LOW CARBON SHIPPING

A SYSTEMS APPROACH

FINAL REPORT

EXECUTIVE SUMMARY 2014

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EXECUTIVE SUMMARY

INTRODUCTION & CONTEXT

In 2007 it was estimated that shipping accounted for 3.3% of global anthropogenic CO_2 emissions. The second International Maritime Organisation (IMO) Greenhouse Gas (GHG) study (Buhaug et al.., 2009) predicted that shipping would account for between 12 and 18% of global CO_2 emissions by 2050 if no action was taken to reduce its emissions. Carbon dioxide is not only the majority driver of shipping's contribution to radiative forcing, but also has the longest-lasting impact, which demonstrates that the challenge is not one of the instantaneous emissions in any one year, but the cumulative emissions over time.

In 2010, there was no holistic understanding of the shipping industry. Its drawn-out contractual, technological and financial evolution prevented access to both a top-down and a bottom-up system-level understanding of its sensitivities, and left many commercial habits ingrained and unchanged. The inescapable truths identified above around both the energy and carbon challenge have created expectations of high uncertainty in the forecast for both the drivers of growth in shipping and the designs and system configuration that will evolve over the next few decades.

The shipping industry in 2010 faced a daunting task: to develop a proportionate response to its responsibilities under the global commitment to avoid dangerous climate change (Copenhagen Accord), to minimise the risk of causing damage to the shipping industry and the global economic system that the industry serves, whilst lacking the toolset with which to evaluate the possible impacts and responses of the shipping system.

Recognising this as a significant challenge, the UK government, five UK universities and a number of shipping industry stakeholders formed a consortium to carry out a three-year research project: ***Low Carbon Shipping – A Systems Approach.*** The aims of the project were:

1. to develop knowledge and understanding of the shipping system, particularly the relationship between its principal components, transport logistics and ship designs, and clarify the many complex interfaces in the shipping industry (port operations, owner/operator relationships, contractual agreements and the links to other transport modes);

2. to deploy that understanding to explore future logistical and ship concepts and how they could achieve cost-effective reduction of carbon emissions; and

3. to develop projections for future trends in the demand for shipping, the impacts of technical and policy solutions and their associated implementation barriers, and the most just measurement and apportionment mechanisms.

As the majority of shipping emissions (75%) come from the freight shipping sector (particularly container ships, dry bulk and general cargo ships), wet bulk (crude, products and chemicals) and gas ships (LPG and LNG), these were the sectors chosen as the focus of the work.

Economic Context

Following the global financial crisis of 2008, the shipping industry entered a new economic paradigm, of sustained high oil prices, progressive regulation on efficiency and emissions and low revenues. It is speculated that this is creating a "two-tier" fleet, with the older low-efficiency fleet losing out commercially to more efficient tonnage built since the beginning of this new paradigm. The performance claims of the "eco-ship" breed are still yet to be extensively verified in the public domain, and whilst some of the higher-end claims (30%) appear lacking in evidence and possibly overinflated, it is expected that this new tonnage will have some advantage over the existing fleet, and will therefore either command higher prices (e.g. time charter day rates), greater market share, or some combination of these parameters.

Policy Context

At the start of the project in 2010, the policy and regulatory backdrop to the CO_2 emissions of shipping was immature, complex and evolving. A number of proposals existed for regulation at several levels (UN, EU, UK), but there was uncertainty around the path and stringency that would become the final implementation. Over the course of the project, the shipping industry has progressed from being the subject of mounting pressure to curb its emissions, to becoming the first industry with international, legally binding commitments on efficiency increases.

Contents of This Report

The research effort was structured into six work packages, the key findings and references from each of which forms a section of this report. Outputs from all of the work packages contribute towards an understanding of what the possible future trajectories of the industry will mean to the shipping system and the ships that service future transport demand. This understanding then will allow policymakers to consider the foreseeable consequences of regulations in advance of their implementation, and firms within the shipping system to plan ahead with an informed strategy.

MODELLING THE SHIPPING SYSTEM

GloTraM

A key output of the project, GloTraM, is a tool used to quantify how the many components of the shipping system interact and explore potential scenarios for the future of the shipping industry. Technologies, alternative fuels and operational interventions are all characterised by their impacts on a ship's performance and economics. The model selects configurations and changes both for the existing fleet and new-builds through the application of profit maximisation at a firm level (ship owners and operators). Unlike the existing literature, which is dominated by Marginal Abatement Cost Curve approaches, this produces insights into how the operational efficiency and technical efficiency interact. The model also analyses how the decarbonisation potential is reduced by the diminishing efficiency increase through compounding of multiple technologies and technical incompatibilities. The model's outputs include quantifications of emissions and the evolution of the shipping industry's fleet sizes, costs and revenues, as well as identification of the market share of different technologies and the future demand for a range of different marine fuels.

Take-back

Take-back in this instance refers to the diminution of energy efficiency gains through an unintended consequence. Informed through the modelling tools, including GloTraM, the occurrence of a take-back phenomenon was found to have the potential to disrupt the sector's decarbonisation ambitions. The results of the analysis showed that maximum profit occurs at a different speed and for a different level of technology uptake in each fuel price/freight rate combination. The results also showed that for any given level of technology uptake in each scenario, the speed at which profits are maximised is higher as the ship becomes increasingly technically energy efficient (the cost of speed increase is proportionately lower and the higher capital costs of a more efficient ship incentivise a higher operating speed). This speed increase represents a decrease in operational energy efficiency, which can offset a large proportion of the energy savings achieved through the implementation of technology.

Slow Steaming

The relationship between the speed of a ship and the power required to propel it presents a substantial opportunity for increased energy efficiency. The investigation into the existing fleet in this era of 'slow steaming' estimated that in 2011, relative to 2007, average operating speeds were 10-15% lower for many of the bulk fleets (tankers, dry bulk), and approximately 25% lower for container ships. The consequence of these observed differences in speed is a significant reduction in fuel consumption, by as much as 30 to 40% for many of the bulk fleets and by 50% and above for some container ship fleets, relative to the estimates presented in the IMO 2nd GHG study. Ultimately the speed reduction, which in turn reduces transport work, absorbs some of the impact of the main engine fuel consumption on energy efficiency, so that the improvement in operational efficiency is approximately 10% (relative to the IMO 2nd GHG study estimates of overall efficiency for many of the bulk fleets), rising to 30% for some of the container fleets.

One observation made by some commentators is that lower ship speeds necessitate the construction of more ships and that the GHG emissions associated with the manufacturing processes can offset the benefits of reduced speed. To test this claim, a formulation of the "total CO_2" was developed and applied to sample ship specifications. For the examples considered the relationship shows a minimum occurs between 2 knots and 5 knots depending on the specific ship type. At lower speeds, the embodied emissions dominate the relationship (i.e. the emissions from the additional ships required outweigh the operational emissions benefits of lower speed), while above the minimum speed the operational emissions dominate. In practice there are also commercial drivers for speed and safety issues, which need to be considered, and these are applied in GloTraM when evaluating future scenarios for the industry.

TECHNOLOGIES & SHIP DESIGN

This part of the research effort was divided into three tasks. The first addressed technical solutions related to improvements in ship and propulsor hydrodynamics; the second looked at technical solutions related to marine engineering systems including main and auxiliary engines and fuels; and the third task developed a ship impact model that could be used to identify the impact of technologies on the ship design in a holistic sense, and act as an interface between the technology assessments and the global shipping model. The ship impact model was developed for each of the ship types considered in the LCS project as a whole, and represents the interactions between design parameters, enabling the development of a full understanding of how the ship design is affected by incorporation of technologies – for example not just reflecting impact on hull resistance, or engine efficiency, but also on stability, lightship and capacity.

The detailed parametric whole ship model was used to correctly size technologies. Each ship size and type are modelled with enough accuracy and detail to ensure they realistically reflect the overall impact of the implementation of efficiency technologies on cargo capacity and cost.

Ship & Propulsor Hydrodynamics

The study examined incremental improvements through refinements in conventional hull forms, as well as the opportunities for radical changes based on new operational procedures relating to ballast loading and trim. Improvements will be assessed across the entire mission profile, including both loaded and ballast conditions, and in a range of expected sea-states.

A significant reduction in CO_2 of the order of 16% is possible, however in order to achieve these changes a substantial change in the overall dimensions of the ship is required. This does mean that these improvements may not be practical when more realistic constructional, operational and financial constraints are imposed, but they are indicative of what may be achieved given a blank canvas.

A set of devices suitable for retrofitting on existing ships (as well as new build) was examined in order to assess the likely gains in ship performance. Device manufacturers often promise substantial performance gains in terms of reduction in fuel consumption and, eventually, carbon emissions. In all cases, the level of savings achieved by using these technologies was lower than that published in the literature, and in many cases substantially so.

There are two possible explanations for this discrepancy. Firstly, many previous studies were based either on model-scale physical tests or simplified Computational Fluid Dynamics (CFD) models; it is possible that either the method or metric (or both) adopted in these studies was not appropriate for predicting the performance of these devices at full scale. Secondly, it might be argued that the devices in the present study did not deliver the expected savings because the designs in this study were not suitably optimised. In this case, it must then be considered that if these devices must be optimised for a given ship in specific operational conditions, it is unclear how the devices behave when the vessel is operating in off-design conditions.

The results of the study into the design of propulsors for in-service conditions were found to depend strongly on ship type and operating profile. For ships that are subject to large weather forces, such as container ships, improvements in efficiency over the basic propeller were found to be as much as 1.5%. Efficiency improvements for ships for which weather loading is less significant, such as fully-laden VLCCs, may be of the order of 0.5%.

Wind Assist

Preliminary analysis was undertaken to assess the performance of wind assistance devices. The results did not imply strong potential for cost-effective implementation, however the analysis methods used required many simplifications. Varying speed and course during the voyage to incorporate the variability of the resource (wind) in the operation of the ship could create differences in the fuel savings achieved, as could the design of bespoke installations or optimised hull/rig combinations. Flettner rotors appear to offer improved performance over conventional sails or kites, but most data are based on relatively small scale or computational studies, and the technical issues related to the energy consumption and the durability of the rotor drive system may not be completely resolved.

Internal combustion technology and electrical propulsion

Marine engineering propulsion systems are developing and the technology is improving with future machines offering efficiency gains over existing technologies. The two-stroke diesel engine propulsion system is likely to improve in efficiency over time through a combination of factors rather than a specific step change in technology. A slow-speed long-stroke diesel engine operating on LNG fuel with digital electronic control to optimise injection, exhaust valve and turbo-charger (scavenge) performance, together with waste heat recovery system, can be expected within a few years. In the long term, however, it is difficult to see what else can be done to further improve slow speed diesel engine efficiency performance beyond 2020.

Electrical technologies are developing rapidly, offering advanced systems that are flexible and more efficient than was previously the case. Advanced motor technologies are now available, whilst the next generation of power electronic drives is on the horizon. Superconductivity is too far away and too immature to enable us to make a significant projection as to its performance.

Alternative Fuels

Unlike many other studies of this nature, this research considered the total carbon footprint of different fuel types used in the full range of marine engine types on a "well-to-hull" basis (or "field-to-hull" basis in the case of biofuels). This therefore included the up-stream carbon cost of fuel production and transportation to the vessel. On this basis, there is strong indication that existing residual and distillate marine fuels are actually already relatively "carbon-effective" choices. A wide variety of biofuels was considered. Under some conditions these can offer a net reduction in carbon cost, but many do not if considered on a "field-to-hull" basis owing to the carbon-intensive production processes (including fertilisers, farming methods, etc.). Given the competition between biofuel and food production, there is also a limit on how much biofuel could actually be used for fuelling shipping transportation and, in some cases, the use of biofuels can increase the emission of species aside from carbon dioxide. The best performers in terms of carbon-footprint were blends with existing fossil fuels. (L)NG as a fuel also can provide carbon (and other) emission reduction benefits against traditional marine fuels, however, again, the picture is not as clear as might be supposed due to the highly carbon-intensive production cost of fossil fuel LNG. Using hydrogen as a fuel was also considered, but under existing production methods this too can be carbon-intensive. If renewable energy sources can be used for hydrogen production then this provides a realistic possibility for a net reduction in carbon footprint.

Fuel Cells

The volume and weight of a Fuel Cell system are higher than those of a combustion engine with the same power output. The fuel cell system can be assumed to be to weigh10% more than an internal combustion engine generator for the same power level, and the system volume and projected area will be approximately 10 and 15 times higher respectively. About 85% of this volume corresponds to the ancillary systems of the fuel cells system. The thermal recuperators, air and fuel heaters, and power converter units, boost converters and DC/AC inverters, each represent about 30% of the whole volume of the ancillary systems.

When compared to a conventional marine diesel generator, a fuel cell system provides higher efficiency. This is translated into lower fuel consumption and also lower carbon emissions per energy unit. Fuel cell systems have a 50% efficiency, based on the fuel low heating value, and also taking into account the parasitic losses exerted by the ancillary systems. In a fuel cell system, there is no internal fuel combustion associated with the power output, and so the SOx , NOx and CO emissions are reduced to a negligible level. Currently, fuel cell systems present a higher initial cost than traditional combustion engine technology, though its maintenance costs are drastically lower once established.

Solar

The limited area available on a realistic commercial vessel means that solar is unviable for main propulsion. Using solar for auxiliary power could achieve a reduction in CO_2 emissions of up to 10%. Installing solar panels leads to the same size generators being used, as power reductions are not large enough to facilitate the installation of a smaller auxiliary power plant. There is, therefore, no difference between a retrofit and new build.

PORTS AND LOGISTICS

Shipping is a derived demand: it exists not for itself but in response to demand from consignors for the transport of freight to consignees. Transport logistics systems, of which shipping is a key component, respond to trade demands and 'lubricate' the global economy by providing nodes and links (ports, distribution centres, transport services, etc.) to fulfil demand for product movement. Transportation, and shipping in particular, is therefore one of the key enablers of globalisation. In fact recent research reported in UNCTAD's Review of Maritime Transport 2013 suggests that containerisation has been a stronger driver of globalisation than trade liberalization has. In order to understand the role and activity of shipping it is necessary to consider its place in the wider transport system, and in turn to understand what drives the demand for international freight transport, which occurs within 'end-to-end' supply chains linking sources of production with the ultimate consumer. Shipping and ports are important links and nodes within many supply chains, both in terms of their costs and their performance. When seeking to mitigate the (growing) CO_2 footprint associated with shipping activity, we need to understand the fit between shipping and the wider supply chains and logistics systems within which shipping operates.

This research largely adopted a bottom-up approach to investigating the logistics aspects of low carbon shipping, including: by examining the role of transhipment activity; by detailing emissions for individual shipping movements; and by mapping the role and impact of shipping within individual supply chains. The starting point for the analysis was to profile the maritime freight traffic flowing into and out of the UK. We then catalogued port-related sustainability initiatives and analysed and estimated port-related CO_2 emissions. These analyses indicated that emissions generated by ships during their voyages between ports are of a far greater magnitude than those generated by the port activities. Thus, while reducing the emissions of ports themselves is worthwhile, the results suggest that ports might have more impact through focusing their efforts on helping / facilitating the reduction of shipping emissions. The work around ports, in terms of the various initiatives and calculation of their carbon emissions, is the first comprehensive review of port-related sustainability issues in the UK and should be of interest to all stakeholders.

The next phase of the work involved estimating the CO_2 emissions associated with UK-centric shipping activity. The results suggest a total of 22.6 MT CO_2 in 2010, compared to 19.7 MT in 2000, with container ships accounting for the largest share (9.3 MT). Levels of transhipment were studied in order to understand whether this practice exacerbates emissions. Consultations and analyses suggest that only around 10% of container traffic is transhipped. Estimations of emissions for transhipped versus direct traffic were carried out and, while these results showed that feeder legs can increase emissions, the real issue to focus on is the total end-to-end emissions comprising all transport legs (not just maritime) and cargo handling activity. This led to work on supply chain mapping, which was of significant interest to the project's industry partners. Analysis of end-to-end supply chain emissions was carried out with the cooperation of three partner companies, and quantified the contribution of maritime transport to total emissions; this also showed how modal shift to maritime can reduce end-to-end emissions.

The work on mapping the shipping network, measuring transhipment, seeking to calculate UK-centric maritime CO_2 emissions, and illustrating the contribution of shipping to end-to-end emissions in the supply chain, is all relevant to a wide range of stakeholders and will serve as a benchmark for future analyses and policy initiatives.

Overarching efforts to connect up all of the work and insights around logistics with future ship designs is a key output, and represents a considered view as to how logistics and ship design will intersect going forward, a topic of clear interest and importance to all stakeholders.

LOW CARBON SHIPPING ECONOMICS

Modelling of the through life environmental impact of shipping and its available carbon mitigation measures (and their associated environmental and economic cost) can inform policy makers at all levels (government, EU, IMO, UNFCCC) and industry stakeholders of the global cost-benefit balance inherent in the attempt to mitigate carbon emissions. Assessment of the balanced environmental impact highlights not only the opportunities to reduce the global impact of shipping, but also unintended consequences of efforts to mitigate fuel combustion-derived emissions.

Economic and Environmental cost of Ships

The impact of emissions from other phases than operation is small but a number of factors can significantly increase it:

- Larger/faster ships demonstrate less impact from other phases
- As speeds are reduced the impact from other phases increases (e.g. VLCC 9% at 13.3 knots, increasing to 44% at 6.7 knots)
- Scrapping a ship after only 10 years of operation may triple the relative impact of emissions from the construction and end of life phases (up to 26%).
- The efficacy of carbon reduction technologies was generally reduced by 1-2% if whole life emissions were considered

A carbon levy on shipbuilding emissions could introduce a new-build price premium of up to 11.8%.

Carbon Reduction Technologies

The whole life cost-benefit ($/t.$CO_2e_{avoided}$) of a majority of CRTs demonstrates a reduction in cost as well as life cycle GHG emissions. Where the potential savings are greatest (e.g. wind assistance technologies) there is also the greatest opportunity for the emissions from manufacture to become significant when a whole systems approach is taken.

Likely Future Demand and Prices for Shipping

Expectations of trends in dry bulk shipping flows to 2050 highlight drivers including Arctic ice melt, canal upgrades, piracy and mode splits. Globally, the expected doubling of raw materials shipments to Western economies and quadrupling elsewhere will be partially offset by expectations of shorter hauls. Moderate annual expected tonnage growth globally compares with rapid annual growth in coal shipments, although more localized and multi-sourcing will shorten global coal hauls.

Predicted changing patterns of maritime oil freight flows to 2050 were conservative. Local sourcing, new Arctic seaways and fossil fuel intolerance will tend to reduce oil freight work but ship re-routing to avoid Emissions Control Areas (ECAs) and piracy would lengthen hauls. In advanced industrial nations, reducing energy intensities and diminishing social tolerance of fossil fuels imply reducing maritime oil shipments. Achieving radical national commitments to carbon emissions reductions will necessitate specialist education for naturally conservative maritime professionals and vigorous oil import reduction policies to curtail domestic demand for oil shipments.

The impact of bunker fuel price changes on spot freight rates for shipping coal revealed a relatively stable market before 2005 followed by high elasticities in a volatile market in subsequent years. In a volatile market, market -based measures to reduce such emissions (which might include a bunker fuel levy) have greater impacts on freight rates.

POLICY AND REGULATION

In order to understand the impacts of possible future regulations, particularly market-based measures, a range of policy scenarios were studied. The results demonstrate a number of important findings, assuming that the cumulative emissions target for the industry (the stringency) remains consistent:

- Early adoption of a measure leads to a less dramatic trajectory of carbon price;
- In all scenarios studied, a sizeable quantity of out-of-sector offsetting is required to reach the target trajectory;
- Increasing the level of out-of-sector offsetting permitted has a small impact on the amount of in-sector decarbonisation achieved, but a large (negative) impact on the carbon price that the industry experiences, so there does not appear to be a significant benefit either to the industry or society of overly constraining offsetting;
- Bioenergy (biofuel and biogas) resources will have a beneficial impact on the sector's operational emissions, but apportioning an equitable share of the expected resource to the shipping industry is expected to have only a modest beneficial impact on the emissions trajectory. To have a greater impact, either the industry needs to justify a requirement for a disproportionately large share of this resource, or a technology breakthrough that increases the resource available needs to be found;
- A policy of emission reductions in shipping consistent with the Copenhagen Accord is likely have a significant impact on the cost base of the industry, applying additional operational costs equal to, and in many cases exceeding, those associated with the fuel cost at current fuel prices.

Implementation Barriers to Low Carbon Shipping

Analysis has suggested that there could be unrealised efficiency improvements and abatement potential that are not being taken up because of market barriers, market failures or more general implementation barriers. Understanding the barriers is important because of their potential to obstruct future regulatory attempts to reduce emissions, as well as for identifying opportunities for commercial opportunity and high cost-effectiveness policy.

A survey was undertaken of nearly 150 ship owners, charterers and ship management companies to quantify their uptake and attitudes towards a variety of operational energy efficiency interventions (weather routing, hull scrubbing, slow steaming, etc.). There were many operational efficiency interventions that the survey respondents believed to have significant potential, with approximately 70% of respondents agreeing on three in particular: fuel consumption monitoring, general speed reduction and weather routing.

This finding is useful in confirming that there are a number of interventions, that a large majority believe to have potential, as this refutes the concept that 'nothing can be done and all potential improvements are already fully embedded in the industry'. The most regular explanations for not implementing solutions included: lack of reliable information on cost and savings, difficulties of implementation under some charter parties and lack of direct control over operation. Both the informational barriers and the consequences of certain charter party clauses have been referred to by many others and are the subject of ongoing discussion in the policy space.

These survey findings were supported by econometric analysis of the relationship between energy efficiency and prices in the time charter, new build and second hand markets, which showed that more energy efficient ships commanded higher prices, but that the price premium was commonly only 20% of the cost savings associated with the energy efficiency differential (i.e. not all of the cost savings are being passed on).

Analysis of a number of standard charter parties was used to evaluate the prevalence of certain clauses that could be obstructing energy efficiency initiatives, and provided further evidence of the presence of a principal agent problem in shipping, more commonly referred to as the 'split-incentive'.

Measurement and Apportionment

'Measurement' refers to the process of estimating the emissions from the shipping industry and 'apportionment' to its allocation to different entities (e.g. firms, countries, regions). Whilst domestic shipping emissions are easily associated with the country from which their transport demand originates, the difficulty of fairly apportioning the emissions from 'international shipping' led to the allocation of their management 'as a whole' to the IMO in the UNFCCC Kyoto Protocol.

Measurement and apportionment are intrinsically linked because the viability of different types of measurement system can affect the implementation of apportionment schemes. Some progress on the subject of measurement has been made at both the IMO Marine Environment Protection Committee (MEPC) and the EU. For these reasons the work was focused on apportionment, although assumptions and recommendations were made for the most valuable measurement variables. A number of conclusions and implications can be drawn:

- The existing literature on the subject of emissions apportionment describes a variety of options and analyses their fairness and effectiveness;

- The concept of international shipping's top-down emission's allocation to individual countries is shown by a variety of authors to lack credibility;
- Nationally accounted fuel sales (normally described as a bottom-up apportionment philosophy) are found wanting with respect to fairness and openness to ease of evasion, and would do little to incentivise emissions reductions;
- This leaves variants of bottom-up options associated with ship movements and trade as the only credible mechanism for emissions allocation;
- The part-utilisation of a ship's cargo capacity, the multi-pick-up multi-drop-off nature of cargo movements and the ballast voyage are all operational details that deserve careful consideration in the design of an apportionment mechanism;
- Different mechanism details can result in substantial differences in emissions allocated;
- Data is difficult to obtain and would also have to be enacted globally for some apportionment methods. For unilateral action, data (such as EEOI) would only be captured at the port of the country enacting the policy or reported by nationally registered vessels. The ports of non-cooperating member states would be under no obligation to capture this data and would be unlikely to adopt the administrative burden. If using a policy based on annually reported EEOI a global classification and verification system would be required. Verification of emissions has not been standardised and therefore an internationally recognised approach would have to be agreed;
- Questions of fair treatment for a country with a role as a regional hub port remain unresolved.

OPERATIONS FOR LOW CARBON SHIPPING

Crew Awareness

A questionnaire was designed, distributed and analysed to identify the levels of seafarers' awareness, knowledge, motivation and ideas about carbon emissions, their reduction, and methods for achieving energy efficiency on board. Key findings were:

- Only 20% of participants have learnt about carbon emissions and their effects via an education or training course and the most common sources for knowledge acquisition are not technical or focused: there are clear education and training needs;
- There is a lack of awareness and focus towards energy efficient operation and a lack of consistent knowledge about best practice;
- There is a clear correlation between how much participants know about carbon emissions and the energy efficient efforts they make, and so there is a real benefit in increasing knowledge;
- There is a lack of knowledge about how individuals can contribute towards energy efficiency improvements (however small) and/or responsibility shifting between individuals and departments;
- Improvements in onshore support for energy efficient ship operation are required in addition to improved operations by seafarers at sea;
- Performance monitoring and performance feedback of the right information to the right people is important for generating awareness and motivation.

Monitoring fuel Consumption and Ship Performance

In order to understand the drivers of operational fuel consumption, noon-report data was collected from a number of ships and processed along with its key explanatory parameters (speed, time, weather). A key point identified by the analysis was the inaccuracy of some of the data fields and entries and hence their reliability to indicate ship performance. Reasons for the inaccuracies included human error, ambiguous observational methods and current procedures. The most significant data inaccuracies and absences relevant to performance monitoring are listed below.

- **Fuel consumption.** Several reasons as to why inaccuracies occur in noon-port report fuel consumption data were identified, including: uncertainties about the amount of fuel bunkered; inaccurate methods for measuring remaining fuel onboard/fuel consumed; and human error recording values. The variance in fuel consumption data is therefore high and provides a scatter of results for performance monitoring.
- **Weather.** The observation of weather effects is a field susceptible to a high level of error for several reasons: recorded values in noon/port reports are predominantly based on an individual's observation on the bridge; the observation recorded may or may not be an accurate representation of the average weather encountered over the reporting period; typically Beaufort and direction fields are recorded where a single Beaufort number encompasses a range of wave heights and wind speeds; wave, wind, swell and current strength and direction all have an effect on vessel performance but are typically not recorded in the noon/port reports.
- **Draft and deadweight.** It is known that the displacement of a ship changes the resistance, and therefore the power and fuel consumption of the ship. The shape of the underwater hull is also important and is influenced by trim. However, whilst these fields are recorded in separate documents they are not always included in the noon/port reports and are therefore rarely correlated to identify and explain ship performance.
- **Power:** Not all (most) ships are equipped with a torque meter and therefore direct power measurements, which would provide valuable information about a ship's performance, are not recorded in the noon/port.

Ship Hull and Propeller Maintenance

A review was made of existing procedures used for ship hull and propeller maintenance. At present most hull and propeller maintenance decisions are based on dry docking intervals, noted observations of significant performance loss and underwater inspections carried out by divers.

The amount and rate of fouling on hulls varies significantly with a ship's operating profile and the type of hull coating used. The gain from hull cleaning and dry dock repairs varies greatly on the condition of the hull before maintenance and the quality of maintenance carried out. Performance monitoring and modelling needs to be incorporated and utilised as a tool for improving hull and propeller maintenance strategies. To identify practical optimal maintenance scheduling, the costs must also be considered, including the cost of maintenance and facilities, paint, hire, and so on.

Voyage Optimisation

There are many aspects to voyage optimisation that should be considered, and the practical and logistical components are just as significant as the performance-related modelling.

The voyage optimisation framework studied in this project had two levels: (1) voyage prediction and planning based on the operational profile, time of the year and the past weather statistics for the voyage dates; and (2) real-time voyage optimisation and decision support system.

For the development of accurate voyage optimisation it is important that the ship's operational profile is recorded accurately and appropriate modelling should be utilised in the performance predictions.

Furthermore, because voyage planning is affected by many factors, charter contracts need to ensure that the operational decisions and communication/relations between ship management, commercial departments and external stakeholder roles are clearly defined.

CONCLUSIONS AND NEXT STEPS

Low Carbon Shipping – A Systems Approach, was deliberately ambitious in its scope and breadth. The need to bring consistency, objectivity and numeracy to the assessment and optimisation of the various options meant that a system-wide approach was needed to understand shipping's potential to decarbonise.

GloTraM is the model developed in this project that links all the issues together, providing transparency of data and overall costs.

In addition to modelling, the project undertook a broad range of fundamental and multidisciplinary analyses in order to address many of the key drivers and the complex interactions that characterise the shipping industry, including:

- Capturing the logistic supply chain/ship design interactions;
- Joining up the technical and operational parameters to properly understand & evaluate energy efficiency interventions;
- Assessing the economic implications of radical departures from current technologies and operating practices;
- Completing the loop between the operational measurements of performance and the tools used to model and optimise ship specification;
- Taking the wider system view of carbon emissions (rather than just the emissions from the ship itself), e.g. work on alternative fuels;
- Capturing the interaction between mitigation policy and climate finance;
- Understanding the reasons for the gap between perception and reality, e.g. analysis of market barriers;
- Making visible the importance of lifecycle assessments.

The project found that shipping is a significant and growing climate change challenge. There is a wide range of evolutionary improvements in ship design that can be applied over the next few decades (enabled both through existing regulation - EEDI and SEEMP, expectations of sustained high energy prices, and technological advancements) that offer modest improvements but will fall short of delivering the levels of decarbonisation required to avoid dangerous climate change. Therefore more radical change is required and the sooner fair frameworks and mechanisms to enable this change are established the less damaging this will be for the industry.

The detailed explanation for this shortfall is that for many technologies, the savings are often found to be less than advertised by the technology's marketing literature. A shift to LNG offers significant improvements but also requires major changes in ship design and shipping infrastructure, and still can only deliver modest reductions in transport carbon intensity. Bioenergy is expected to be supply-constrained, solar energy provides insufficient power outputs, and the evaluation of the potential of wind-assistance shows that its potential and future role remain uncertain.

Operational measures (other than ship speed reduction) also offer improvements through better-informed hull/propeller maintenance and voyage optimisation. In combination with many of the technology and operational solutions, significant speed reduction has the potential to close the gap but markets alone won't do this, since slowing down beyond a certain speed is uneconomic and has an increasingly negative impact on the supply chains that shipping serves.

Given the expected long-term growth which is the backdrop to the emissions trajectories of the industry, all of the above changes are unlikely to achieve progress proportionate to shipping's responsibilities (as taken from the Copenhagen Accord) under the current tendency towards 'business as usual'.

There is therefore a need to develop further voluntary measures or regulation (market-based or command-and-control measures).

Owing to this project's outputs and an increase in the research activity on this subject internationally in recent years, the knowledge and understanding required to enable shipping to make its contribution to minimising the risks of dangerous climate change are now better understood and shared across the sector. However, a number of significant uncertainties remain:

- A lack of clarity on the drivers of ship performance in real conditions (fouling, speed, weather, crew), owing to the complexity of the marine environment and the low standard of data monitoring and analysis that is currently used in many firms.
- A lack of confidence that theoretical and experimental modelling of ship performance (particularly with respect to performance characterisation of energy efficiency technology) is representative of 'real world' performance. This is related to the complexity of the physical processes determining ship performance, a lack of clarity on the drivers of ship performance, and also the lack of standardisation in the way theoretical and experimental modelling is undertaken and the inevitable simplifications that are necessary to generate analysis affordably.
- The potential of step-change technologies to be commercially viable and create significant change in the industry (e.g. wind assistance, hydrogen and fuel cells). Mainly due to uncertainty in the performance and costs of the technology, uncertainty in infrastructure development and the

high costs associated with the rigorous analysis of performance combined with a shortage of investment in research and development.

- The interaction between global and regional mitigation scenarios and their impact on global demand for different energy commodities, and shipping's transport demand. This is currently dominated in terms of mass lifted by crude oil movements, as well as substantial shares of its transport supply devoted to coal, oil products and gas transport demands.

- Shipping's responsibility to decarbonise, given the social benefits it supplies, e.g. in enabling global markets, which enable energy and food security.

- In the event that the ambition of the Copenhagen Accord is missed, and dangerous climate change modifies the production and consumption patterns of food, fuel, raw materials and goods, how this could affect shipping transport demand and therefore the wider shipping system.

- Opacity in the shipping markets (particularly the lack of transparency in the way prices are set) leads to challenges in forecasting the incentivisation of the investors in technology (typically ship owners) and therefore the technology uptake and flow of capital to the sector's technology providers.

The first round of EPSRC-funded projects have established a cadre of newly educated champions. A further EPSRC & Industry funded project is commencing shortly: ***Shipping in Changing Climates*** will build on investments made to date, pick up many of the areas identified as the source of continued uncertainty, and research how to transition shipping to a low carbon, more resilient future.

- **Theme 1:** Understanding the scope for greater efficiency on the transport's supply side

- **Theme 2:** Understanding demand side drivers and trends – trade and transport demand

- **Theme 3:** Understanding supply/demand interactions – transition and evolution of the shipping system

Pulling together the complementary strengths of the UK universities involved in this project and the support of key industry players, together with the volunteering of data and knowledge from across the shipping stakeholder space have been critical to the success of this project, as they will be for the successor project ***Shipping in Changing Climates.***


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