	0.9 %

(1) Annual average growth in world GDP for the period 2000 to 2050 [8]

3.4.2 Transport efficiency

Shipping has a long history of increasing efficiency. One of the principal drivers for this has been economies of scale, i.e. the use of larger ships. Wherever possible, this has been exploited. Naturally, there is always a need for ships of various sizes, and over time certain 'standard' sizes of ships have prevailed. For a given ship size, speed is the most critical defining parameter with respect to fuel consumption. A certain speed is typically associated with 'standard' ship operating patterns. Typically, the ship owner will order a ship with a certain speed reserve to give the vessel limited additional speed flexibility which may be very valuable on certain occasions such as canal and harbour slots or when freight rates are high. This also gives the world fleet a degree of flexibility to handle fluctuations in demand for transport services. Over time, technological developments have resulted in increased efficiency. Examples include the move from steam turbines to diesel engines and the subsequent improvements of these, better hull and propeller design and optimization with improved knowledge, manufacturing and analytical tools and many other aspects. It should also be mentioned that the efficiency of ships today is a reflection of what has been perceived to be the economic optimum at the time of design.

In consideration of the above, when modelling future scenarios, we have decided to split the efficiency into three main elements:

- Efficiency of scale, larger ships being more efficient (provided there is enough cargo to take advantage of the capacity offered)
- Speed
- Ship design and operation

3.4.2.1 Efficiency of scale

When larger ships are added to replace smaller ships this typically results in increased transport efficiency and vice versa. Scale effects are implemented in our scenario model by way of changes to the composition of the future fleet. In this study, the composition of the fleet in 2020 was estimated by Lloyds Register Fairplay Research (LRFPR). This fleet projection is broadly similar to the 2020 fleet estimate given by the IMO expert group [12]. The 2020 fleet will have a certain nominal transport capacity. However, since the transport demand in terms of tonne-miles is different in the various scenarios (see above), the 2020 fleet estimate must be scaled to fit the scenario in question. In order to do this, total gross tonnage was then used as an indicator for the transport work potential of each of the categories. The total gross tonnages for the 2007 fleet and the 2020 fleet estimate are shown in Table 38.

Table 38. Total Gross Tonnage for fleet categories and growth index

	2007	2020	Nom GT index
Ocean-going shipping	536 731 017	954 049 435	178
Coastwise shipping	80 986 919	95 022 648	117
Container	126 217 091	348 078 393	276

Scaling factors for scenario specific fleet compositions were calculated by dividing the nominal GT index by the tonne-mile projection index given for each scenario. The following example illustrates the method: For 2020, according to A1B, the transport demand index for ocean-going shipping has increased to 131 while the projected fleet (expressed by the Nom GT index) is 178 (Table 39). A scaling factor is then calculated to harmonize these. This factor is subsequently applied to the number of ships of each category for the scenario in question.

Table 39. Calculation of scaling factor

2020	A1B* (1)	Nom GT index (2)	Scale factor (2)/(1)
Ocean-going shipping	131	178	0,74
Coastwise shipping	131	117	1,12
Container	194	276	0,70

*Projected tonne-mile index

The fleet for scenario A1B in 2020 is then estimated by multiplying the number of ships within each ship category in the *nominal* 2020 fleet by the appropriate scale factor. The overall approach to our future fleet calculation for 2020 is shown in Figure 18 below.

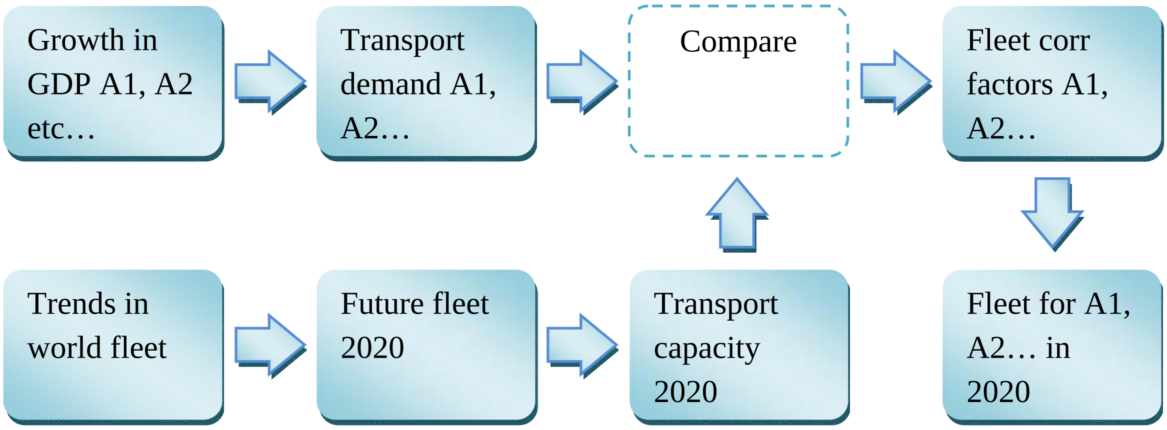


Figure 18. Process for determining the future fleet composition for 2020

Predicting a 2050 fleet composition is significantly more challenging than predicting the 2020 fleet composition. For this reason, no structural change is modelled between 2020 and 2050. Instead, for 2050, we took the 2020 fleet structure for each individual scenario and applied growth factors corresponding to the change in projected tonne-miles. Potential efficiency improvements with changes to fleet structure in this period were considered in the subsequent assessment of efficiency. For instance, calculation of the growth factor for the A1B between 2020 and 2050 is shown below:

Table 40. Calculation of scaling factor

2020	A1B 2020	A1B 2050	Growth factor
Ocean-going Shipping	131	245	1,87
Coastwise shipping	131	245	1,87
Container	194	900	4,64

*Projected tonne-mile index

Selected future fleets used in this study are shown in the Appendix to this report. It should be noted that in many cases, the number of ships expected in 2020 according to our scenarios is lower than what is projected by Lloyds Register Fairplay Research. This is mainly a result of lower expectations for transport demand in our scenarios than what is predicted by Lloyds Register Fairplay Research, whose prediction is not tied to SRES economic developments.

3.4.2.2 Speed

At lower speeds, hull frictional resistance dominates and the propulsion power requirement is roughly proportional to the third power of speed. At higher speeds, wave generation resistance becomes prominent and this additional resistance makes the power demand increase at more than the third power of speed. Therefore, reducing speed is an effective measure to reduce power consumption; particularly so for faster ships. On the other hand, when there is a shortage of transport capacity and rates are high, increasing speed is a way of meeting transport demand.

The vessel speed in operation will be determined by economic considerations including freight rates, bunker prices, and other fixed and variable costs. For instance, in a situation where bunker prices are increasing and transport capacity grows faster than demand, market-driven speed reductions may be expected. Also, in the long-term perspective, if fuel costs are expected to increase relative to other costs, the fleet may be expected to adapt by expanding and reducing speed and vice versa.

The scenario model incorporates possible market-driven speed changes based on assumptions for 2020 and 2050 regarding the fleet average speed relative to the current fleet average speed. This set of speed reduction values was used across all scenario families.

Table 41. Scenario Inputs: Fleet average market-driven speed changes

2050	**All scenarios**		
	Base	High	Low
Inter Continental	-10 %	- 20 %	0
Coastwise shipping	- 10 %	- 20 %	0
Container	- 20 %	- 40 %	0
2020	**All scenarios**		
	Base	High	Low
Inter Continental	-5 %	- 10 %	0
Coastwise shipping	- 5 %	- 10 %	0
Container	- 10 %	- 20 %	0

The net efficiency gain from the speed reduction is modelled by assuming a third power relationship between speed and power. Since changes to vessel speed affect the transport capacity of the ship, the model adjusts the fleet size in order to maintain a constant fleet productivity. As a simplification, the speed reduction is also applied to auxiliary power although this results in a slight overestimation of the benefit. The net effect of speed reductions and other measures is shown in Table 43.

3.4.2.3 Ship design, technology and operation

Improvements can be made to new and existing ships to increase their energy efficiency. A more detailed review of this topic will be made for Phase 2 of this study; however a preliminary assessment has been made to facilitate the scenario modelling. This assessment indicates the expected technology development within the various scenarios.

Technology improvements that have been considered in the discussion include;

- Recovery of rotational energy (contra-rotating propellers, efficiency rudders, asymmetric hulls, boss cap fins etc.)
- General hull improvement and changing design priorities *except use of larger ships*
- Engine technology improvements
- Increased use of waste heat recovery
- Operational improvements beyond speed reductions already discussed
- Alternative power sources such as sails, solar cells, etc.

Since there is no explicit regulation on fuel consumption, the change in technology factor reflects improvements that are cost effective in the various scenarios rather than full technological potential.

Additional to these technologies, regulatory developments to improve other aspects of shipping may have impacts on ship energy efficiency. Such regulatory developments include topics like anti-fouling, air emission reductions, ballast water requirements, whale strike speed regulations, double hull requirements, new construction standards, and ice strengthening requirements. These factors were discussed and their impacts were considered when determining scenario values for technological improvements. The transport efficiency improvement parameters are shown in Table 42 below. These values are applied to the fleet average. Since only a limited portion of the fleet will be changed by 2020, the technology-driven part of the efficiency improvement is assumed to be modest.

Table 42. Scenario Inputs: Market-driven technology changes and regulatory side effects affecting transport efficiency (fleet average values)

2050	**All scenario families**		
	Base	High	Low
Ocean-going shipping	-20%	-35%	-5%
Coastwise shipping	-25%	-45%	-5%
Container	-17.5%	-30%	-5%
2020	**All scenario families**		
	Base	High	Low
Ocean-going shipping	-2%	-4%	0%
Coastwise shipping	-2%	-4%	0%
Container	-2%	-4%	0%

3.4.2.4 Aggregate improvements in transport efficiency

Aggregate improvement assumption in transport efficiency is shown in Table 43. These values are derived from the above discussion, acknowledging than different pathways could lead to similar reductions. The aggregate values for 2050 also account for structural changes to the fleet that could occur in the period beyond 2020. Historic average efficiencies of new build vessels are calculated in Section 4.4. In order to put the scenario inputs into perspective, aggregate baseline efficiency improvements are plotted on a time line with indicated historic efficiencies from Section 4.4. in Figure 19.

Table 43. Scenario Inputs: Aggregate efficiency improvements (fleet average values)

2050	All scenario families		
	Base	High	Low
Ocean-going shipping	-35%	-58%	-5%
Coastwise shipping	-39%	-65%	-5%
Container	-47%	-75%	-5%
2020	**All scenario families**		
	Base	High	Low
Ocean-going shipping	-12%	- 22%	0
Coastwise shipping	-12%	- 22%	0
Container	-21%	- 39%	0

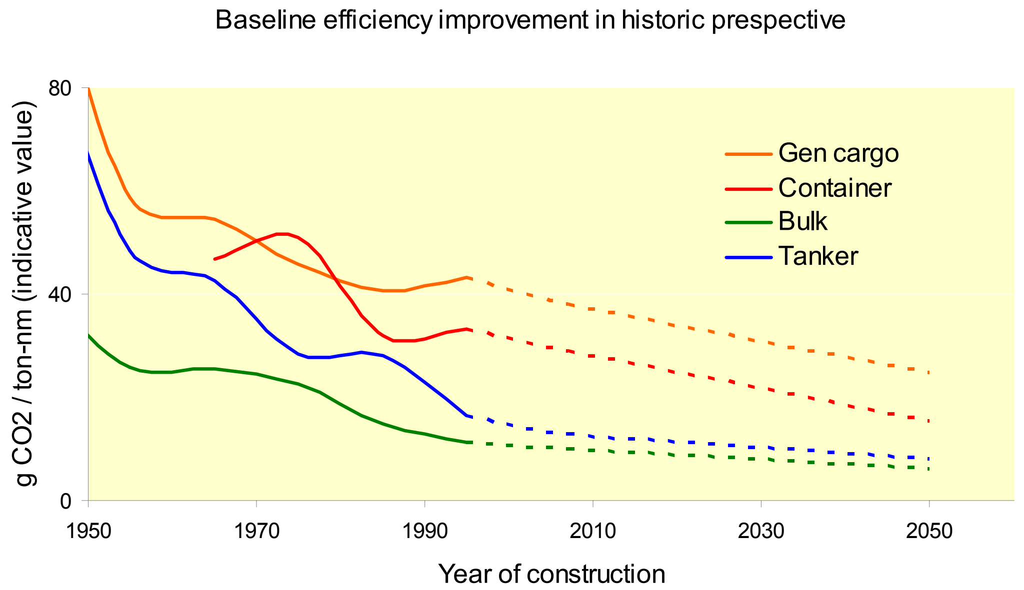


Figure 19. Baseline efficiency improvements and indicated historic improvements

3.4.3 Developments in marine fuels

The amount of CO_2 emitted from ships depends on the fuel type. For instance, certain fuels may contain more carbon per energy output than other fuels, and hence may produce more CO_2 emissions per work unit done. To capture this effect, future scenarios must contain assumptions of future fuel use. The choice of future fuels will depend on a number of factors such as availability, price, practical suitability for use onboard ships, and regulations. With respect to fuel, regulations considered are those given in the upcoming revised MARPOL Annex VI.

The SRES scenarios contain predictions of world energy use by primary energy source. Primary energy is the source of all energy on earth and, therefore, the ultimate source of all useful work. At an aggregate level, these are

- Coal
- Oil
- Gas
- Nuclear (Labelled non-fossil electric for B1)
- Biomass
- Other renewable

Naturally, global energy trends will be reflected in shipping to a certain extent; however a move away from traditional oil-fuels would require a significant pull. In these scenarios, the pull would be economic since there is no regulatory development in these scenarios to demand fuel switching. A brief discussion on the suitability of the above fuels for use onboard ships follows.

3.4.3.1 Coal

Technically, coal propulsion could be realized with a boiler / steam turbine arrangement. This is not considered attractive due to aspects such as the need to remove sulphur oxide (SO_x) emissions, low thermal efficiency, boiler heating requirements in port and the need for disposal of the combusted coal residuals and ash. It is also possible to manufacture liquid fuels from coal which would be very suitable for use onboard ships. Such synthetic fuels would be virtually sulphur free [13]. There is currently a strong interest in coal to liquid technology and such plants are being planned in the USA and China [14]. These synthetic hydrocarbon fuels would have a carbon fraction different from coal but similar to diesel fuels, however CO_2 emissions related to their production is higher than that of petroleum fuels.

3.4.3.2 Oil

Oil is currently the only significant energy source for international shipping. A significant driving force would be needed to change this; hence oil-derived fuels are considered the default choice in all scenarios. Taking the upcoming revised MARPOL Annex into account, oil-derived marine fuels can be classified as ‘Global distillates’ and ‘ECA distillates’ The principal difference between these fuels is the difference in sulphur limits. The carbon content of these fuels would not be very different when measured on an energy basis.

3.4.3.3 Gas

Natural gas, when stored in a liquid state, as liquefied natural gas (LNG) is predicted by many as a coming fuel for ships. Key drivers for this expected development is low nitrogen oxides (NO_x), SO_x and particulate matter (PM) emissions from LNG fuelled ships and the attractive price of LNG compared to distillate fuels. The most important technical challenge is finding the necessary space for storage of the fuel onboard the ship and the availability of LNG in the bunkering ports. Therefore, LNG is primarily interesting in a Coastwise shipping context where the ship range is less of an issue and the next port of bunkering is more predictable. LNG could also become an interesting fuel for tankers since there is considerable space available for LNG fuel tanks on deck. LNG ships would be particularly attractive in NO_x emission control areas since they can meet Tier III emission levels without after-treatment. Natural gas can also be processed to Fischer-Tropsch diesel for use in diesel engines. However in this case, the NOx benefit associated with LNG operation would be lost.

LNG contains more hydrogen and less carbon than diesel fuels, hence CO_2 emissions are reduced. Unfortunately, increased emissions of methane (CH_4) reduce the net effect to about 15% reduction of CO_2 equivalents [15]. The bulk LNG cost is about the same as that of residual fuel oil, and significantly cheaper than distillate fuels.

3.4.3.4 Nuclear

Installing nuclear reactors onboard is not foreseen to be an interesting option for international shipping due to environmental, political, security and commercial reasons. The use of electric power derived from nuclear plants or other non-fossil electricity sources for propulsion (as opposed to use while at berth) is not considered feasible due to the low power density, cost, weight and the size of batteries.

3.4.3.5 Biomass

These fuels include current, ‘first-generation’ biofuels made from sugar, starch, vegetable oil, or animal fats using conventional technology. Among these, biodiesel (i.e. Fatty Acid Methyl Esters, FAME) and vegetable oils can readily be used for ship diesels. In rough terms, biodiesel could substitute distillate fuels and vegetable oils could substitute residual fuels. With some biofuels, there may be certain issues such as storage stability, acidity, lack of water-shedding, filter plugging, wax formation and more which suggest that care must be exercised in selecting the fuel and adapting the engine [16][17][18][19]. Blending bio-derived fuel fractions into diesel or heavy fuel oil is also feasible from a technical perspective; however compatibility must be checked as is also the case with bunker fuels. Future biomass-to-liquid fuels processes can be designed to synthesize various fuels that are suitable for use onboard ships. Currently, biofuels are significantly more expensive than oil-derived fuels [16]. This would have to change if there is to be an incentive to use such fuels onboard ships in these non-regulated scenarios.

3.4.3.6 Other renewable

Other renewable energy sources for ships include the renewable energy that can be generated onboard (principally wind, solar and ship motion generated energy) and renewable energy generated onshore and transferred to the ship by way of an energy carrier such as hydrogen. Within the structure of the scenario model, the generation of renewable power onboard the ship would be modelled as energy savings and not affect the fuel carbon content while the use of renewable energy from land would be considered a fuel and the fuel carbon content would be affected accordingly. The use of renewable energy from land would have to be more cost effective than alternative fuels (such as oil-derived) if they are to be used in these non-regulated scenarios.

3.4.3.7 Penetration of new fuels into the maritime transport industry

For this analysis, we considered the market penetration potential for each scenario family based on seven potential fuels: (1) marine distillates; (2) heavy fuel oil; (3) LNG; (4) LPG; (5) biodiesel; (6) synthetic diesel such as FTD; and (7) other renewable fuels. When considering market penetration for the various scenarios it is noted that:

- Oil is a significant primary energy source in 2020 and 2050 in all scenarios (16-28% of world primary energy in 2050)
- In 2050, fossil fuels contribute from 57-82% of all primary energy in the SRES scenarios
- Previous estimates based on SRES scenarios [11] range fuel consumption for shipping in 2050 from 400-810 million tonnes. This corresponds to 22-32 EJ or 10-15% of the global primary oil energy as specified for 2050 in the SRES scenarios.

Further, it is assumed that the sulphur regulations proposed in the revised MARPOL Annex VI are adopted and that a global 0.5% sulphur cap is applied in 2020, with the opening for alternative equivalent compliance routes.

It is thus considered that the SRES scenarios permit the continued use of oil-based fuels, although the cost would be expected to be higher. Therefore, in these non-GHG regulation scenarios, the move from oil-derived fuels would have to be motivated by economy. Since there are already binding emission targets for GHG reductions on land it is assumed that biofuels would fetch a better price there and would not be used by ships. The same situation would apply for the use of renewable energy from land.

It may be assumed that coal-to-liquid fuels could become economically attractive in scenarios A1FI and A2 where coal is a major energy source. Some of this fuel could be directed to the market. Natural gas is an important energy source in all SRES scenarios. LNG propulsion would appear attractive for Coastwise shipping in all scenarios. LNG could be particularly interesting on tank ships where fuel tank storage above deck is expected to be feasible with limited negative impacts. Based on the above, we established the general assumptions for market penetration shown in Table 39 and Table 40.

Table 44. Future fuel scenarios for 2020

2020	A1B	A1FI	A1T	A2	B1	B2
LNG	5% Coastwise	5% Coastwise	10% Coastwise + 5% tank ships**	5% Coastwise	10% Coastwise + 5% tank ships**	10% Coastwise + 5% tank ships**
Synthetic diesel*	None	None	None	None	None	None
Distillates	Balance	Balance	Balance	Balance	Balance	Balance

*Based on coal or other competitive feedstock

** Ocean-going crude oil tankers, all size categories

Table 45. Future fuel scenarios for 2050

2050	A1B	A1FI	A1T	A2	B1	B2
LNG	25% Coastwise +10% tank ships**	25% Coastwise + 10% tank ships**	50% Coastwise + 20% tank ships**	25% Coastwise + 10% tank ships**	50% Coastwise + 20% tank ships**	50% Coastwise + 20% tank ships**
Synthetic diesel	None	20% all ships	None	20% all ships	None	None
Distillates	Balance	Balance	Balance	Balance	Balance	Balance

*Based on coal or other competitive feedstock

** Ocean-going crude oil tankers, all size categories

Carbon fractions (gC/MJ) for each fuel type were calculated based on assumptions regarding future fuel characteristics, such as impurities, hydrocarbon molecular formula, energy content, and physical density as shown in Table 46. These carbon fractions by fuel were applied to the market penetration values to determine a weighted average carbon fraction for each vessel category. Average carbon fractions for each scenario family are shown in the input summary of the Appendix.

Table 46. Fuel specific carbon fractions used in scenario model

Fuel	Carbon fraction (gC/MJ)	Emission factor ($kgCO_2$/kg fuel)
LNG	15,4	2,75
Synthetic diesel	19,7	3,13
Distillates	20,2	3,17*

*A higher emission factor is estimated than current inventory due to assumption of less average impurities in future fuels

3.5 Results

The scenario analysis involved creating specific scenarios in each of the six scenario families described above. In total, we looked at all possible combinations of demand growth (base, low, high), transport efficiency (base, low, high), and speed reduction impacts (base, low, high). We used the vessel-based carbon fraction identified for each scenario family as described above.

This approach gave us a total of 3 x 3 x 3 = 27 scenarios for each scenario family, or a total of 6 x 27 = 162 scenarios for each year (2020 and 2050). Emission trajectories for base scenario values as well as the maximum and minimum values observed within these 162 scenarios are shown in Figure 20. The range of results observed in our scenarios for 2020 and 2050 is shown in Figure 21 and Figure 22 respectively. The results are also presented in Table 47, Table 48 and Table 49.

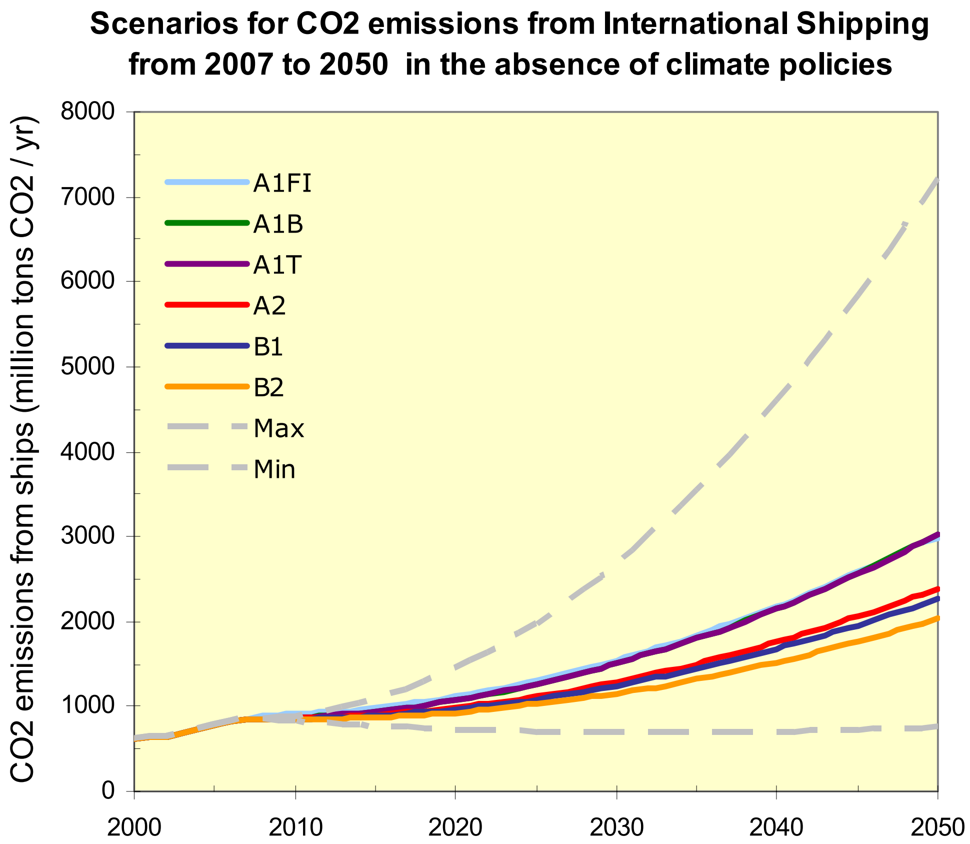


Figure 20. Emission trajectories for different scenarios

Aside from the Min and Max scenarios, the scenarios in Figure 20 are characterized by their similarities. This is a result of the broadly similar technology pathway suggested for ships in these scenarios in spite of different storylines and composition of primary energy sources. The difference between the scenarios is driven principally by differences in demand and the type of fossil fuel used. In these scenarios, increased use of non-emitting energy which may have impact on a global scale such as nuclear and biomass does not penetrate significantly into the shipping sector.

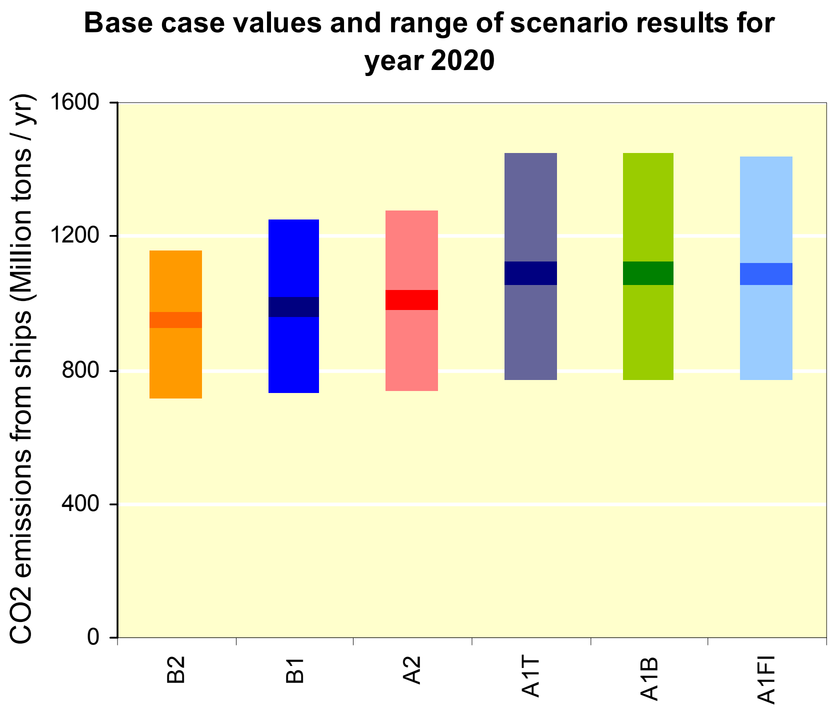


Figure 21. Range of scenario results for 2020

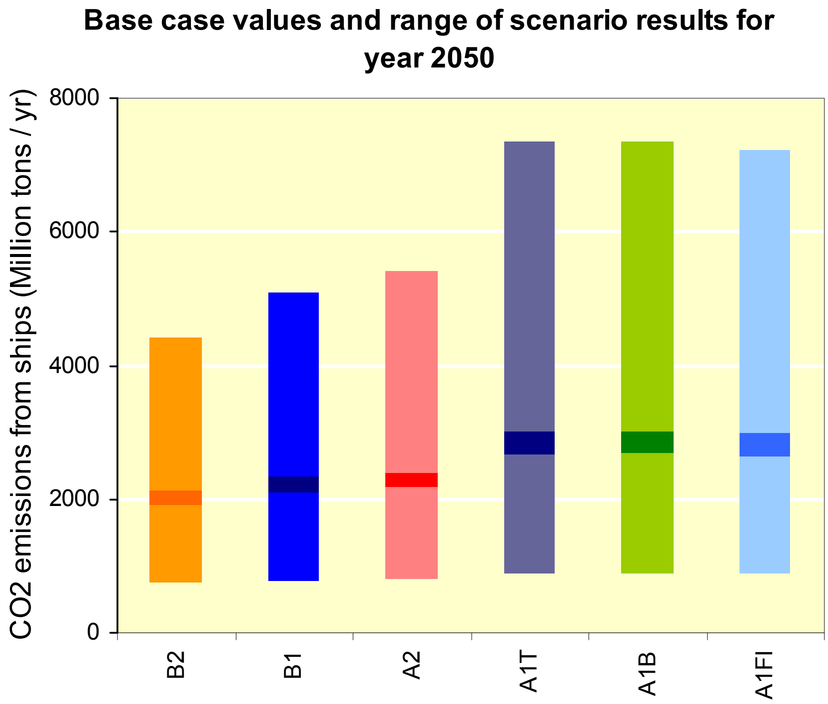


Figure 22. Range of scenario results for 2050

Table 47. CO_2 emissions from international shipping in 2020 [million tonne/ yr]

	Base	High	Low	Mid	St.Dev.	SD up	SD down
A1FI	1058	1440	770	1073	195	1268	877
A1B	1057	1447	770	1075	199	1273	876
A1T	1058	1447	771	1076	199	1274	877
A2	982	1275	740	987	150	1138	836
B1	959	1252	734	970	145	1115	825
B2	925	1160	719	926	121	1046	805

Table 48. CO_2 emissions from international shipping in 2050 [million tonne/ yr]

	Base	High	Low	Mid	St.Dev.	SD up	SD down
A1FI	2648	7228	880	2989	1668	4657	1321
A1B	2681	7344	885	3029	1701	4730	1327
A1T	2668	7341	879	3021	1704	4725	1316
A2	2194	5426	804	2392	1178	3570	1214
B1	2104	5081	781	2273	1091	3364	1182
B2	1903	4407	746	2036	915	2951	1120

Table 49. Projected annual growth in CO_2 emissions from shipping 2007-2050

	Base	High	Low
A1FI	2.7 %	5.1 %	0.1 %
A1B	2.7 %	5.2 %	0.1 %
A1T	2.7 %	5.2 %	0.1 %
A2	2.2 %	4.4 %	-0.1 %
B1	2.1 %	4.3 %	-0.2 %
B2	1.9 %	3.9 %	-0.3 %

*The same growth rate is assumed to apply to domestic and international shipping

These results are also plotted in Figure 23, which shows the trajectory of emissions of CO_2 from the current inventory up to 2050. The solid centre line in each figure represents the average of our scenario model runs for each year. The dashed lines represent a band that captures the standard deviation of the scenario results. Finally, the highest and lowest dotted lines represent the minimum and maximum scenario values. Figure 24 shows emission projections based on 1: baseline assumptions, 2: baseline assumptions for demand and maximum assumptions for efficiency improvement, 3: minimum emissions resulting from minimum demand and maximum efficiency. The emission scenarios are put in a historic perspective in Figure 25, Figure 26 and Figure 27. The implications of these results are discussed in the following section.

Figure 23. CO_2 trajectories for each scenario family, showing average and plus/minus one standard deviation, and minimum and maximum

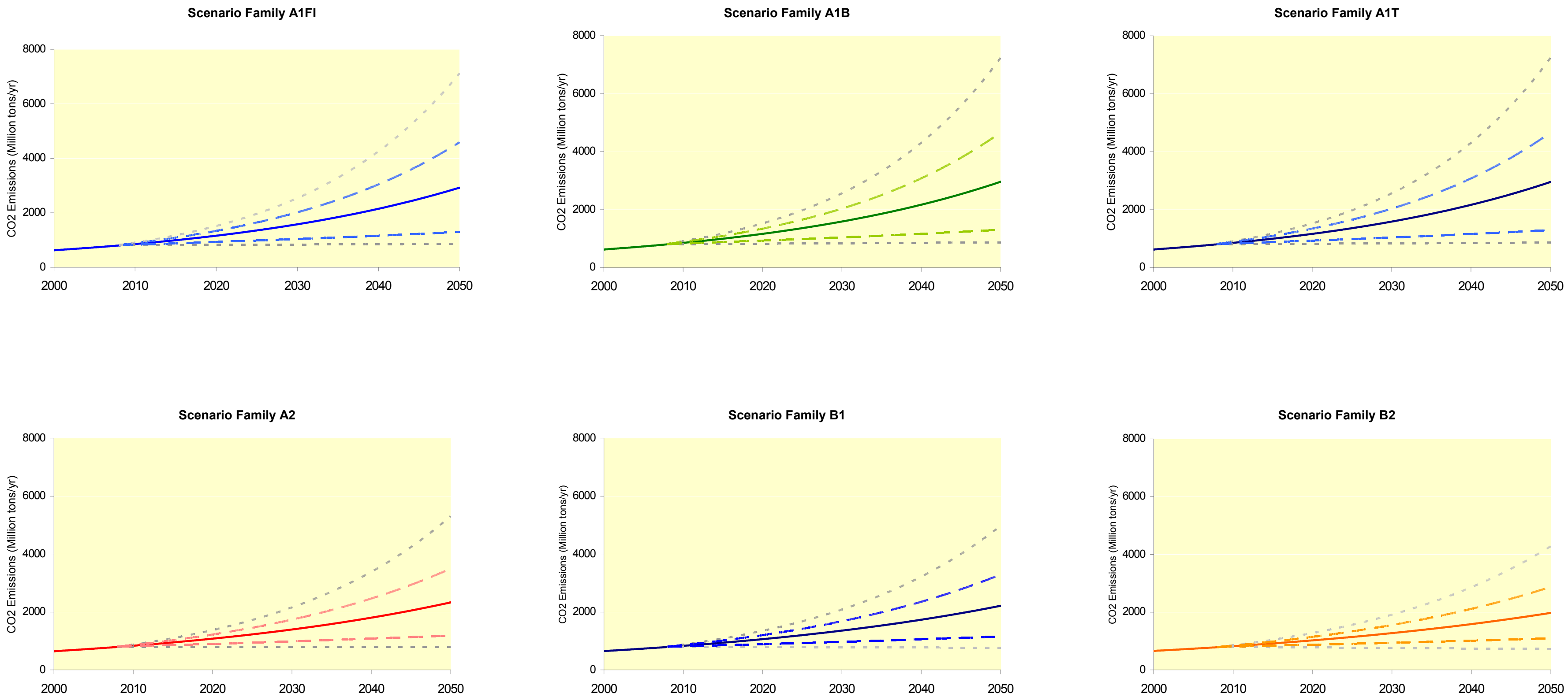
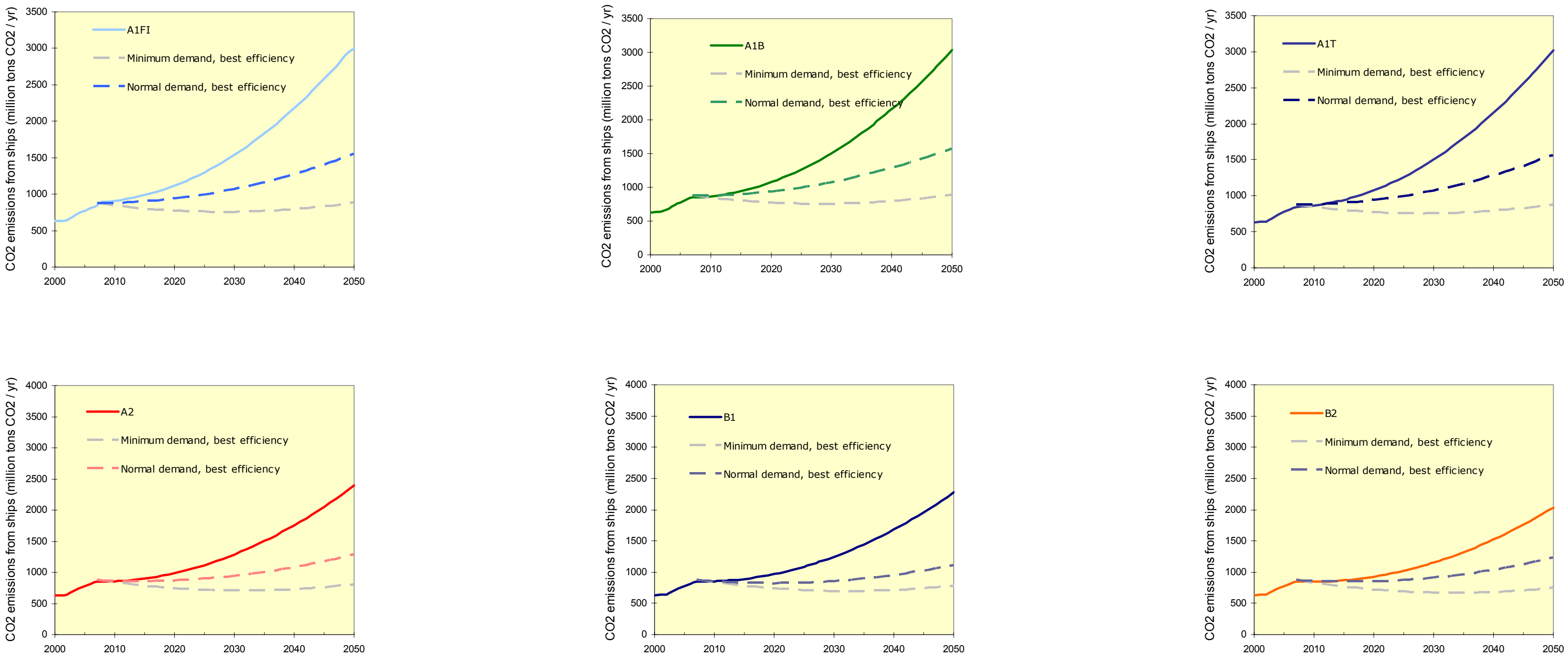


Figure 24. CO_2 trajectories showing baseline emission estimates (top line), baseline demand and maximum transport efficiency (middle line) estimates and minimum emissions (bottom line)



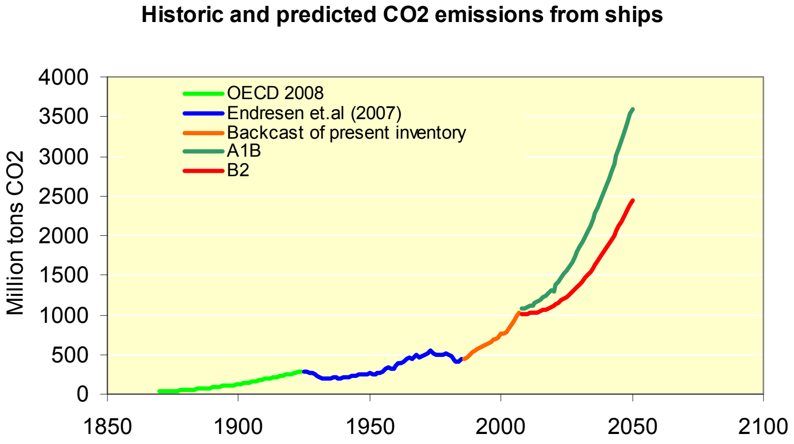


Figure 25. Historic and predicted emissions from ships

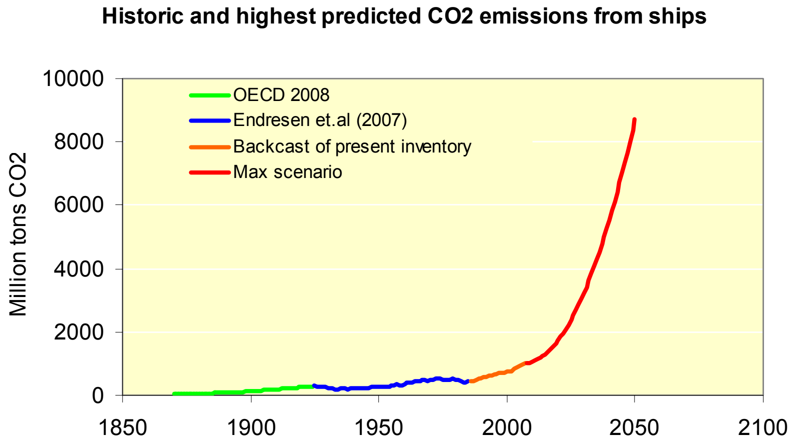


Figure 26. Historic and predicted highest emissions from ships

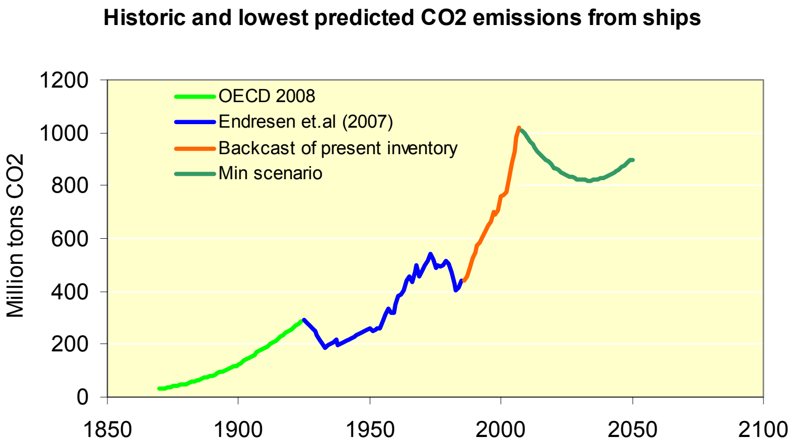


Figure 27. Historic and predicted best case emissions from ships

3.6 Discussion

The scenarios developed show significant increases in activity and thus also CO_2 emissions from ships. This is also the result of previous research on future ship emissions including the 2000 IMO Study on greenhouse gas emissions from ships. Compared to other studies based on the IPCC scenarios, the predicted future CO_2 emissions in this study are higher than previous estimates published by Eyring et al. (2005) [11] but in the same range as recently developed shipping scenarios up to 2050 from the EU project Quantify. (OECD, 2008, [23]).

There are a number of important observations that can be made from our scenario analysis results. One of the key insights is that transport demand is the most important variable affecting the growth in future CO_2 emissions and this result will be highlighted in this section.

Our CO_2 scenarios explored a broad array of variable values. In the end, the role of the growth in shipping demand plays the most significant part. Although CO_2 emission reductions will be achievable through improving transport efficiency, incorporating speed reductions, and moving to low-carbon fuels, these reduction efforts will be limited if the demand for international shipping increases at a pace equal to or even less than the expected global economic growth. This is illustrated in the average scenario results across the six scenario families (see Figure 20). Even our low growth families (e.g., B1, B2, and A2) show emission increases to levels about 2.5 times current emissions.

Having said this, there are scenarios that show reductions in emissions. Figure 23 shows minima that demonstrate emissions remaining essentially flat or with modest reductions over time. These scenarios have very low growth estimates. Reduced growth in seaborne transport does not necessitate reduced growth in world wide economy. Increased recycling, more regional trade and a more service oriented economy could contribute to decouple economic growth from seaborne trade.

The low emission values seen in Figure 23 rely also on aggressive transport efficiency advancements, significant speed reduction, and the transition towards low-carbon fuels.

Another insight is based on the comparison of the A1 families of scenarios, all of which cluster around common emission values. The differences in the A1 families are mostly driven by assumptions in changing energy patterns globally. In the IPCC SRES scenarios, the differences between a “balanced”, a “fossil intensive”, and a “technologically advanced” future are more significant due to the role that alternative, low-carbon fuels have in non-shipping sectors, such as electricity production, light-duty vehicles, and industrial processes. However, with international shipping, the movement of global energy markets from high-carbon to low-carbon fuels may have a less significant impact. This is because the transition to low-carbon fuels in a sector as large as the shipping industry is likely to take decades. Also we expect that this transition will be realized in other sectors before marine shipping.

None of the scenarios show very significant reductions in future emissions. This does not eliminate the possibility that this could happen, however this would require radical changes compared to the assumptions in our model. Examples of such changes include:

- Abrupt decoupling between seaborne trade and global economic growth. In our model the growth in transport demand is already lower than the correlation with GDP suggests, hence such decoupling must be rapid and very significant.
- Global economic growth rates that are significantly lower than the B2 scenario.
- Extreme fossil energy shortages compared to the SRES scenarios. According to SRES scenarios, by 2050, the total primary energy consumption ranges from 160-284% of 2010 values and fossil fuels cover from 57 - 82% of global primary energy demand
- Introduction of unexpected technologies

Therefore, the scenarios do not eliminate the possibility of CO_2 reductions. However, they do signal a need for fundamental change in order to achieve such reductions.

Our highest CO_2 emission scenarios are essentially based on extrapolations of business as usual and minimum levels of efficiency improvements. A prerequisite for these scenarios is sustained low energy prices towards 2050. Therefore, the highest emission scenario does not appear likely. Moreover, there are no assumptions in the SRES scenarios or other that could be reasonably altered to produce emissions exceeding these assumptions. The rapid growth rates in the previous 50 years and the resulting strain on global energy and other resources can be appreciated by looking at some key figures presented by the World Watch Institute, see Table 50 [20]. It is intuitive that growth rates as shown here cannot be sustained indefinitely.

Table 50. Global developments 1950 to 2006

	1956	2006
World population	2,8 billion	6,5 billion
Living in cities	0,9 billion	3,2 billion
Global oil consumption	5 billion barrels	31 billion barrels
Number of cars	90 million	580 million
Air passengers	70 million	1700 million

On the whole, marine shipping shows significant advantages in carbon emissions when compared to road and air freight, and is competitive on this front with respect to rail, as will be seen in Chapter 4. Thus, although international shipping may show emission increases due to increasing demand between now and 2050; these increases may be designed to offset what would be higher emissions from other modes (i.e., road and air). Mode-shifting from truck to ship, for example, may increase emissions from ships, but will have an overall beneficial impact on emissions from the goods movement system as a whole.

Climate stabilization will require significant reductions in CO_2 emissions by 2050. To reduce CO_2 emissions from international shipping, it appears necessary to either move away from the current path of continued growth in seaborne transport, since the efficiency gains expected in a non-regulatory scenario cannot deliver reductions in competition with such growth; and / or develop mechanisms that will result in the introduction of technologies that bring significantly less emissions than that anticipated in these scenarios.

Emission reduction mechanisms and their potential will be discussed in more detail in Phase 2 of this project.

3.7 References

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4. Comparison of CO_2 emissions from ships with other modes of transport

4.1 Introduction

This chapter contains estimates of the transport efficiency of cargo ships based on the CO_2 emission inventory calculations and assumptions regarding average utilization of cargo carrying capacity. The figures are compared with similar figures for other modes of transport. Information on progress made in terms of efficiency is also given.

4.2 Definitions and methodology

The CO_2 emission efficiency of transport can be expressed as mass CO_2 / tonne*kilometre where CO_2 expresses the total emission from the activity and tonne*kilometre expresses the total transport work. For a given period, the CO_2 emission efficiency is then defined as:

$$CO_2 efficiency = \frac{CO_2}{ton * kilometre}$$

where

CO_2 = Total CO_2 emission emitted from the vehicle within the period

Tonne*kilometre = Total actual tonne-kilometres transported within the same period

Using this definition, it is implied that all CO_2 emissions from a vehicle occurring within the reporting period are counted, whether or not the train, ship, lorry or other is loaded with goods. It is also implied that the CO_2 efficiency will be dependent on the load factor, i.e. the amount of cargo that is actually carried when loaded. This principle is upheld in the IMO CO_2 index, as described in the Interim Guidelines for Voluntary ship CO_2 emission indexing for use in trials (MEPC/Circ.471)

It should be noted that there are other definitions of CO_2 efficiency that also result in g CO_2/tonne-kilometre figures. For instance, calculations can be made which show the efficiency of transport when fully loaded, i.e. not accounting for average loading factors and empty running. For this reason, figures published in other sources may be very different from those presented here. It is therefore necessary to ensure that the same definitions are used when comparisons are made. In the case of shipping, nautical miles are frequently used for distance in which case CO_2 efficiency can be measures as g CO_2 / tonne-mile. To convert from g CO_2 / tonne-mile to g CO_2 / tonne-km, one must multiply by 0.540.

4.3 Comparison of the CO_2 efficiency of transport modes

4.3.1 CO_2 efficiency of sea transport

In order to assess the transport efficiency of the various segments of the world cargo fleet, CO_2 emission estimates from the 2007 inventory are used as a starting point, however it is necessary in addition to also estimate the transport work (tonne-kilometres) that is being done by each segment in the fleet. For this study, the kilometres were estimated based on average vessel category service speed from the Fairplay database and main engine operating days (days at sea) from the 2007 inventory. The CO_2 efficiency does not depend on the assumed number of main engine operating days since the CO_2 emitted is also proportional to number of operating days; therefore these cancel each other. The tonnes transported were estimated as the product of the assessed cargo weight capacity of the ship and the assessed average utilization factor. The average utilization factor takes into account the degree to which various ships typically need to do empty repositioning (ballast) voyages, multiple port deliveries as well as typical capacity utilization when loaded. Shortage of demand where there is not enough cargo to fill the ship is not considered although in reality this is common due to seasonal variations, degree of competition and fluctuations in world trade.

When estimating cargo weight capacity, a net container cargo weight of 7 tonnes has been used for Container ships. For Ro-Ro ships, a weight of 2 tonnes / lane metre is used, while 1.5 tonnes per car equivalent unit is used for Pure Car Carriers. Results from the calculation are shown in Table 51.

The figures in Table 51 are intended to indicate realistic levels of transport efficiencies of various categories of ships. The actual values of individual ships and annual averages will depend on a range of factors including fluctuation in trade demand. This latter effect is illustrated using fleet productivity data from UNCTAD [1]. This figure shows that the ratio of estimated seaborne trade in tonne-miles to fleet transport capacity as indicated by deadweight tonnage can vary significantly from one year to the next. This will result in variations in a number of parameters including days at sea, speed and cargo utilization factors.

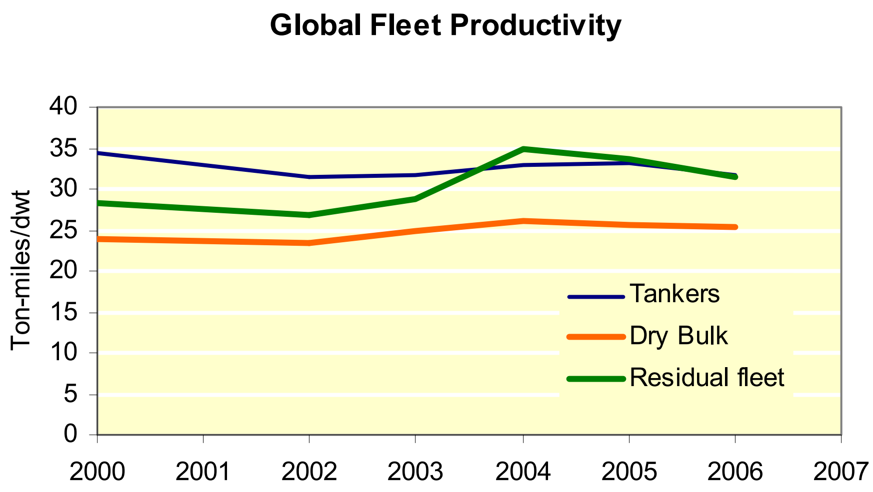

Figure 28. Fleet productivity data, based on data from UNCTAD [1]

4.3.2 CO_2 efficiency of road transport

The transport efficiency on roads is affected by many of the same factors as that in shipping, i.e. the efficiency will depend significantly on the load factor, vehicle efficiency and cargo type, heavier cargo and larger vehicles will improve the cargo/vehicle weight ratio resulting in better CO_2 / tonne-km values. Transport in areas with steep hills, winding roads and / or heavy traffic will contribute to increased consumption. A detailed study of road emissions has not been undertaken; however efficiency data that are comparable to the ship data have been retrieved from the literature as shown in Table 52. From these figures, it is concluded that the efficiency of road freight ranges from 80-180 g CO_2 / tonne-km with a typical average value of 150.

Table 51. CO_2 efficiency estimates for cargo ships

Type	Size	Average cargo capacity [tonne]	Average yearly capacity utilization	Average Service speed [knots]	Transport work per ship [tonne*nm]	Loaded efficiency [g CO2/ tonne-km	Total efficienyt [g CO2/ tonn-km]
Crude oil tanker	200,000+ dwt	295237	48 %	15.4	14197046742	1.6	2.9
Crude oil tanker	120 -199,999 dwt	151734	48 %	15.0	7024437504	2.2	4.4
Crude oil tanker	80 -119,999 dwt	103403	48 %	14.7	4417734613	3.0	5.9
Crude oil tanker	60 -79,999 dwt	66261	48 %	14.6	2629911081	4.3	7.5
Crude oil tanker	10 -59,999 dwt	38631	48 %	14.5	1519025926	5.2	9.1
Crude oil tanker	-9,999 dwt	3668	48 %	12.1	91086398	20.7	33.3
Products tanker	60,000+ dwt	101000	55 %	15.3	3491449962	3.3	5.7
Products tanker	20 -59,999 dwt	40000	55 %	14.8	1333683350	7.2	10.3
Products tanker	10 -19,999 dwt	15000	50 %	14.1	464013471	11.3	18.7
Products tanker	5 -9,999 dwt	7000	45 %	12.8	170712388	14.8	29.2
Products tanker	-4,999 dwt	1800	45 %	11.0	37598072	26.5	45.0
Chemical tanker	20,000+ dwt	32200	64 %	14.7	1831868715	5.7	8.4
Chemical tanker	10 -19,999 dwt	15000	64 %	14.5	820375271	7.3	10.8
Chemical tanker	5 -9,999 dwt	7000	64 %	14.5	382700554	10.7	15.1
Chemical tanker	-4,999 dwt	1800	64 %	14.5	72147958	18.6	22.2
LPG tanker	50,000+ cbm	46656	48 %	16.6	2411297106	5.2	9.0
LPG tanker	-49,999 cbm	3120	48 %	14.0	89631360	27.0	43.5
LNG tanker	200,000+ cbm	97520	48 %	19.6	5672338333	5.4	9.3
LNG tanker	-199,999 cbm	62100	48 %	19.6	3797321655	8.4	14.5
Bulk carrier	200,000+ dwt	227000	50 %	14.4	10901043017	1.5	2.5
Bulk carrier	100 -199,999 dwt	163000	50 %	14.4	7763260284	1.8	3.0
Bulk carrier	60 -99,999 dwt	74000	55 %	14.4	3821361703	2.7	4.1
Bulk carrier	35 -59,999 dwt	45000	55 %	14.4	2243075236	3.8	5.7
Bulk carrier	10 -34,999 dwt	26000	55 %	14.3	1268561872	5.3	7.9
Bulk carrier	-9,999 dwt	2400	60 %	11.0	68226787	22.9	29.2
General cargo	10,000+ dwt	15000	60 %	15.4	866510887	7.6	11.9
General cargo	5,000-9,999 dwt	6957	60 %	13.4	365344150	10.1	15.8
General cargo	-4,999 dwt	2545	60 %	11.7	76945792	10.9	13.9
General cargo	10,000+ dwt, 100+ TEU	18000	60 %	15.4	961054062	8.6	11.0
General cargo	5-9,999 dwt, 100+ TEU	7000	60 %	13.4	243599799	13.8	17.5
General cargo	-4,999 dwt, 100+ TEU	4000	60 %	11.7	120938043	15.5	19.8
Refridgerated cargo	All	6400	50 %	20,0	392981809	12.9	12.9
Container	8,000+ teu	68600	70 %	25.1	6968284047	11.1	12.5
Container	5 -7,999 teu	40355	70 %	25.3	4233489679	15.2	16.6
Container	3 -4,999 teu	28784	70 %	23.3	2820323533	15.2	16.6
Container	2 -2,999 teu	16800	70 %	20.9	1480205694	18.3	20.0
Container	1 -1,999 teu	7000	70 %	19.0	578339367	29.4	32.1
Container	-999 teu	3500	70 %	17.0	179809363	33.3	36.3
Vehicle	4,000+ ceu	7908	70 %	19.4	732581677	25.2	32.0
Vehicle	-3,999 ceu	2808	70 %	17.7	226545399	47.2	57.6
Roro	2,000+ lm	5154	70 %	19.4	368202021	45.3	49.5
Roro	-1,999 lm	1432	70 %	13.2	57201146	55.2	60.3

Note: Loaded efficiency is the theoretical maximum efficiency when the ship is fully loaded at service speed / 85% load. Since engine load at fully loaded condition is higher than average including ballast and other, the difference between columns ‘loaded efficiency’ and ‘total efficiency’ cannot be explained by difference in utilization only.

Table 52. CO_2 efficiency figures for road freight

	CO_2 [g/tonne-km]	Method	Source
Heavy Goods Vehicles	138	Output based measures combining data from "National Road Traffic Survey" and "Continuing Survey of Road Goods Transport"	[3]
Road freight	127	Top-down approach. Trend Database. Data from Eurostat . Data only from EU region	[3]
Trucks > 40 tonnes	80	Sample survey, 109 Vehicles	[1]
Trucks < 40 tonnes	181	Sample survey, 44 Vehicles	[1]
Road freight	153	Top-down approach. Data from *National Transportation Statistics 2007*; U.S. Department of Transportation, Research and Innovation Technology Administration: Washington, DC, 2007; and Energy Information Administration Annual Energy Outlook 2007 with Projections to 2030, Supplemental Transportation Tables	Authors calc.
Road freight	156	Top-down calculation based on EU statistics	[4]
Road freight 2007	144 *	Top-down calculation based on National Japanese statistics	[5]

*The 2007 truck transport efficiency in Japan of 144 g/kWh is significantly better than the 2004 value which was 174 g/kWh. This improvement of 20% is attributed in part to the implementation of speed limits for all Japanese trucks following a major road accident.

4.3.3 CO_2 efficiency of rail freight

Unlike road and sea, electricity is an important source of energy for rail transport. When assessing the CO_2 efficiency of electric trains, consideration must be given to the CO_2 emitted from the production of the electricity. The transport efficiency of rails depends on the speed, weight and length of the train as well as the terrain, type of cargo, height restrictions, availability of return cargo and the efficiency in handling empty car logistics. Efficiency data are presented in Table 53. The effect of cargo type is quite important, bulk cargos are shown to be significantly more efficient to transport than typical intermodal cargo such as containers. Also, when taking into account electricity production from coal-fuelled power plants (CO_2 marginal power) and electric transmission losses in the grid, electric trains are only marginally more CO_2 efficient than diesel-fuelled trains.

From these figures, it is concluded that the efficiency of rail freight ranges from 10-119 g CO_2 / tonne-km, with a typical value around 48.

Table 53. CO_2 efficiency figures for rail freight

	[g CO_2 /tonne-km]	Method	Source
Diesel locomotives	49	UK National Atmospheric Emissions Inventory data, (1990-2004)	[3]
Rail freight	119	Top-down approach. Data from Eurostat. Data only from EU region	[3]
Rail freight (EU average)	81	Top-down approach. Data from Eurostat	[4]
Rail freight (US national average)	14	Top-down approach. Data from *National Transportation Statistics 2007*; U.S. Department of Transportation, Research and Innovation Technology Administration: Washington, DC, 2007; and Energy Information Administration Annual Energy Outlook 2007 with Projections to 2030, Supplemental Transportation Tables	Authors calc.
Bulk cargo trains	10-14	Calculated from typical US train sizing of bulk trains 0,6-0,8 hp / short ton (0,49-0,65 kW/metric ton)	Authors calc
Intermodal (container) train	35-50	Calculated from typical US train sizing of bulk trains 3-4 hp / short ton (2,2-2,9 kW/metric ton)	Authors calc

4.3.4 Air freight

Air freight is fast but expensive and is limited to special types of cargo where speed in essential such as perishable goods, mail, critical spare parts etc. Air freight is carried in dedicated freight planes but to a certain extent also on passenger carrying planes. Due to fuel burn for take off and climb, efficiency will improve with longer flights, however at extended range the weight of the fuel will contribute to reduced efficiency since the aircraft drag increases with weight. At long range, fuel weight may limit the maximum weight of the cargo. Efficiency figures for two widely used freight planes are shown Table 54. Differences between these two planes indicate difference in engine technology and aircraft size.

Table 54. CO_2 efficiency figures for air freight

	[g CO_2 /tonne-km]	Method	Source
Boeing 747 F	435-474	Direct calculation on case study: Total capacity 113 tonnes, average utilization 70%, 453-493 kJ/km, depending on distance	[8]
Ilyushin IL 76T	1100-1800	Direct calculation on case study: Cargo capacity 28-50 tonnes (depending on range), average 70% utilization, range 500-5500 km.	Authors calc, data from [9]

4.3.5 Comparison of modes

The efficiency of ships is compared with that of other modes in Figure 29. This figure illustrates that CO_2 efficiency gains can be achieved by increased multi-modal transport. When considering figures of this kind, the effect of cargo type should be borne in mind. Heavy (bulk) cargos can be more efficiently transported than lighter (manufactured goods) onboard ships, on rail and on the road. Figure 30 shows the same comparison but includes also airfreight.

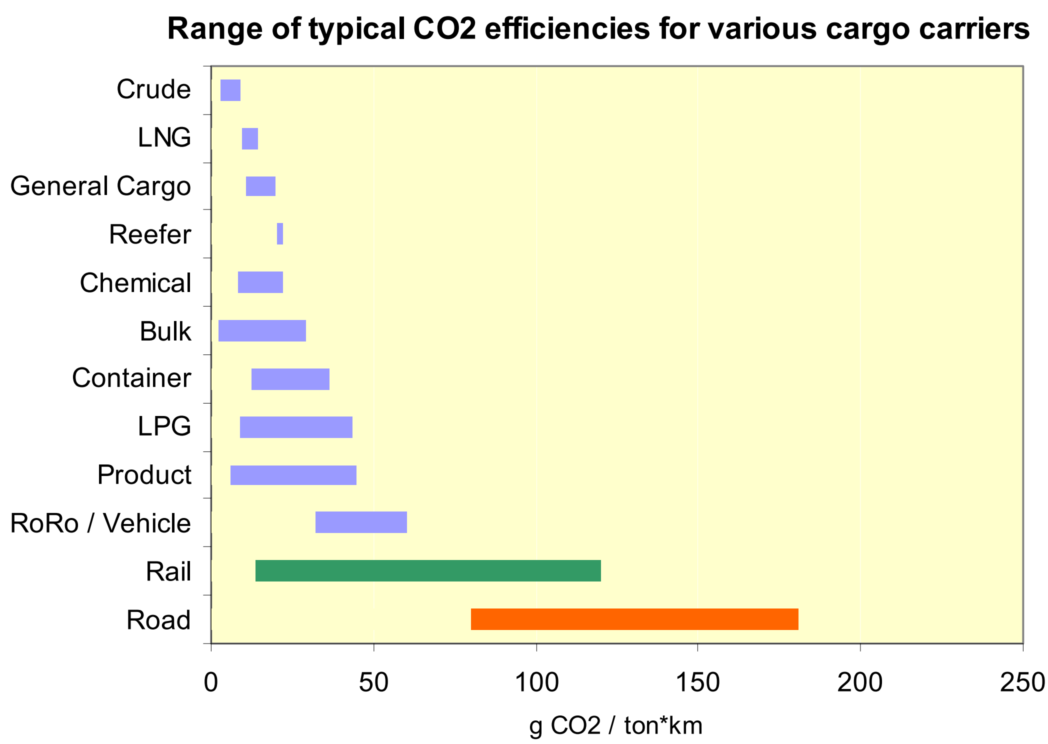

Figure 29. CO_2 Typical range of ship efficiencies compared to rail and road

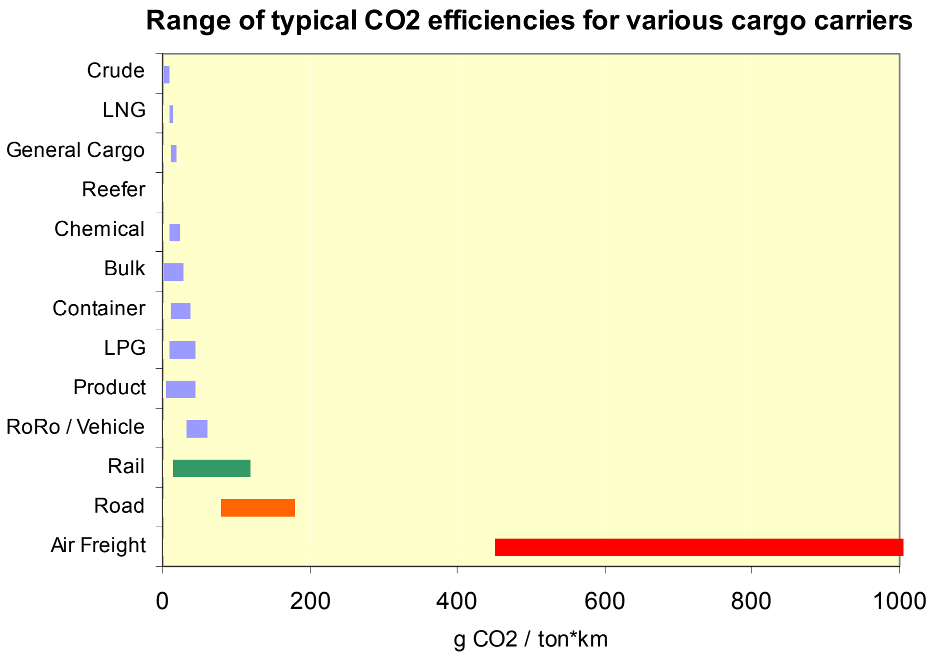

Figure 30. CO_2 Typical range of ship efficiencies compared to rail, road and airfreight

4.4 Historic efficiency figures for shipping

Technological improvements and increasing ship sizes have increased the efficiency of seaborne transport over time. In order to investigate historic trends in the efficiency of ships, data from Lloyds Register Fairplay were analysed. For this purpose, a fuel efficiency index was developed based on deadweight, speed and fuel consumption data in the database. The efficiency values are calculated on an assumption that the average transport load is 50% of deadweight for all ships and ages. The index is defined as follows:

$$Efficiency\ index = \frac{Fuel\ consumption * 3.09}{0.5 * dwt * v}$$

where fuel consumption is given in g/h and vessel speed v is given in knots.

The efficiency values have been calculated to identify trends and are not directly comparable to the figures given in Table 51 above. It should be noted that the fuel consumption figures in the database generally refer to fuel consumption for vessel charter and include auxiliary fuel consumption and also a certain safety margin.

When analysing the fleet statistics for trends in fuel consumption values, an attempt was made to disaggregate the effects of technology, speed and vessel size. In general, this did not reveal any insights as trends were generally very difficult to identify. The lack of precision in the fuel consumption data may be an important reason. However, the statistics did show a clear trend in the overall best efficiency of the fleet which combines scale, speed and technology effects.

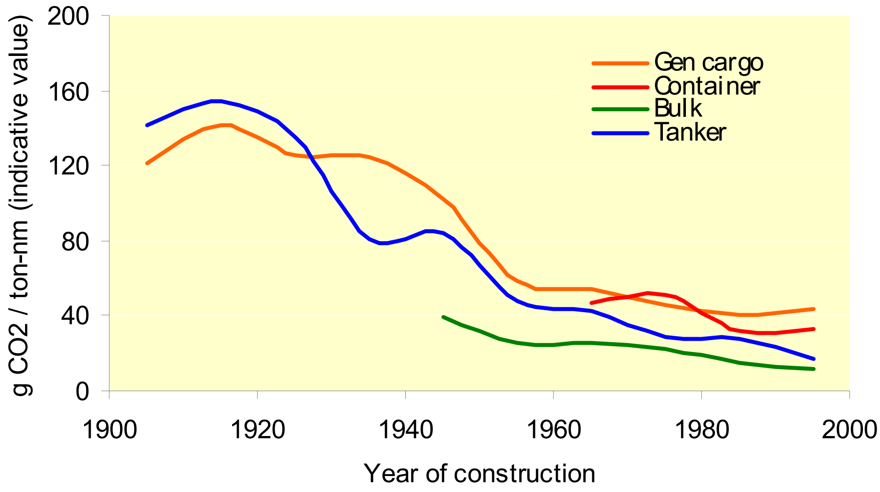

Figure 31. Indicative development in average ship design transport efficiency

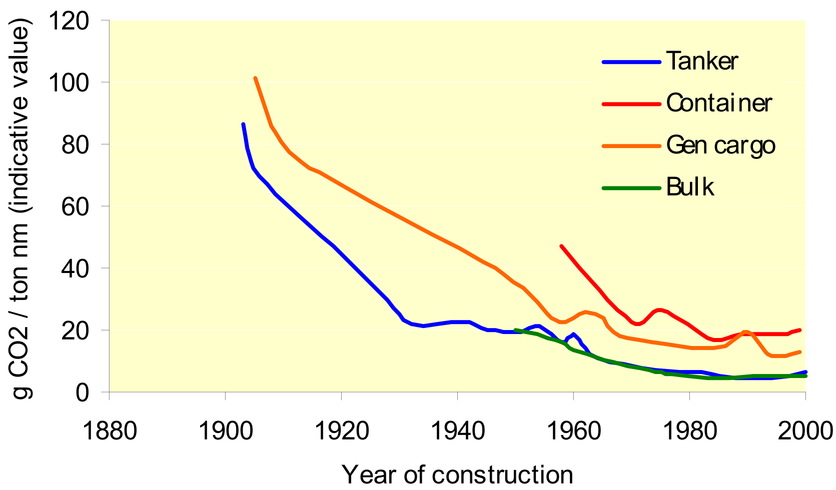

Figure 32. Indicative development in maximum ship design transport efficiency

4.5 Total emissions by transport mode

The total of CO_2 emissions from ships is compared to other transport modes based on fuel consumption data reported for other sectors in IEA statistics [26]. Although some of the problems with global statistics discussed in Section 2.5.1 apply to fuel consumption statistics for all modes, the problems associated with classifying domestic vs. internationals and possible offshore bunkering is specific to shipping and aviation.

Aviation fuel use is classified similarly to marine bunker statistics, although the nature of air travel is such that aircraft make fewer flights between refuelling to manage power, weight, and lift requirements. If ships were to fuel before every voyage, the IEA fuel statistics for marine would be more accurate; however, ships fuel at major bunkering market locations for multi-port voyages over weeks.

Domestic-only statistics for road and rail aggregated by IEA are gathered without the classification conflict between international and domestic activity and fuel sales recorded in compliance with IEA policy. Moreover, the volume of fuel used on road is significantly larger than the quantity of fuel used by ships. Together, this suggests that statistical confidence in the fuel data collected by IEA from reporting nations may be better for road and rail than for marine modes. Where domestic fuel sales are taxed while international marine fuels are not, the requirements to accuracy and revision of road fuels would be increased compared to international marine fuels. In the case of aviation, fuel consumption is closely monitored since fuel weight and aircraft range is important for the planning and approval of flights.

Since global IEA data are only available up to 2005, 2005 values for the emissions from ships are used. This results in the figures given in Table 55 and in Figure 33 and Figure 34. Road diesel is the total amount of diesel sold for road use and includes fuel use for cargo freight, passenger transport and diesel cars.

Table 55. CO_2 emissions from transport mode (million tonnes, 2005)

Rail (IEA)	Road diesel (IEA)	Aviation (IEA)	International shipping	Domestic/ fishing
133	4757	735	774	157

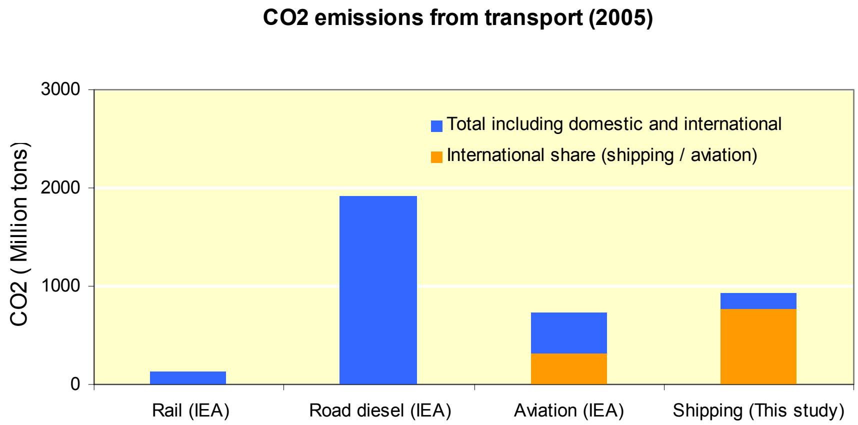

Figure 33, 2005 CO_2 emissions from shipping compared to other transport modes

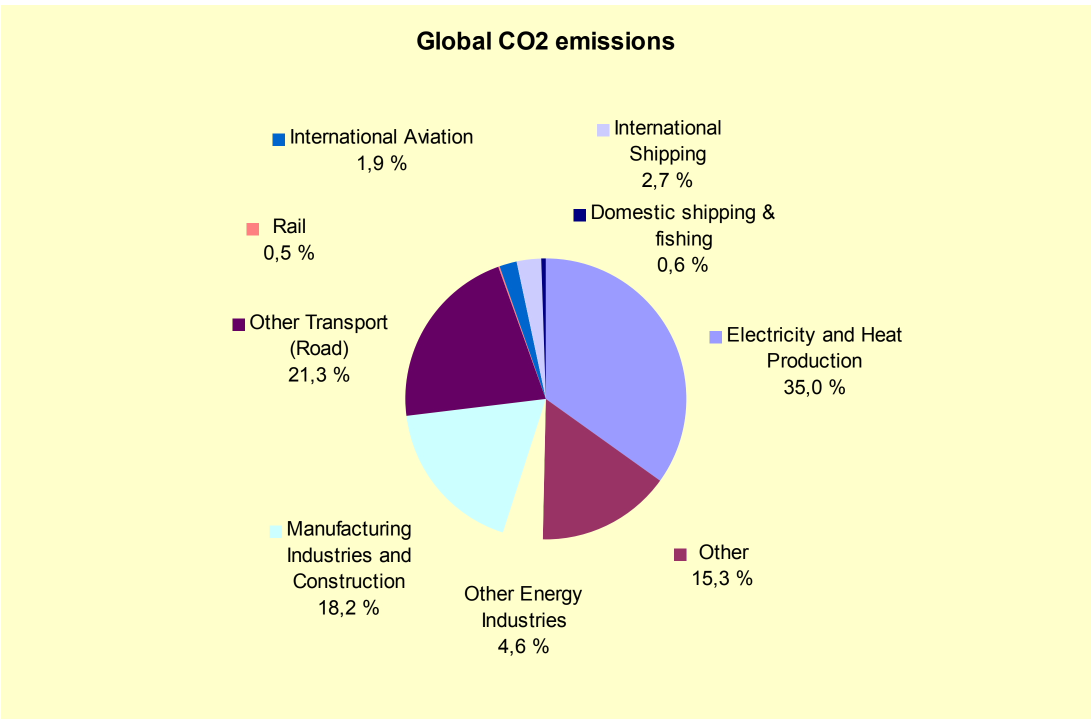

Figure 34. CO_2 emissions from shipping compared with global total emissions

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5. Radiative forcing impacts of CO_2 emissions from shipping

5.1 Introduction

Over recent years, there have been questions over the nature and magnitude of the impact of the shipping sector on climate. Ship emissions have been recognized as a growing problem for environmental policy makers (Corbett, 2003). This is because it has been realized that such emissions give rise to direct impacts on human health, contribute towards regional acidification and eutrophication and influence radiative forcing of climate.

Shipping results in a number of emissions. In the first phase of the study we focus on CO_2 radiative impacts while radiative impacts of other ship emissions will be assessed in Phase 2. The emissions from shipping affect the radiative forcing of climate (RF), which is the conventional climate metric, expressed in watts per square metre ($W\ m^{-2}$) used by climate science and the Intergovernmental Panel on Climate Change (IPCC). RF is usually expressed as a global mean and positive numbers imply warming while negative ones imply cooling. Carbon dioxide is a direct greenhouse gas which has a warming effect and a positive RF. In the following section, the methodology by which the shipping CO_2 RF is calculated is described, and in the final section, the results are presented and discussed.

CO_2 remains in the atmosphere for a long time and will continue to have a warming effect long after its emission. Therefore, emissions data from ships starting as early as 1870 has been used when calculating the RF of shipping CO_2 emissions. Since this old data does not distinguish between international and domestic shipping, RF calculations are based on total shipping emissions rather than international shipping only.

5.2 Calculation methodology and model description

In order to calculate the 'impacts' of shipping we use a linear climate response model to calculate the contribution of CO_2 emissions to marginal CO_2 concentrations and the consequential radiative forcing. This model takes emission rates, calculates the resultant atmospheric concentrations of CO_2 and then the RF which arises from changes in CO_2 concentration.

The model is a development of Sausen and Schumann (2000), previously applied to aviation emissions scenarios, which in turn is based upon the approach of Hasselmann et al. (1993; 1997). Some modifications and developments have been made to the model, which is now able to address the full suite of aviation and shipping impacts (CO_2, NO_x impacts on O_3, particles, CH_4 and contrails; see Lim et al., 2007; Lee et al., 2007). A more complete analysis of concentrations, ranges of radiative forcing and temperature changes is performed in Eyring et al. (2008b). However, for this first phase of the present work, only the CO_2 aspects are considered for shipping.

The contribution of CO_2 emissions from shipping is assumed to be the difference of total 'background' emissions to the calculated shipping contribution to concentrations as follows. The response of CO_2 concentrations, $C(t)$, to a CO_2 emission rate, $E(t)$, is modelled as following Hasselmann et al. (1997), which approximates to the results of the carbon cycle model of Meier-Reimer and Hasselmann (1987) so that

$$\Delta C(t) = \int_{t_0}^{t} G_C(t-t')E(t')dt'$$

[1]

and

$$G_C(t) = \sum_{j=0}^{5} \alpha_j e^{-t/\tau_j}$$

[2]

where τ_j is the e-folding time of mode j and the equilibrium response of mode j to a unit forcing is $\alpha_j \tau_j$, using the mode parameters given in Table 1 ??50.

Table 56. Coefficients of the impulse function G_C for CO_2 concentration (Schumann and Sausen, 2000)

j	1	2	3	4	5
α_j [ppbv/Tg(C)]	0.067	0.1135	0.152	0.097	0.041
τ_j [yr]	∞	313.8	79.8	18.8	1.7

The RF of CO_2 is dependent upon its own concentration because of spectral saturation, such that in calculating the impacts of CO_2 from shipping, it is necessary to know the 'background' RF (Equation 3).

$$\Delta RF_{SHipping} = \Delta RF(C_{Background}) - \Delta RF(C_{Background} - C_{Shipping}) \quad [3]$$

Historical CO_2 concentration data from 1800 until 1995, and thereafter SRES scenario data (IPCC, 2000) until 2100 (all natural and anthropogenic sources including shipping emissions) were used as background. The contribution of shipping CO_2 is calculated explicitly using Equations [3] and [4], the concentration being assumed to be the difference between background and shipping concentrations.

From the CO_2 concentrations, the radiative forcing is calculated. According to IPCC, the radiative forcing of CO_2 can be estimated from the logarithm of the concentration, which approximates the effect of saturation in radiative forcing with increased CO_2 concentrations. Sausen and Schumann (2000), following Hasselmann et al. (1993), calculated a normalized radiative forcing (RF^*) to a RF=1 for a doubling in CO_2 concentrations is using the formulation of:

$$RF^*(t) = \frac{\ln(C_{(t)}/C_{(0)})}{\ln 2} \quad [4]$$

where C_0 is the observed pre-industrial CO_2 concentration for 1800. Here, we use the more recent expression from Ramaswamy et al. (2001) which uses an updated coefficient of 5.35 from Myhre et al. (1998):

$$RF(t) = \alpha\left[\ln(C_{(t)}/C_{(0)})\right] \quad [5]$$

This has the advantage of not requiring any normalization and the CO_2 forcing is calculated directly. As the model at present only calculates the shipping fraction of CO_2 concentrations, background concentrations of CO_2 must be prescribed – these are taken from observations (IPCC, 2001) and concentrations arising from IPCC SRES emission scenarios, as calculated with MAGICC model (as used in IPCC assessment reports).

The shipping emissions and scenarios used in this work are described elsewhere in the report, including a description of the underlying assumptions. Figure 35, presents the historical and present day emissions used. From 1870 to 1925 estimates from OECD (2008) are used. The CO_2 time series is continued with estimates from Endresen et al. (2007) between 1925 and 1985. The estimate of CO_2 in 2007 from this study is 1919 Tg(CO_2)/yr. Between 1886 and 2007 we use the backcast calculated from the time evolution of freight tonne-miles (Fearnleys, 2007) with the point estimates from this study in 2007 taken as the reference year. This results in a smooth curve over the entire period from 1870 to 2007, as the backcast CO_2 of the present inventory agrees well with the Endresen et al. (2007) estimate in 1985.

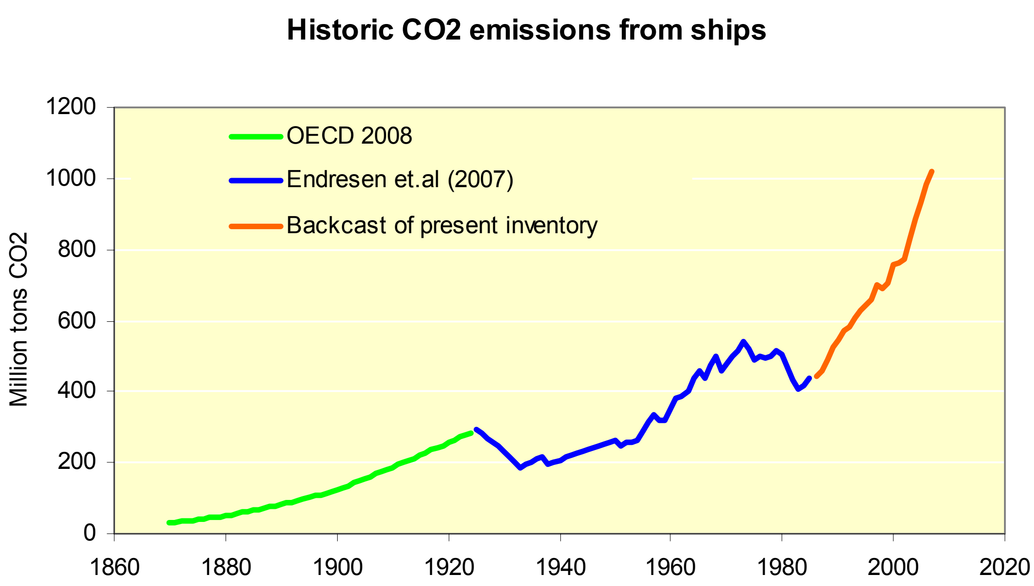

Figure 35. Historical and present-day emissions of CO_2 from shipping

5.3 Results: Radiative Forcing

Carbon dioxide emissions have a long residence time in the atmosphere and become well-mixed. Equation 5 uses the changes in CO_2 concentrations to calculate the radiative forcing. The basic results are presented as time-series for the historical and present day forcing arising from the corresponding emission estimations, and a range of outcomes according to the emission scenarios (see Figure 36).

The CO_2 RF from shipping in 2005 amounted to 46 mW m^{-2}. For comparison, aviation has a similar – if slightly smaller – present day annual emission rate (733 Tg CO_2, 2005) but the RF is only 28 mW m^{-2}. The somewhat larger forcing from shipping in this comparison can be easily explained by both the residence time of CO_2 in the atmosphere and the time-period of the activity. Carbon dioxide does not have a single lifetime but can be approximated as 100-150 years. Shipping activities date back to the late 19^{th} century with coal-fired ships, taking over from sailing ships; by contrast, significant aviation is usually taken to date back to 1940. Fuglestvedt et al. (2007) recently examined transportation impacts on climate but shipping-specific CO_2 RFs were not tabulated. From their Figure 1, shipping CO_2 RF in 2000 appears to be ~40 mW m^{-2}, which is in good agreement with our estimate which is based on more refined input emissions data.

After 2005, a number of CO_2 emission scenarios described in Section 3.5 are assumed. Not all the variants within the main SRES A and B-based families have been modelled but rather the overall scenario within the families, i.e. A1FI, A1B, A1T, B1, and B2. In addition, the two scenarios which represent the maximum and minimum from the spreads from the subsets of these scenarios have also been modelled. Corresponding CO_2 emissions between 2007 and 2050 for the various scenarios are presented in Figure 21.

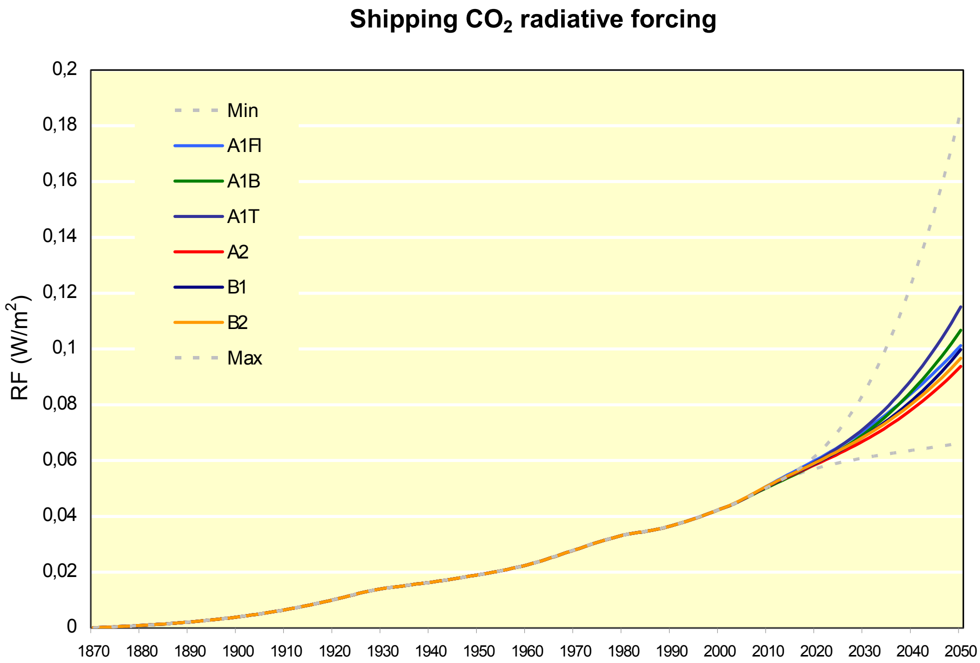

Figure 36. Radiative forcing of CO_2 attributable to shipping from 1870 to 2005, and thereafter according to a range of scenarios to 2050

The various main emission scenarios yield CO_2 RFs at 2050 between 96 to 115 mW m^{-2}. The minimum in 2050 is 66 mW m^{-2} and the maximum 185 mW m^{-2}, illustrating the uncertainty range arising from the emission scenarios and their underlying assumptions. RFs arising from other ship emissions will be assessed in Phase 2.

5.4 Shipping and climate stabilization

An early description of climate stabilization was given by Wigley et al. (1996) and has been studied by the IPCC from its Second Assessment Report (IPCC, 1996) onwards. The word 'stabilization' is applied rather interchangeably to atmospheric concentrations and temperature and also inaccurately to emissions (since stabilization of emissions will not achieve stabilization of either CO_2 concentrations or temperature within the 21st century). Strictly, stabilization applies to CO_2 concentrations in the context of the so-called WRE (from Wigley, Richels and Edmonds) scenarios.

Stabilization concepts and emissions pathways for CO_2 are discussed because of the complicated response of the climate to CO_2. Firstly, CO_2 is well-known to have a long residence time in the atmosphere, which is of the order 300 years or more. Strictly speaking, CO_2 does not have a single lifetime because of multiple sources and sinks with different exchange times (see, e.g. Harvey, 2000; IPCC, 2007[2]). Secondly, in

[2] See 'Frequently Asked Questions 7.1 (http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_FAQs.pdf) accessed 06-08-2008

terms of temperature, the phenomenon of the thermal inertia of the climate system delays the response between CO_2 emission and changes in temperature because of timescales of heat exchange between the oceans and the atmosphere: this is of the order of decades. Hence, in order to limit *temperature* response, early action needs to be taken on emission reductions in order for the climate system to respond by about 2100.

The stabilization of atmospheric CO_2 concentrations by the end of the 21st century will require significant reductions in future global CO_2 emissions. The resultant temperature from stabilizing CO_2 concentrations at various levels (e.g. 450 ppm, 550 ppm etc.) depends on climate sensitivity. Climate sensitivity is common test of climate models to the global mean surface temperature arising from a doubling of CO_2 concentrations. This is usually estimated to be between 2 and 4.5°C.

A recent assessment of climate stabilization concluded that 550 ppm, a target of 2°C would be exceeded, and 450 ppm would result in a 50% likelihood of achieving this target (Tirpak et al., 2005). More recently, Professor Jim Hansen, Director of NASA Goddard Institute for Space Studies has suggested that 350 ppm CO_2 is a more appropriate level to avoid ‘dangerous climate change’, which is *below* current atmospheric levels of CO_2 of 385 ppm (Hansen et al., 2008). This assertion is based on analyses of paleoclimate data.

In order to achieve the more commonly-discussed stabilization goal of 450 ppm CO_2, global total CO_2 emissions must be limited to the values shown in WRE450 in Figure 36 below; similarly, the WRE550 emission trajectory is also shown.

In the following, the concept of CO_2 stabilization pathways is discussed in the context of the shipping emission scenarios developed for this work. It is important to note that this is merely illustrative: the shipping emission scenarios in this report inherently assume no climate-policy intervention (as is the case with the SRES background scenario storylines of the IPCC). Thus, a stabilization scenario clearly represent climate policy intervention, such that the two ‘storylines’ are inherently different.

Figure 36 illustrates the potential conflict between the predicted growth in emissions from shipping under scenarios that assume no climate-intervention policy, and the stabilization of CO_2 in the atmosphere at 450 ppm. As given in Figure 36, 2050 shipping emissions predicted in the base scenarios would comprise 12–18% of the WRE 450 scenario total emissions at that date.

The WRE stabilization scenarios are not prescriptive concerning the make-up of the emissions since they are achieved by inverse modelling to achieve stabilized concentrations of CO_2 in the atmosphere. The shipping scenarios presented in this report are based on SRES-type assumptions which are not climate-intervention policy scenarios *cf* the WRE scenarios, hence they are not compatible in philosophy. Nonetheless, it is useful to present the SRES-based shipping emission projections in the context of the stabilization emission pathways in order to illustrate that if shipping is to play a role in stabilization, it is highly likely that reductions over those projected will be necessary.

Table 57. Shipping as share of global total as per WRE scenarios in 2050

	A1FI	A1B	A1T	A2	B1	B2
WRE 450	17.6 %	17.9 %	17.8 %	14.1 %	13.4 %	12.0 %
WRE 550	9.7 %	9.9 %	9.8 %	7.8 %	7.4 %	6.6 %

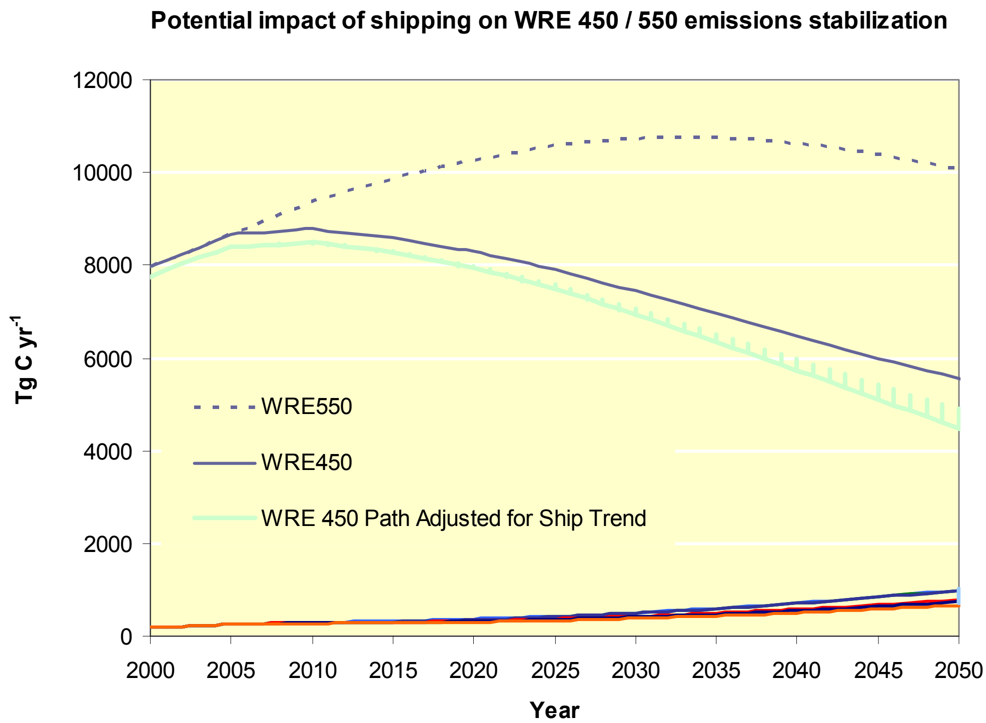

Figure 37. Comparison of modelled shipping emissions, curves for WRE 450 and WRE 550, and WRE 450 adjusted for ship emissions (Global total less shipping emissions)

5.5 Conclusions

- Increases in well-mixed greenhouse-gases such as carbon dioxide lead to a positive radiative forcing and to global warming.
- The RF from shipping CO_2 for 2005 was calculated to be 46 mW m^{-2}, contributing approximately 2.8% to the total anthropogenic CO_2 RF.
- For a range of 2050 scenarios, the shipping CO_2 RF was calculated to be between 96 and 115 mW m^{-2} bounded by a minimum/maximum uncertainty range (from the scenarios) of 66 mW m^{-2} and 185 mW m^{-2}. We emphasize, that CO_2 remains in the atmosphere for a long time and will continue to have a warming effect long after its emission. Other radiative effects from shipping emissions will be considered in Phase 2.
- While the control of NO_x, SO_2 and particle emissions from ships will have beneficial impacts on air quality, acidification and eutrophication, CO_2 reductions from all sources, including ships and other freight modes, are required to reduce global warming. Moreover, a shift to cleaner combustion and cleaner fuels may be enhanced by a shift to lower CO_2 technologies and activity by ships.
- Climate stabilization will require significant reductions in future global CO_2 emissions. The shipping emissions for 2050 developed for this work – which are based on SRES non-climate intervention policy assumptions – constitute 12–18% of the WRE450 scenario which corresponds to the total global CO_2 emissions permissible in 2050 if the increase in global average temperature is to be limited to 2°C with a probability greater than 50% .

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6. Appendix

- SRES plots and descriptions
- Ship category description
- Scenario fleets
- Scenario carbon fractions

SRES data plots

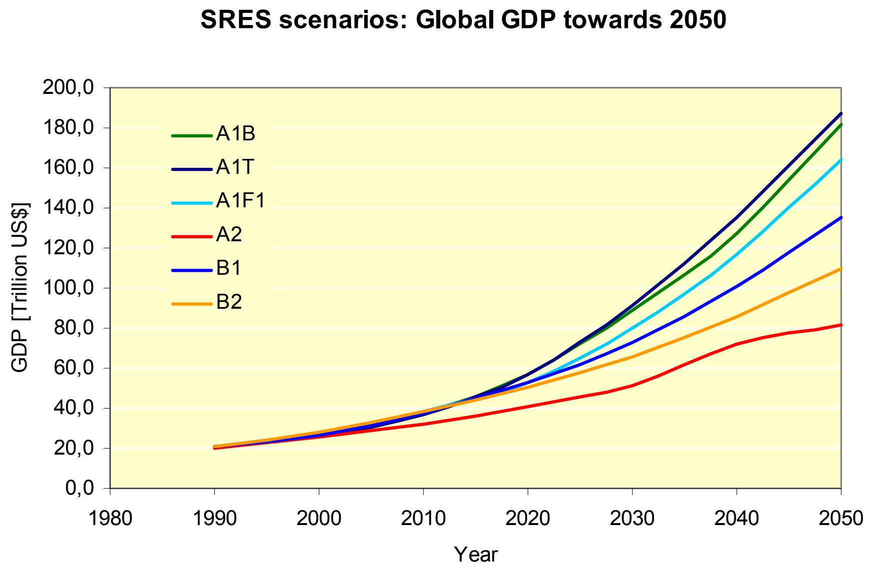


Figure 38. SRES – Global GDP towards 2050

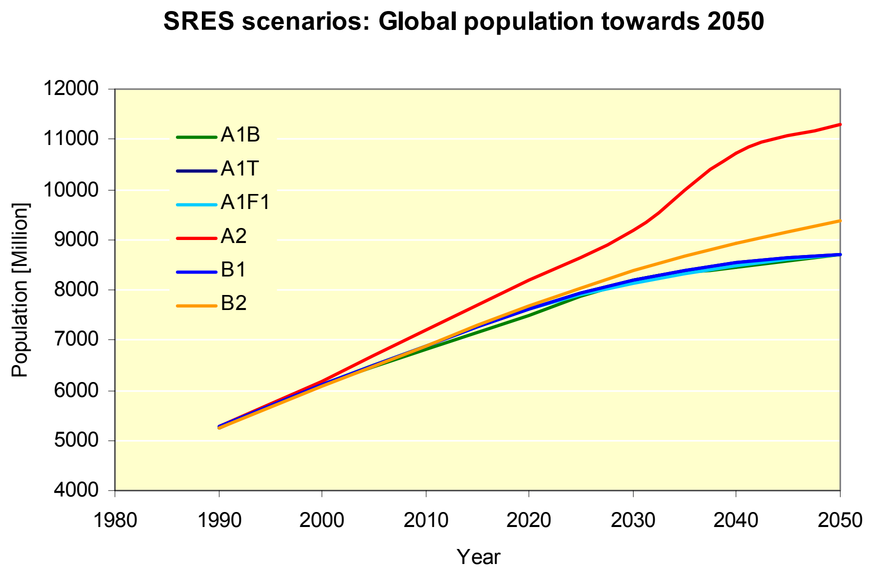


Figure 39. SRES – Global population towards 2050

DATA: http://sres.ciesin.org/final_data.html.

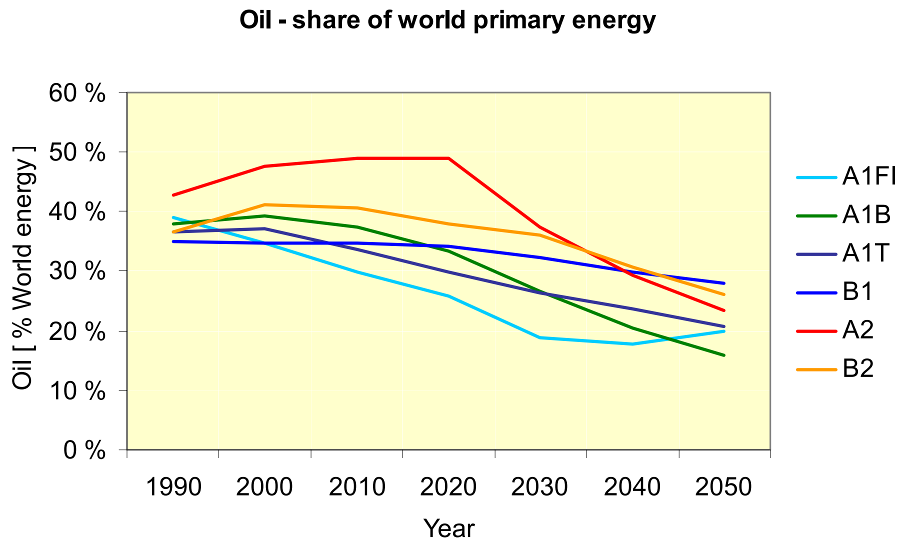


Figure 40. SRES – Oil, share of world primary energy demand towards 2050

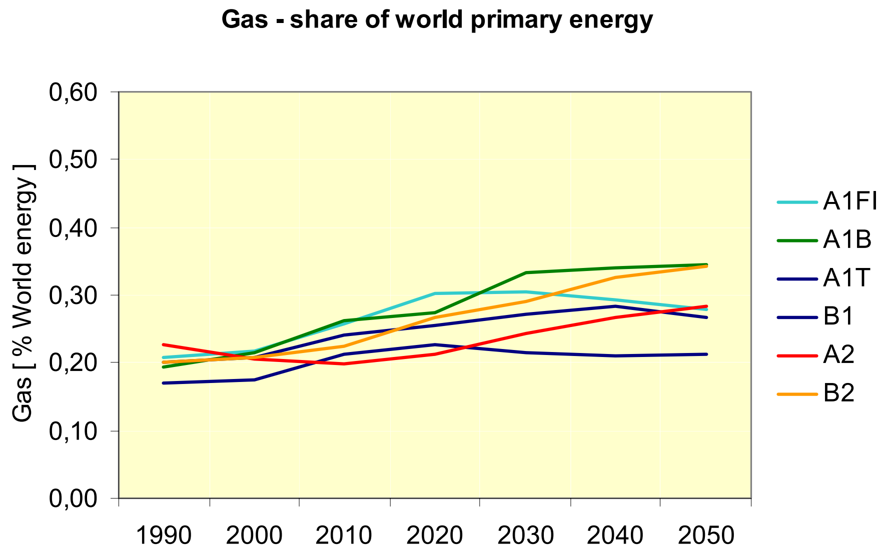


Figure 41. SRES – Gas, share of world primary energy demand towards 2050

DATA: http://sres.ciesin.org/final_data.html.

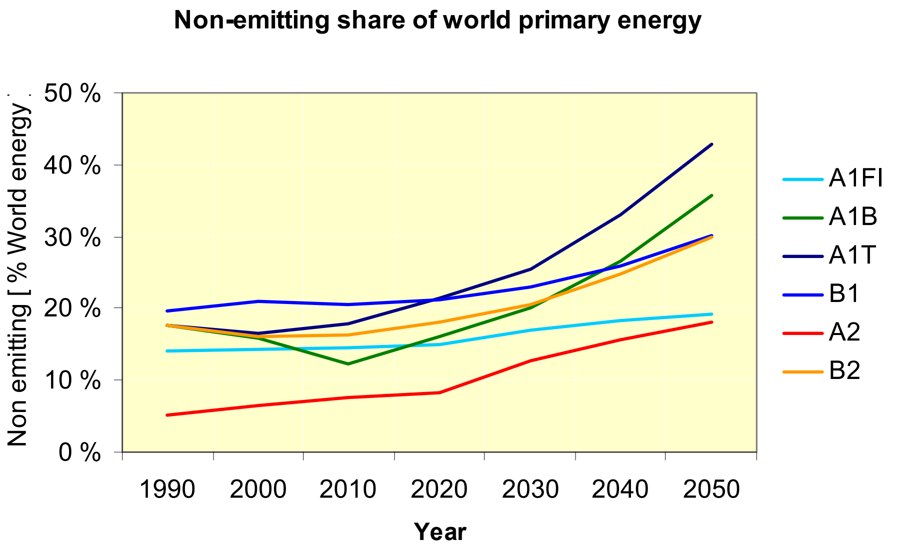
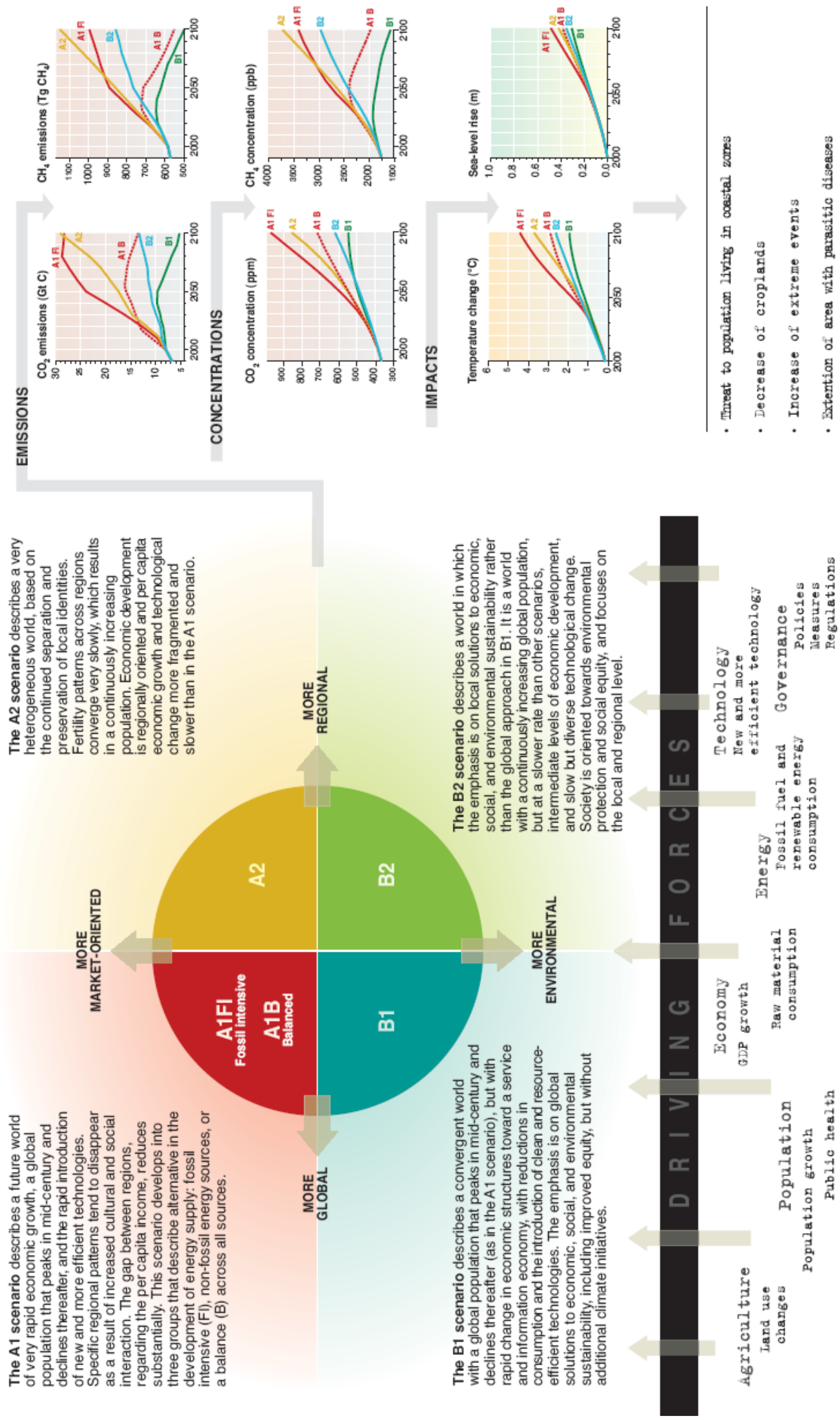


Figure 42. SRES – Non-emitting[3], share of world primary energy demand towards 2050

Figure 43. SRES – Sources of world primary energy

[3] Non-emitting is the sum of nuclear (Labelled non-fossil electric for B1), biomass and other renewables in the SRES scenarios



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Ship category description

Crude This category includes tank ships which are intended for carrying crude oil.

Products These are tankers that carry various types of refined petroleum products.

Chemical These are tankers that carry various types of industrial chemicals.

LPG Specialized tankers for the carriage of Liquefied Petroleum Gas and often also other products like ammonium.

LNG Specialized tankers for the carriage of Liquefied Natural Gas.

Other tanker This group includes a large number of bunker tankers and also a wide range of liquid niche products such as orange juice, bitumen, wine and water.

Bulk These are ships designed to carry bulk goods such as grain, iron ore, coal and more.

General cargo This category includes a wide variety of cargo ships from small one-hold vessels to highly advanced Multi-Purpose Vessels. Some of the ships are designed to carry containers as well as break bulk cargoes. Many of these ships are equipped with their own lifting gear.

Other dry These are carriers of refrigerated cargo and other special dry cargo ships.

Container These are pure container ships that are built to carry containerized cargo and nothing else, i.e. fully cellular ships designed to carry containers both on and under deck.

Vehicle These are ships designed to carry (new) cars, trucks and sometimes other special cargo on wheels.

RoRo These are ships that are loaded and discharged by driving the cargo onboard on wheels.

Ferry These ships carry cars and passengers on regular schedules. This also includes overnight ferries.

Cruise These ships carry passengers on pleasure voyages.

Yacht These are large pleasure vessels.

Offshore This category encompasses a wide range of platform supply and offshore support vessels. Drilling rigs are not included in this figure.

Service These are mainly tugs but also work boats, dredgers, research vessels and more.

Misc These are mainly fishing vessels. Pontoons are not included.

Scenario fleets

Projected World Fleets, Selected scenarios 2020

Projected	2020 World Fleets	Fairplay Estimate	Worst A1B	A1FI	A1B	A1T	A2	B1	B2	Best B2
	Scenario		30	14	41	68	95	122	149	160
	Demand (Level)		3	2	2	2	2	2	2	1
	Transport Eff. (Level)		1	2	2	2	2	2	2	3
	Speed Red. (Level)		1	2	2	2	2	2	2	3
01 Crude	A 200,000+ dwt	624	527	474	474	474	438	434	412	398
01 Crude	B 120 -199,999 dwt	560	473	425	425	425	393	389	370	357
01 Crude	C 80 -119,999 dwt	1116	942	847	847	847	782	776	737	712
01 Crude	D 60 -79,999 dwt	158	133	120	120	120	111	110	104	101
01 Crude	E 10 -59,999 dwt	198	167	150	150	150	139	138	131	126
01 Crude	F -9,999 dwt	118	151	136	136	136	131	124	124	117
02 Products	A 60,000+ dwt	705	595	535	535	535	494	490	466	450
02 Products	B 20 -59,999 dwt	804	678	610	610	610	564	559	531	513
02 Products	C 10 -19,999 dwt	159	134	121	121	121	111	111	105	101
02 Products	D 5 -9,999 dwt	737	942	848	848	848	815	776	776	732
02 Products	E -4,999 dwt	3912	5001	4499	4499	4499	4327	4121	4121	3888
03 Chemical	A 20,000+ dwt	2385	2013	1810	1810	1810	1672	1658	1575	1522
03 Chemical	B 10 -19,999 dwt	1188	1003	902	902	902	833	826	785	758
03 Chemical	C 5 -9,999 dwt	1355	1732	1558	1558	1558	1499	1427	1427	1347
03 Chemical	D -4,999 dwt	817	1044	940	940	940	904	861	861	812
04 LPG	A 50,000+ cbm	242	204	184	184	184	170	168	160	154
04 LPG	B -49,999 cbm	1105	1413	1271	1271	1271	1222	1164	1164	1098
05 LNG	A 200,000+ cbm	136	115	103	103	103	95	95	90	87
05 LNG	B -199,999 cbm	582	491	442	442	442	408	405	384	371
06 Other tanker	B Other	455	582	523	523	523	503	479	479	452
07 Bulker	A 200,000+ dwt	383	323	291	291	291	269	266	253	244
07 Bulker	B 100 -199,999 dwt	1600	1350	1215	1215	1215	1122	1113	1057	1021
07 Bulker	C 60 -99,999 dwt	2667	2251	2024	2024	2024	1870	1855	1762	1702

Projected	*2020 World Fleets*	*Fairplay*	*Worst*							*Best*
		Estimate	*A1B*	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario		*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)		*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)		*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)		*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
07 Bulker	D 35 -59,999 dwt	3176	2680	2411	2411	2411	2227	2208	2098	2027
07 Bulker	E 10 -34,999 dwt	2881	2431	2187	2187	2187	2020	2003	1903	1838
07 Bulker	F -9,999 dwt	1168	1493	1343	1343	1343	1292	1230	1230	1161
08 General cargo	A 10,000+ dwt	914	771	694	694	694	641	636	604	583
08 General cargo	B 5,000-9,999 dwt	1990	2544	2288	2288	2288	2201	2096	2096	1978
08 General cargo	C -4,999 dwt	10762	13759	12376	12376	12376	11904	11337	11337	10695
08 General cargo	D 10,000+ dwt, 100+ TEU	1347	1137	1022	1022	1022	944	937	890	859
08 General cargo	E 5,000-9,999 dwt, 100+ TEU	3144	4019	3616	3616	3616	3478	3312	3312	3124
08 General cargo	F -4,999 dwt, 100+ TEU	1500	1918	1725	1725	1725	1659	1580	1580	1491
09 Other dry	A Reefer	960	1227	1104	1104	1104	1062	1011	1011	954
09 Other dry	C Special	240	307	276	276	276	265	253	253	239
10 Container	A 8,000+ teu	1355	1332	1010	1010	1016	917	901	859	704
10 Container	B 5 -7,999 teu	952	936	710	710	714	644	633	604	495
10 Container	C 3 -4,999 teu	1562	1535	1165	1165	1171	1057	1039	991	812
10 Container	D 2 -2,999 teu	1033	1015	770	770	774	699	687	655	537
10 Container	E 1 -1,999 teu	2053	2017	1531	1531	1539	1389	1365	1302	1067
10 Container	F -999 teu	1534	1507	1144	1144	1150	1038	1020	973	797
11 Vehicle	A 4,000+ ceu	835	705	634	634	634	585	581	552	533
11 Vehicle	B -3,999 ceu	447	377	339	339	339	313	311	295	285
12 Roro	A 2,000+ lm	386	326	293	293	293	271	268	255	246
12 Roro	B -1,999 lm	1361	1740	1565	1565	1565	1505	1434	1434	1353
13 Ferry	A Pax Only, 25kn+	1132	1447	1302	1302	1302	1252	1192	1192	1125
13 Ferry	B Pax Only, <25kn	2303	2944	2648	2648	2648	2547	2426	2426	2289
13 Ferry	C RoPax, 25kn+	294	376	338	338	338	325	310	310	292
13 Ferry	D RoPax, <25kn	2635	3369	3030	3030	3030	2915	2776	2776	2619
14 Cruise	A 100,000+ gt	53	45	40	40	40	37	37	35	34

Projected	*2020 World Fleets*	*Fairplay*	*Worst*							*Best*
		Estimate	*A1B*	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario		*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)		*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)		*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)		*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
14 Cruise	B 60-99,999 gt	122	103	93	93	93	86	85	81	78
14 Cruise	C 10-59,999 gt	187	158	142	142	142	131	130	124	119
14 Cruise	D 2-9,999 gt	70	59	53	53	53	49	49	46	45
14 Cruise	E -1,999 gt	381	487	438	438	438	421	401	401	379
15 Yacht	Yacht	1652	2112	1900	1900	1900	1827	1740	1740	1642
16 Offshore	A Crew/Supply Vessel	990	1266	1138	1138	1138	1095	1043	1043	984
16 Offshore	B Platform Supply Ship	2506	3204	2882	2882	2882	2772	2640	2640	2490
16 Offshore	C Offshore Tug/Supply Ship	628	803	722	722	722	695	662	662	624
16 Offshore	D Anchor Handling Tug Supply	2040	2608	2346	2346	2346	2256	2149	2149	2027
16 Offshore	E Support/safety	656	839	754	754	754	726	691	691	652
16 Offshore	F Pipe (various)	272	348	313	313	313	301	287	287	270
16 Offshore	G FPSO, drill	328	419	377	377	377	363	346	346	326
17 Service	A Research	955	1221	1098	1098	1098	1056	1006	1006	949
17 Service	B Tug	15686	20054	18039	18039	18039	17350	16524	16524	15588
17 Service	C Dredging	1196	1529	1375	1375	1375	1323	1260	1260	1189
17 Service	D SAR & Patrol	1266	1619	1456	1456	1456	1400	1334	1334	1258
17 Service	E Workboats	1219	1558	1402	1402	1402	1348	1284	1284	1211
17 Service	F Other	923	1180	1061	1061	1061	1021	972	972	917
18 Misc	A Fishing	11691	14946	13445	13445	13445	12931	12316	12316	11618
18 Misc	B Trawlers	8358	10685	9612	9612	9612	9245	8805	8805	8306
18 Misc	C Other fishing	1056	1350	1214	1214	1214	1168	1112	1112	1049
18 Misc	E Other	787	1006	905	905	905	871	829	829	782
Total		**120992**	**141773**	**126356**	**126356**	**126388**	**120494**	**115592**	**114499**	**107705**

Projected World Fleets, Selected scenarios 2050

Projected	*2050 World Fleets*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
01 Crude	A 200,000+ dwt	1593	1284	1284	1284	1078	1058	933	868
01 Crude	B 120 -199,999 dwt	1430	1152	1152	1152	967	950	838	779
01 Crude	C 80 -119,999 dwt	2850	2296	2296	2296	1928	1893	1669	1552
01 Crude	D 60 -79,999 dwt	403	325	325	325	273	268	236	220
01 Crude	E 10 -59,999 dwt	506	407	407	407	342	336	296	275
01 Crude	F -9,999 dwt	301	246	243	243	221	200	200	175
02 Products	A 60,000+ dwt	1800	1450	1450	1450	1218	1196	1054	980
02 Products	B 20 -59,999 dwt	2053	1654	1654	1654	1389	1363	1202	1118
02 Products	C 10 -19,999 dwt	406	327	327	327	275	270	238	221
02 Products	D 5 -9,999 dwt	1882	1535	1516	1516	1383	1250	1250	1093
02 Products	E -4,999 dwt	9989	8150	8048	8048	7343	6634	6634	5804
03 Chemical	A 20,000+ dwt	6090	4907	4907	4907	4120	4045	3567	3317
03 Chemical	B 10 -19,999 dwt	3033	2444	2444	2444	2052	2015	1777	1652
03 Chemical	C 5 -9,999 dwt	3460	2823	2788	2788	2543	2298	2298	2010
03 Chemical	D -4,999 dwt	2086	1702	1681	1681	1533	1385	1385	1212
04 LPG	A 50,000+ cbm	618	498	498	498	418	410	362	337
04 LPG	B -49,999 cbm	2821	2302	2273	2273	2074	1874	1874	1639
05 LNG	A 200,000+ cbm	347	280	280	280	235	231	203	189
05 LNG	B -199,999 cbm	1486	1197	1197	1197	1005	987	870	809
06 Other tanker	B Other	1162	948	936	936	854	772	772	675
07 Bulker	A 200,000+ dwt	978	788	788	788	662	650	573	533
07 Bulker	B 100 -199,999 dwt	4085	3292	3292	3292	2764	2713	2393	2225
07 Bulker	C 60 -99,999 dwt	6810	5487	5487	5487	4607	4523	3989	3709
07 Bulker	D 35 -59,999 dwt	8109	6534	6534	6534	5486	5386	4750	4417
07 Bulker	E 10 -34,999 dwt	7356	5927	5927	5927	4976	4886	4309	4006

Projected	*2050 World Fleets*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
07 Bulker	F -9,999 dwt	2982	2433	2403	2403	2192	1981	1981	1733
08 General cargo	A 10,000+ dwt	2334	1880	1880	1880	1579	1550	1367	1271
08 General cargo	B 5,000-9,999 dwt	5081	4146	4094	4094	3735	3375	3375	2952
08 General cargo	C -4,999 dwt	27479	22421	22140	22140	20200	18251	18251	15967
08 General cargo	D 10,000+ dwt, 100+ TEU	3439	2771	2771	2771	2327	2284	2015	1873
08 General cargo	E 5,000-9,999 dwt, 100+ TEU	8028	6550	6468	6468	5901	5332	5332	4665
08 General cargo	F -4,999 dwt, 100+ TEU	3830	3125	3086	3086	2815	2544	2544	2225
09 Other dry	A Reefer	2451	2000	1975	1975	1802	1628	1628	1424
09 Other dry	C Special	613	500	494	494	450	407	407	356
10 Container	A 8,000+ teu	13500	7372	7543	7546	5959	5780	5174	3394
10 Container	B 5 -7,999 teu	9485	5179	5300	5302	4187	4061	3635	2384
10 Container	C 3 -4,999 teu	15562	8498	8696	8699	6869	6663	5964	3912
10 Container	D 2 -2,999 teu	10292	5620	5751	5753	4543	4407	3944	2587
10 Container	E 1 -1,999 teu	20454	11169	11429	11434	9029	8758	7839	5142
10 Container	F -999 teu	15283	8346	8540	8543	6746	6544	5857	3842
11 Vehicle	A 4,000+ ceu	2132	1718	1718	1718	1442	1416	1249	1161
11 Vehicle	B -3,999 ceu	1141	920	920	920	772	758	669	622
12 Roro	A 2,000+ lm	986	794	794	794	667	655	577	537
12 Roro	B -1,999 lm	3475	2835	2800	2800	2555	2308	2308	2019
13 Ferry	A Pax Only, 25kn+	2890	2358	2329	2329	2125	1920	1920	1679
13 Ferry	B Pax Only, <25kn	5880	4798	4738	4738	4323	3906	3906	3417
13 Ferry	C RoPax, 25kn+	751	613	605	605	552	499	499	436
13 Ferry	D RoPax, <25kn	6728	5490	5421	5421	4946	4469	4469	3909
14 Cruise	A 100,000+ gt	135	109	109	109	92	90	79	74
14 Cruise	B 60-99,999 gt	312	251	251	251	211	207	182	170
14 Cruise	C 10-59,999 gt	477	385	385	385	323	317	280	260

Projected	*2050 World Fleets*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
14 Cruise	D 2-9,999 gt	179	144	144	144	121	119	105	97
14 Cruise	E -1,999 gt	973	794	784	784	715	646	646	565
15 Yacht	Yacht	4218	3442	3399	3399	3101	2802	2802	2451
16 Offshore	A Crew/Supply Vessel	2528	2063	2037	2037	1858	1679	1679	1469
16 Offshore	B Platform Supply Ship	6399	5221	5155	5155	4704	4250	4250	3718
16 Offshore	C Offshore Tug/Supply Ship	1603	1308	1292	1292	1179	1065	1065	932
16 Offshore	D Anchor Handling Tug Supply	5209	4250	4197	4197	3829	3460	3460	3027
16 Offshore	E Support/safety	1675	1367	1350	1350	1231	1112	1112	973
16 Offshore	F Pipe (various)	695	567	560	560	511	461	461	404
16 Offshore	G FPSO, drill	837	683	675	675	616	556	556	487
17 Service	A Research	2438	1990	1965	1965	1793	1620	1620	1417
17 Service	B Tug	40052	32679	32270	32270	29442	26601	26601	23272
17 Service	C Dredging	3054	2492	2460	2460	2245	2028	2028	1774
17 Service	D SAR & Patrol	3233	2638	2604	2604	2376	2147	2147	1878
17 Service	E Workboats	3113	2540	2508	2508	2288	2067	2067	1809
17 Service	F Other	2357	1923	1899	1899	1732	1565	1565	1369
18 Misc	A Fishing	29851	24356	24051	24051	21944	19826	19826	17345
18 Misc	B Trawlers	21341	17413	17195	17195	15688	14174	14174	12400
18 Misc	C Other fishing	2696	2200	2172	2172	1982	1791	1791	1567
18 Misc	E Other	2009	1640	1619	1619	1477	1335	1335	1168
Total		**371834**	**279941**	**278705**	**278724**	**244917**	**227000**	**218409**	**185951**

Projected Carbon Fractions

Projected	*2050 Carbon Fractions*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	3	2	2	2	2	2	2	1
	Transport Eff. (Level)	1	2	2	2	2	2	2	3
	Speed Red. (Level)	1	2	2	2	2	2	2	3
01 Crude	A 200,000+ dwt	0,837	0,837	0,837	0,827	0,837	0,827	0,827	0,827
01 Crude	B 120 -199,999 dwt	0,837	0,837	0,837	0,827	0,837	0,827	0,827	0,827
01 Crude	C 80 -119,999 dwt	0,837	0,837	0,837	0,827	0,837	0,827	0,827	0,827
01 Crude	D 60 -79,999 dwt	0,837	0,837	0,837	0,827	0,837	0,827	0,827	0,827
01 Crude	E 10 -59,999 dwt	0,837	0,837	0,837	0,827	0,837	0,827	0,827	0,827
01 Crude	F -9,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
02 Products	A 60,000+ dwt	0,847	0,837	0,837	0,827	0,847	0,827	0,827	0,827
02 Products	B 20 -59,999 dwt	0,847	0,837	0,837	0,827	0,847	0,827	0,827	0,827
02 Products	C 10 -19,999 dwt	0,847	0,837	0,837	0,827	0,847	0,827	0,827	0,827
02 Products	D 5 -9,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
02 Products	E -4,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
03 Chemical	A 20,000+ dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
03 Chemical	B 10 -19,999 dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
03 Chemical	C 5 -9,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
03 Chemical	D -4,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
04 LPG	A 50,000+ cbm	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
04 LPG	B -49,999 cbm	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
05 LNG	A 200,000+ cbm	0,823	0,798	0,798	0,798	0,823	0,798	0,798	0,798
05 LNG	B -199,999 cbm	0,823	0,798	0,798	0,798	0,823	0,798	0,798	0,798
06 Other tanker	B Other	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
07 Bulker	A 200,000+ dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
07 Bulker	B 100 -199,999 dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
07 Bulker	C 60 -99,999 dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
07 Bulker	D 35 -59,999 dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
07 Bulker	E 10 -34,999 dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846

Projected	2050 Carbon Fractions	Worst							Best
		A1B	A1FI	A1B	A1T	A2	B1	B2	B2
	Scenario	30	14	41	68	95	122	149	160
	Demand (Level)	3	2	2	2	2	2	2	1
	Transport Eff. (Level)	1	2	2	2	2	2	2	3
	Speed Red. (Level)	1	2	2	2	2	2	2	3
07 Bulker	F -9,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
08 General cargo	A 10,000+ dwt	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
08 General cargo	B 5,000-9,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
08 General cargo	C -4,999 dwt	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
08 General cargo	D 10,000+ dwt, 100+ TEU	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
08 General cargo	E 5,000-9,999 dwt, 100+ TEU	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
08 General cargo	F -4,999 dwt, 100+ TEU	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
09 Other dry	A Reefer	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
09 Other dry	C Special	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
10 Container	A 8,000+ teu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
10 Container	B 5 -7,999 teu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
10 Container	C 3 -4,999 teu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
10 Container	D 2 -2,999 teu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
10 Container	E 1 -1,999 teu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
10 Container	F -999 teu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
11 Vehicle	A 4,000+ ceu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
11 Vehicle	B -3,999 ceu	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
12 Roro	A 2,000+ lm	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
12 Roro	B -1,999 lm	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
13 Ferry	A Pax Only, 25kn+	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
13 Ferry	B Pax Only, <25kn	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
13 Ferry	C RoPax, 25kn+	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
13 Ferry	D RoPax, <25kn	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
14 Cruise	A 100,000+ gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
14 Cruise	B 60-99,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
14 Cruise	C 10-59,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850

Projected	2050 Carbon Fractions	Worst							Best
		A1B	A1FI	A1B	A1T	A2	B1	B2	B2
	Scenario	30	14	41	68	95	122	149	160
	Demand (Level)	3	2	2	2	2	2	2	1
	Transport Eff. (Level)	1	2	2	2	2	2	2	3
	Speed Red. (Level)	1	2	2	2	2	2	2	3
14 Cruise	D 2-9,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
14 Cruise	E -1,999 gt	0,850	0,825	0,825	0,800	0,850	0,800	0,800	0,800
15 Yacht	Yacht	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
16 Offshore	A Crew/Supply Vessel	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
16 Offshore	B Platform Supply Ship	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
16 Offshore	C Offshore Tug/Supply Ship	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
16 Offshore	D Anchor Handling Tug Supply	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
16 Offshore	E Support/safety	0,823	0,822	0,822	0,798	0,823	0,798	0,798	0,798
16 Offshore	F Pipe (various)	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
16 Offshore	G FPSO, drill	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
17 Service	A Research	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
17 Service	B Tug	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
17 Service	C Dredging	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
17 Service	D SAR & Patrol	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
17 Service	E Workboats	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
17 Service	F Other	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
18 Misc	A Fishing	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
18 Misc	B Trawlers	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
18 Misc	C Other fishing	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846
18 Misc	E Other	0,847	0,846	0,846	0,846	0,847	0,846	0,846	0,846

Projected	*2020 Carbon Fractions*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
01 Crude	A 200,000+ dwt	0,846	0,846	0,846	0,841	0,846	0,841	0,841	0,841
01 Crude	B 120 -199,999 dwt	0,846	0,846	0,846	0,841	0,846	0,841	0,841	0,841
01 Crude	C 80 -119,999 dwt	0,846	0,846	0,846	0,841	0,846	0,841	0,841	0,841
01 Crude	D 60 -79,999 dwt	0,846	0,846	0,846	0,841	0,846	0,841	0,841	0,841
01 Crude	E 10 -59,999 dwt	0,846	0,846	0,846	0,841	0,846	0,841	0,841	0,841
01 Crude	F -9,999 dwt	0,841	0,841	0,841	0,879	0,841	0,879	0,879	0,879
02 Products	A 60,000+ dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
02 Products	B 20 -59,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
02 Products	C 10 -19,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
02 Products	D 5 -9,999 dwt	0,841	0,841	0,841	0,837	0,841	0,837	0,837	0,837
02 Products	E -4,999 dwt	0,841	0,841	0,841	0,837	0,841	0,837	0,837	0,837
03 Chemical	A 20,000+ dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
03 Chemical	B 10 -19,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
03 Chemical	C 5 -9,999 dwt	0,841	0,841	0,841	0,837	0,841	0,837	0,837	0,837
03 Chemical	D -4,999 dwt	0,841	0,841	0,841	0,837	0,841	0,837	0,837	0,837
04 LPG	A 50,000+ cbm	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
04 LPG	B -49,999 cbm	0,841	0,841	0,841	0,837	0,841	0,837	0,837	0,837
05 LNG	A 200,000+ cbm	0,798	0,798	0,798	0,798	0,798	0,798	0,798	0,798
05 LNG	B -199,999 cbm	0,798	0,798	0,798	0,798	0,798	0,798	0,798	0,798
06 Other tanker	B Other	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
07 Bulker	A 200,000+ dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
07 Bulker	B 100 -199,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
07 Bulker	C 60 -99,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
07 Bulker	D 35 -59,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
07 Bulker	E 10 -34,999 dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
07 Bulker	F -9,999 dwt	0,841	0,841	0,841	0,837	0,841	0,837	0,837	0,837

Projected	*2020 Carbon Fractions*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	3	2	2	2	2	2	2	1
	Transport Eff. (Level)	1	2	2	2	2	2	2	3
	Speed Red. (Level)	1	2	2	2	2	2	2	3
08 General cargo	A 10,000+ dwt	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
08 General cargo	B 5,000-9,999 dwt	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
08 General cargo	C -4,999 dwt	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
08 General cargo	D 10,000+ dwt, 100+ TEU	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
08 General cargo	E 5,000-9,999 dwt, 100+ TEU	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
08 General cargo	F -4,999 dwt, 100+ TEU	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
09 Other dry	A Reefer	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
09 Other dry	C Special	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
10 Container	A 8,000+ teu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
10 Container	B 5 -7,999 teu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
10 Container	C 3 -4,999 teu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
10 Container	D 2 -2,999 teu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
10 Container	E 1 -1,999 teu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
10 Container	F -999 teu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
11 Vehicle	A 4,000+ ceu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
11 Vehicle	B -3,999 ceu	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
12 Roro	A 2,000+ lm	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
12 Roro	B -1,999 lm	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
13 Ferry	A Pax Only, 25kn+	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
13 Ferry	B Pax Only, <25kn	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
13 Ferry	C RoPax, 25kn+	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
13 Ferry	D RoPax, <25kn	0,840	0,840	0,840	0,840	0,840	0,840	0,840	0,840
14 Cruise	A 100,000+ gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
14 Cruise	B 60-99,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
14 Cruise	C 10-59,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
14 Cruise	D 2-9,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850

Projected	*2020 Carbon Fractions*	*Worst*							*Best*
		A1B	*A1FI*	*A1B*	*A1T*	*A2*	*B1*	*B2*	*B2*
	Scenario	*30*	*14*	*41*	*68*	*95*	*122*	*149*	*160*
	Demand (Level)	*3*	*2*	*2*	*2*	*2*	*2*	*2*	*1*
	Transport Eff. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
	Speed Red. (Level)	*1*	*2*	*2*	*2*	*2*	*2*	*2*	*3*
14 Cruise	E -1,999 gt	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
15 Yacht	Yacht	0,850	0,850	0,850	0,850	0,850	0,850	0,850	0,850
16 Offshore	A Crew/Supply Vessel	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
16 Offshore	B Platform Supply Ship	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
16 Offshore	C Offshore Tug/Supply Ship	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
16 Offshore	D Anchor Handling Tug Supply	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
16 Offshore	E Support/safety	0,841	0,841	0,841	0,841	0,841	0,841	0,841	0,841
16 Offshore	F Pipe (various)	0,846	0,841	0,841	0,841	0,841	0,841	0,841	0,841
16 Offshore	G FPSO, drill	0,846	0,841	0,841	0,841	0,841	0,841	0,841	0,841
17 Service	A Research	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
17 Service	B Tug	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
17 Service	C Dredging	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
17 Service	D SAR & Patrol	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
17 Service	E Workboats	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
17 Service	F Other	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
18 Misc	A Fishing	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
18 Misc	B Trawlers	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
18 Misc	C Other fishing	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846
18 Misc	E Other	0,846	0,846	0,846	0,846	0,846	0,846	0,846	0,846