Initial Estimates On Shipping's Cost Impacts and Emissions for a Range of Policy Options - A Prototype Model

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ABSTRACT

Shipping was estimated, in 2007, to be responsible for 3.3% of anthropogenic CO2 emissions. Scenarios for future growth in transport demand suggest that this share could substantially increase in the next 40 years, and without regulation the growth in emissions associated with that demand growth would be uncontrolled. Modelling can be used to understand the potential trajectories of emissions from the shipping industry and its potential development and impacts under foreseeable economic scenarios. Modelling can also be used to estimate the response (in terms of changes to those emissions trajectories and impacts on the industry) due to hypothetical regulation and policies. This paper proposes methods for conceptualizing the different components of the shipping industry for these purposes.

ship, economics, energy efficiency, policy

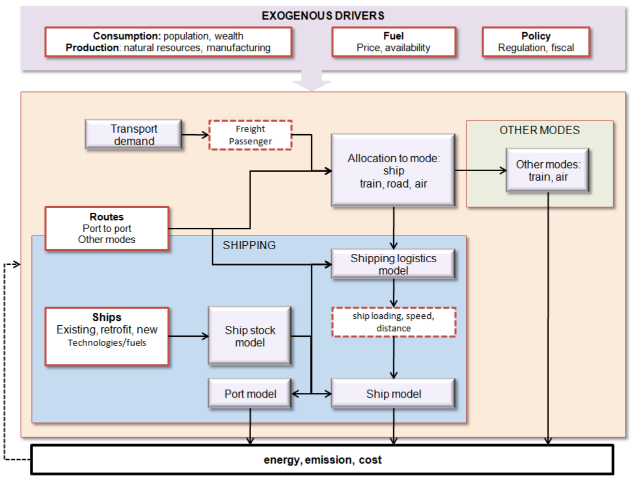
1. INTRODUCTION AND BACKGROUND

The Low Carbon Shipping project is undertaking a detailed and holistic analysis of the global shipping system, its energy use, and its potential to abate its future CO2 emissions.

A model is being produced in Work Package 1 (WP1) to simulate the shipping 'system'. GloTraM-2 is the latest version of this model representing progress during the first year. Over the remaining two years, this model will be further evolved both by work on going in WP1 and through input from WP's 2-6 which are undertaking associated research.

The fundamental concept of the modelling work is to determine demand and allocate it to shipping and other modes, assign ships to demand with a logistical model and calculate the energy, emissions and costs of operating the system.

1.1 MODELLING THE GLOBAL SHIPPING SYSTEM



A number of models are have been employed for shipping emissions analysis. Miola et al (2010), summarised the different approaches in a report, categorising them as follows:

1. Full bottom-up approach: the pollution that a single ship emits in a specific location is evaluated.
2. Bottom-up approach: evaluation of total emissions, but top-down in the geographical characterisation: a single vessel is considered in the analysis, but nothing is known about its position.
3. Top-down approach in the evaluation of total emissions, but bottom-up in the geographical characterisation: this analysis starts by considering a single maritime route or a particular geographic cell and evaluating the global activity which is carried out on it, no matter which vessel carries out the activity.
4. Full top-down approach: total emissions are calculated without considering the characteristics of the individual vessels, and are later spatially assigned.

The ultimate ambition of this research is to build a category 1 model, as this allows consideration of: the impact of trade pattern changes, the preference to transport goods on shipping over alternative modes (air/land), the simulation of technical and operational changes in the fleet and regional regulatory schemes. Therefore, the model needs to produce meaningful characterisations of:

- Trade demand between regions and within a region
- Shipping route selection for different vessels between regions
- Allocation of trade flows to the ships within the global fleet

Whilst progress is ongoing to produce models to simulate all three of these aspects of the global shipping system, the GloTraM-2 model can currently best be described by category 2 above, that is:

- Globally aggregated transport demand for each ship type (container ships, wet bulk, dry bulk)
- Bottom up simulation of the distance covered by individual ships, the cargo load carried and the technical (hull form, machinery, abatement options etc) and operational (speed, distance traveled etc) selections made for individual ships
- Aggregation of the emissions of CO2 globally, which are not then allocated to geographical regions (as the impact of CO2 is global)

2. MODEL THEORY

2.1 EXOGENOUS DRIVERS

GloTraM-2 represents the exogenous drivers as a sequence of Excel spreadsheets containing input data that describe:

- Global GDP projections to 2050
- Policy/regulation projections (required EEDI levels (from IMO), SOx and NOx levels (from MARPOL Annex VI), user defined Fuel Levy prices)
- Cost data projections (operating costs, fuel/carbon costs (user defined), periodic maintenance costs, capital costs and port costs)

The purpose of incorporating these data as Excel spreadsheets is so that they can be easily modified if a more authoritative source can be found, or if the user wants to input their own preferred values

2.2 TRANSPORT DEMAND

Transport demand T_d is defined for a given year as the total mass of freight multiplied by the distance it is transported, in GloTraM-2 it is given the units tenm.

The shipping industry only exists to meet the demand for the transport of goods deriving from global trade flows. Therefore, fundamental to calculating realistic future emissions of the shipping industry is the collation of ‘reasonable’ data describing the future transport demand.

For an initial estimate of trajectories of transport demand, GloTraM-2 correlates historical trade data for groups of commodities (containers, wet bulk commodities, dry bulk commodities) with historical GDP data to obtain trends which are then projected into the future using the global GDP projections (exogenous drivers).

In future evolutions of Glo-TraM, the database and code will be adapted to provide a breakdown of transport demand along specific shipping routes, along with scenarios for the evolution of trade patterns.

2.3 SHIPPING LOGISTICS MODEL

Mode choice in GloTraM-2 is constrained to shipping, no other transport modes are selectable.

GloTraM-2 considers global aggregates of transport demand, in order to determine how many ships will be required to meet that demand, the transport supply (T_s in tenm) provided by ships within the ship stock is calculated each year. This is found from the sum of the transport supply provided by individual ships according to:

$$T_s = dwt.F_{cap}.V_{op}.T_l.\eta_{voyage} \qquad \textbf{(1)}$$

Where *dwt* is the deadweight (te) of the ship a proxy for the payload it can carry, F_{cap} is the average capacity factor of the ship - the proportion of its cargo capacity that is on average occupied by cargo, V_{op} is the operational speed of the ship in knots, T_l is the total hours spent at sea per year in the loaded condition and η_{voyage} is the voyage efficiency.

The variables *dwt* and V_{op} are calculated in the ship model for existing and future ships. T_l is calculated as a function of V_{op} and an assumption on the annual availability of the ship and the days it spends in port per nm travelled. Values specific to a ship type and size of the remaining variables have been sourced from literature (e.g. Buhaug et al) and are assumed to remain constant over the time period evaluated by the model.

The value η_{voyage} is not commonly recorded as average values for a fleet of ships, and so this is estimated and where possible t calculated performance (found using estimated values) can be compared against operational data to validate these estimates. The variable is intended to represent a number of operational realities, which in different ways decrease a vessel’s efficiency (economic and energy). These realities include, among other things:

- Arbitrage – Ships can sometimes start a voyage without having an exact destination confirmed. Alternatively, they can start out on a voyage from A to B, only to modify their destination to C mid route. One cause of this is arbitrage – the simultaneous buying and selling of a ship’s cargo or part cargo, whilst en route. In the event that this happens it can result in a change of route so that the ultimate distance traveled (from origin to destination) is longer than the direct sailing distance.

- Weather – Technical data on ship's performance is obtained in still (or near still) water. Whereas in practice, voyages across oceans are rarely in still water. The consequence of weather (wind, waves and currents) is to either increase the voyage time or increase the power needed to travel at the same speed as in calm water.
- Voyage planning efficiency – At both the origin, destination and any points of constriction along the route (e.g. canals), there is a risk of congestion. That congestion can increase the voyage time and increase the energy consumed by auxiliary (e.g. cargo) machinery during the voyage.

In future versions of the model, this estimated parameter may be broken down further to allow closer control and observation of the impact of these individual contributing effects.

The transport supply calculation also informs the annualised average of a ship's Energy Efficiency Operational Index (EEOI) which is discussed in greater detail in Section 2.6, and the calculation of the demand for new ships in the ship stock model.

Future evolutions of GloTraM will include a more comprehensive model of shipping logistics and will:

- Calculate the share of transport demand carried by shipping (allocation to mode)
- Calculate the specific routes that the shipping trade flows will be carried on
- Allocate vessels from the global ship stock to satisfy that shipping demand
- Explore relaxations of the assumption that the logistics variables F_{cap} , η_{voyage} are not constants from 2010 to 2050.

2.4 SHIP STOCK MODEL

The ship stock model maintains a database of the ships that make up fleets of ship type/size used to represent the global shipping system. Variables associated with individual ships are stored to represent a ship's technical and operational characteristics so that they can be used in other subroutine's calculations. The variables are known collectively in the model as *ship_data*.

Ship data includes:
TEU capacity, DWT capacity, build year, installed main engine power and fuel type, installed auxiliary engine power and fuel type, design speed, operating speed (cruise speed at sea), SOx abatement specification, NOx abatement specification, CO2 abatement specification and MCR (max continuous rating) of main engine at the operating speed.

In the start year of the model (2010), this database is produced from a commercial database: Clarksons World Fleet Register, which contains data collected for all ships greater the 400 GT in operation around the world.

In every year simulated by GloTraM-2, the database is updated using the following sequence of calculations:

1. The existing stock is inspected and ships that reach the scrappage criterion (age greater than 30 years) are removed
2. The existing stock is evaluated (using *ship model*) to see whether there is economic or regulatory justification for it to be given retrofit technology or changes made to its operational characteristics (operating speed)
3. The total transport supply for this revised ship stock is calculated (using *shipping logistics model*) and this is deducted from the total transport demand (*transport demand*) in order to calculate the transport supply that needs to be satisfied by building new ships
4. The characteristics of newbuild stock are calculated (calculated using *ship model*) and the newbuild stock demand is transformed (through the evaluation of these ship's transport supply characteristics with the *shipping logistics model*) into a specific number of newbuild ships in each ship type and size category.

In steps 2 and 4, the characteristics of the existing and newbuild ships are found such that they simultaneously satisfy regulations (*exogenous drivers)* and maximise the owner's profits. In GloTraM-2, the characteristics are selected from a range of options of:

- fuel choice for main engines (new and existing ships) when at operating speed
- design speed (new ship) and operating speed (existing ships)
- CO2 abatement measures (new and existing ships)

The CO2 abatement options are technical and operational options that can be employed to either increase the energy efficiency of a ship or reduce its CO2 emissions. They can individually be specified as either suitable for newbuild and retrofit or just for newbuild.

The profit maximising analysis finds the combination of options that returns the equilibrium net present value (NPV) given a discount rate (currently set to 10% (taken from (IMO MEPC 61 Inf. 18)). The time-period used to evaluate the NPV can be varied between 1 year (which can be used to represent short-term decision making) and the ship's remaining life.

In GloTraM-2, an option exists for SOx and NOx emissions of the selected technical specification to be evaluated relative to prescribed regulation (MARPOL Annex VI). In the event that the selected fuel and machinery exceeds the stipulated emission levels, the technical characteristics are modified to represent the inclusion of SOx and NOx abatement technologies.

It is recognised that in practice, scrappage and newbuld decisions are functions of the shipping markets, sentiment etc. However, it is assumed for the purposes of this initial model that the rate of scrappage and newbuild will average out over the long-run and be related to a long-run equilibrium between transport demand and transport supply.

A further assumption is that as the model time-steps into the future, the proportions of a fleet of ship types will remain similar (e.g. for a tanker the ratio of VLCC:capemax:aframax:handy are constant with time). In practice this is not likely to be the case and further work is ongoing to provide some realism for how the demand for newbuild ships will be allocated to different ship size categories.

2.5 SHIP MODEL

The purpose of the ship model is to calculate the annualised:

- Fuel use and energy consumption,
- CO2 emission
- Capital and operating costs

for a ship with prescribed technical and operational characterisation (*ship_data*). The evaluation is performed using characterisations of a ship's annual activity defined by the *ship logistics model*.

Annual fuel use *F* and associated CO2 emissions E_{CO2} are calculated for annualised totals of a:
ship's time at its main operating speed/manoeuvring

- ship's time in port including
- the emission from machinery on the ship
- the emsission from the port activity that services the ship

The model includes the emissions from both the main and auxiliary machinery.

In order to undertake the NPV in the *ship stock model* calculations that are required for a ship's capital costs, operating costs and revenue (freight rate).

Costs are broken down as

- operating costs (manning, stores, repairs and maintenance, insurance, general costs)
- periodic maintenance (refits, dry dock maintenance)
- voyage costs (bunkers, carbon costs, port costs and cargo handling costs, canal costs)
- capital costs are intended to represent interest,dividend and/or debt repayment

For everything except voyage costs, the costs are calculated by interpolating (using dwt) from data tables listing cost breakdowns per ship type and size category in a given year (*exogenous drivers*).

Voyage costs are calculated from a ship's annual fuel use (given a prescribed portion of the total transport work) and the associated carbon emissions. The number of days each ship spends in port are calculated and a rate for cost per day in port used to calculate the total port cost.

This also forms the basis of the freight rate calculation that is used in the NPV analysis. A fleet of ships for each ship type/size is analysed to find median and mean characteristics (costs, emissions etc). The freight rate for a given ship type/size on a given route is calculated, in order to produce a working value, as the 'mean' value of operational costs capital costs for that fleet. i.e. an investment choice is made if the newbuild or retrofitted ship has an improved NPV relative to the average fleet characteristics.

Extension could be made to these algorithms and datasets to include social costs and/or lifecycle costs so that these could also be incorporated into the decision making and work is ongoing in WP4 on this.

Further work is ongoing (WP1 and WP2) to increase the fidelity of the annual fuel use calculation, particularly to represent:

- the off-design efficiency of the hull and propulsion system
- the change in performance and efficiency between the loaded, part loaded and ballast condition
- the aging of a hull and machinery and efficiency deterioration over time

Further refinement is needed on the abatement performance of specific measures, particularly the co-benefits of combinations of measures and their impact on the design of future ships, and this will be incorporated as it becomes available from WP2.

The contentious subject of freight rate forecasting is the subject of ongoing work in WP1 and 4 to determine how a meaningful value can be generated for use in the NPV analysis.

2.6 PORT MODEL

GloTraM-2 includes the calculation of emissions from the port and included in the total shipping emission using:

- exogenous data defining the emissions produced by a generic port to service a ship of a certain size per day
- a calculation of the total number of port days for all ships of a specific type and size category

This could be extended to include the representation of ship's use of shore-power and port interventions to incentivise low carbon shipping.

2.7 ENERGY, EMISSIONS, COST

An Excel database is generated by GloTraM-2 which contains, for each year of the simulation, aggregations for each category of ship type and size of:

- Number of ships
- Total dwt
- Mean EEOI (gCO2 emitted per tenm transport work)
- Revenue ($/tenm transport work)
- Opex + Capex ($/tenm transport work)
- Total fuel consumed (te)
- Total CO2 emission (te)

Many more output variables are available and can be added to this list with minor modification to the code. In addition to the values above, a Matlab database stores the technical and operational data (all the variables from the ship stock model) for each ship type/size category and each year of the simulation.

In GloTraM-2, both these sets of output data can be inspected using the user-interface and plotting function built in Matlab, or manually using Excel.

2.8 UNCERTAINTY

GloTraM-2 is deterministic, and so the results provide no illustration of the uncertainty inherent in a calculation of future emissions. Examples of uncertainties within the model's analysis include:
uncertainties in the input data, including:

- the transport demand associated with different ship types
- the abatement potential, availability dates and costs of different abatement options
- the magnitude of the different cost components
- uncertainties in the model's algorithms including:
- the applicability of NPV analysis for representing selection decisions on ship technical and operational specification
- the estimation of the long-term trend in freight rate for the sector
- the time-period that is used to formulate investment decisions
- the decision influences for scrapping old ships and the ordering quantities for new build ships
- the assumption that the proportions of transport demand fulfilled by different ship sizes remains constant with time

Progress has been made to include some of these uncertainties in a model described in (IMO MEPC 61/5/13), but not in a model that carries out a full bottom up analysis. In the referenced model, Monte Carlo simulation and characterisations of the model's parameters as probabilistic variables is used to calculate the uncertainty on the output parameter (CO2 emisions).

It is intended that a similar modification will be considered in future evolutions of GloTraM, however, based on the computational resource demanded by the existing model, care will need to be taken that the additional iterations required to provide meaningful probabilistic quantifications of emissions do not make the problem computationally intractable.

2.9 LIMITATIONS

GloTraM-2 has so far received only limted verification and validation. The data used for these initial runs contains mainly public domain values sourced from existing reports and studies (e.g. Buhaug et al. (2009)). Where public domain values are unavailable, data has been interpolated, extrapolated or in some cases obtained by best guess/ judgment.

The purpose of this version of the model is to illustrate potential capabilities of a future model, not authoritative and rigorous estimations of future emissions. Whilst the refinement of the quality of the input data and assumptions is an ongoing task, it is emphasised that this version of the model's outputs are currently only suitable for qualitative rather than quantitative analysis and should not be used for policy development or any commercial decision making.

3. CONCLUDING REMARKS

This paper presents and discusses methods for conceptualizing and modeling the shipping industry, for the purpose of analysis of CO2 emissions trajectories and impacts. The aim is to indicate the breadth and depth of the modeling required and to advocate the employment of a systems approach and a holistic approach when considering the possible future scenarios of the shipping industry.

Whilst much of the model is developed and working, unfortunately it was not possible to include preliminary output from that modeling in this paper. This work is ongoing and these outputs will be available shortly.

4. ACKNOWLEDGEMENTS

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