Technical Options for Cleaner and More Efficient Shipping

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Abstract
The paper outlines how ships and shipping need to evolve to meet market and legislative pressures from rising fuel prices and stricter emission regulations. Speed reduction, particularly design for lower speeds, is a highly effective option. But even for given speed, there are many technical and operational options to increase fuel efficiency. Modern computer application helps to unlock previously unused potential for saving, as illustrated in several examples. Formal optimisation of lines is an attractive option in design; formal optimisation of trim for least fuel consumption is the corresponding fleet-in-service option. Refits with propulsion-improving devices may improve fuel efficiency, but not in all cases. Here, modern simulation technology allows a detailed assessment before investment decisions are taken. Abatement technologies are only effective for SOx, NOx, and particulate matter. Alternative fuels, in particular gas, are seen as an important factor in meeting goals for emission reductions in shipping. A concept study for a hydrogen powered open-top container ship shows that zero-emission shipping is technically feasible with today’s technologies.

Keywords: efficiency, emissions, fuel, gas, optimization

Introduction
The importance of environmental aspects has increased both for ship design and ship operation. The general trend towards stricter environmental legislation for the maritime industries reflects general political trends driven by a society that places more importance on the environment (and is implicitly willing to spend more on sustainable industry practices), at least in the highly industrialised countries (USA, EU, Australia, Japan and Korea). This has been reflected by a proliferation of amendments to the original MARPOL Convention of IMO (International Maritime Organisation).

While widely acknowledged as highly efficient mode of transport, the sheer volume of transported goods makes shipping a major contributor to man-made emissions. Shipping fares best for CO₂ emissions, but even here the world-wide contribution is comparable to that of England. (If global shipping were a country, it would rank 6th world-wide in CO₂ emissions.) Subsequently, the current debate is not about whether shipping should reduce CO₂ emissions, but about how this is best achieved. Independent of which scheme for CO₂ reduction will eventually be favoured, it is generally accepted that direct or indirect taxes will increase fuel costs and legal thresholds will curb port access at least in Europe and North America. For other emissions (SOx, NOx, and particulate matter PM) shipping contributes more significantly. Subsequently, IMO has addressed these problems and imposed a stepwise reduction in MARPOL.

The year 2008 brought first a rapid increase in bunker fuel prices, rising to three times the level of 2003, before the global financial crisis hit. The year 2009 brought then a rapid drop in transport demand, freight rates, building prices and also fuel prices. Fuel prices dropped to a third of the 2008 peak, but recovered quickly. It is widely expected that they will top the all-time high record of 2008 within the next three years and then continue to increase on average with the customary short-term fluctuations superimposed. The main causes for this medium to long-term increase are the following:

- Increased cost for oil exploration, e.g. exploring smaller fields or less accessible fields
- Increased taxation on CO₂ emissions (expected to range from 25 to 70 $/t CO₂ corresponding to 75 to 200 $/t fuel)
- Imposed higher fuel quality. By 2020, current standards for sulfur emission control areas (SECA) will be globally imposed. This will impose a universal change from heavy fuel oil to marine diesel oil with an associated jump in fuel costs.

In sum, fuel prices are expected to exceed 1000 $/t fuel before 2020, i.e. twice the level of early 2010, Fig.1. Already, bunker costs account for 60% of the total costs in the operation of a 4300 TEU containership. Five years ago, it was 40%. If all other cost items remain constant, fuel cost would account for 75% in 2020 for the same ship following a “business as usual” strategy. But “business as usual” is not an option. Unless we adapt ships and shipping operation to the new market environment, particularly the fuel cost item, we will not be able to survive economically.

We will elaborate in the following how we can adapt, particularly how we can substantially increase transport efficiency and reduce emissions.

Emission reduction by speed reduction
Speed reduction is a very effective way to reduce fuel consumption and emission. Slow steaming reduces fuel consumption significantly. However, the ship is then operated in off-design, thus sub-optimal conditions for engine, propeller
and hull (particularly bulbous bow). It is far more effective and economical to design ships in the first place for lower speeds.

In 1950, Karman and Gabrielli, [1], investigated the transport efficiency of various vehicles, plotting a transport efficiency indicator over speed. The Karman-Gabrielli diagram has been updated since then, Fig.2, but in essence the conclusions are unchanged, [2]:

In 2020, SOx-limits for fuel globally apply. Diesel quality fuels demand a premium, estimated to be 50% of HFO price. A CO2-emission trading may start in 2013. Associated costs are based on IPCC reports. Price for HFO will continue to increase in the long run (2.5% per year assumed).

Fig.1: Forecast for fuel price development, source: GL internal research

Fig.2: Transport efficiency vs speed for various vessels (modified Karman-Gabrielli diagram)
- Slow, large ships (tankers and bulkers) have unrivalled transport efficiency
- For medium speeds (100 km/h), trains are most efficient
- For high speeds (500 km/h), airplanes are most efficient
- Transport efficiency decreases as speed increases

The effect of fuel saving by designing for slower speeds is dramatic and often not fully appreciated by ship owners and financing experts. Let us illustrate the potential by a concrete example. Germanischer Lloyd developed a prototype design for a 13000 TEU containership in cooperation with major clients in Korea, [3]. Variations of this basic design were ordered and built in large numbers. These mega-carriers were designed for much lower fuel prices and had typical design speeds around 24 knots. We used our mega-carrier base design to create now a fit-for-the-future fuel-saver version. The hull form was re-designed for the slower speed, increasing the block coefficient and increasing the width of the ship to add one row of containers. The speed was reduced from 24 knots to 17 knots. The speed reduction led thus to a 70% decrease in required power despite the hydrodynamically less favorable larger width and block coefficient. Thus all emissions would be reduced by 70% based on existing off-the-shelf technology.

The much smaller engine for the reduced power requirement could be arranged in a smaller engine room located further aft, adding a bay of container stacks in longitudinal direction. The reduced bunker costs for a single ship, would add up to more than 125 - 250 m€ over an expected operational time of 25 years, based on fuel cost of 500 $/t to 1000 $. The increased container capacity would translate into 150 - 200 m€ over the life cycle. The freight rates were considered to correlate linearly with the reduced transport costs here, yielding lower freight rates for slower transport. The total life cycle benefit (lower cost and higher turnover) for a single would then add up to 275 – 450 m€.

Despite the uncertainty of predictions over 25 years and despite the industry practice of reselling ships after several years, the overall conclusion is unchanged: There is a very large incentive to design ships now for lower speeds. In fact, the benefits are so large that re-specification of existing contracts should be considered.

**Emission reduction by fuel saving**

The largest levers lie in designing for lower speed. A moderate reduction of design speed by 10% may save more than 30% fuel for the individual ship, mainly due to the exponential resistance curve, but also due to improved propeller efficiency and secondary savings for a smaller, lighter ship.

For given speed and size of a vessel, modern design approaches using simulation-based design, [4], [5], allow significantly improved fuel efficiency compared to older designs.

We can again revert to a case study to illustrate the potential. This time the case study is a typical Panamax containership with 4300 TEU capacity. The following actions led to a decrease of 25% in fuel consumption:

- 6% due to formal lines optimization based on computational fluid dynamics (CFD) investigating more than 10000 design variants in a highly automated process on a massively parallel computer cluster (more than 500 processors), [6], Fig.3
- 5% due to trim optimization of the ship, yielding optimum trim for each speed and load conditions (taking also shallow-water effects into account), [7], Fig.4
- 4% due to optimization of appendages, particularly the rudder
- 6% due to re-designing the system of auxiliary generators and main on-board consumers, optimizing the E-balance based on engineering expertise and latest simulation tools, [7], [8]
- 4%  due to on-board detailed monitoring, decision support and awareness of the crew

![Fig.3: Lines optimization based on CFD, 6% savings in this case](image1)

![Fig.4: User interface for “ECO assistant” advising on optimum trim; 2.5% savings in this case](image2)
The saving potential varies depending on ship type, size, speed and sophistication of original design. However, two-digit reduction in fuel consumption and thus emissions are generally feasible with positive payback, i.e. these measures pay for themselves.

For refits, propulsion improving devices (PIDs) have been widely discussed. There is no consensus on the effectiveness of such PIDs, even among experts in ship hydrodynamics. However, there is large consensus that the effectiveness of PIDs varies from ship to ship and depends on individual flow conditions. The appropriate tool these days is full-scale CFD analysis, Fig.5, [9], which then allows rational assessment of a PID before an investment decision is made. The CFD analysis allows not only an assessment of the effectiveness, but also an explanation why a given device may or may not be effective in a particular design.

For example, Germanischer Lloyd developed a marginal abatement cost curve for measures improving the energy efficiency of the world’s container fleet, Fig.6, [10]. The curve was based on a price of $700 per ton heavy fuel oil (HFO). The analysis yielded a theoretical abatement potential of 24% for profitable measures (i.e. measures that pay for themselves by saving fuel, assuming 5% interest rate on the capital).

![Fig.5: CFD analysis for a tanker with (bottom) and without (top) propulsion improving device](image)

**Emission reduction by abatement techniques**

There are no filtering techniques for CO\textsubscript{2} reductions and most of the fuels used today in shipping (heavy fuel oil HFO, marine diesel fuel MDO, intermediate fuel oil IFO) has very similar carbon content, hence similar CO\textsubscript{2} emissions. Hence, the focus on the options described so far, aiming at a reduction of fuel consumption which benefits all
emissions. For NOx, SOx and PM, there are various alternative abatement (reduction) techniques.

MARPOL IV aims at controlling air pollution through gaseous emissions by ships. The sulphur limit for fuel oil lies at 4.5%, and in special emission control zones (SECA = sulphur oxides emission control area) like the North Sea and the Baltic Sea at 1.5%. One option is the use of low-sulphur fuels, e.g. MDO. Another possibility to fulfill SECA requirements is the use of an approved technology to reduce the ship’s total sulphur oxide emissions to below 6 g/kWh. Such a technology may evolve in the form of exhaust gas scrubbing which has been under investigation on P&O ferries since 2007. There are conflicting reports regarding long-term effectiveness of the approach and robustness of the systems. While scrubbing technology has progressed considerably in the past 5 years and there is a growing number of installations, we generally believe that sulphur removal at the source (e.g. in the form of low-sulphur fuel) is preferable.

The quest for reducing nitrogen oxides (NOx) has resulted in a three-tiered roadmap documented in Marpol, Annex VI. The tier II, scheduled to be in effect from the year 2011 on, is expected to increase fuel consumption by 2%. The reason is the so-called “diesel dilemma”. With better fuel combustion, more nitrogen oxides are produced. The decrease in NOx leads in turn to lower engine efficiencies, hence more fuel consumption and increased CO2 production. The transition from tier II to tier III, reducing NOx emission even further in selected emission control areas (ECAs), may see widespread use of SCR (selective catalytic reduction). More recently, EGR (exhaust gas recirculation) has been proposed as a viable alternative for NOx reduction. EGR may reduce NOx emissions by 80%. The EGR directs part of the exhaust gas back into the scavenge air of the engine. This reduces the oxygen content of the air in the combustion chamber, thereby reducing the combustion temperature. The lower combustion temperature results in a reduced formation of NOx.

Alternative fuels
Another option lies in using alternative fuels. Natural gas as fuel would bring down CO2 emissions by 30% simply by having more hydrogen and less carbon than traditional marine fuels. Natural gas contains also very little sulphur and nitrogen and thus offers superior performance in terms of emissions. In addition, there are large gas reserves ensuring a sufficient supply for decades to come. This explains the wide interest in gas as an alternative fuel for the near and medium-term future. The legal framework has already set the conditions gas as a widely used ship fuel. In 2009, the IMO interim guideline for natural gas as a fuel not only for liquid natural gas tankers went into force. By 2013, this guideline shall be finalised within the IGF code of IMO.

Gas requires 70% more space in storage than diesel fuel. The typical cylindrical gas tanks are more difficult to arrange than fuel tanks that can use “odd” spaces. This poses particular constraints for volume carriers like container vessels, ro-ro and ro-pax vessels. Nevertheless, ship designs using gas as a fuel have been presented for many ship types, Fig.7, and built for ferries and cargo vessels. Here the combined effect of space requirements and arrangement leads typically to 250% larger fuel space requirements than in conventional ships. Due to voluminous tanks, gas as a fuel is more attractive for short sea shipping where frequent refuelling is possible.

Gas is more attractive for weight carriers where space is not at a premium. Gas is lighter than HFO or MDO per calorific value (energy content). However, a detailed analyses is needed to assess whether gas offers still weight advantages, e.g. for tankers or bulkers, when insulation and tank weights are added in the balance.

Fig.7: Concept of cruise ship driven by gas, source: Meyer-Werft Papenburg

Still further in the future, hydrogen may be a clean fuel. Already Germanischer Lloyd has developed a concept design for a zero-emission container feeder, based on existing technologies, Fig.8. The vessel uses liquid hydrogen as fuel to generate power with a combined fuel cell and battery system. The open-top concept for short port turnover times, the large width for extra container stowage and minimum ballast, fuel cells, and the unconventional bow design are key features of the design that may influence future ship designs well before liquid hydrogen is used on cargo ships. For example, for fuels cells research is active and by 2018 fuel cells may become commercially viable alternatives for onboard generators.
Fig.8: Concept study of hydrogen powered open-top containership (1000 TEU)

References