INCORPORATING LIFECYCLE ELEMENTS INTO THE ENERGY EFFICIENCY DESIGN INDEX

C. Walsh and **A. Bows**

Sustainable Consumption Institute, Department of Earth, Atmospheric and Environmental Sciences, Tyndall Centre for Climate Change Research, Sackville Street, University of Manchester, M13 9PL, UK
conor.walsh@manchester.ac.uk

ABSTRACT
The energy efficiency design index (EEDI) measures the carbon efficiency of ocean going transport in terms of gCO_2/tonne nautical-mile and has been proposed by the International Maritime Organisation (IMO) as a means of establishing a baseline for the carbon intensity of new ship builds. While the direct emissions associated with the combustion of fuel at sea represent the primary impact of ocean going transport, the indirect emissions associated with ship construction and fuel production should not be underestimated. Using data provided by Lloyd's marine intelligence unit (LMIU) the relationship between ship size and capacity is approximated for 8 ship types. Estimates of the deadweight coefficient (C_D) are used to relate ship capacity to ship weight. Data from lifecycle analysis (LCA) studies are used to estimate the carbon embodied in the production of ship material (assumed to mostly correspond to reinforced steel) and marine fuel. The results suggest that the incorporation of lifecycle elements may increase the EEDI by up to 20%, the majority of which is associated with the production of fuel. This will be dependent on the size/capacity of the vessel and the choice of fuel, as the use of marine diesel oil incurs greater upstream emissions than the production of heavy fuel oil. This increase in the EEDI demonstrates the importance of lifecycle elements in emission accounting and suggests that they are an important component of shipping efficiency which should not be overlooked.
Keywords: life cycle assessments, efficiency index, CO_2, construction, fuel production,

1. INTRODUCTION

As the challenges posed by climate change become increasingly apparent, greater prominence is given to the means by which goods are transported. Given the increasing globalized nature of modern economies, the international transport of goods has received particular attention. Air transport has been recognised as potentially the most energy intensive mode of transport, and must be instrumental in any attempt to implement emission reductions within the transport sector (Bows and Anderson, 2007). Although accounting for a similar proportion of global emissions, the transport of goods and people by ships has been viewed by some as being relatively benign. Buhaug et al. (2009) estimate that the total Carbon Dioxide (CO2) emissions associated with oceangoing shipping accounting for 870 Mt or 2.7% of global anthropogenic emissions. The perception that emission reductions are less pivotal for shipping than other modes of transport stems partly from its high energy efficiency in the transport of heavy goods, in addition to a greater range of potential significant technical developments than is available to the aviation sector in particular. However the growth in international shipping experienced within the last 30 years has been both consistent and considerable. The United Nations estimate that the quantity of cargo carried on ocean going vessels, as measured in tonne-miles, doubled between 1980 and 2009 (UNCTAD, 2009). The recent economic downturn notwithstanding the global demand for materials is expected to increase. The increasing economic development of industrialising countries, as well as the consumer demands placed on them by developed regions means that this growth in shipping is likely to continue.

In order to inform the future mitigation and management initiatives numerous studies (Eyring et al., 2009; Buhaug et al., 2009; ENTEC, 2005, Endresen et al. 2003, CE Delft, 2009) have quantified the global emissions due to shipping. While individual methodological decisions (such as the use of top down, as opposed to bottom up or activity based analyses) provide differing results, all studies agree that the emissions due to shipping are increasing. The main implication of this is that growth in the shipping sector may potentially offset emission reductions in other sectors. Comparing growth scenarios for shipping emissions (Buhaug et al. 2009) with emission pathways necessary to avoid a likely increase of 2° C demonstrate how a failure to decarbonise the shipping sector may negate emission reductions in all other sectors (Gilbert et al. 2010).

1.1 MEASURING EMISSIONS ASSOCIATED WITH SHIPPING

In order to reflect the scale of the emissions associated with shipping "top-down" emission estimates may be calculated based on national or global scale data such as bunker fuel sales. However, as suggested by Gilbert et al. (2010), such data for sub-global or regional emission accounting may not fully reflect the full scale of international emissions attributable to a given country or region. Alternatively bottom up, or activity based metrics may be applied to provide greater detail or regional specificity in emissions accounting.

The International Maritime Organisation (IMO) has proposed two similar methods to estimate emissions to transported cargo during cruising at sea. In essence both methods calculate emissions based on the amount of fuel consumed per unit of work done (e.g. g CO_2/tonne-km). The energy efficiency operational indicator (EEOI) is calculated based on the recorded fuel consumed during a given voyage in (IMO, MEPC.1/Circ.684).

The unit of EEOI depends on the measurement of cargo carried or work done, e.g. tonnes CO_2 per tonne nautical miles, tonnes CO2 per TEU nautical miles, tonnes CO_2 per person nautical mile, etc. However the mass of fuel associated with the transport of goods is dependent on a number of factors which may not be readily apparent.

In comparison, the energy efficiency design index (EEDI) is intended to inform design decisions by estimating the emissions associated with the transportation of goods by ships (IMO, MEPC.1/Circ.681). The EEDI attempts to take cognisance of design considerations such as engine size, load, the presence of energy recovery systems such as shaft generators or the presence of innovative energy systems. An abridged version of the EEDI equation published by the IMO (MEPC.1/Circ.681) is shown below. This estimates the carbon intensity of shipping in terms of grams CO_2 per tonne-nautical mile. It is hoped that placing limits or bench marking the EEDI will inform future ship designs and hence improve the overall efficiency of the fleet.

$$gCO_2/tnm = \frac{\sum_{i=1}^{nME} P_{ME(i)} \cdot Cf_{ME(i)} \cdot SFC_{ME(i)} + \sum_{i=1}^{nAE} P_{AE} \cdot Cf_{AE} \cdot SFC_{AE}}{Capacity\, V_{ref}}$$

(Eq 1)

- The subscript ME and AE refer to main engines and auxiliary engines respectively.
- P_{ME}(i) = 75 % of the maximum continuous rating (MCR) for each main engine measured in kW and deducted by 75% of the output of any shaft generators.
- Cf is a non dimensional emission factor measured in terms of g (emission) /g (fuel).
- SFC is the certified specific fuel consumption certificate measured in terms of g/kWh.
- PAE is the required auxiliary power to supply normal maximum sea load. If specific engine output and engine loading is unavailable then auxiliary demand can be estimated as a function of the total MCR of main engines.
    - (MCR>10000 kW) PAE = 2.5% . MCR + 250.
    - (MCR<10000 kW) PAE = 5% . MCR.
- Capacity refers to the amount of cargo that the ship can carry, measured in deadweight tonnes. In this case 100% utilisation is assumed.
- V_{ref} refers to the associated service speed measured in knots.

Another distinction between both the EEOI and the EEDI is that the latter is used to generate emission baselines that illustrate the impact of ship size on the emissions allocated to transport services. The direct emissions associated with ship propulsion at sea represent the majority of the emissions associated with transportation of cargo. However the indirect emissions associated with the production of the ship itself and fuel it consumes, should not be discounted. Life cycle assessment (LCA) represents an additional method to quantify the environmental impact of shipping by estimating the contribution of the different product stages including ship construction, operation and disposal. The impacts of any activity are allocated to a specific reference unit (termed the functional unit). Accounting for upstream or indirect emissions demonstrates that an increase (or indeed) reduction in the demand for shipping can increase the impact of shipping on emissions pathways or reduction targets. Facanha and Horvath (2007) demonstrate that in the case of CO_2 and NO_x, accounting only for direct emissions may underestimate total lifecycle emissions by up to 38%, depending on the mode. The above authors did not include transport by ship in their assessment. This paper seeks to present a similar assessment by comparing direct CO_2 emissions with overall emissions associated with the production (and dismantling) of ship material and fuel. It is argued that lifecycle impacts are equally valid for consideration at the design stage and there is merit in their incorporation into emission baselines such as the EEDI. Lifecycle accounting tools such as Simapro (Pre consultants, 2010) will also include the upstream emissions associated with transport. However such a tool may not provide insight on to the impact of different vessel sizes types or utilization on the lifecycle emissions associated with 1 tonne nautical mile or 1 tonne km. In order to gauge the impact of such consideration the ratio between direct and total lifecycle emissions have been estimated for a range of different ship types and sizes.

2. METHODOLOGY

2.1 DIRECT EMISSIONS

The direct emissions associated with shipping are estimated using equation 1 for a range of vessels and sizes. Vessel capacity, engine size and speed estimates for cargo vessels arriving in the UK are provided by Lloyd's marine intelligence unit (LMIU).

For ease of comprehension, the relationship between ship size and emissions are used to generate region curves. It is assumed that the main and auxiliary engine use heavy fuel and diesel respectively. Fuel consumption and emission factors for both engine and fuel types are taken from Buhaug et al. (2009).

2.1 INDIRECT EMISSIONS

2.1 (a) Ship Construction

In order to estimate the carbon emissions embodied in the construction of a ship, the actual weight of the ship is necessary. This is found by using the deadweight coefficient (C_{dw}) which translates cargo capacity into overall displacement. Subtracting deadweight from displacement provides the actual weight of the ship itself, termed the lightweight. Deadweight coefficient estimates for a number of vessels across different capacity ranges are taken from Barass (2003), Watson (1998) and European Commission. (2004). The lightweight tonnage estimate is further disaggregated into steel-weight, machinery weight and joinery weight. The relative contribution of steel, machinery and joinery for different ship sizes is taken from Andersen et al. (2001) and are summarised in Table 1 below.

Table 1: Distribution of steel and ancillary weight.

Ship Size	Steel weight %	Joinery and Machinery %
400,000 DWT	85	15
200,000 DWT	84	16
100,000 DWT	80	20
70,000 DWT	77	23
20,000 DWT	69	31
Average	75	25

Steel weight is assumed to relate to reinforcing steel, machinery weight is assumed to reflect cast and stainless steel in equal measure and joinery is assumed to include low alloyed steel and wood components. Additional elements such as copper and zinc consumption are quantitatively negligible in comparison to structural and machinery components. The lifecycle carbon emissions associated with the production of material used in ship construction is estimated using lifecycle emission data from Pre Consultants (2010). Because of its relative contribution, the lifecycle emissions are heavily influenced by the emissions embodied in reinforced steel (1.31 t CO_2/LWt). Overall emissions range from 1.41 t CO_2/LWt for smaller vessels to 1.35 t CO_2/LWt for larger vessels.

However estimating the carbon emissions associated with the production of structural material does not fully reflect all the emissions attributable to a ship. The construction phase will incorporate numerous activities such as welding, forming, sea trials etc., as well the transportation of the construction material itself. The electricity consumption at an Asian shipyard necessary for the construction of a 10,000 short-tons (approximately 9,070 tonnes) bulk carrier is taken from Kameyama et al. (2004). These are summarised in Table 2 below.

Table 2: Ship yard electricity use.

Category	Electricity kWh
Cutting	230,000
Plate forming	20,000
Welding	120,000
Goughing	80,000
Crane	90,000
Magnet Crane	5,000
Compressor	320,000
Lighting	110,000
Fan Use	110,000
Air conditioning	230,000
Pumping out	10,000
Out fitting	10,000
Office Work	198,000
Design Work	60,000
Leak, etc	80,000

The carbon emissions associated with electricity use at the ship yard are estimated using the average carbon intensity of electricity produced in China, the Republic of Korea and Japan (IEA, 2010). Collectively these countries were responsible for over half of the global new builds (when measured in $) in 2007 (ITC, 2007) or 86% of new builds (when measured in vessel number) in 2008 (Worldyards, 2008). However the emissions related to shipyard activities are not attributable solely to electricity. Other emission sources include direct emissions associated with construction (e.g. use of gas as opposed to electricity welders) as well as sea trials and truck movement within the yard. Emissions estimates based on these activities are taken from Kameyama et al. (2004) and Gratos et al. (2010) and are allocated per ship lightweight tonne. Kameyama et al. (2004) estimate that the construction of the study ship will necessitate 4,300,000 tkm. This is assumed to be satisfied by coastal/domestic shipping, oceangoing shipping and trucks which respectively account for 82%, 12% and 6% of the above estimate. Carbon emission factors for transport services are taken from DECC (2010). (However such results should be viewed with caution given the regional concentration of shipbuilding industries.)

The emissions associated with recycling are estimated based on ship breaking. Gratos et al. (2010) suggest that the cutting of 1 tonne of steel requires approximately 60 kg of liquid propane. Based on the carbon content of propane, this results in an emission estimate of 0.18 t CO_2 per tonne of steel. Data from (European commission,

2009) suggest that approximately 80% of a ship's lightweight consists of recyclable material. It is assumed 100% of this material is recycled. These ancillary emissions are also aggregated and allocated to ship lightweight in the same manner as the emissions embodied in structural material.

The overall emissions associated with the production of a vessel are allocated to transport services based on the average dismantling age published by (EU commission) and the average annual transport service (measured in tonne-km) per ship type and size published in Buhaug et al. (2009).

2.1 (b) Fuel Production

Corbett and Winebrake (2008) report on a study which adopts a whole lifecycle approach to account for the emissions associated with fuel production and transportation. The Total Energy and Environmental Analysis for Marine Systems (TEAMS) model (Winebrake et al., 2007) is used to apply total fuel cycle analysis for marine vessels. This model in effect estimates the energy inputs and associated (combustion and non-combustion) emissions of both upstream (production, transport etc.) and downstream operational use. The emissions are calculated using a "per-trip" basis including fossil energy use (petroleum, natural gas, and coal), direct petroleum use, as well as the emissions, including CO_2. The main advantage of this method is that it allows the upstream emissions to be compared with direct emissions in order to estimate lifecycle multipliers.

The transport distances used in the TEAMS model reflect conditions within the US. This includes a large degree of transport by road which may not reflect European or UK conditions. In order to gauge the impact of changing existing assumptions a plausible pathway for crude and heavy fuel oil (HFO) imports to the UK was incorporated into the model. (Model inputs require single length distances for individual journey segments for crude, HFO and diesel fuel). Based on information from Bolt (2006) and Koldenhof and Bolt (2007) it was assumed that HFO was transported from Rotterdam to Immingham.

- The fuel oil itself was assumed to be produced as by product of refining in the Gordof/wessing area in Germany and pumped to and from the port (Melieste, 2006).
- The crude oil used in the production of HFO was assumed to be exported from the King Fahad Industrial Port in Saudi Arabia stopping at Said port in Egypt.
- The crude itself is assumed to pumped from the eastern oilfields to King Fahad port.
- Direct imports of crude oil are assumed to be transported from Mongstad in Norway to the port of Liverpool (Koldenhof and Bolt, 2007).
- This crude oil was assumed to be originally piped from North Sea oilfields via the troll 1 pipe line.

Port to port distances are calculated using a distance calculator provided by www.Vesseltracker.com. The individual journey legs are shown in Table 3.

Table 3: Crude and HFO transportation assumptions.

Origin	Destination	Distance (km)
Crude to HFO		
Saudi Arabian Oil Fields	King Fahad Industrial Port	1,207 By pipe
King Fahad Industrial Port	Port of Said Egypt	1,218 By ship
Port of Said Egypt	Port of Rotterdam Netherlands	6,030 By ship
Port of Rotterdam Netherlands	Gordof/Wessling Refineries	277 By pipe
Port of Rotterdam Netherlands	Port of Immingham, UK	492 By ship
Crude		
North Sea Fields	Port of Mongstad Norway	64 By ship
Port of Mongstad Norway	Port of Liverpool UK	548 By ship

Diesel was assumed to be produced in the UK and pumped on average 300 miles. This represents an upper limit based on the existing map of oil pipe infrastructure. In examining the emissions associated with shipping it is important not to discount the impact of capacity utilization. For this reason the emission factors for different ship types and sizes published in Buhaug et al. (2009) are analysed and the contributing factors (ship size, engine use, under utilization of capacity etc) are identified. The lifecycle emissions and fuel based multipliers are applied to these ship characteristics. This assists in illustrating the impact of actual ship characteristics on the ratio between direct and indirect CO_2 emissions associated with 1 tonne-km.

3. RESULTS

The impact of incorporating lifecycle emissions on shipping emissions is described below. It should be clarified that any LCA will be dependent on the specific study boundary and elements included in the study and therefore may complicate comparisons with other studies.

3.1 INDIRECT EMISSIONS

The relative contribution of categories included within ship production are shown in Figure 1 demonstrating the dominance of the emissions associated with the production of ship structural material. It should be noted that the emissions shown in the figure below are based on a specific distribution between steel weight, machinery and joinery which will vary depending on the ship size. Although this is not shown to significantly impact the relative contribution of other emission categories such as sea trials.

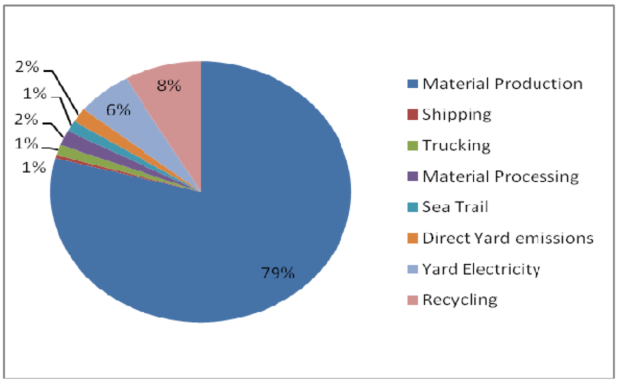

Figure 1: Relative contribution of emissions associated with ship construction for ship of 10,000 short tons lightweight. Based on data published in Kameyama et al. (2004).

However ancillary categories such as yard based electricity should not be ignored as they contribute to over 20% of the CO_2 emissions emitted during the production stage.

Based on data used within the TEAMS model the proportion of upstream and direct emissions for the reference trip using both HFO and diesel is summarised in Table 4.

Table 4: Upstream and direct emissions associated with fuel production and use. Estimated using TEAMS model V 1.3 modified to reflect specific data.

	Feedstock	Fuel	Operation
t CO2/trip	540	761	14,836
%	3.35%	4.72%	91.93%

Using this tool allows multipliers between direct and indirect emission to be estimated (e.g. g CO_2 total fuel cycle/g CO_2 operation). The main advantage of this method is that it lessens the impact of variation between vessel types and simplifies the inclusion of lifecycle impacts into emission curves such as the EEDI. (However this comparability is dependent on the accuracy of some key assumptions, such as the carbon content of the fuels themselves). Based on the relative contribution of the emissions associated with the operation phase of fuel use, a multiplier of 108.7% is estimated to reflect emissions throughout the whole lifecycle of the fuel. As said this was based on a reference voyage. Alternating the assumptions regarding ship size etc will change the emissions (per trip) associated with each individual stage but will not have a pronounced effect on the multiplier. For example increasing the estimated horsepower of the reference vessel five fold was seen to reduce the associated multiplier to 108.6% or by 0.11%.

3.2 FULL LIFECYCLE EMISSION CURVES.

Based on data provided by LMIU emission curves have been calculated using equation 1 to reflect both direct emissions and also incorporating the lifecycle elements described above. The inclusion of lifecycle emissions was shown to increase the CO_2 emissions allocated to 1 tonne-nm undertaken by a Chemical Tanker by 12%.

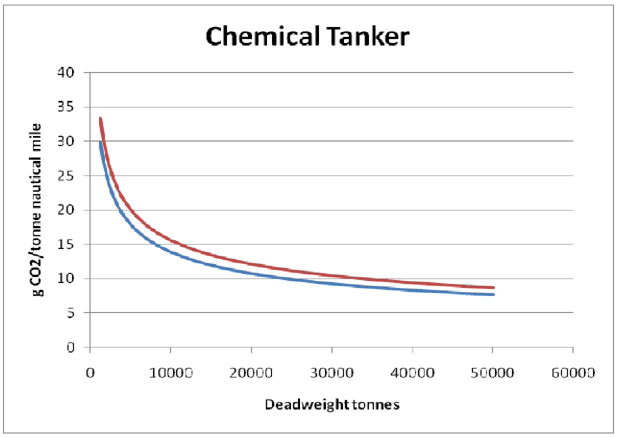

Figure 2: Direct and overall emissions associated with Chemical Tankers.

Similarly the CO_2 emissions allocated to 1 tonne-nm undertaken by a container and RORO ship increase by 13% on average.

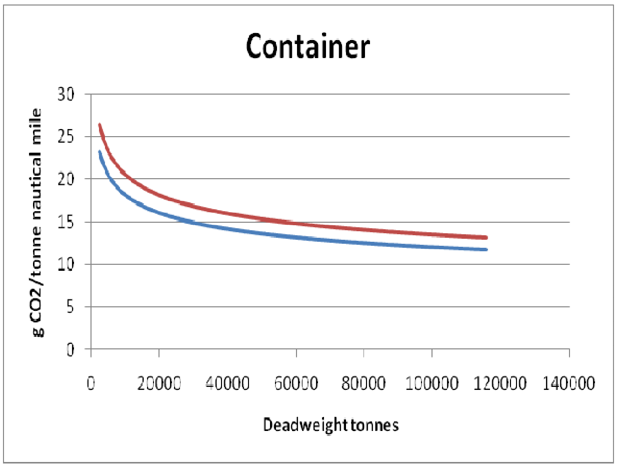

Figure 3: Direct and overall emissions associated with Container ships.

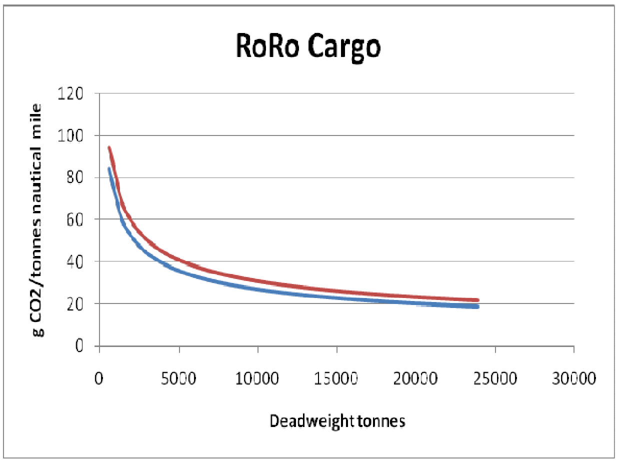

Figure 4: Direct and overall emissions associated with RoRo Cargo.

The emissions associated with Gas Carriers are increased by 14% by including lifecycle impacts.

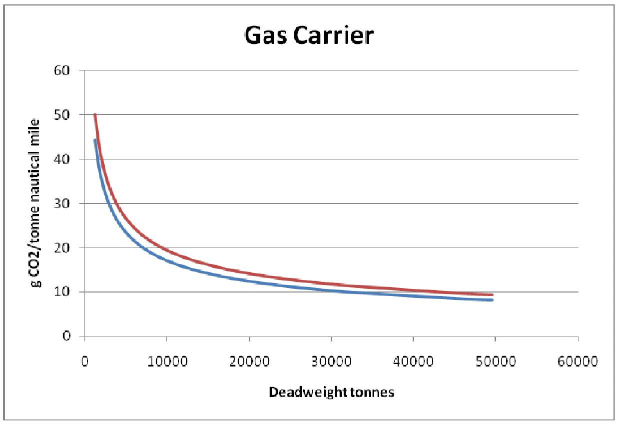

Figure 5: Direct and overall emissions associated with Gas carriers.

For Oil Tankers, Bulk carriers and product Tankers the overall life cycle emissions attributable to material taken on a product tanker exceed direct emissions by 15%.

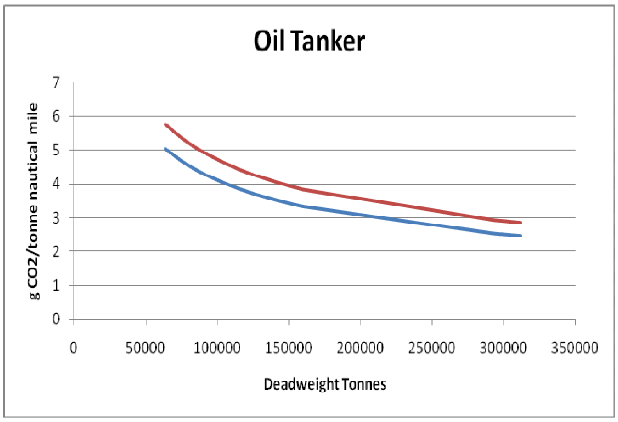

Figure 6: Direct and overall emissions associated with Oil Tankers.

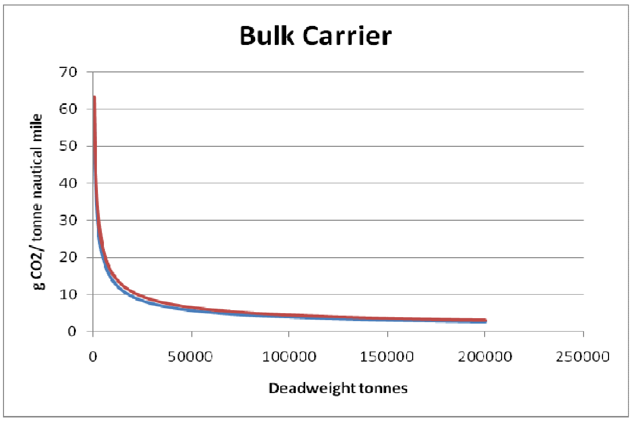

Figure 7: Direct and overall emissions associated with Bulk Carriers.

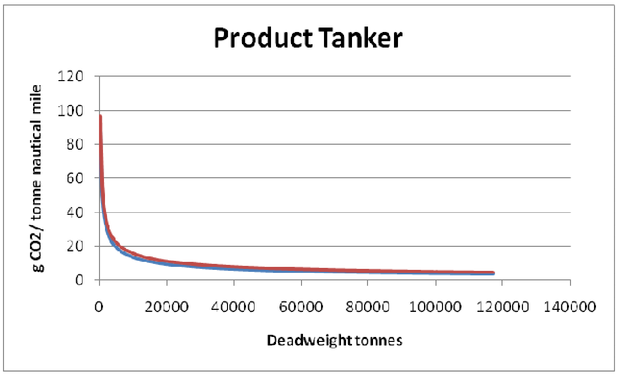

Figure 8: Direct and overall emissions associated with Product Tankers.

Incorporating indirect emissions was seen to have the greatest impact on General Cargo vessels, increasing emissions by 18% on average.

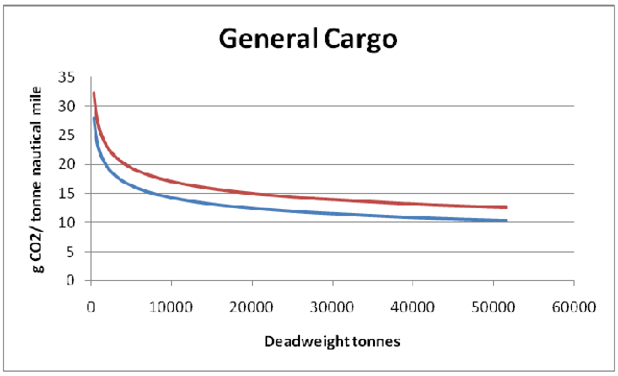

Figure 9: Direct and overall emissions associated with General Cargo category.

Based on these results it may be suggested that the total carbon emissions associated with shipping exceed direct emission by approximately 14%. As stated previously the calculation of an emission index such as the EEDI does not take into account the issues associated with under utilization. In order to reflect conditions that are more representative of actual operations the emissions factors published in Buhaug et al. (2009) are recalculated and augmented by incorporating the same indirect emission factors and multipliers. These results are summarised in Table 5 below.

Table 5: Upstream and direct emissions associated with fuel production and use. Based on data published in Buhaug et al. (2009).

	g CO2/tkm		
Size	**Direct**	**Total**	**Increase**
Crude oil tanker			
200,000+ dwt	2.9	3.26	14%
120,000–199,999	4.4	4.92	12%
80,000–119,999	5.9	6.57	11%
60,000–79,999	7.5	8.32	11%
10,000–59,999	9.1	10.08	10%
0–9,999 dwt	33.3	36.58	10%
Products tanker			
60,000+ dwt	5.7	6.42	12%
20,000–59,999 dwt	10.3	11.48	12%
10,000–19,999 dwt	18.7	20.63	10%
5,000–9,999 dwt	29.2	32.13	10%
0–4,999 dwt	44.9	49.37	10%
Chemical tanker			
20,000+ dwt	8.4	9.27	11%
10,000–19,999 dwt	10.8	11.91	10%
5,000–9,999 dwt	15.1	16.59	10%
0–4,999 dwt	22.2	24.37	10%
LPG tanker			
50,000+ m3	9.0	9.91	10%
0–49,999 m3	43.5	47.87	10%
LNG tanker			
200,000+ m3	9.3	10.22	9%
0–199,999 m3	14.5	16.04	10%
Bulk carrier			
200,000+ dwt	2.5	2.86	15%
100,000–199,999 dwt	3.0	3.41	13%
60,000–99,999 dwt	4.1	4.59	11%
35,000–59,999 dwt	5.7	6.36	12%
10,000–34,999 dwt	7.9	8.78	11%
0–9,999 dwt	29.2	32.07	10%
General cargo			
10,000+ dwt	11.9	13.14	10%
5,000–9,999 dwt	15.8	17.62	11%
0–4,999 dwt	13.9	15.89	14%
10,000+ dwt 100+ TEU	11	12.13	11%
5,000-9,999 dwt 100+ TEU	17.5	19.37	11%
0-4,999 dwt 100+ TEU	19.8	22.30	13%
Container			
8,000+ TEU	12.5	13.77	10%
5,000–7,999 TEU	16.6	18.23	10%
3,000–4,999 TEU	16.6	18.23	10%
2,000–2,999 TEU	20	21.95	10%
1,000–1,999 TEU	32.1	35.11	9%
0–999 TEU	36.3	39.81	10%
Vehicle			
4,000+ ceu	32	35.14	9%
0–3,999 ceu	57.6	63.39	10%
Ro-Ro			
2,000+ lm	49.5	54.27	10%
0–1,999 lm	60.3	67.12	11%

When including actual operational conditions such as under-utilization, incorporating indirect elements increases the associated carbon emission by a lesser margin of 11 % than estimated using the EEDI.

4. DISCUSSION

The most apparent impact of incorporating lifecycle emissions is that it reinforces the assertion that focusing purely on the direct emissions under estimates the impact of freight transport. As suggested above, theses upstream emissions may increase the carbon footprint of shipping by between 11 and 14%. This may appear meagre particularly given shipping's position as the least emission intensive mode of freight transport. However, allocating emissions to a single functional unit may belie the overall impact of indirect emissions. For example Buhaug et al. (2009) estimate the global CO_2 emissions attributable to shipping to be 1,050 MT in 2007. If the lifecycle multipliers implied in this paper are accepted, then the global indirect emissions associated with shipping may range from 115-147 MT. By way of illustration the relative contribution of the various emission stages estimated (per tonne km) are shown in Table 6 below. These relate to a similar ship as referred to in Table 2 and Figure 6.

Table 6: Relative contribution of emission stages associated with a bulk carrier of approximately 10,000 short tons lightweight.

Stage	Relative % g CO2/tkm
Operation	90.18%
Fuel	7.85%
Material	1.56%
Shipping	0.01%
Trucking	0.03%
Material Processing	0.04%
Sea Trail	0.03%
Direct Yard emissions	0.04%
Yard Electricity	0.12%
Recycling	0.16%

The productivity and relatively long functional life of modern cargo vessels means that many of the impacts associated with ship construction are effectively obfuscated by larger elements. For example a ship will contain significant quantities of lead, aluminium, copper and zinc (European commission, 2004) respectively. While the aggregated emissions associated with the production of these components may be significant they are effectively negated once emissions are allocated to tonne km. It is important that the ongoing analysis of the emissions associated with international shipping should not loose sight of the importance of aggregated estimates.

Comparing the results demonstrated in Figures 2-9 and in Table 4 demonstrates that assumptions regarding engine size, capacity, speed, and under utilization are important for quantifying lifecycle emissions. Incorporating actual ship operational data (including speed and utilization) increases the relative contribution of lifecycle emissions. This may be attributable to two factors. Incorporating the effects of capacity underutilization increases the direct emissions allocated to a single tonne kilometre (or tonne nautical miles). As an equivalent lifetime and annual service provision (tkm per year for each ship type and size range) is assumed in this will reduce the relative contribution of emissions associated with the construction of the ship.

The results presented above highlight that increasing specificity regarding ship type and size is as relevant for indirect as direct emissions. Assuming a standard lifecycle multiplier for shipping in general may be justifiable for some categories but not all. For example the general cargo ship category demonstrates the largest lifecycle multiplier regardless of whether actual operational conditions are reflected or not.

For some ship categories the lifecycle emission multiplier is increased for larger vessels. This may be due to the size of the ship increasing by a greater margin than the average annual activity of the ship in question (i.e. the numerator increasing relative to the denominator). However given the aggregated nature of the annual service provision estimates, further data is necessary to determine the accuracy of this statement.

The LCA tool Simapro (Pre consultants, 2010) includes two levels of analysis for each module, system and unit modules. System modules reflect all the emissions embodied in a product, including both upstream and direct emissions, while unit modules only make the direct emission explicit. Comparing the ratio between both system and unit emission allows the impact of upstream activities to be assessed. In order to assess the representativeness of the lifecycle multipliers generated in this study, results estimated in this study are compared with those implied by other life cycles assessments such as those generated within Simapro. Based on these data the overall carbon emissions associated with 1 tonne-nautical mile of freight transportation exceed direct emissions by 13.2% while transport by tankers increases by 13.5%. While accepting that different methods are not strictly comparable due to boundary issues etc…, this would seem to corroborate the range of emission multipliers suggested in this study.

As with all studies the results presented should be viewed with a caveat. While it is not the purpose of this paper to critique methodologies such as the EEDI, its accuracy will impact upon any lifecycle multiplier. It should be stated that any given EEDI estimate represents a single design point and is susceptible to significant variation. Variations in speed, engine size, capacity will result in significant scatter. Indeed the emission curves generated in Figures 2 to 7 generally demonstrate low regression correlation (R^2) estimates. However this should not be seen as a reflection of the methodology itself but rather inherent variation in the data used. Within the raw emissions estimates used to generate the emission curves lifecycle multiplier is seen to reach a maximum of 120% for most ship categories.

The EEDI is intended to be applied to new builds which may be expected to exhibit less scatter than the range of ships included in this study. What the results do suggest is that lifecycle elements can feasibly be incorporated into emission baseline estimates. This highlights the impact of different design or operational choices which may not be readily apparent. As stated previously, the lifecycle emission savings may be minute when expressed in terms of a unit of transport service like a tonne-kilometre but realise significant savings when expressed in terms of the whole lifecycle. For example a small reduction in the steel weight may yield significant carbon savings when viewed collectively.

It is debatable as to how the inclusion of such elements into the EEDI may be received. Detractors of the EEDI may cite the relative importance of fuel based lifecycle emissions as an enhancement of the impact of slow steaming and simply provide a greater incentive for the construction of under powered ships in order to achieve emission reduction targets (at the cost genuine innovation). Alternatively including such upstream emissions reinforces how the impact of shipping is not relegated to the operation of the ship and that decarbonising the entire lifecycle of a product or service is as much a priority as the direct operations phase.

Implied in any discussion regarding the impact of carbon emissions is the illustration of relevant timeframes. It is accepted that cumulative emissions are likely to have the greatest capacity to influence global temperature change (Allen et al., 2009). The construction of a ship takes places in a relatively short time frame before it is placed in active operations and its associated emissions may remain in the atmosphere for a relatively long period. By contrast the direct emissions due to operation represents the majority of emissions but are released throughout the lifetime of the vessel up until it is decommissioned. This implies a distinction between short term and longer term emission gains and suggests that potentially complex trade-offs may exist in seeking to reduce the overall impact of the shipping (and indeed general transport) sector.

However the method used in this paper distinguishes the lifecycle emissions associated with both ship and fuel production. This is a core distinction as increasing the use of the ship (by increasing the tonne kilometres associated with its functional lifetime) will reduce the attributed construction based emissions. By contrast each quantity of fuel consumed will have an upstream emission associated with its use. Increasing the distance travelled will naturally increase both the direct and indirect emissions due to fuel combustion. Given that these emissions can be up to 3 times those associated with construction, the lifecycle assessment of shipping may be justifiably considered an examination of potential tradeoffs. An increase in the emissions associated with construction will be justified if it can demonstrate a reduction in fuel consumption.

This distinction is even more pronounced if the fuel in question is diesel. Presently HFO (due to its relative cost) represents the vast the majority of the fuel combusted within the shipping sector. Recent concerns over local areas pollutants such as particulates, NO_x and SO_x emissions have resulted in marine diesel being considered as an alternative fuel source for use in the main engines. However this will result in greater direct and indirect fuel use as diesel has a higher carbon content and a greater indirect emission estimate due to the fact that it is more refined. (HFO in reality is a by-product of the refining process). Based on the TEAMS emission model a ship using low sulphur diesel is shown to demonstrate a lifecycle multiplier of approximately 119%., increasing the overall lifecycle multiplier to over 120%. This increase begs the question as to what constitutes the areas that the shipping sector has the capacity to directly influence. As stated previously any reduction in fuel consumption will reduce the actual (direct and indirect) emissions associated with shipping. However ship designers/operations may not have the capacity to influence the upstream emissions associated with refining or fuel processing and therefore may not be able to affect the ratio between carbon due to the production and combustion of fuel.

It could be argued that the treatment of recycling within this method does not accurately reflect the environmental impact of recycling as dismantled material will be used either within the region itself or perhaps exported to less developed regions. Gratsos et al. (2010) allocate carbon savings to ship recycling as they offset the need for the production of virgin material. However without realistic data on the actual material substituted by resources recovered from dismantling yards, any estimates of potential carbon savings will be hypothetical.

5. CONCLUSION

Despite representing the most efficient mode of freight transport, the shipping sector also faces significant challenges to decarbonise. Taking into account the emissions associated with shipping requires consideration of construction, fuel refining and transport, dismantling and transport. Based on this, the extent to which indirect emissions are shown to increase the climate impacts associated with shipping with shipping is dependent on a number of factors. Different vessel types and sizes demonstrate different lifecycle multipliers. The weight of the ship, its material components and its use throughout its functional life determine the construction emissions allocated to shipping. By contrast the upstream emissions associated with fuel production are dependent on the extent to which it is refined but also the distance travelled. Emission released through construction stages are estimated to be between 1 and 3% of direct emission with fuel bases emission shown to be 8.7 or 19.3% of direct emissions depending on whether the fuel was HFO or diesel. While the results presented are comparable with those estimated within other lifecycle studies. However altering ship size, engine use and capacity utilization factors is shown to decrease the relative contribution of indirect emission from 14 to 11% and may be considered a more accurate reflection of the current state of the shipping sector. The results presented here demonstrate the feasibility in incorporating indirect emissions into a methodology such as the EEDI although their formal inclusion would require much greater data sophistication than presented here.

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REFERENCES

Allen, M.R., et al. (2009). ‘Warming caused by cumulative carbon emissions towards the trillionth tonne’, Nature, Vol. 458, pp. 1163–1166.

Andersen, A., et al. (2001). 'Technological and Economic Feasibility Study of Ship Scrapping in Europe', Report commissioned by European Commission, carried out by Det Norske Veritas and Appledore International.

Barass, B. (2003). 'Ship Design and Performance for Masters and Mutes', Butterworth-Heinemam, UK.

Bolt, E. (2006) 'Crude Oil and Residual Fuel Oil Transport on the North Sea'. Safety at Sea Demonstration Project A Report No A01-2.

Bows, A., Anderson, K. & Upham, P. (2008). 'Aviation and Climate Change: Lessons for European Policy', 1st ed. Routlege, London.

Buhaug, Ø., et al. (2009). 'Second IMO GHG Study 2009', London: International Maritime Organization (IMO); 2009.

CE Delft. (2009). 'Technical Support for European action to reducing Greenhouse Gas Emissions from international maritime transport', The Netherlands: Report to European Commission; 2009.

Corbett, J. & Winebrake J. (2008). 'Emissions Tradeoffs among Alternative Marine Fuels: Total Fuel Cycle Analysis of Residual Oil, Marine Gas Oil, and Marine Diesel Oil', Journal of. Air & Waste Management Association, Vol. 58, pp. 538–542

Endresen. Ø., et al. (2003). 'Emission from International Sea Transportation and Environmental Impact', Journal of Geophysical Research, Vol. 108, No D18, pp. 4560,

Entec. (2005) 'Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments', Task 2b and c – NOx and SO2 Abatement, UK, Report prepared for the European Commission.

EU Commission. (2004) 'EU Oil Tanker Phase Out and the Ship Scrapping Industry'. European Commission Directorate-General Energy and Transport, Brussels

EU commission. (2009). 'Support to the impact assessment of a new legislative proposal on ship dismantling', European Commission Directorate-General Energy and Transport, Brussels.

Eyring, V., et al. (2009). 'Transport Impacts on Atmosphere and Climate,' Shipping, Atmospheric Environment; Vol. 44, No. 37, pp. 4735-4771.

Facanha, C. & Horvath, A. (2007). 'Evaluation of Life-Cycle Air Emission Factors of Freight Transportation', Environmental Science and Technology, Vol. 41, No. 20, pp. 7138–7144.

Gratsos, G., Psaraftis, H., & Zachariadis, P. (2010). 'Life cycle co2 emissions of bulk carriers: A comparative study', International Journal of Maritime Engineering', Vol. 152, pp. 119- 134.

Gilbert, P. & Bows, A. (2011). 'Apportioning international shipping emissions to nations to support the development of sub-global mitigation policies', Submitted to global environmental change.

Gilbert, P., Bows, A. & Starkey, R. (2010). 'Shipping and climate change: scope for unilateral action', Tyndall Centre for Climate Change Research and The Sustainable Consumption Institute, Manchester.

IEA (2010). 'CO2 emissions from fuel combustion', International Energy Agency. 9 rue de la Fédération, Paris, France.

ITC (2007). 'International shipbuilding ranking', International Trade Centre. Geneva.

Kameyama, M., K. et al (2004). 'Development of LCA software for ships and LCI analysis based on actual ship building and operation', Proceedings of the 6th International Conference on EcoBalance, Oct.25- Oct. 27, Tsukuba, Japan、pp. 159-162.

Koldenhof, Y. & Bolt, E. (2007). 'Inventory, Classification and Risk Assessment of Oil Transport on the North Sea', Safety at Sea Demonstration Project A Report No A05

Melieste, R. (2006). 'Energy and Processing industries', Energy & Industry department, port of Rotterdam. Netherlands.

Pre Consultants (2010). 'Simapro lifecycle analysis software. V. 7.2', Amersfoort, The Netherlands.

Winebrake, J., Corbett, J. & Meyer, P. (2007). 'Total Energy & Emissions Analysis for Marine Systems (TEAMS) model V 1.3', The centre for energy analysis and policy. Rochester, New York. Results based on modification undertaken by the authors.

Worldyards. (2008). 'Ranking of shipbuilding countries in terms of compensated gross tonnage (CGT) and vessel number', Data accessed through www.intertanko.com