CO₂ EMISSIONS STATISTICS FOR THE WORLD COMMERCIAL FLEET¹

Harilaos N. Psaraftis and Christos A. Kontovas
Laboratory for Maritime Transport
National Technical University of Athens
Greece

August 2008
Revised: October 2008

Abstract

Carbon dioxide (CO₂) emissions from commercial shipping are currently unregulated, but nevertheless they are a subject of intense scrutiny by the world shipping community. According to the Kyoto protocol, definite measures to reduce CO₂ emissions are necessary in order to curb the projected growth of greenhouse gases (GHG) worldwide. Shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO₂ and other GHGs, but it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO₂ growth are being sought with a high sense of urgency. Various analyses of many aspects of the problem have been and are being carried out and a spectrum of measures are being contemplated. It is clear that a reliable emissions inventory is essential for both scientists and policy-makers in order to formulate and evaluate the implementation of relevant regulations. To contribute to this debate and possibly complement other studies on the subject, the authors of this paper have conducted their own analysis on emissions of the world fleet database and can herein present some preliminary results of the emissions statistics of the following major ship types: bulk carriers, crude oil tankers, container vessels, product/chemical carriers, LNG carriers, LPG carriers, reefer vessels, Ro-Ro vessels and general cargo ships. A separate analysis was carried out for small vessels under 400 GRT and for passenger vessels.

Key words: Ship CO₂ emissions, Ship Air Pollution

1. Introduction

Carbon dioxide (CO₂) emissions from commercial shipping are currently unregulated. Nevertheless, they are a subject of intense scrutiny by the world shipping community. According to the Kyoto protocol to the United Nations Framework Convention on Climate Change -UNFCCC (1997), definite measures to reduce CO₂ emissions are necessary in order to curb the projected growth of greenhouse gases (GHG) worldwide. Shipping has thus far escaped being included in the Kyoto global emissions reduction target for CO₂ and other GHGs, but it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO₂ growth are being sought with a high sense of urgency. CO₂ is the most prevalent of these GHGs, and it is therefore clear that any set of measures to reduce the latter should primarily focus on CO₂. In parallel, the broader analysis of other greenhouse gases (such as CH₄ and N₂O) and other, non-greenhouse gases, such as SO₂, NOₓ and others is already very high on the International Maritime Organization’s (IMO) agenda. Various analyses of many aspects of the problem have been and are being carried out and a spectrum of measures are being contemplated. It is clear that a reliable emissions inventory is essential for both scientists and policy-makers in order to formulate and evaluate the implementation of relevant regulations.

To contribute to this debate and possibly complement other studies on the subject, the authors of this paper have conducted their own analysis on emissions of the world fleet database (as provided by Lloyds Fairplay for year 2007) and can herein present some preliminary results of the emissions statistics of the following major ship types: bulk carriers, crude oil tankers, container vessels, product/chemical carriers, LNG carriers, LPG carriers, reefer vessels, Ro-Ro vessels and general cargo ships. A separate analysis was carried out for small vessels under 400 GRT and for passenger vessels. The study was conducted by the National Technical University of Athens (Laboratory for Maritime Transport) for the Hellenic Chamber of Shipping (HCS).

The study had the following objectives: (a) develop a web-based tool for calculating the exhaust gas emissions (CO$_2$, SO$_2$ and NO$_x$) of specific types of ships under a variety of operational scenarios, and (b) produce various statistics of CO$_2$ emissions, based on data from the world fleet database.

Reporting on objective (a) is outside the scope of this paper and is done elsewhere. The reader is referred to the study’s public final report for more details (see Psaraftis and Kontovas, 2008). The emissions web tool is freely available on-line$^2$ and is the analog of what some airlines have available on their web sites (tools available on-line) and of what some container lines have available for their customers (tools not available on-line).

One main output statistic of the analysis of this paper is the ratio of emitted grams of CO$_2$ per tonne-km of transported cargo in a year. The authors of this paper consider this statistic (which has been used for other transport modes as well) as reasonably representative of a vessel’s environmental performance in an operational setting. Another emissions statistic is an estimate of total CO$_2$ emitted (in million tonnes per year) per size bracket for the above ship types (as compared to billions of tonne-kilometers carried by the same size bracket). Such statistics, and some others, have been estimated for a variety of ship types and sizes and under a variety of scenarios as regards sea-to-port time, ship speed and fuel consumption at sea and in port. Some sensitivity analysis of these results has also been conducted.

The rest of this paper is organized as follows. Section 2 reports on relevant literature. Section 3 describes the methodology used in the paper. Section 4 describes the runs performed on the world shipping database. Section 5 comments on comparison with other studies and other modes. Finally Section 6 presents the paper’s conclusions.

2. Relevant Literature

Looking at the literature on the broad area of this paper (including both scientific work and regulation-related documents- IMO and others), it is no surprise that the relevant material is immense. MEPC 57$^3$ alone had some 65 submissions, and the GHG intersessional group meeting in Oslo, Norway in June of 2008 had some 20 submissions. Still, we collected and studied a large number of such documents by focusing (a) on relations linking parameters such as bunker consumption, engine type and horsepower, to produced emissions of various exhaust types, (b) on data that can be used as inputs for our study (for instance, bunker consumption for various ship types) and (c) on various other reported statistics (for instance, bunker consumption). The latest documents that were reviewed before the study was completed were related to recent submissions to MEPC 57 and to BLG 12$^4$. After the study was completed, and as this paper was being written, we also had the privilege of reviewing

$^2$ Please go to www.martrans.org/emis.
$^3$ MEPC: IMO’s Marine Environment Protection Committee. MEPC 57 is the committee’s 57th session, held in London on March 31- April 4, 2008.
$^4$ BLG: IMO’s Subcommittee on Bulk Liquids and Gases. BLG 12 is the subcommittee’s 12th session, held in London, on February 4-8, 2008.
the results of Phase 1 of the update the 2000 IMO GHG Study (Buhaug et al (2008)), which were presented at MEPC 58 (London, October 2008). More on this will be reported in section 5.1.

Among the number of related IMO documents, perhaps the most seminal one from 2000 to mid-2008 was IMO (2000), in which an international consortium led by Marintek (Norway) delivered a report on GHG emissions from ships which included an estimation of the 1996 emissions inventory and the examination of emission reduction possibilities through technical, operational and market-based approaches.

The Secretary-General of the IMO at MEPC 56 (London, July 2007) proposed the setting up of an informal Cross Government/Industry Scientific Group of Experts to evaluate the effects of the different fuel options proposed under the revision of MARPOL Annex VI and the NOx Technical Code. IMO(2007a) presented the inputs from the four subgroups to the final report. Among others, there is a section which contains the estimations of the fuel consumption and emissions for 2007 as well as the predicted trends leading to 2020. IMO(2007b) is the report on the outcome of this group of experts.

In addition, IMO (2008a) provided general viewpoints on the issue of GHG emissions and foremost CO$_2$ and encouraged the IMO to take early action. IMO (2008b) proposed the development of a mandatory CO$_2$ design index for new ships that reflects only the technical performance and IMO(2008d) provided relevant information to this proposal, namely a study by Det Norske Veritas according to which a design index appears to be a feasible policy instrument to reduce CO$_2$ emissions. Besides, IMO (2008c) proposed a practical index of CO$_2$ emissions taking into account actual shipping conditions. Additional proposals (too recent to review here) were made at MEPC 58 (London, October 2008).

Outside IMO documents, detailed methodologies for constructing fuel-based inventories of ship emissions have been published by Corbett and Köhler (2003), Endresen et al (2003, 2007), Eyring et al (2005), and in EMEP/CORINAIR (2002). The third edition of the Atmospheric Emission Inventory Guidebook was released by the EMEP Task Force on Emission Inventories. The guidebook outlined two methodologies (simple and detailed) for reporting national marine emissions for EU member states. The emission factors that were recommended in EMEP/CORINAIR in their 1999 study are widely used in the estimation of emission inventories (see, for example, IMO(2000) and EMEP/CORINAIR(2002)).

Corbett and Köhler (2003) estimate global fuel consumption for ships greater than 100 GRT by using engine power and vessel activity data. Shipping transport was derived from the Comprehensive Ocean-Atmosphere Set (ICOADS). Endresen et al (2003) did a similar work but improved the spatial representation of global ship air emissions by weighting ship reporting frequencies using the Automated Mutual-assistance Vessel Rescue system (AMVER) data set.

The estimates of fuel consumption and emissions derived by Endresen et al. (2003; 2007) were significantly lower than those in Corbett and Köhler (2003) and Eyring et al. (2005). These differences have given rise to a debate about the veracity of the methods and results in the respective studies. The key input differences are the assumed utilization of installed engine power and the number of days vessels are assumed to spend at sea. Furthermore, the Endersen et al (2003) comment on Corbett’s and Köhler’s work led to a new paper from Corbett and Köhler (2004) where they published an updated version of their estimations by considering alternative input parameters in their activity-based model.

3. Methodology
3.1 Emissions factor

CO₂ emissions in our study were calculated as follows. Fuel consumption was used as the main input, as opposed to horsepower, since fuel consumption data was the main input data that was solicited and received. Then, independent of type of fuel, one multiplies total bunker consumption (in tonnes per day) by a factor of 3.17 to compute CO₂ emissions (in tonnes per day).

The 3.17 CO₂ factor has been the empirical mean value most commonly used in CO₂ emissions calculations based on fuel consumption (see EMEP/CORINAIR (2002) Table 8.1). According to the IMO GHG study (IMO, 2000), the actual value of this coefficient may range from 3.159 (low value) to 3.175 (high value), that is, the maximum variation differential is about 0.5%.

Ship horsepower information was also used occasionally, in the event actual fuel consumption was not available. In this case, fuel consumption was computed indirectly, as proportional to the total kilowatt-hours (kWh) consumed, with the coefficient of proportionality taken on a case by case basis.

3.2 Data collection

Incredible as this may seem, no reliable world bunker sales data exists that can be used to accurately estimate world fleet fuel consumption. In fact, all emissions studies that we have seen use modelling to estimate fuel consumption on board a ship, mainly in order to convert engine horsepower to fuel consumption. Our study’s approach was to try using fuel consumption information (on a per ship basis) directly as an input, and only if such information was not available, compute it by other methods, for instance via engine horsepower. Thus, and for the purposes of this study, the Hellenic Chamber of Shipping (HCS) solicited from its members and provided to the authors a variety of data, and said data was subsequently analyzed. Solicited data included:

- Ship type
- Year of built
- DWT
- Average cargo payload per laden trip
- Engine type
- Horsepower
- Speed (laden, ballast)
- Time in port (loading, discharging)
- Fuel type (sea, port)
- Fuel consumption (sea/laden, sea/ballast)- by type of fuel
- Fuel consumption (port/loading, port/discharging)- by type of fuel

Variants of such data for specific ship types (for instance, number of passengers for passenger ships) were also solicited.

We should clarify here that although perhaps a primary use of such data was for the study’s web tool, the data was also used as a valuable real-data cross-reference for the analysis of the world fleet.

---

5 The update of the IMO 2000 study (Buhaug et al (2008)) uses slightly lower coefficients, different for Heavy Fuel Oil and for Marine Diesel Oil. If the new coefficients are adopted, our emission statistics will have to be proportionally scaled down (less than 5%), but the major conclusions of our study will not change.
The response to the data solicitation was very good. Some 29 member companies responded, providing data for some 375 ships of various types and covering a broad spectrum of ship types and sizes. On the down side, data collected was of non-homogeneous quality, and quite some time was spent to sift through it. Some companies provided details, some not. Format was also non-homogeneous. As a result, data was missing in many instances, including times in port (loading, discharging) and type of fuel used, at sea and in port.

To alleviate these deficiencies, contact was made with selected companies to collect the missing data. Search through the internet and other sources (such as Clarksons) was also made to complement data that was (and still is) missing.

3.3 Algebra of emissions

Assuming we have the data, the approach for computing emissions per tonne-km is straightforward. In the simplest scenario, assume a ship that carries a cargo payload of $W$ (tonnes) from point A to point B, which are L kilometers apart, going laden from A to B at speed $V$ (km/day) and returning empty on ballast at speed $v$ (km/day). $W$ is a function of ship’s deadweight and its capacity utilization, and the ship’s deadweight is an upper bound to it. If cargo quantities and speeds are given in units different from the above (eg, short tons or knots), appropriate conversions are made. Ship spends time $T$ (days) loading at port A and time $t$ (days) discharging at port B.

Although obviously for some categories of vessels (for instance, container vessels) the assumption of a symmetric route in which the ship is full in one direction and empty in the other is factually not valid, this was made only for uniformity and comparison purposes, and for the web tool only. An extension to cover cases of routes with multiple port stops and the ship being partially full in all legs or sailing triangular routes would be straightforward. Such extension would take as input the entire route sequence, the distance of each leg, the port time in each port stop and the ship’s capacity utilization (from 0 to 100%) on each route leg.

Assume also the following known fuel consumptions (all in tonnes per day):

At loading port, $G$
At sea, laden, $F$
At discharging port, $g$
At sea, on ballast, $f$.

In essence, both $F$ and $f$ are functions of speeds $V$ and $v$ respectively, a cube law applying in each case. That is, $F$ is proportional to the cube of $V$ and $f$ is proportional to the cube of $v$. The coefficients of proportionality are not the same, as ship sails laden in the first case and on ballast in the second case. As all fuel consumptions are assumed known, the cube law will not be used here, as its use would only be if variations on fuel consumption versus speed were to be studied (which is not the case).

Alternatively, both $F$ and $f$ can be considered functions of the horsepowers that are for sailing laden and on ballast at speeds $V$ and $v$ respectively. Coefficients of grams of fuel spent per kWh exist and are provided by the engine manufacturers, but such coefficients will not be used in our study except in cases fuel consumption information is missing. So unless otherwise noted, we shall assume that fuel consumptions are known.

Based on the above, it is straightforward to compute the following variables:

Transit time from A to B (days): $L/V$
Transit time from B to A (days): $L/v$
Total fuel consumption per round-trip (tonnes): GT + FL/V + gt + fL/v
Total tonne-km’s carried per round-trip: WL
Total CO₂ produced in this round-trip: 3.17(GT + FL/V + gt + fL/v)
CO₂ per tonne-km for this round-trip: 3.17(GT + FL/V + gt + fL/v)/WL
= 3.17[(GT+gt)/L + F/V+ f/v]/W

Tonne-km’s for this scenario are computed by multiplying the amount of cargo carried on the laden part of the trip by the appropriate distance. Zero tonne-km’s are registered in the ballast leg of the trip (although obviously this leg, plus times in port, do count as far as exhaust gases are concerned).

One can see that CO₂ per tonne-km is a decreasing function of distance L, which makes sense since the less the ship travels, the more time it spends fuel without hauling cargo (something that increases its per tonne-km emissions). It is also a decreasing function of the speeds V and v, but this is misleading, as F and f are cubic functions of these speeds. In that sense, CO₂ per tonne-km is a quadratic function of ship speed.

The analysis is slightly different, but similar in spirit, if we do not have information on parameters L, T and t, but only aggregate information on percentages of sea-to-port times through the year. In this case we assume that we are given again the ship’s payload W, and we assume the ship to be operational during a period of D days per year (where D is a user input ≤ 365). Then we assume to know s, the fraction of D the ship is at sea (0 ≤ s ≤ 1). Then the fraction of D the ship is at port is p = 1-s.

Then,
Sea days in a year: sD
Port days in a year: pD
(and idle days in a year: 365-D)

In the analysis of the world ship database, and for each ship type and size bracket combination, an average fuel consumption of F (tonnes/day) was assumed for the sea voyage, and an average fuel consumption of G (tonnes/day) was assumed in port. An average speed of V was assumed for the sea voyage, and an average cargo capacity utilization of w (0 < w < 1) is assumed for all sea legs. If a ship travels full in one direction and empty on ballast, then w=0.5, but in case of triangular routes w could be higher than 0.5.

Then we would have (for the specific ship under consideration):

Sea kilometers in a year (km): sDV
Total fuel consumption in a year (tonnes): (sF + pG)D
Total CO₂ in a year (tonnes): 3.17(sF + pG)D
Total tonne-km’s in a year: (wW)(sDV)
CO₂ per tonne-km: 3.17(sDF + pDG)/wWsDV = 3.17(sF+pG)/wWV

= 3.17[F +(p/s)G]/wWV

Total tonne-km’s here are computed by multiplying the average payload carried by the ship when at sea (wW) by the total sea kilometers traveled by the ship in a year (sDV). Note that in the absence of trip distance information, it is impossible to know the total amount of cargo hauled in a year by a ship, although the equivalent tonne-km’s can be estimated. In fact, one can have two identical ships A and B, with ship A engaged in a trade with trip distance double that of ship B. If fractions s and p are the same for both ships, both would register the same tonne-km’s in a year, but the total amount of cargo carried by ship A would be half of that carried by ship B.
Some more observations are in order: First, it is interesting to see that, as much as total CO₂ emitted is an increasing (in fact, linear) function of D (days per year the ship is operational), the total CO₂ emitted per tonne-km is independent of D (which is probably not a surprise). Second, as much as total CO₂ emitted is –as expected- an increasing function of the sea-to-port time ratio (s/p), the per tonne-km emissions statistic is a decreasing function of that ratio. This is similar to the previous result that CO₂ emitted per tonne-km is a decreasing function of trip distance L. If this result looks counter-intuitive, it is not, since while in port the ship on the one hand produces emissions that are lower than those produced at sea (on a per day basis), on the other hand in port the ship hauls zero cargo, thus produces zero tonne-km’s, and this is what is the decisive factor.

As before, an inverse relationship with speed V is seen, but this is again misleading as F is a cubic function of V, therefore overall the CO₂ produced per tonne-km is a quadratic function of speed.

In addition to the above, we could also compute other statistics on a fleet or size bracket basis, such as total bunkers consumed, total CO₂ produced, and others (see also next section).

In case of pure passenger vessels, W should be replaced by the passenger number and statistics should be in terms of CO₂ per passenger-km.

More difficult is the issue what should be the denominator for Ro-Pax vessels, which carry a combination of passengers, private cars, buses, motor-cycles, and trucks carrying cargo. Theoretically, both calculations can be performed, one with W being the cargo payload, and one with W being the passenger number. However, such ships are typically used in a mixed mode, making virtually impossible to apportion CO₂ emissions among passengers, and among each of vehicle categories being carried, including trucks carrying cargo. A fortiori, doing this on a per tonne-km basis is practically impossible and maybe even meaningless. On top of that, it turned out that in the analysis of the Lloyds Fairplay database there was difficulty of obtaining reliable and representative fuel consumption data for this category of ships. As a result of all this, no per tonne-km statistic was produced for passenger ships.

It should also be mentioned that for any specialized category of ships, different emissions statistics can conceivably be produced. For instance, for containerships one can compute grams of CO₂ per TEU-km and for car carriers grams of CO₂ per car-km, where “car” is the unit for a private car. For uniformity and comparison purposes, no such statistics were produced in this study, but this would be possible if specialized analyses in these or other sectors are conducted.

4. Runs of world fleet database

4.1 Main runs

The analysis of the world fleet database (source: Lloyds Fairplay) was extensive and has produced CO₂ emission statistics for the following ship types, broken down in several size brackets for each type: bulk carriers, crude oil tankers, container vessels, product/chemical carriers, LNG carriers, LPG carriers, reefer vessels, Ro-Ro vessels and general cargo ships. A separate analysis was carried out for small vessels under 400 GRT and for passenger vessels. The main output of the analysis for each ship type and size bracket has been the ratio of emitted grams of CO₂ per tonne-km of transported cargo in a year. Another output has been the total CO₂ produced per size bracket for the above ship types. All this has been estimated under a variety of scenarios as regards sea-to-port time, ship speed and fuel consumption at sea and in port. Some sensitivity analysis of these results has also been conducted.
It should be mentioned that whereas the Lloyds-Fairplay ship database (Lloyds Maritime Information Services, 2007) includes some 100,293 vessels greater than 100 GRT. 49,748 of these are either non-commercial or non self-propelled ships, including barges, dredgers, drilling ships, fishing vessels, fire-fighting vessels, ice-breakers, offshore vessels, tugs, naval vessels, and a variety of others. The analysis carried out concerns the rest of the database (50,545 vessels) and includes cargo and passenger vessels. This subgroup represents 95% of the total gross tonnage of the ocean-going fleet and is mostly relevant for the IMO as the provisions of MARPOL’s Annex VI concern commercial ships of 400 GRT and above and oil tankers of 150 GRT and above.

This subgroup of the fleet was further broken down into major categories of ships such as bulk carriers, crude oil carriers and containerships, among others. A number of vessels (4,925) were left out of the analysis either because of insufficient data (for example no registered engine horse power), or because they did not belong to any major category (for example non-crude oil tankers such as sulphur tankers, water tankers, other unspecified tankers, non-dry bulk carriers, livestock carriers and others). With these vessels excluded, our analysis was carried out using data from 45,620 vessels. As the 4,925 vessels that were left out are typically of very small size, it is speculated that their effect on overall emissions statistics, should they be eventually included in the analysis, would be very small.

Details of this analysis are included herein and in the Annex of this document.

The Lloyds-Fairplay world fleet database (2007) was broken down by ship type and size bracket as follows (Table 1).

### Table 1: Break down of world fleet database

<table>
<thead>
<tr>
<th>Vessel type DWTx1000</th>
<th>Number of vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small Vessels 0-5'</td>
<td>517</td>
</tr>
<tr>
<td>Coastal 5-15'</td>
<td>236</td>
</tr>
<tr>
<td>Handysize 15'-35'</td>
<td>1,774</td>
</tr>
<tr>
<td>Handymax 35'-60'</td>
<td>1,732</td>
</tr>
<tr>
<td>Panamax 60'-85'</td>
<td>1,383</td>
</tr>
<tr>
<td>Post-Panamax 85'-120'</td>
<td>98</td>
</tr>
<tr>
<td>Capesize &gt;120'</td>
<td>722</td>
</tr>
<tr>
<td><strong>Total Dry Bulk</strong></td>
<td><strong>6,462</strong></td>
</tr>
<tr>
<td>Feeder 0-500 TEU</td>
<td>363</td>
</tr>
<tr>
<td>Feedermax 500-1000</td>
<td>757</td>
</tr>
<tr>
<td>Handysize 1000-2000</td>
<td>1,143</td>
</tr>
<tr>
<td>Sub-Panamax 2000-3000</td>
<td>689</td>
</tr>
<tr>
<td>Panamax 3000-4400</td>
<td>568</td>
</tr>
<tr>
<td>Post Panamax &gt;4400</td>
<td>712</td>
</tr>
<tr>
<td><strong>Total Container</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vessel type DWTx1000</th>
<th>Number of vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reefer 0-5</td>
<td>508</td>
</tr>
<tr>
<td>Reefer 5-10</td>
<td>358</td>
</tr>
<tr>
<td>Reefer &gt;10</td>
<td>225</td>
</tr>
<tr>
<td><strong>Total Reefer</strong></td>
<td><strong>1,091</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vessel type DWTx1000</th>
<th>Number of vessels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Product, chemical 0-5'</td>
<td>3125</td>
</tr>
<tr>
<td>Product, chemical 5'-15'</td>
<td>1407</td>
</tr>
<tr>
<td>Product, chemical 15'-25'</td>
<td>430</td>
</tr>
<tr>
<td>Product, chemical 25'-40'</td>
<td>643</td>
</tr>
<tr>
<td>Product, chemical 40'-60</td>
<td>705</td>
</tr>
<tr>
<td>Product, chemical &gt;60</td>
<td>238</td>
</tr>
<tr>
<td><strong>Total Chemical</strong></td>
<td></td>
</tr>
<tr>
<td>Category</td>
<td>Count</td>
</tr>
<tr>
<td>------------------------</td>
<td>-------</td>
</tr>
<tr>
<td>Small tanker 0-10</td>
<td>115</td>
</tr>
<tr>
<td>Handysize 10-60</td>
<td>240</td>
</tr>
<tr>
<td>Panamax 60-80</td>
<td>177</td>
</tr>
<tr>
<td>Aframax 80-120</td>
<td>648</td>
</tr>
<tr>
<td>Suezmax 120-200</td>
<td>332</td>
</tr>
<tr>
<td>VLCC/ULCC &gt;200</td>
<td>516</td>
</tr>
<tr>
<td><strong>Total Crude oil</strong></td>
<td><strong>2,028</strong></td>
</tr>
<tr>
<td>LNG 0-50</td>
<td>29</td>
</tr>
<tr>
<td>LNG &gt;50</td>
<td>221</td>
</tr>
<tr>
<td><strong>Total LNG</strong></td>
<td><strong>250</strong></td>
</tr>
<tr>
<td>LPG 0-5</td>
<td>651</td>
</tr>
<tr>
<td>LPG 5-20</td>
<td>235</td>
</tr>
<tr>
<td>LPG 20-40</td>
<td>68</td>
</tr>
<tr>
<td>LPG &gt;40</td>
<td>135</td>
</tr>
<tr>
<td><strong>Total LPG</strong></td>
<td><strong>1,089</strong></td>
</tr>
<tr>
<td>RO-RO excl. Pax 0-5000</td>
<td>932</td>
</tr>
<tr>
<td>RO-RO excl. Pax 5-15</td>
<td>674</td>
</tr>
<tr>
<td>RO-RO excl. Pax 15-25</td>
<td>342</td>
</tr>
<tr>
<td>RO-RO excl. Pax 25-40</td>
<td>51</td>
</tr>
<tr>
<td><strong>Total RO-RO</strong></td>
<td><strong>1,999</strong></td>
</tr>
<tr>
<td>General Cargo 0-5</td>
<td>9,009</td>
</tr>
<tr>
<td>General Cargo 5-15</td>
<td>3,014</td>
</tr>
<tr>
<td>General Cargo 15-35</td>
<td>816</td>
</tr>
<tr>
<td><strong>Total General Cargo</strong></td>
<td><strong>12,839</strong></td>
</tr>
<tr>
<td><strong>SUBTOTAL: 36,538 vessels</strong></td>
<td></td>
</tr>
<tr>
<td>Other categories</td>
<td></td>
</tr>
<tr>
<td>Vessels 0-400 GT</td>
<td>6,281</td>
</tr>
<tr>
<td>Passenger Vessels (&gt;400GT)</td>
<td>2,801</td>
</tr>
<tr>
<td><strong>TOTAL: 45,620 vessels</strong></td>
<td></td>
</tr>
</tbody>
</table>

The “base-case” scenario is presented in Table 2 below, which shows the selected size brackets for the examined vessel categories. For each ship type and size bracket, sea and port fuel consumption figures have been estimated from the data solicited from shipping companies operating ships within these brackets and from other sources. We believe that the use of real data for this part of the input provides an advantage over studies that use only modelling to estimate fuel consumption and emission statistics.
One critical source of uncertainty in this analysis concerned the values of sea-to-port time ratios (s/p) that were used for the above type-size combinations. In reality, these ratios may vary even within the same ship type and size category, and the only way to ascertain them with precision would be to perform an analysis of all ship movements worldwide. As this was way outside the scope of our study, we took both parameters s and p as best estimates, after discussions with industry representatives and perusal of other sources. In our study these ratios ranged from 70/30 to 80/20, depending on ship type and size, and parameter D (operational days per year) was assumed equal to 320 days. Even though the per tonne-km emission statistics do not depend on this value, the absolute emissions statistics have a linear relationship with it, and it is our conjecture that the assumed value of 320 days overestimates D (and therefore the absolute levels of fuel consumption and emissions). In fact, Corbett et al (2004) and Endresen et al (2004) in their activity-based calculations (see Table 3 below) use a parameter D that varies from 240 to 300 days. In that sense, our calculations are more conservative. But even in an extreme scenario of uniformly assuming 355 operational days per year, total CO2 emissions from cargo vessels would rise 10% versus ours.
It is also clear that alternative estimates on fractions s and p (of sea and port time) would produce different results on all of the statistics of Table 2. However, sensitivity analysis on the s/p ratio has revealed negligible changes in the CO$_2$ per tonne-km statistics of the larger size vessel categories, and larger (but still small) changes in the smaller size categories, irrespective of ship type. For instance, varying this ratio even outside the above range from 60/40 to 90/10 in the Capesize bulker category would only reduce its CO$_2$ per tonne-km emissions from 2.8 to 2.7 gr/tonne-km respectively, whereas doing the same in the Handy-size bulker category would reduce this figure from 9.1 to 8.6 gr/tonne-km. As noted earlier, increasing the s/p ratio reduces CO$_2$ per tonne-km emissions.

Of course, the apparent lack of sensitivity of the per tonne-km emissions statistics on the s/p ratio does not hold for the statistics on the absolute quantities of total bunkers consumed and total CO$_2$ emitted. These are sensitive to the assumed values of sea and port times, all of them being increasing functions of the s/p ratio. Therefore the values of these statistics in our study should be interpreted with caution if the intent is to use them to estimate total world bunker consumption or global CO$_2$ emissions of the world fleet. However, we were able to cross check some annual bunker consumption figures with industry representatives for various types of ships, and, as a result, we have a reasonable degree of confidence on bunker consumption figures for several types of ships (most notably bulk carriers, crude oil carriers and container vessels).

In all ship categories, maximum payload was assumed equal to 95% of DWT, and several average capacity utilizations (w) when at sea were assumed, ranging from 70% for container vessels to 50% for tankers. The 50% figure for tankers means that the ship spends half of its sea time full and half empty (on ballast), while higher figures (60%) are possible for bulk carriers due to possible triangular routes and for container vessels (70%) due to the nature of the container trades. Again, statistics of Table 1 depend on the assumed values of these capacity utilizations. In terms of sensitivity analysis, changing the figures of capacity utilization (w) was found to change the CO$_2$ per tonne-km figures uniformly (down for increasing utilization), with no change in the relative standing among ship categories.

Various charts that can show the results of Table 2 in graphical form can be produced. Figures 1, 2 and 3 show the emissions performance of dry bulk carriers, container vessels and crude oil carriers (respectively). Figure 4 groups all ship categories together and displays CO$_2$ emissions absolute levels for 2007.
Fig. 1: Emissions statistics, dry bulk carriers

Fig. 2: Emissions statistics, containerships
Fig. 3: Emissions statistics, crude oil carriers

CO2 emissions per vessel category  (million tonnes)

Fig. 4: CO2 emissions, all ships
More charts are shown in Psaraftis and Kontovas (2008).

Looking at these results, one can see that, as expected, faster ships (such as containerships) emit more (both in absolute levels and per tonne-km) than slower ships. Similarly, smaller ships emit more per tonne-km than larger ships. Another observation is that tankers and bulkers are pretty similar with respect to emissions statistics, although tankers generally have slightly higher CO₂ per tonne-km figures both because of higher port fuel consumption and lower capacity utilization than bulkers.

Perhaps the most interesting observation is the degree of dominance of the container sector in terms of both higher CO₂ per tonne-km figures as compared to the other two ship types, and, overall quantity of bunkers consumed and CO₂ emissions produced per size bracket. The top size category of container vessels is seen to produce CO₂ emissions comparable on an absolute scale to that produced by the entire crude oil tanker fleet (in fact, the top-tier containership emissions are slightly higher).

In terms of sensitivity analysis, changing the figures of capacity utilization (w) was found to change the CO₂ per tonne-km figures uniformly (down for increasing utilization), with no change in the relative standing among ship categories.

4.2 Passenger vessels and vessels less than 400 GRT

A special effort to calculate emissions from passenger vessels and from those below 400 GRT was made. The reason these were treated separately was lack of reliable and representative information on fuel consumption and other data, as will be seen below.

A number of 6,281 vessels below 400 GRT were identified. These were treated as a homogenous group, assuming an average fuel consumption of 210 gr/kWh and 300 operational days per year (of which 180 at sea). The fuel consumption figure was taken from IMO (2007b) and is supported by Endresen (2004) and Corbett and Köhler (2004).

The case of passenger ships was more difficult. A total fleet of 2,801 vessels was broken down into three basic categories: cruise vessels, multihulls and general Ro-Pax vessels. We assumed a fuel consumption of 160-180 gr/kWh (which is a typical fuel consumption for medium speed and high speed main engines according to engine manufacturers) and 300 operational days per year (of which 240 at sea). Based on this, the total CO₂ emissions of this part of the fleet were calculated, based on the total recorded horsepower for these ships (as per Lloyds – Fairplay database).

In trying to cross-reference this information, we also obtained data from two Greek Ro-Pax shipping companies, operating modern ferries in the Adriatic and Aegean seas. Actual fuel consumption figures were on the order of 120 to 160 gr/kWh, some 12-25% lower than the ones assumed above. By contrast, annual days at sea were higher (as high as 270, as opposed to 240, i.e. about 12% higher), and we were unable to distinguish operational time in port (in which the ship’s auxiliary engines are running) from idle time in port (in which there are no emissions).

With all these caveats, we are in a position to say that, based on the methodology, information and assumptions outlined above, aggregate estimates of total CO₂ emissions and bunker consumption are as follows (2007):
Table 4: Emissions estimates

<table>
<thead>
<tr>
<th>Type of Vessels</th>
<th>Number of Vessels</th>
<th>CO₂ emissions (million tonnes/yr)</th>
<th>Bunker consumption (million tonnes/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cargo Vessels (Annex VI)</td>
<td>36,538</td>
<td>839.95</td>
<td>264.97</td>
</tr>
<tr>
<td>Vessels below 400 GT</td>
<td>6,281</td>
<td>9.82</td>
<td>3.10</td>
</tr>
<tr>
<td>Passenger Vessels</td>
<td>2,801</td>
<td>93.67</td>
<td>29.55</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>45,620</strong></td>
<td><strong>943.44</strong></td>
<td><strong>297.62</strong></td>
</tr>
</tbody>
</table>

One can immediately see that the contribution of the small vessel group to total emissions is negligible (order of 1%). If alternative assumptions are made, it is speculated that this percentage will not change that much.

The contribution of passenger vessels is much higher, on the order of 10%. However, this number can change depending on the actual scenario. In terms of sensitivity analysis, if the number of assumed operational days per year increases from 200 to 320 (and the s/p ratio remains the same) emissions of passenger vessels will rise to about 150 million tonnes per year, or about 15% of the total. Total bunkers will then rise to about 315 million tonnes per year, or slightly less than 6% more than the base-case value computed above. Given the wide variety of passenger ships and trading patterns across the globe, we feel it is impossible to be precise on the fuel consumed (let alone the average values of D and s/p) without access to detailed bunker consumption and ship movement information.

Equally speculative is any attempt to calculate CO₂ emissions per tonne-km from these numbers. Perhaps the only one that we can venture (with all caveats listed above) is the one for vessels below 400 GRT, which is about 67.7 gr/tonne-km, higher than any other ship type/size combination examined (as expected). For passenger vessels, any aggregate per tonne-km figure would likely be misleading, or even meaningless, as cruise ships (that carry no cargo) are different from Ro-pax ships (that carry a mixture of passengers, vehicles and cargo), or multi-hull ships (that may or may not carry cargo).

5. Comparison with other studies and other modes

5.1 Comparison with other studies

In trying to compare our estimates of global fuel consumption and overall emissions with those of similar studies that estimate these figures, it is not surprising to see that this task is anything but straightforward. Usually the basis for such a comparison (for instance, the fleet whose emissions are studied, the year for which the emissions estimate is made, the breakdown of the fleet into ship types and size brackets, and a variety of other parameters) varies across studies, and one would have to look carefully at all of the assumptions, modeling and others, of these studies to be able to compare them properly, both against each other and against ours. Suffice it to say that wide differences exist even among expert estimates of global fuel consumption, and even within the IMO expert group study (IMO (2007a,b)) different databases of the fleet were given by the various parties who were engaged in the study, and some adjustments were necessary to achieve compatibility.

Still, we can venture showing some results of other studies. Table 5 shows bunker consumption estimates of years 2000 and 2001 projected to 2007 as given by IMO (2007a).
IMO (2007b) itself estimates global fuel consumption for 2007 at 369 million tonnes, using quite a few modeling assumptions. This is a figure that is about 24% higher than our base-case estimate and about 17% higher than our highest estimate.

As the final version of this paper was being completed, we had the opportunity to review the report of Phase 1 of the update the 2000 IMO GHG Study, which was conducted by an international consortium led by Marintek (Norway) and was presented at MEPC 58 in London in October 2008 (Buhaug et al (2008)). The objectives of Phase 1 have been as follows: (1) to undertake an assessment of present day CO₂ emissions from international shipping; (2) to estimate future shipping emissions towards 2050; (3) to compare shipping emissions with other transportation modes; and (4) to assess climate impacts from shipping. Then Phase 1 will be followed by Phase 2 which also addresses greenhouse gases other than CO₂ and possibilities and mechanisms for emissions reductions.

It is clear that the scope of the Phase 1 study was much broader than that of ours, although obviously there are some common elements, such as for instance the estimation of emissions from the world fleet. Although a detailed comparison of results could not be conducted within the time frame of this paper, in Table 6 below we reproduce one of the main results of that study.

<table>
<thead>
<tr>
<th>Study</th>
<th>Scope</th>
<th>Reference year</th>
<th>Result (mill tons)</th>
<th>Projected to 2007, incl. boiler consumption (mt)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Endresen et al; September 2003</td>
<td>All Int. Ships GT&gt;100</td>
<td>2000</td>
<td>193</td>
<td>282 *</td>
</tr>
<tr>
<td>Corbett &amp; Köhler; October 2003</td>
<td>All Int. Ships GT&gt;100</td>
<td>2001</td>
<td>289</td>
<td>405 **</td>
</tr>
<tr>
<td>Eyring, Köhler, et al; 2005</td>
<td>All Int. Ships GT&gt;100</td>
<td>2001</td>
<td>280</td>
<td>393</td>
</tr>
<tr>
<td>EnSys 2007</td>
<td></td>
<td>2001</td>
<td>278</td>
<td>391</td>
</tr>
</tbody>
</table>

* -23 mt for ships 100-400 GT ships; +19 mt for aux engines
** -41 mt for Navy ships; -40 mt for 100-400 GT ships.

Table 6: Consensus estimate 2007 CO₂ emissions [million tonnes CO₂] (from Buhaug et al (2008))

<table>
<thead>
<tr>
<th>Total ship emissions¹</th>
<th>Low bound</th>
<th>Consensus estimate</th>
<th>High bound</th>
<th>Consensus estimate % Global CO₂ emissions</th>
</tr>
</thead>
<tbody>
<tr>
<td>International shipping²</td>
<td>854</td>
<td>1019</td>
<td>1224</td>
<td>3.3</td>
</tr>
</tbody>
</table>

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.

It can be seen that both a low bound and a high bound for CO₂ emissions are provided, and there is a differentiation between emissions from the total world fleet and emissions from 'international shipping’, the latter defined as everything excluding domestic voyages. In both cases, a 'consensus estimate' of emissions is also provided. We can see that our study’s estimate of 943.44 million tonnes of CO₂ for 2007 lies within the range provided, being some 7.5% lower than the consensus estimate of 1,109 million tonnes.
Again we note that a detailed comparison of the differences among all of these studies (including ours) would require additional analysis which is beyond the scope of this paper.

5.2 Comparison with other modes

A different kind of comparison of ship emissions is the comparison with emissions of other modes. Although again such comparison, if properly conducted, can be quite involved, we cite here some figures (Table 7):

<table>
<thead>
<tr>
<th>Mode</th>
<th>CO₂ (gr/tonne-km)</th>
<th>SO₂ (gr/tonne-km)</th>
<th>NOₓ (gr/tonne-km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Boeing 747-400</td>
<td>552</td>
<td>5.69</td>
<td>0.17</td>
</tr>
<tr>
<td>Heavy truck</td>
<td>50</td>
<td>0.31</td>
<td>0.00005</td>
</tr>
<tr>
<td>Rail-diesel</td>
<td>17</td>
<td>0.35</td>
<td>0.00005</td>
</tr>
<tr>
<td>Rail-electric</td>
<td>18</td>
<td>0.44</td>
<td>0.10</td>
</tr>
<tr>
<td>S-type container vessel (11,000 TEU)</td>
<td>8.35</td>
<td>0.21</td>
<td>0.162</td>
</tr>
<tr>
<td>PS-type container vessel (6,600 TEU)</td>
<td>7.48</td>
<td>0.19</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The reason a direct comparison of these results with our results is not straightforward is that it is not clear what detailed set of assumptions were made (for instance, what was the assumed value of capacity utilization of all modes, if less than 100%). However, both results give the appearance to be compatible with one another. The CO₂ per tonne-km figure we have calculated for the top-tier containership size bracket (Post-Panamax, ships above 4,400 TEU) is 10.8 gr/tonne-km, assuming a capacity utilization of 70% (the equivalent figure for 100% capacity utilization would be 7.56 gr/tonne-km). For the VLCC/ULCC class this figure is 3.6 gr/tonne-km (capacity utilization 50%) and for the Capesize bulker class it is 2.7 gr/tonne-km (capacity utilization 60%). Based on these figures, a heavy truck produces per tonne-km more than 18 times CO₂ than a Capesize bulker and a 747 jumbo jet produces more than 200 times CO₂. But the ratios for SO₂ and NOₓ emissions are different and all merit further investigation. A more comprehensive comparison may help put the discussion on priorities as regards emissions reduction across transport modes on a proper perspective.

6. Conclusions

There is no question that the subject of this study is of non-trivial complexity, at least as documented by the extent of related activity at IMO/MEPC and elsewhere. A possible advantage of this study over others that try to predict emissions on a global basis is that, in addition to modelling, it also uses real data collected from industry. Such data was used both directly and as a cross-reference mechanism. Any limitations of this study (and of others, for that matter) mainly concern the availability and quality of the data that was used. In order to perform a more in-depth and accurate analysis than the one reported here, it is clear that additional information is necessary, including ship movements on a world-wide basis and accurate bunker consumption figures for the world fleet.

Another conclusion of this study concerns the relative impact of the various ship type and size brackets on ship CO₂ emissions. In this paper, estimates of such impact were made, both on an absolute size scale (tonnes of CO₂), and on an efficiency scale (grams of CO₂ per tonne-

---

6 Maersk Line (2007), Brochure: “Constant Care for the Environment”. The source of Table 7 is the Swedish Network for Transport and the Environment.
km). Both attributes can be used for policy-making purposes, if the intent is to investigate priorities for reducing GHG shipping emissions.

At the latest MEPC (58th session in London, October 2008) it was clear that the subject of GHG emissions from shipping is still a very difficult one to resolve. In spite of various studies and much of debate as regards where we stand and where we should be going, the IMO is yet to reach a consensus on what should be done to effectively curb CO₂ and other GHG emissions. More important, significant divergence of opinion seems to exist among IMO member states on how to proceed. Phase 2 of the GHG study is just underway, and the hope is that this may used to bring about the action that is necessary to move ahead on this difficult problem. One thing is certain: it will not be easy.

7. Acknowledgments

Funding for this study was provided by the Hellenic Chamber of Shipping. We want to thank the shipping companies that provided data for our study. These are, alphabetically,

ANDRIAKI SHIPPING CO LTD
AEOLOS MANAGEMENT SA
ALPHA TANKER
BLUE STAR FERRIES
ANANGEL SHIP ENTERPRISES SA
ATLANTIC BULK CARRIER MGT
CARRAS HELLAS SA
CELEBRITY CRUISES
CENTROFIN MANAGEMENT INC
CHANDRISSHELLAS INC
COSTAMARE
DANAOS SHIPPING CO LTD
EASTERN MEDITERRANEAN MARITIME
EASY CRUISE
ELETSON CORP.
EUROPEAN PRODUCT CARRIERS
FAFALIOS SHIPPING
HALKIDON SHIPPING COPR
HELLENIC SEAWAYS
KRISTEN NAVIGATION
MINERVA MARINE INC
NEDA MARITIME
NEPTUNE LINES
NEREUS SHIPPING SA
SKYROS SHIPPING
SPRINGFIELD SHIPPING CO
SUPERFAST FERRIES
TSAGARIS PROS
TSAKOS HELLAS
VASSILOS SHIPPING CO

8. References


ANNEX: Selected charts (all charts are available at www.martrans.org/emis).

LPG Carriers

LNG Carriers
Ro-Ro (excl. passenger)

General Cargo Vessels