CO_2 EMISSIONS STATISTICS FOR THE WORLD COMMERCIAL FLEET[1]

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Abstract

Carbon dioxide (CO_2) 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 CO_2 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 CO_2 and other GHGs, but it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO_2 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 CO_2 emissions, Ship Air Pollution

1. Introduction

Carbon dioxide (CO_2) 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 CO_2 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 CO_2 and other GHG, but it is clear that the time of non-regulation is rapidly approaching its end, and measures to curb future CO_2 growth are being sought with a high sense of urgency. CO_2 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 CO_2. In parallel, the broader analysis of other greenhouse gases (such as CH_4 and N_2O) and other, non-greenhouse gases, such as SO_2, NO_x 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.

[1] ELINT Conference, November 27-28, 2008.

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 at 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

CO_2 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 CO_2 emissions (in tonnes per day).

The 3.17 CO_2 factor has been the empirical mean value most commonly used in CO_2 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%[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 accurate 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 CO_2 produced in this round-trip: 3.17(GT + FL/V + gt+ fL/v)
CO_2 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 CO_2 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, CO_2 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 ($0 \le s \le 1$). 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 CO_2 in a year (tonnes): 3.17(sF + pG)D
Total tonne-km's in a year: (wW)(sDV)
CO_2 per tonne-km: 3.17(sDF + pDG)/wWsDV = 3.17(sF+pG)/wWsV
= 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 CO_2 emitted is an increasing (in fact, linear) function of D (days per year the ship is operational), the total CO_2 emitted *per tonne-km* is independent of D (which is probably not a surprise). Second, as much as total CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 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 CO_2 per TEU-km and for car carriers grams of CO_2 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 CO_2 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 CO_2 per tonne-km of transported cargo in a year. Another output has been the total CO_2 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

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

Vessel type DWTx1000	Number of vessels
Reefer 0-5	508
Reefer 5-10	358
Reefer >10	225
Total Reefer	**1,091**
Product, chemical 0-5'	3125
Product, chemical 5'-15'	1407
Product, chemical 15'-25'	430
Product, chemical 25'-40'	643
Product, chemical 40'-60	705
Product, chemical >60	238
Total Chemical	

	4,232
Small tanker 0-10	115
Handysize 10-60	240
Panamax 60-80	177
Aframax 80-120	648
Suezmax 120-200	332
VLCC/ULCC >200	516
Total Crude oil	**2,028**
LNG 0-50	29
LNG >50	221
Total LNG	**250**
LPG 0-5	651
LPG 5-20	235
LPG 20-40	68
LPG >40	135
Total LPG	**1,089**

	6,548
RO-RO excl. Pax 0-5000	932
RO-RO excl. Pax 5-15	674
RO-RO excl. Pax 15-25	342
RO-RO excl. Pax 25-40	51
Total RO-RO	**1,999**
General Cargo 0-5	9,009
General Cargo 5-15	3,014
General Cargo 15-35	816
Total General Cargo	**12,839**

SUBTOTAL: 36,538 vessels

Other categories

Vessels 0-400 GT	**6,281**
Passenger Vessels (>400GT)	**2,801**

TOTAL : 45,620 vessels

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.

Table 2: Base case scenario: Emissions statistics

		Average Ship										per size bracket		
Typical Vessel types and sizes per vessel segment	Number of vessels in size group	Payload	Speed	Sea days %	Port days %	cargo capacity utilization at sea	Total CO2, yr (tonnes)	**Total bunkers, YR**	Total tonne-kms, yr	gr CO2 PER TONNE-KM		total CO2 per size bracket (million)	% of total	Total billion MT-km per size bracket
Small Vessels 0-5'	517	1,937	12	70	30	60%	4,717	1,488.00	139,158,763	33.9		2.44	1.60	72
Coastal 5-15'	236	9,895	12	70	30	60%	10,641	3,356.80	710,876,741	15.0		2.51	1.70	168
Handysize 15'-35'	1774	24,876	14	70	30	60%	18,513	5,840.00	2,084,935,872	8.9		32.84	21.70	3,699
Handymax 35'-60'	1732	43,522	14	70	30	60%	22,804	7,193.60	3,647,781,825	6.3		39.50	26.20	6,318
Panamax 60'-85'	1383	68,469	14	70	30	60%	27,095	8,547.20	5,738,689,444	4.7		37.47	24.80	7,937
Post-Panamax 85'-120'	98	87,129	14	80	20	60%	37,066	11,692.80	8,345,885,855	4.4		3.63	2.40	818
Capesize >120'	722	160,425	15	80	20	60%	45,202	14,259.20	16,464,276,593	2.7		32.64	21.60	11,887
Total Dry Bulk	**6462**						166,037		37,131,605,092	4.5		151.03		30,898
Feeder (0-500)	363	5,169	13	70	30	70%	14,810	4,672.00	469,332,853	31.6		5.38	2.00	170
Feedermax (500-1000)	757	9,873	16.5	70	30	70%	22,773	7,184.00	1,137,846,685	20.0		17.24	6.40	861
Handysize (1000-2000)	1,143	19,515	20	70	30	70%	37,279	11,760.00	2,726,036,069	13.7		42.61	15.80	3,116
Sub-Panamax (2000-3000)	689	34,088	20	70	30	70%	58,328	18,400.00	4,761,738,206	12.2		40.19	14.90	3,281
Panamax (3000-4400)	568	47,907	21	70	30	70%	94,502	29,811.20	8,030,486,625	11.8		53.68	19.90	4,561
Post Panamax(>4400 TEU)	712	75,190	24	70	30	70%	155,000	48,896.00	14,404,444,807	10.8		110.36	41.00	10,256
Total Container	**4,232**						382,693		31,529,885,245	12.1		269.45		22,246
Small tanker (0-10)	115	3,159	12	80	20	50%	6,289	1,984.00	216,120,361	29.1		0.72	0.70	25
Handysize (10-60)	240	37,841	14.5	80	20	50%	32,664	10,304.00	3,128,483,055	10.4		7.84	7.40	751
Panamax (60-80)	177	64,838	15	80	20	50%	36,113	11,392.00	5,545,193,472	6.5		6.39	6.00	981
Aframax (80-120)	648	97,921	14.7	80	20	50%	46,460	14,656.00	8,207,170,707	5.7		30.11	28.30	5,318
Suezmax (120-200)	332	146,099	15	80	20	50%	51,329	16,192.00	12,495,006,794	4.1		17.04	16.00	4,148
VLCC/ULCC (>200)	516	279,208	15	80	20	50%	85,615	27,008.00	23,879,106,183	3.6		44.18	41.60	12,322
Total Crude oil	**2,028**						258,469		53,471,080,573	5		106.00		23,545
LNG (0-50)	**29**	23,588	17	80	20	50%	52,167	16,456.50	1,902,263,069	27.4		1.51	7.60	55
LNG (>50)	**221**	71,099	19	80	20	50%	83,400	26,309.00	6,408,488,501	13.0		18.43	92.40	1,416
Total LNG	**250**						135,567		8,310,751,570	16.3		19.94		1,471
LPG (0-5)	**651**	2,012	13	80	20	50%	6,137	1,936.00	130,496,886	47.0		4.00	26.80	85
LPG (5-20)	**235**	9,069	15	80	20	50%	17,093	5,392.00	678,646,370	25.2		4.02	26.90	159
LPG 20-40	**68**	25,764	16	80	20	50%	29,194	9,209.60	2,056,555,856	14.2		1.99	13.30	140
LPG (>40)	**135**	48,904	17	80	20	50%	36,356	11,468.80	4,147,643,575	8.8		4.91	32.90	560
Total LPG	**1,089**						88,780		7,013,342,687	12.7		14.91		944
Reefer (0-5)	**508**	2,060	13	80	20	60%	9,363	2,953.60	203,228,700	46.1		4.76	22.30	103
Reefer (5-10)	**358**	6,827	17.5	80	20	60%	25,838	8,150.80	906,791,981	28.5		9.25	43.40	325
Reefer (>10)	**225**	11,512	20	80	20	60%	32,410	10,224.00	1,747,605,300	18.5		7.29	34.20	393
Total Reefer	**1,091**						67,611		2,857,625,981	23.7		21.30		821
Product, chemical 0-5'	3125	2,009	11.5	70	30	60%	8,651	2,729.10	142,654,101	60.6		27.04	20.80	446
Product, chemical 5'-15'	1407	8,230	13	70	30	60%	15,953	5,032.50	660,522,652	24.2		22.45	17.30	929
Product, chemical 15'-25'	430	18,083	14.4	70	30	60%	26,571	8,382.00	1,607,649,695	16.5		11.43	8.80	691
Product, chemical 25'-40'	643	32,443	15	70	30	60%	44,668	14,091.00	3,004,401,819	14.9		28.72	22.10	1,932
Product, chemical 40'-60	705	43,512	14.7	70	30	60%	42,053	13,266.00	4,513,046,136	9.3		29.65	22.80	3,182
Product, chemical >60	238	78,339	15	70	30	60%	45,401	14,322.00	8,291,118,437	5.5		10.81	8.30	1,973
Total Chemical	**6,548**						183,298		18,219,392,840	10.1		130.08		9,153
RO-RO (excl. Pax) 0-5000	932	1,729	13	70	30	60%	8,394	2,647.80	138,768,467	60.5		7.82	18.20	129
RO-RO (excl. Pax) 5-15	674	9,334	17	70	30	60%	28,532	9,000.50	979,619,744	29.1		19.23	44.90	660
RO-RO (excl. Pax) 15-25	342	17,605	18	70	30	60%	38,981	12,296.80	1,956,459,426	19.9		13.33	31.10	669
RO-RO (excl. Pax) 25-40	51	27,680	19	70	30	60%	48,726	15,371.00	3,246,941,650	15.0		2.49	5.80	166
Total RO-RO	**1,999**		15.4				124,632		6,321,789,286.69	19.7		42.87		1,624
General Cargo (0-5)	9,009	2,138	11	70	30	60%	3,943	1,244.00	145,225,951	27.2		35.53	42.60	1,308
General Cargo (5-15)	3,014	7,549	13	70	30	60%	10,872	3,429.80	605,853,976	17.9		32.77	39.30	1,826
General Cargo (15-35)	816	19,570	14	70	30	60%	18,477	5,828.80	1,691,497,286	10.9		15.08	18.10	1,380
Total General Cargo	**12,839**						33,293		2,442,577,212	13.6		83.37		4,515
GRAND TOTAL	**36,538**							**Total CO2 (million tonnes per year)=**				**838.95**		
							Bunker Consumption (million tonnes per year)=					**264.65**		

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 CO_2 emissions from cargo vessels would rise 10% versus ours.

Table 3: Summary of Engine Running Days (from Endresen et al (2004), Corbett et al (2004))

Summary of Cargo Ship Engine Hours and Days at Sea, in Port, and Laid Up, Derived From *Endresen et al.* [2004a]

	Values Taken From *Endresen et al.* [2004a]				Values Derived From *A* Through *D*				
Vessel Size, dry weight	Engine Hours *A*	In-Service Days *B*	Port Calls *C*	Days in Port $D = C \times 1.5$	Engine Running Days $E = A/24$	Days When Engines Not Running (in Port) $F = B - (A/24)$	At-Sea Days $G = B - D$	Laid Up Days (Not in Service) $H = 360 - B$	Maximum Sea Days (~5 Days Laid Up) $I = 360 - D$
<5,000	4000	240	100	150	167	73	90	120	210
5,000 – 100,000[a]	5000	270	60	90	208	62	180	90	270
>100,000[b]	6000	300	35	53	250	50	247	60	307
Fleetwide averages[c]	5840	300	70	105	243	57	210[c]	60	255

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 word 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.

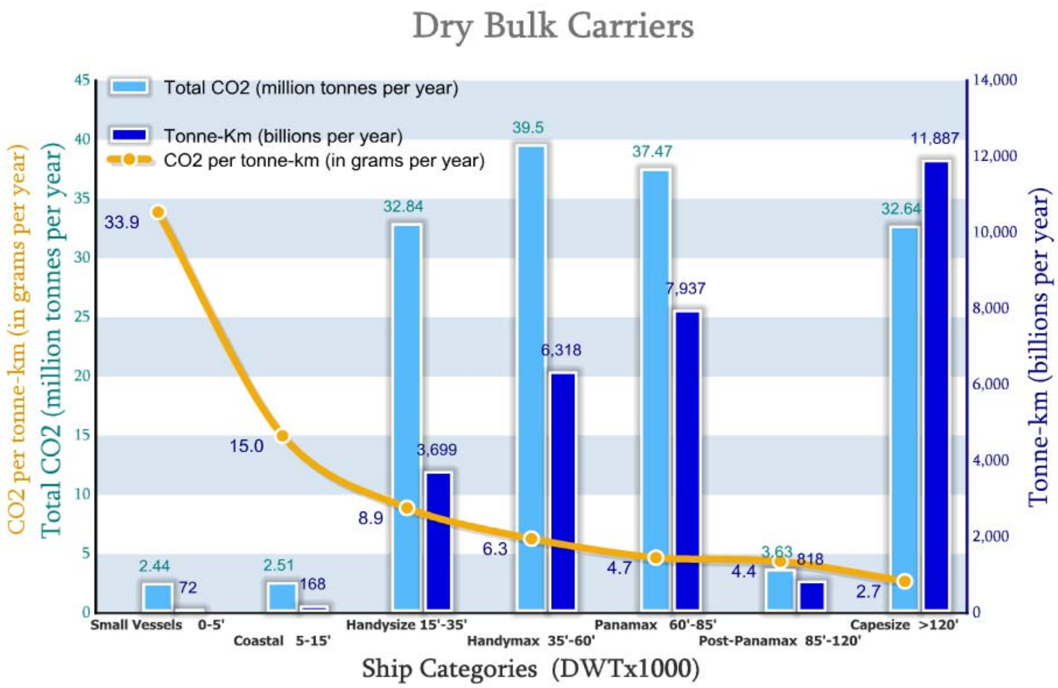

Fig. 1: Emissions statistics, dry bulk carriers

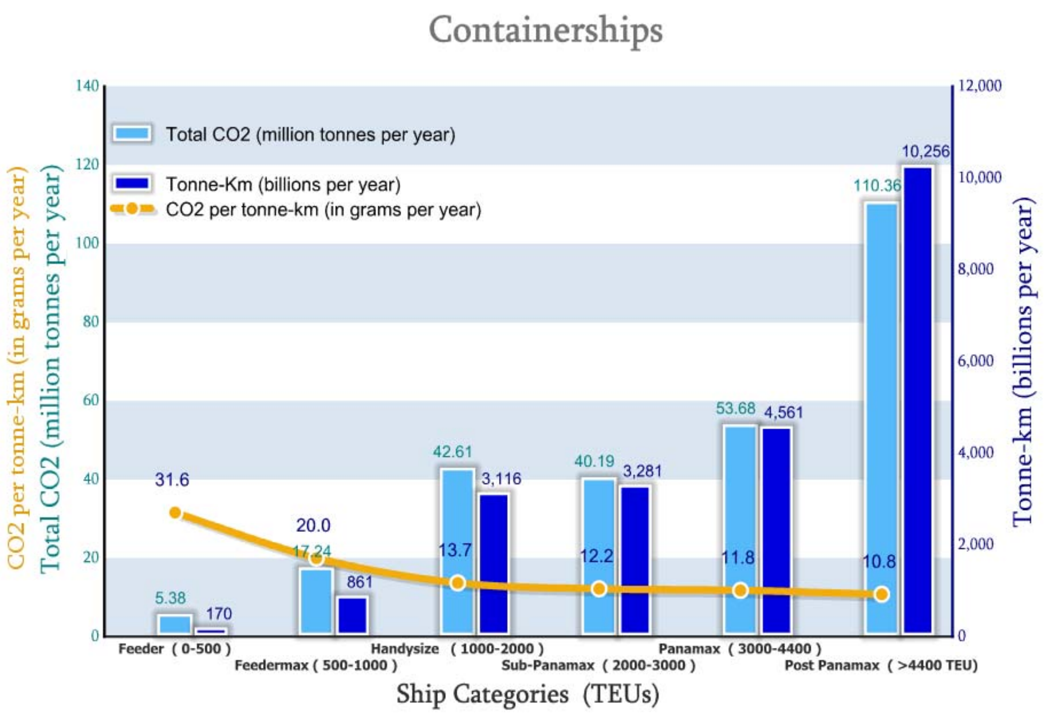

Fig. 2: Emissions statistics, containerships

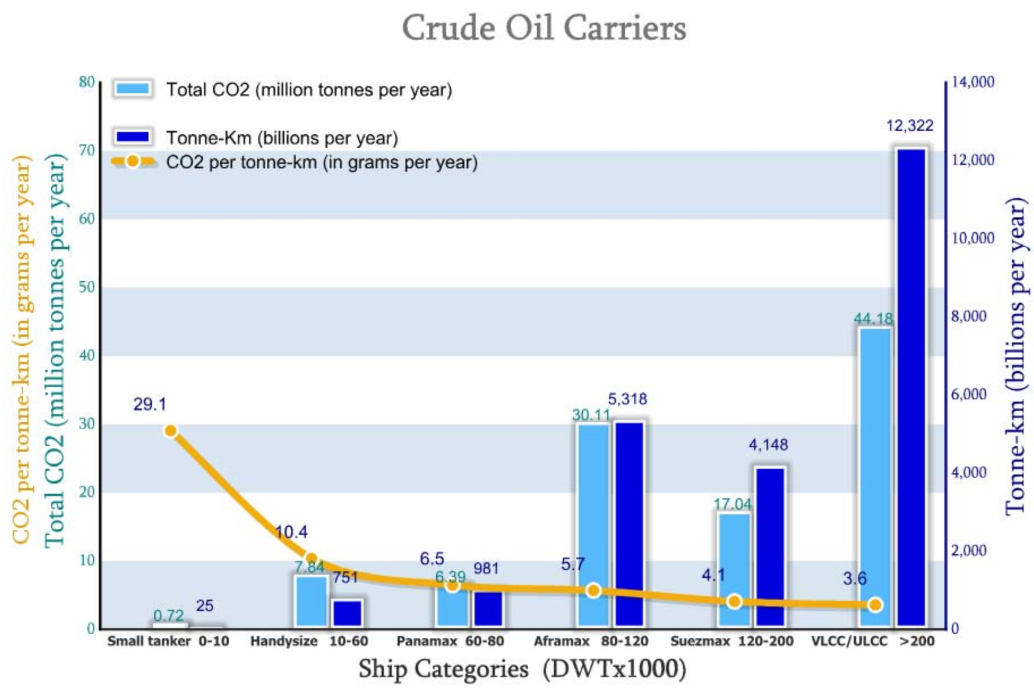

Fig. 3: Emissions statistics, crude oil carriers

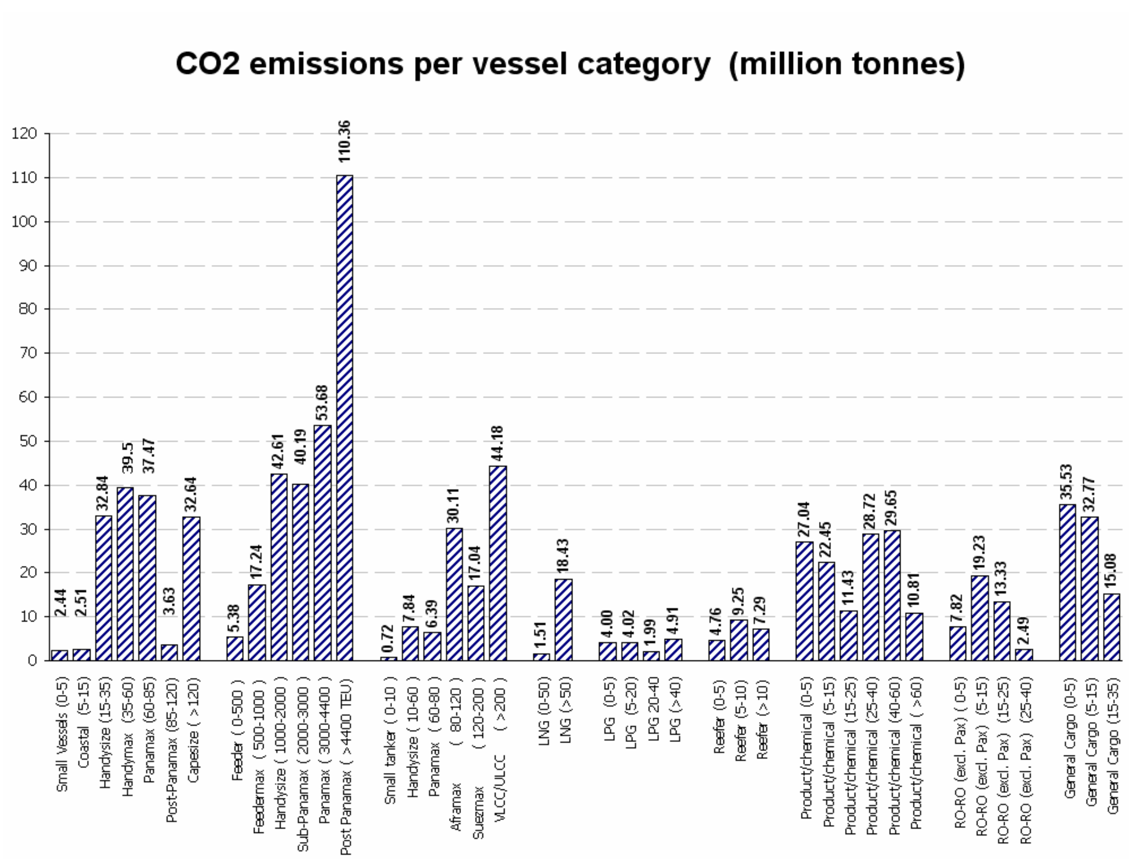

Fig. 4: CO_2 emissions, all ships

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 CO_2 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 CO_2 per tonne-km figures as compared to the other two ship types, and, overall quantity of bunkers consumed and CO_2 emissions produced per size bracket. The top size category of container vessels is seen to produce CO_2 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 CO_2 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 CO_2 emissions and bunker consumption are as follows (2007):

Table 4: Emissions estimates

Type of Vessels	Number of Vessels	CO_2 emissions (million tonnes/yr)	Bunker consumption (million tonnes/yr)
Cargo Vessels (Annex VI)	36,538	839.95	264.97
Vessels below 400 GT	6,281	9.82	3.10
Passenger Vessels	2,801	93.67	29.55
Total	**45,620**	**943.44**	**297.62**

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 CO_2 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 meaninglesss, 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).

Table 5: Comparison of Bunker Consumption Results of Various Studies (from IMO (2007a))

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

* -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.

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 CO_2 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 CO_2 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 6: Consensus estimate 2007 CO_2 emissions [million tonnes CO_2] (from Buhaug et al (2008))

	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.

It can be seen that both a low bound and a high bound for CO_2 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 CO_2 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 7: Emissions statistics across different modes (source: Maersk Line[6]).

Mode	CO_2 (gr/tonne-km)	SO_2 (gr/tonne-km)	NO_x (gr/tonne/km)
Boeing 747-400	552	5.69	0.17
Heavy truck	50	0.31	0.00005
Rail-diesel	17	0.35	0.00005
Rail-electric	18	0.44	0.10
S-type container vessel (11,000 TEU)	8.35	0.21	0.162
PS-type container vessel (6,600 TEU)	7.48	0.19	0.12

The reason a direct comparison of these results with our results is not straightforward is that 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 CO_2 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 CO_2 than a Capesize bulker and a 747 jumbo jet produces more than 200 times CO_2. But the ratios for SO_2 and NO_x 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 CO_2 emissions. In this paper, estimates of such impact were made, both on an absolute size scale (tonnes of CO_2), and on an efficiency scale (grams of CO_2 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 shippping 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 CO_2 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

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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
CHANDRIS HELLAS 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
VASSILIOS SHIPPING CO

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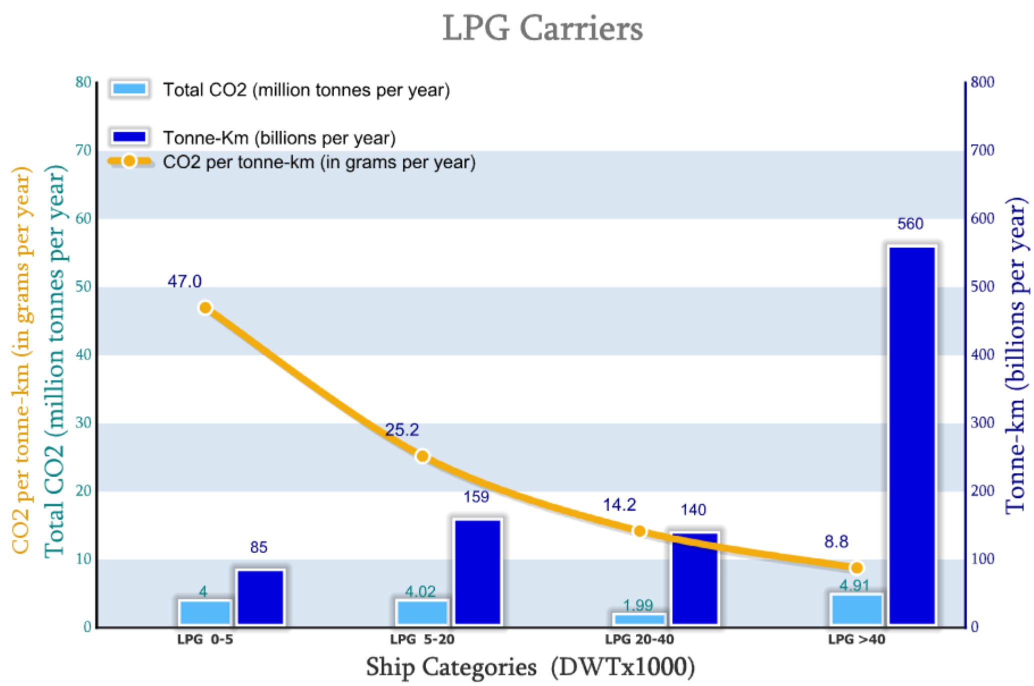
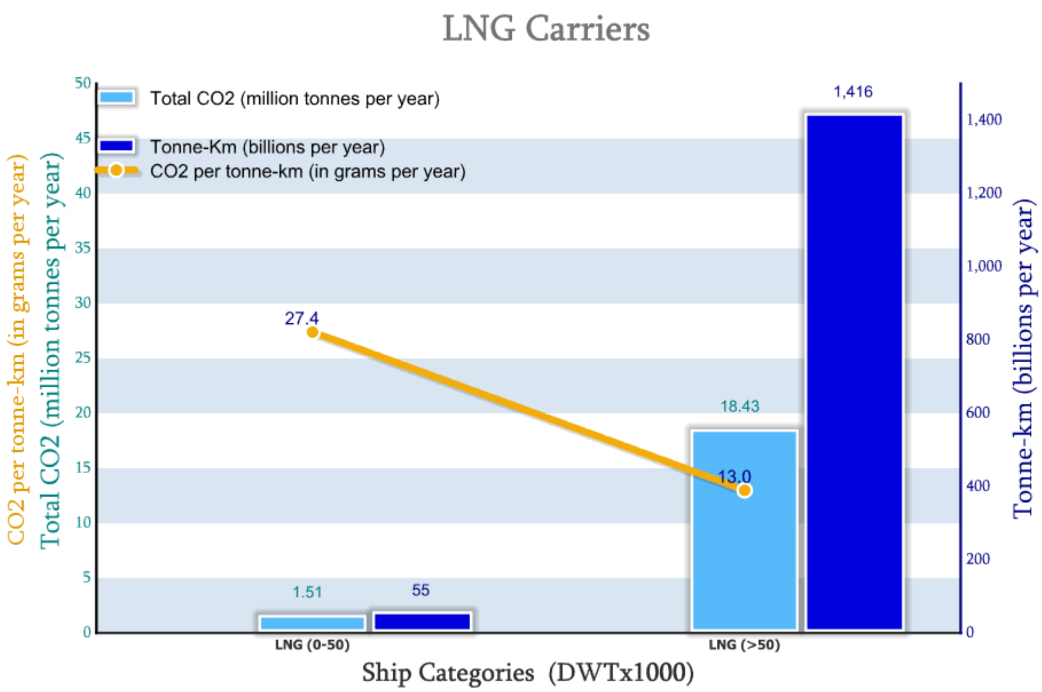
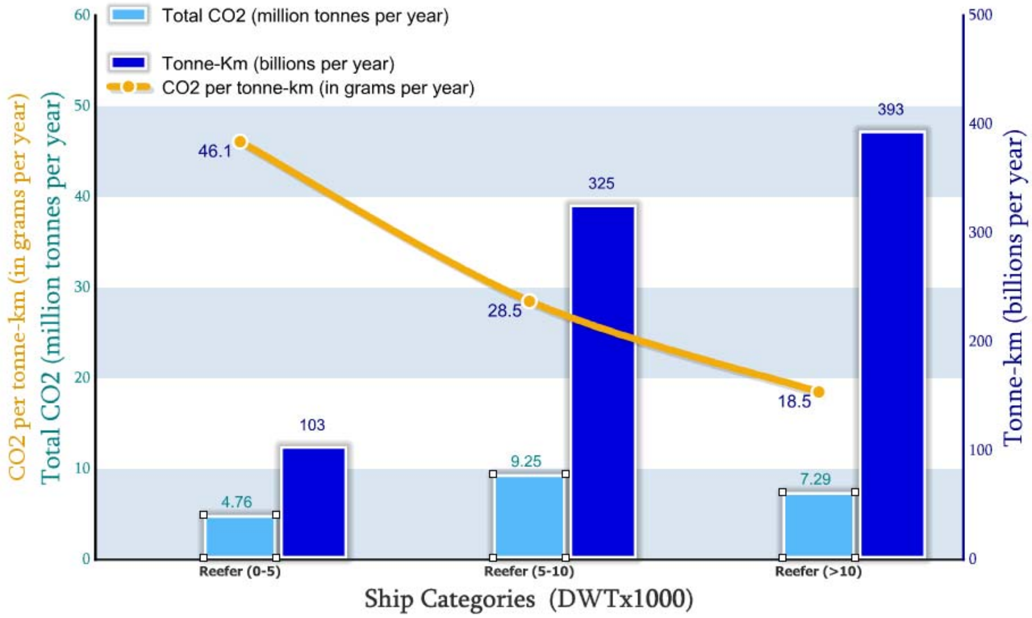
ANNEX: Selected charts (all charts are available at www.martrans.org/emis).

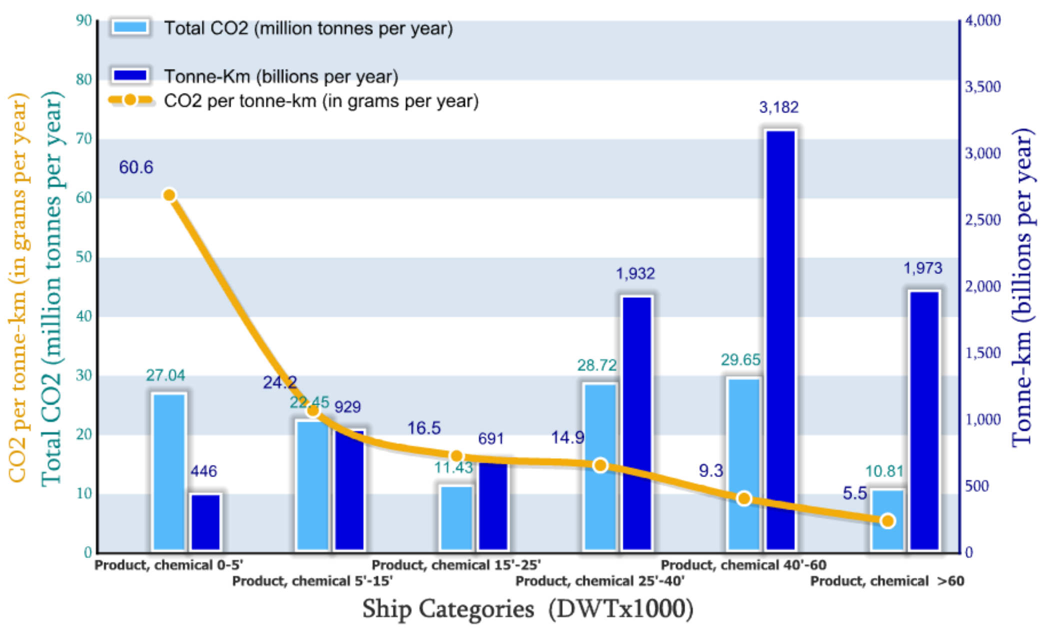




Reefers



Chemical/Product Carriers



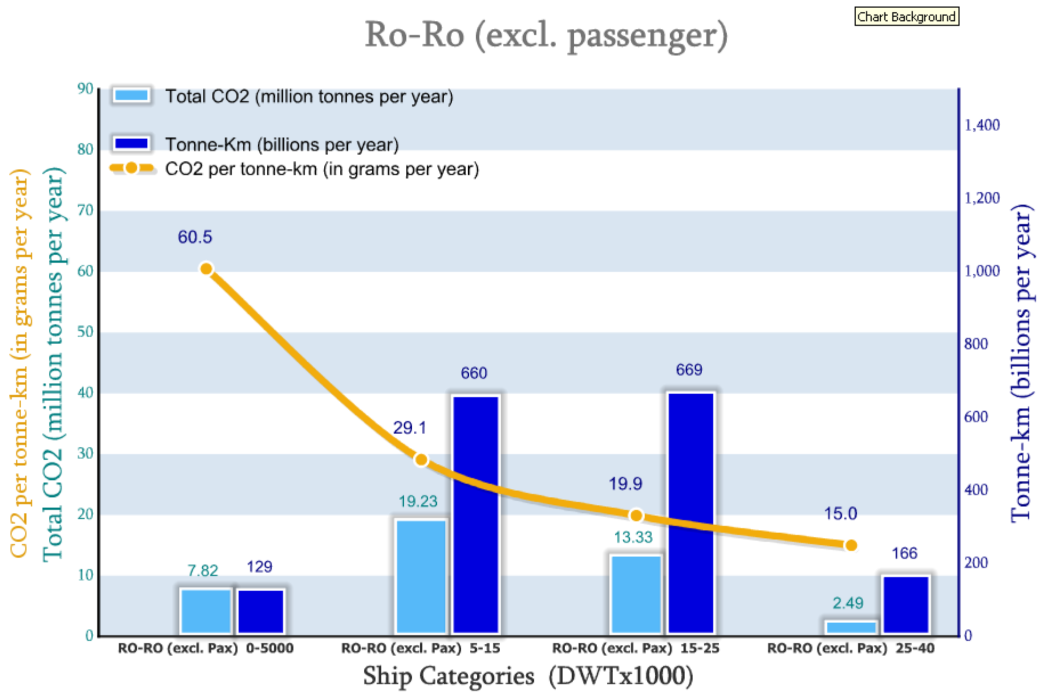
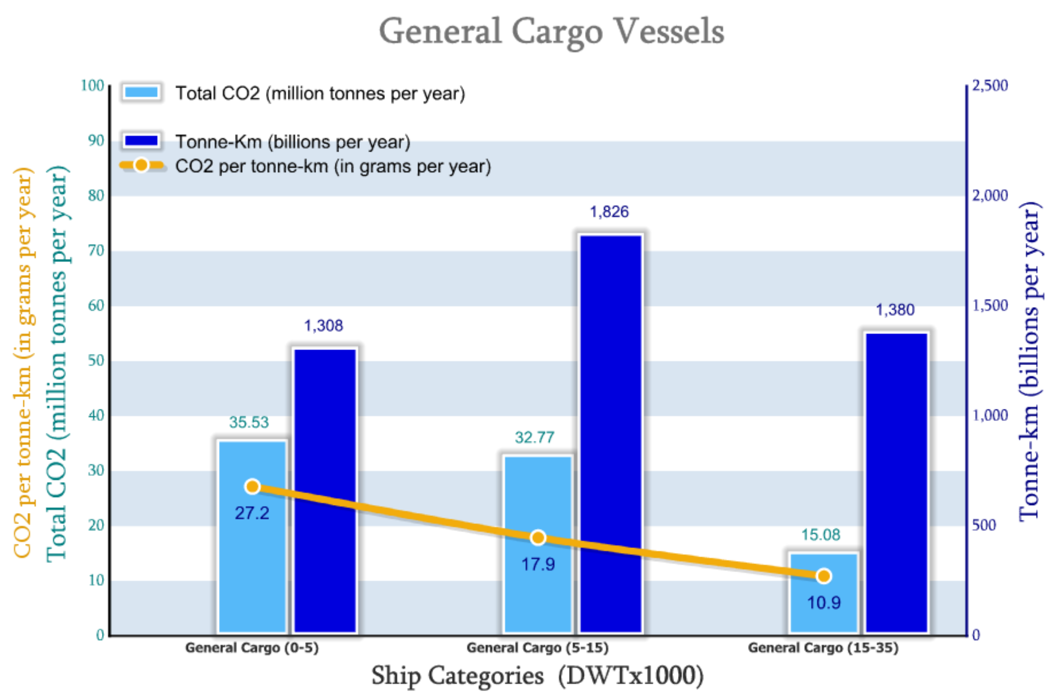


Chart Background
Ro-Ro (excl. passenger)
Total CO2 (million tonnes per year)
Tonne-Km (billions per year)
CO2 per tonne-km (in grams per year)
CO2 per tonne-km (in grams per year)
Total CO2 (million tonnes per year)
Tonne-km (billions per year)
60.5
29.1
19.9
15.0
7.82
129
19.23
660
13.33
669
2.49
166
RO-RO (excl. Pax) 0-5000
RO-RO (excl. Pax) 5-15
RO-RO (excl. Pax) 15-25
RO-RO (excl. Pax) 25-40
Ship Categories (DWTx1000)



General Cargo Vessels
Total CO2 (million tonnes per year)
Tonne-Km (billions per year)
CO2 per tonne-km (in grams per year)
CO2 per tonne-km (in grams per year)
Total CO2 (million tonnes per year)
Tonne-km (billions per year)
35.53
1,308
27.2
32.77
1,826
17.9
15.08
1,380
10.9
General Cargo (0-5)
General Cargo (5-15)
General Cargo (15-35)
Ship Categories (DWTx1000)