DESIGN METRICS FOR EVALUATING THE PROPULSIVE EFFICIENCY OF FUTURE SHIPS

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ABSTRACT

There is an increasing need for the ship design process to take account of environmental issues such as the emission of greenhouse gases and the likely extension of a carbon dioxide charging mechanism to international shipping. These issues, together with the need for economic viability, provide further incentives to improve the efficiency of propulsion of ships. The main components of powering are firstly reviewed. Individual components and other power saving devices are identified which should contribute to improvements in the overall efficiency of propulsion. Suitable design metrics and procedures, taking into account economic and environmental factors, are recommended for the design of future ships.

KEY WORDS

Ship resistance; Propulsive efficiency; Emissions; Greenhouses gases

NOMENCLATURE

B	Breadth (m)	R	Resistance (kN)
BAR	Blade area ratio	RFR	Required freight rate (£/tonne)
C_B	Block coefficient	*sfc*	Specific fuel consumption (kg/kW.hr)
D	Propeller diameter (m)	T	Draught (m) or thrust (kN)
L	Length (m)	WSA	Wetted surface area (m^2)
LCB	Longitudinal centre of buoyancy	V	Speed (knots or m/s)
NPV	Net present value (£)	∇	Displacement volume (m^3)
P	Power (kW) or propeller pitch (m)		

INTRODUCTION

Background

Ship design is driven primarily by the economic rate of return on the owner's investment. The likely extension of a Carbon Dioxide based emissions control mechanism to international shipping will influence the selection of propulsion system components together with ship particulars. Fuel costs have always provided an economic imperative to improve propulsive efficiency. The relative importance of fuel costs to overall operational costs influences the selection of design parameters such as dimensions, speed and trading pattern. Current economic and environmental pressures thus combine to create a situation which demands a fresh appraisal of the estimation of ship propulsive power and the choice of suitable machinery.

Of basic environmental concern are the emissions from ships which include NOx, SOx and CO_2, a greenhouse gas. Whilst NOx and SOx mainly affect coastal regions, carbon dioxide (CO_2) emissions have a global climatic impact and a concentrated effort is now being made worldwide towards their reduction. IMO is co-ordinating efforts in the marine field, and the possibilities of CO_2 Emissions Control and an Emissions Trading Scheme is under consideration, DfT (2007), ECSA (2008). This paper addresses how the CO_2 emissions from ships might be lowered by making improvements in the efficiency of their propulsion.

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In the marine field, the main impact is from tankers, bulk carriers and container ships which collectively, in about equal proportions, contribute to over 75% of CO_2 emissions from ships. Hence the current review and study has concentrated on these ship types. A high speed ferry is included as a comparator as these vessels can also have high fuel consumption due to their high speed. Values of CO_2 emitted per day are typically 300 tonne for a 250000 tonne deadweight tanker, 900 tonne for a 10000 TEU container ship and 150 tonne for an 80m fast ferry. These are significant quantities leading to the need to lower CO_2 emissions over the coming years by careful design of new tonnage and optimising the operation of existing tonnage.

Criterion for measuring CO_2 environmental impact

In order to monitor and quantify CO_2 emissions with the future possibility of establishing a CO_2 emissions control regime, IMO is developing a CO_2 index, IMO (2008).
The general form of the CO_2 index proposed by IMO is as follows:

$$CO_2 \text{ Design index} = \frac{P \ x \ sfc \ x \ C_F}{C \ x \ V} \quad \text{gm } CO_2\text{/tonne.mile} \qquad [1]$$

where P is power (kW), *sfc* is specific fuel consumption (gm/kW.hr), C_F is a CO_2 conversion (tonne CO_2/tonne fuel), C is the capacity of the ship (deadweight tonnes, TEU or Gross Tonnage) and V the speed (nautical miles /hr (knots), or km/hr). As such, the CO_2 Design Index can be seen as a measure of a ship's CO_2 efficiency. This is very much the general, or generic, form of the equation as the power will be made up of the propulsive and auxiliary power, the capacity C of the ship will in the main be deadweight tonnes, including container ships although TEU is favoured by some; passenger ships will use gross tonnage. Speed is not clearly defined as it could be taken as the design speed, or some average speed expected in operation. Similarly, power may be the design calm water propulsive power, or power taking into account average increases due to weather. There might be a case for having a design index and an operational index, and this is under discussion by IMO.

When considering the overall form of the CO_2 index it is clear that in order to reduce the index for a given ship at a given speed, a decrease in propulsive power must be achieved and/or improvements made in engine efficiency with a reduction in *sfc*.

For explanatory and comparative purposes, this paper will use the general form of the equation, Equation [1], with P as the service propulsive power, capacity C as deadweight tonnes and V the service speed in knots. For example, a cargo ship with C = 12000 tonnes, V = 14 knots, P = 3700 kW, *sfc* = 190 gm/kW.hr and C_F = 3.17 tonne CO_2/tonne fuel (IMO, 2005) would have a CO_2 Design Index = 13.3 gm/tonne.mile.

As there are proposals to introduce a form of CO_2 emissions control, there will be a need to set a limit on the CO_2 Index for new builds. This immediately sets great importance on the specific definition of each of the components in Equation [1] and is the subject of ongoing debate.

Aims of current work

The overall aims of the current work may be summarised as follows:
- review the main components of powering and relative proportions for different ship types;
- identify where improvements in the individual components may be made, leading to improvements in the overall efficiency of propulsion; and
- recommend suitable design metrics for future ship designs.

ECONOMIC and ENVIRONMENTAL DRIVERS

The factors driving current research and investigation into improving the overall efficiency of propulsion of ships are both economic and environmental. The main economic drivers amount to the construction costs, disposal costs, ship speed and, in particular, fuel costs. These need to be combined in such a way that the shipowner makes an adequate rate of return on the investment. The main environmental drivers amount to emissions, pollution, noise, anti-foulings and wave wash,

Fundamentally, improvements in efficiency of propulsion should lead directly to improvements in the economic return and a decrease in greenhouse gas emissions. This means there is now a double incentive to pursue such efficiency

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improvements. There are, however, some possible technical changes that will decrease emissions, but which may not be economically viable. Many of the auxiliary powering devices using renewable energy sources, and enhanced hull coatings, are likely to come into this category. There are suggestions that emissions trading for ships may be introduced in the future. If this is the case, all means of improvement in powering and reduction in greenhouse gas emissions should be explored and assessed, even if such improvements may not be directly economically viable.

POWERING

Overall concept

The overall concept of the powering system may be seen as converting the energy of the fuel into useful thrust (T) to match the ship resistance (R) at the required speed (V), Figure 1. It is seen that the overall efficiency of the propulsion system will depend on:
- fuel type, properties and quality;
- the efficiency of the engine in converting the fuel energy into useful transmittable power; and
- the efficiency of the propulsor in converting the power (usually rotational) into useful thrust (T).

The present study concentrates on the performance of the hull and propulsor, primarily considering, for a given situation, how resistance (R) may be reduced and thrust (T) may be increased. Accounts of the properties and performance of engines are summarised later and detailed accounts may be found in sources such as Woodyard (2004) and Molland (2008).

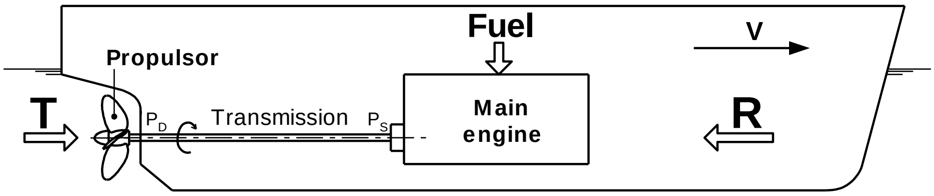

Figure 1 Overall concept of energy conversion

Components of powering

The main components of powering are identified and summarised. This allows assessments to be made of the areas where changes and potential improvements may be made.

Propulsive power
The power delivered to the propeller, delivered power (P_D), may be defined as:

$$\text{Delivered power } (P_D) = \frac{\text{Effective power } (P_E)}{\text{Quasi propulsive coefficient } (\eta_D)} \quad [2]$$

Effective power (P_E)

$$P_E = R \,.\, Vs \quad [3]$$

where R is total resistance (kN) of the naked hull and appendages together with above water air drag of the hull and superstructure. Vs is ship speed (m/s).

The total naked hull resistance is made up of friction, viscous pressure (or form) and wave components, as shown in Figure 2. These basic hull components are applicable to displacement ships and most semi-displacement ships. For faster vessels, other components arise such as transom, spray and induced drag. These, together with a further breakdown of the frictional and wave components are shown in Figure 3. The ships used as examples in the current study are mainly single screw and appendage drag is generally relatively small. Air drag may be significant and is discussed later.

Propulsive efficiency
The components of quasi propulsive coefficient (η_D) may be written as:

$$\eta_D = \eta_0 \,.\, \eta_H \,.\, \eta_R \quad [4]$$

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where η_0 is the open water efficiency of the propeller, η_H is the hull efficiency and η_R is the relative rotative efficiency. η_R takes account of the differences between the propeller in the open water condition and when behind the hull, and lies typically between 0.98 to 1.02.

η_H takes account of the interaction between the hull and propeller and is defined as:

$$\eta_H = \frac{(1-t)}{(1-w_T)} \quad [5]$$

where t is the thrust deduction factor and w_T the wake fraction. η_H lies typically between 1.10 and 1.25 for displacement ships. The formula indicates how changes in thrust deduction (t) due, for example, to the presence of a rudder or other device will influence overall propeller efficiency. Similarly, the influence of wake fraction (w_T) can be seen and quantified.

η_0 is the open water efficiency of the propeller and will depend on the propeller diameter (D), pitch ratio (P/D) and revolutions (rpm). Clearly, an optimum combination of these parameters is required to achieve maximum efficiency. Theory and practice indicate that, in most circumstances, an increase in diameter with commensurate changes in P/D and rpm will lead to improvements in efficiency. Propeller tip clearances will normally limit this improvement. For a fixed set of propeller parameters, η_0 can be considered as being made up of:

$$\eta_0 = \eta_a . \eta_r . \eta_f \quad [6]$$

where η_a is the ideal efficiency, based on axial momentum principles and allowing for finite blade number, η_r accounts for losses due to fluid rotation induced by the propeller and η_f accounts for losses due to blade friction drag, Dyne (1994, 1995). Theory would suggest typical values of these components as η_a = 0.80 (depending on thrust loading), η_r = 0.95 and η_f = 0.85, leading to η_0 = 0.646. This breakdown of the components of η_0 is important as it indicates where likely savings might be made, such as the use of pre and post swirl devices to improve η_r or surface treatment of the propeller to improve η_f.

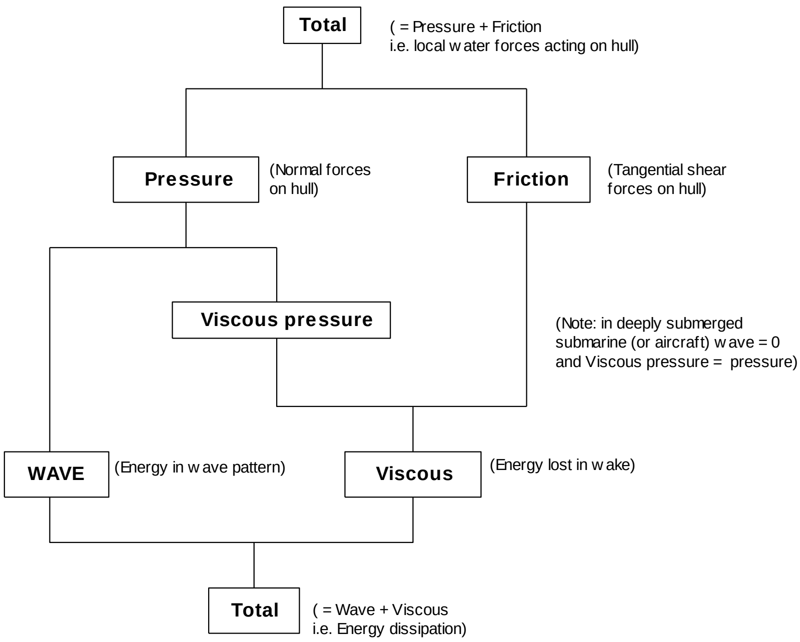

Figure 2 Breakdown of basic hull resistance components

Relative levels of powering components for different ship types

A breakdown of the hull resistance components, as a proportion of total, has been made for representative ship types, namely tankers, bulk carriers, container ships and a high speed catamaran passenger and vehicle ferry. These are summarised in Table 1. It is interesting to note from Table 1 how the slower hull form tankers and bulk carriers have a high proportion of viscous drag (friction plus form), whilst for the higher speed container ships with the finer hulls, wave

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resistance plays a more important part. For the fast ferry, the most significant component is the wave resistance, and much research has been carried out pursuing a reduction in this component, for example by increasing length displacement ratio or altering the spacing of catamaran hulls to reduce wave interference, Molland et al. (1996, 2004).

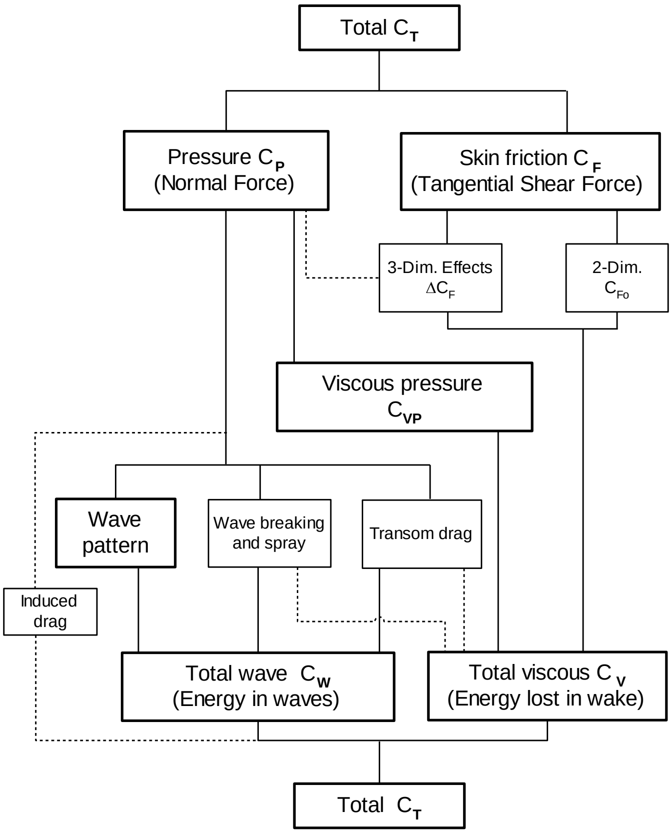

Figure 3 Detailed breakdown of resistance components

Table 1 Approximate distribution of resistance components

Type	Lbp (m)	C_B	Dw (tonnes)	Service speed (Knots)	Service power (kW)	Fn	Hull resistance component Friction %	Form %	Wave %	Air drag %
Tanker	330	0.84	250000	15	24000	0.136	66	26	8	2.0
Tanker	174	0.80	41000	14.5	7300	0.181	65	25	10	3.0
Bulk carrier	290	0.83	170000	15	15800	0.145	66	24	10	2.5
Bulk carrier	180	0.80	45000	14	7200	0.171	65	25	10	3.0
Container	334	0.64	100000 10000 TEU	26	62000	0.234	63	12	25	4.5
Container	232	0.65	37000 3500 TEU	23.5	29000	0.250	60	10	30	4.0
Catamaran ferry	80	0.47	650 pass 150 cars	36	23500	0.700	30	10	60	4.0

Propulsion machinery types

The main propulsion machinery is responsible for converting the energy in the fuel into useful mechanical power, Figure 1. The main types of engine, suitable for the propulsion of commercial ships may be summarised as follows:

- Low, medium and high speed diesel engines
- Gas turbines
- Electric motor, inboard or within a podded drive

These alternatives are described in some detail in Woodyard (2004) and Molland (2008). The large bore slow speed diesel engine (90-120 rpm) with direct drive to the propeller is that mainly used for tankers, bulk carriers and container

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ships. Medium speed diesels (500-600 rpm) coupled to the propeller via a gearbox are commonly used in ships such as ferries, tugs, trawlers and coastal vessels. High speed diesels (800-1000 rpm) are normally used in high speed craft such as ferries and naval craft. Gas turbines have been employed in naval vessels and high speed ferries. More recently they have been used to drive electrical generators. The electrical drive is gaining in popularity, mainly because of the facility to have a central generating area which can generate electricity efficiently for both propulsion and hotel loads. The principal properties of the various propulsion engines, such as size, mass, fuel consumption and emissions are described by Woodyard (2004). It should be noted that engine manufactures have made significant improvements in overall engine efficiency leading to reductions in the fuel consumption and emissions over recent years. Finally, whatever the choice of propulsion machinery, for ocean-going merchant ships it must be robust, reliable and safe.

Potential savings in power

This section seeks to identify key areas where changes and improvements in powering might be made and decreases in power and hence CO_2 index achieved. The likely economic viability of any changes is discussed later.

Table 2 Potential savings in resistance and propulsive efficiency

RESISTANCE (a) Hull resistance	Principal dimensions: main hull form parameters, U or V shape sections
	Local detail: bulbous bows, vortex generators
	Frictional resistance: WSA, surface finish, coatings
(b) Appendages	Bilge keels, shaft brackets, rudders: careful design
(c) Air drag	Design and fairing of superstructures. Stowage of containers
PROPULSIVE EFFICIENCY (d) Propeller	Choice of main dimensions: D,P/D, BAR, optimum diameter, rpm.
	Local detail: section shape, tip fins, twist, tip rake, skew etc
	Surface finish
(e) Propeller-hull interaction	Main effects: local hull shape, U,V or 'circular' forms [resistance v propulsion]
	Changes in wake, thrust deduction, hull efficiency.
	Design of appendages: such as shaft brackets and rudders.
	Local detail: such as pre and post swirl fins, upstream duct, twisted rudders.

Table 2 lists the principal areas where improvements might be expected to be made. It is divided into sections concerned firstly with resistance and then propulsive efficiency, but noting that the two are closely related in terms of hull form, wake fraction and propeller-hull interaction.

1. Calm Water

Resistance

(a) Hull Resistance

This is dominated by the principal hull parameters such as $L/\nabla^{1/3}$, C_B, B/T and LCB. Local detail, such as the use of V or U shaped sections forward and/or aft, will have an effect, as will the use of bulbous bows. The use of bulbous bows should be made with caution in that there are relatively specific areas where they can be used to advantage. These areas, for the loaded condition, are usefully illustrated in BSRA(1971). For a low speed tanker form, relatively little gain is made in the loaded condition, although decreases in the viscous resistance are expected in the ballast condition, Ferguson and Dand (1970), Shearer and Steele (1970). On the other hand, for a higher speed finer form container ship, decreases in wave resistance can be achieved in the design loaded condition. It is clear that the choice, and cost, of employing a bulbous bow is design specific. Vortex generators are employed to re-align the aft end flow and delay separation. This is often done to provide a cleaner flow into the propeller, rather than necessarily reducing resistance, Anon (2008c).

Hull surface finish is fundamental to the levels of hull skin friction resistance. Much research has been carried out to demonstrate the benefits of a good surface finish, for example Townsin et al.(1980, 1981, 1986). The frequency of docking to clean the hull has normally been assessed on economic grounds. The emphasis might change to a reduction in power in respect of a reduction in CO_2 emissions if an emissions trading scheme were to be introduced.

(b) Appendages

Appendages, such as bilge keels, shaft brackets and rudders require careful design. This might entail flow visualisation tests or CFD investigations to optimise the alignment of bilge keels and shaft brackets. Rudders should be considered as part of the propeller-rudder combination in respect of thrust deduction and propulsive efficiency changes, Molland and Turnock (2007), Anon (2008c).

(c) Air Drag

Air drag of the above water hull and superstructure is generally a relatively small proportion of the total resistance for tankers, bulk carriers and container ships, see Table 1. However, for a large vessel, any reductions in air drag may be worth pursuing. The air drag values shown are for the ship travelling in still air. The proportion will of course rise significantly in any form of head wind. Air drag values for commercial ships can typically be found in Isherwood (1973), van Berlekom (1981), Gould (1982) and Molland and Barbeau (2003).

Improvements to the superstructure drag of commercial vessels with boxed-shape superstructures may be made by rounding the corners, leading to reductions in drag. It is found that the rounding of sharp corners can be beneficial, particularly for box shaped bluff bodies, Hoerner (1965) and Hucho 1998. However, a rounding of at least r/B_S=0.05 (where r is the rounding radius and Bs is the breadth of the superstructure) is necessary before there is a significant impact on the drag. At and above this rounding, decreases in drag of the order of 15 – 20% can be achieved for rectangular box shapes, although it is unlikely such decreases can be achieved with shapes which are already fairly streamlined. It is noted that this procedure would conflict with design for production, and the use of 'box type' superstructure modules.

Investigations by Molland and Barbeau (2003) on the superstucture drag of large fast ferries indicated a reduction in drag coefficient (based on frontal area) from about 0.8 for a relatively bluff fore end down to 0.5 for a well streamlined fore end.

Propulsive efficiency

(d) Propeller

The propulsor on the majority of large displacement ships is the simple cast fixed-pitch propeller. Several alternatives exist, usually being some hybrid of the simple propeller, which can improve overall efficiency. These include controllable pitch propellers, ducted propellers, contra-rotating propellers and other hybrids, ITTC (2002, 2005, 2008). All have advantages and disadvantages relative to the simple propeller which are discussed later.

Propeller efficiency is dominated by its main dimensions, D, P/D and BAR, together with the application of the correct rpm. Many series propeller data are available in order to allow selection of optimum dimensions for a given situation, together with a check on cavitation avoidance. Attention to local detail can have beneficial effects. This includes section shape, skew and the use of tip fins and raked tips etc.

The propeller surface finish is known to have an effect on efficiency, see the component η_f in Equation [6]. Regular cleaning and polishing of propellers in service is carried out by many ship operators, Townsin et al.(1985). More recently, appropriate propeller coatings have been investigated, Atlar et al. (2002, 2003).

(e) Propeller-hull interaction

This in an area that can have a significant effect on the overall propulsive efficiency. For example, examination of Equation [5] indicates how thrust deduction (t) and wake fraction (w_T) affect hull efficiency, whilst Equation [6] includes the rotational losses η_r for the propeller which might be recovered by the application of suitable devices. The propeller-hull interaction is dominated by propeller hull clearances and aft end hull shape, for example fineness of waterline endings, depending on C_B and LCB, and/or the use of U or V or 'bulbous' sections upstream from propeller. This is modified by the possible presence of shaft brackets and rudders. Further improvements might be made by the application of an asymmetric stern, an upstream duct to clean and accelerate the flow into the propeller, pre-swirl fins on the hull, or post swirl fins on the rudder or a twisted rudder, all of which help to recover rotational losses, Anon (2008c,d.) An integrated twisted rudder, bulb and propeller hubcap is described in Anon (2008e).

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2. Rough water

Historically, rough water performance has taken a secondary role to that of calm water performance. Rough water performance can be improved by changes in the main hull parameters and to local hull shape. These changes can often conflict with the calm water performance. Efforts have been made to combine the two in the hull optimisation process, whereby suitable weightings are applied to the calm water performance and performance in the likely sea conditions and their duration, for example Karayannis and Molland (2001, 2003). In almost all cases, seakeeping performance is usually improved (for the same displacement and payload) if ship length is increased. This might fit with the philosophy, discussed later, of using longer ships (higher L/B and $L/\nabla^{1/3}$) in respect of reducing power and emissions.

3. Operation

Typical operational actions that might be applied to reduce power and CO_2 emissions are discussed.

Speed

For most displacement ships, power varies as speed cubed. Any reduction in speed can therefore offer significant reductions in power and the emission of greenhouse gases. On an economic basis, the reduction in speed leads to a saving in fuel but a loss of earnings and there is a fine balance between them to derive the 'optimum economic' speed. In order to illustrate this, a study was carried out for the smaller bulk carrier in Table 1 where, for a given fuel cost and given voyage pattern, speed was systematically varied and the required freight rate (RFR) derived. Ship design software, designated 'ShipDes', developed at the University of Southampton, was used for the investigation. ShipDes is primarily a technical design program which evaluates ship principal dimensions for given input values of deadweight, speed and range. The program is capable of dealing with tankers, bulk carriers, container ships and cargo vessels. Empirical formulae used for the derivation of dimensions and masses can be found in Watson (1998), Schneekluth and Bertram (1998) and Molland (2008). The power estimate is based on effective power using the regression data for the BSRA Series and propeller open water efficiency using polynomial data for the Wageningen Series. Wake fraction, thrust deduction and correlation factors are based on empirical data. The facility exists to change the main parameters such as L/B, B/T, C_B and propeller diameter. The program has a subroutine which carries out a simplified economic analysis to evaluate Required Freight Rate (RFR) for given ship dimensions, speed and running costs, Buxton (1972), Schneekluth and Bertram (1998). Input requirements are such that the effects of changes in ship speed, fuel cost, port turnround time, interest rate and number of years of repayments/analysis can be investigated in a systematic manner. The results of the study are shown in Figure 4 and show classical trends, namely, for a given fuel cost there is an optimum speed for minimum freight rate. Initially, starting from a low speed, as speed is increased the increase in earnings increases at a greater rate than the power and fuel. This continues until a speed is reached when the increase in fuel is greater than the increase in earnings. It is noted that optimum speed decreases with increase in fuel costs and provides the reason for the use of lower speeds in periods of high fuel costs. The shortcoming of this approach is that it is based on supply rather than demand. In other words, if a cargo is say perishable or of high value, then it will be beneficial to run the ship at a speed greater than the 'basic economic' speed. It is interesting to note that, as power varies as speed cubed, a reduction in speed in the CO_2 index, Equation [1], should lead to a reduction in the index. This could be attractive if a CO_2 based charging mechanism were to be introduced. This aspect is discussed again later.

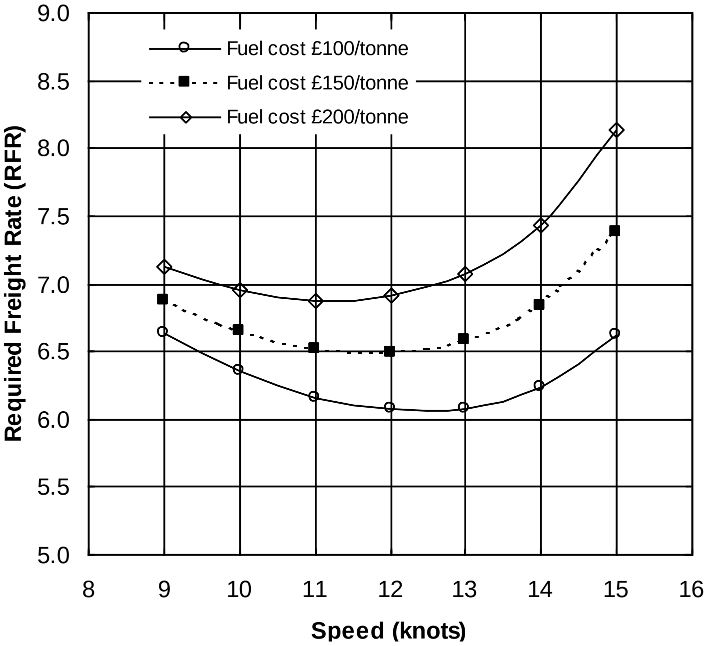

Figure 4 Variation in Required freight with change in speed

The other aspect that can affect the assessment of ship speed, in respect of saving overall power and greenhouse gases, is that if a given amount of cargo is required to be shipped each year, whether it be bulk cargo or manufactured goods, then reducing ship speed will mean that more ships are required which will to some extent negate the savings. It can be concluded that reductions in ship operational design speeds may then not make significant reductions in the overall emission of greenhouse gases from ships.

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Weather routeing
Weather routeing is now a well practised procedure by many shipping companies. It entails trading a relative decrease in fuel consumption for an increase in distance to travel around bad weather. To work effectively, a knowledge is required of the performance of the ship in a seaway, in particular, speed losses in the various forecasted sea conditions. Such procedures are, for example, described by Satchwell (1989). The practice should lead overall to the emission of less greenhouse gases.

Optimum trim
Ships are normally designed for level trim in the load condition and some trim by the stern in ballast condition. This will normally ensure adequate propeller immersion in the ballast case together with forefoot immersion. The results in Lackenby and Parker (1966) would indicate that trim can have a significant effect on resistance indicating that this should be exploited during operation. There is also some potential for designing a larger propeller if an increased ballast draught and/or trim is considered. In this case, an increase in propeller efficiency is being traded against an increase in resistance.

Hull coatings
A smooth surface, with low roughness, will normally lead to lower frictional and viscous pressure resistance. From a hydrodynamic point of view, the underlying objective is to provide a smooth hull surface finish when the vessel is constructed and to maintain a clean smooth surface in service. Research by Candries and Atlar (2003) indicates that reductions in skin friction resistance may be achieved with foul release coatings.

Hull/propeller cleaning
Hull cleaning is known to decrease overall power, but has usually been carried out on a strictly economic basis, see Townsin et al.(1981, 1985, 1986). The decrease in CO_2 emissions, and possible emissions trading for increases in maintenance costs, could provide the operator with the incentive to clean the hull and propeller over shorter intervals of time.

Roll stabilisation
There is potential for a decrease in overall resistance and power if the added resistance due to roll is minimised. Roll stabilisation may be achieved by tanks or fins, Molland (2008), tanks being preferred if a net overall decrease in resistance is required, although a loss in payload occurs. Both incur investment which may still be attractive if suitable compensation were forthcoming from an emissions trading scheme.

Propulsion machinery
The most efficient machinery installation for a particular application might be achieved as follows:
- choose the appropriate engine for a particular task;
- correctly match the propeller to the engine;
- if possible, run the engine close to its design condition, leading to minimum fuel consumption and emissions; the possible use of a controllable pitch propeller should be considered; and
- consider the use of an electric drive with the generator engines running in their design condition.

Auxiliary propulsion devices.

There are a number of devices that provide propulsive power using renewable energy. The energy sources are wind, wave and solar, and devices using these sources are outlined in the following sections.

(a) Wind
Wind assisted propulsion can be provided by sails, rotors, kites and wind turbines. Good reviews of wind assisted propulsion are given in RINA (1980) and Windtech'85 (1985).
Sails: Sails may be soft or rigid. Soft sails generally require complex control which may not be robust enough for large commercial vessels. Rigid sails in the form of rigid vertical aerofoil wings are attractive for commercial applications. They can be robust in construction and controllable in operation. Prototypes, designed by Walker Wingsails, were applied successfully on a coaster in the 1980s.
Rotors: These rely on Magnus effect and were demonstrated successfully on a cargo ship by Flettner in the 1920s. There is renewed interest in rotors with significant contributions to propulsive power being claimed, Anon (2008a). It may be difficult to achieve adequate robustness when applied to large commercial ships.
Kites: These have been developed over the past few years and significant contributions to power of the order of 10-35% are estimated, Anon (2008b). Their launching and retrieval might prove too complex and lack robustness for large commercial ships.

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Wind turbines: These may be vertical or horizontal axis and were researched in some detail in the 1980s, Windtech'85 (1985). They are effective in practice, but require large diameters and structures to provide effective propulsion for large ships. Drive may be direct to the propeller, or to an electrical generator to supplement an electric drive. A Japanese Eco-Ship incorporates a vertical axis turbine to provide auxiliary electrical power, NYK (2004).

(b) Wave
The wave device comprises a freely flapping symmetrical foil which is driven by the ship motions of pitch and heave. With such vertical motion, the flapping foil produces a net forward propulsive force. Very large foils, effectively impractical in size, tend to be required in order to provide any significant contribution to overall propulsive power.

(c) Solar, using photovoltaic cells
A lot of interest has been shown recently in this technique. Large, effectively impractical, areas of panels are required to provide any significant amounts of electricity for propulsive power.

General comments

It is important to take note of the interaction between auxiliary sources of thrust such as sails, rotors or kites and the main propulsion engine(s), Molland and Hawksley (1988). Basically, at a particular speed, the auxiliary thrust causes the propulsion main engine(s) to be off-loaded and possibly to move outside its operational limits. This may be overcome by using a controllable pitch propeller or multiple engines (via a gearbox) which can be individually shut down as necessary. This also depends on whether the ship is to be run at constant speed or constant power. Such problems can be overcome at the design stage for a new ship, perhaps with added cost. Such requirements can, however, create problems if auxiliary power is to be fitted to an existing vessel.

Whilst a number of the devices described may be impractical as far as propulsion is concerned, some, such as wind turbines and solar panels, may be used to provide supplementary power to the auxiliary generators. This will lead to a decrease in *overall* power (propulsion and auxiliary electrical generation) and an overall reduction in emitted greenhouse gases.

RELATIVE COSTS and ENVIRONMENTAL BENEFITS

General
The previous Sections have identified areas where potential reductions in power and emission of greenhouse gases might be made. This Section attempts, where possible, to quantify the levels of power reduction for a number of these areas, to identify where the best savings might be made and to indicate where future research and design metrics should be directed.

Resistance
Overall dimensions and form
Fundamental parameters that affect the resistance of displacement ships are L/B, $L/\nabla^{1/3}$, B/T, C_B and LCB. Optimisation studies have been carried out over many years to derive the most suitable combination of these parameters for a particular vessel at a particular speed with a given fuel cost. Analysis is usually based on some economic measure of merit, such as NPV, yield or required freight rate. The resulting dimensions will depend on speed and fuel cost. For example, if speed is reduced the vessel will tend to be shorter, and construction costs will reduce, whilst for higher fuel costs, optimum length and L/B tend to be larger, the decrease in power and fuel offsetting the increase in build cost. Parametric changes in main hull dimensions for tankers have been carried out by a leading oil company, providing indications of what savings in power might be achieved, SSPA(2007).

A study has been made into the effects of parametric changes in hull parameters for the small tanker in Table 1. This entailed running the ship at 14.5 knots over 17 voyages/year. The ship design software ShipDes, described earlier, was used for the investigation. The results are shown in Figure 5. Changes in the construction costs/annual charges and fuel cost changes follow expected trends, namely, as L/B increases, construction costs increase and fuel costs decrease. Observation of the RFR results in Figure 5 indicate that with fuel at £100/tonne the L/B should be about 6.0 whilst at £200/tonne the L/B should between 7.0 and 8.0. What is important to note is that, with high fuel prices, and pressure to reduce emissions and power, it may well be necessary to move to higher L/B ratios than is currently the practice. On the same basis, suitable values for the other variables such as B/T, C_B and LCB should also be re-visited.

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Bulbous bows

The bulbous bow shows its best advantage for certain values of ship form and for certain speeds. The need for a bulb should therefore be confirmed at the design stage. The performance of the bulb will normally be assessed by tank tests. In the case of tankers and bulk carriers, these will also include the performance in the ballast condition, where the largest reductions in resistance might be achieved. It can be concluded that with higher fuel costs and the need to reduce emissions, further reductions in resistance and power might be achieved from careful analysis and application of bulbous bows. It is an area of investigation, particularly concerning the flow direction characteristics, where CFD investigations might be used to advantage.

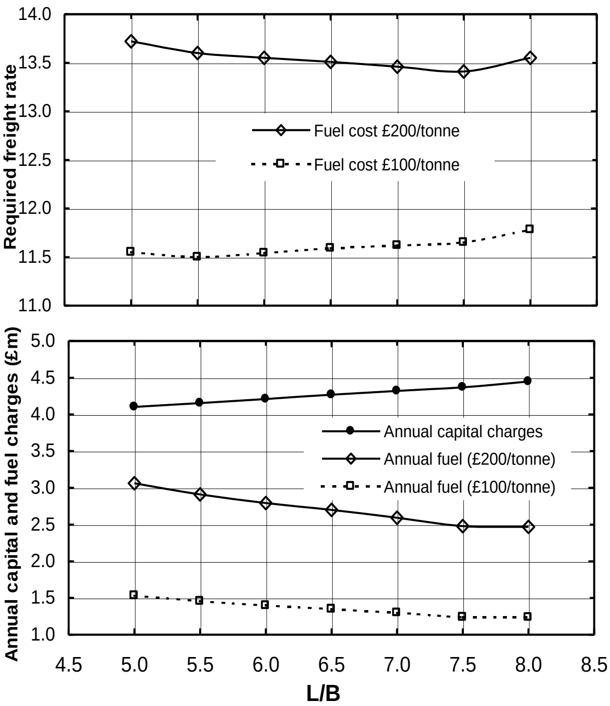

Figure 5 Variation in capital charges and fuel costs with change in L/B

Running trim

Tankers and bulk carriers will normally be designed to trim by the stern in the ballast condition, providing adequate immersion of the propeller and forefoot. It is clear that changes in trim will lead to changes in resistance, see Lackenby and Parker (1966). This would imply that there should be some optimum trim. At the design stage this may be investigated when tank testing and/or by the use of CFD investigations. In operation, the optimum trim may be derived by trial and error, appropriate measurements of power being made for various ballasted trims.

Hull surface finish

The maintenance of a clean hull in service is now common practice, the phasing of dry docking tending to be chosen solely on economic grounds, Townsin (1981, 1986).

The smoothness of the hull when new has been receiving more attention, partly arising from the increases in oil prices but also from the required changes in anti-fouling paints. Following the ban on the tin based self-polishing anti-foulings, new alternatives are being investigated. These include tin-free self polishing coatings and foul release coatings, Candries and Atlar (2003), where it is shown that reductions in skin friction resistance of 2-5% can be achieved with the foul release coatings compared with self polishing. If this level of reduction were achieved with the large tanker in Table 1, this would represent about a 1-3% reduction in total resistance and power and annual savings of up to about 900 tonnes of fuel and 2800 tonnes of CO_2 emissions. It is clear that hull coatings should be investigated further.

Air drag

It has been noted earlier in the paper that worthwhile savings in power can be made with suitable design and fairing of superstructures. It was seen that a 15-20% reduction in drag can be achieved by rounding the corners of box shaped rectangular superstructures. This reduction in air drag would lead to a decrease of about 1% in overall resistance in the case of the large container ship in Table 1, leading to annual savings of up to about 900 tonnes of fuel and 2800 tonnes of CO_2 emissions.

The work of Molland and Barbeau (2003) on the superstructure drag of fast ferries realised significant reductions in drag coefficient when moving from a relatively bluff fore end to a well streamlined fore end. For example if a 30% reduction in drag coefficient were achieved for the fast ferry in Table 1, then this would lead to over 1% decrease in power. Much higher savings would be achieved when the vessel has to travel in anything approaching head winds.

It has been reported that significant increases in air drag can occur with container ships that have gaps between the vertical columns of stowed deck containers. This would suggest that more work could be done on devising the best layout of containers when there is only a part load of containers on deck.

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Propulsor efficiency

Propeller diameter

The significance of maximising propeller diameter to improve efficiency was discussed earlier in the paper. A survey of container ships built over the past few years indicates that the choice of propeller diameter was between 65% and 73% of the design load draught. The lower values are presumably applied where operation is expected at draughts significantly less than the design load case. This creates a significant power penalty. For example, were this range of diameters applied to the smaller 232m container ship in Table 1, then the propeller diameter would be between 7.0m and 7.85m. If this were transformed into propeller efficiency improvements, then the order of increases are shown in Figure 6, with the propeller efficiency η_D (Equations [2 and 4]) improving from 0.683 to 0.718, an improvement of some 5%. To be able to incorporate such a large increase in diameter is unlikely in a particular design situation, but the attraction of applying any increase in diameter is apparent.

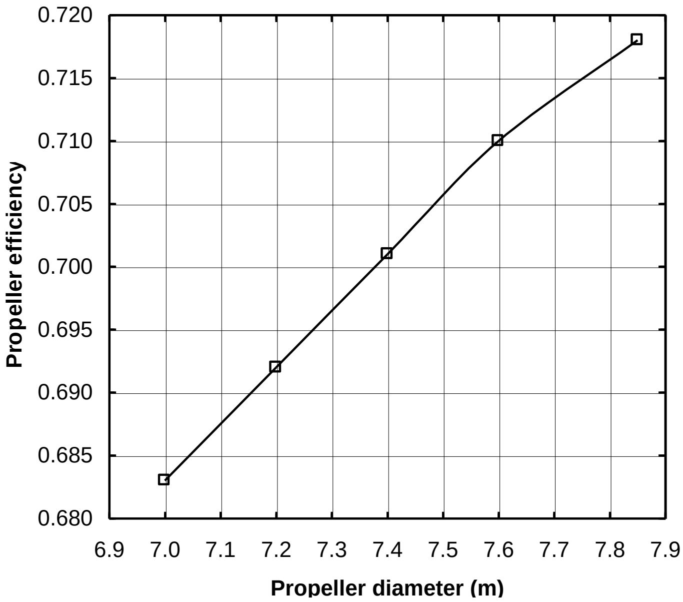

Figure 6 Change in propeller efficiency η_D with change in diameter

Inclined keel

The pressure of increased oil prices and the need to reduce power and emissions would suggest that it may be worthwhile investigating further the inclined keel concept. In this case, the keel is inclined (equivalent to designing in trim) and a significantly larger propeller can be employed, Winters (1998). This is similar to the approach used for tugs and trawlers. In the case of a larger vessel, such as a container ship, the draught amidships would be the design draught and the ship would ballast back to level keel if required by port draught limitations. As an example, if the 232m container ship in Table 1 had a 2.0m trim by the stern, and assuming this could be transformed (by the redesign of the aft end) into an increase of 1.0m in propeller diameter then, using Figure 6, this would suggest an expected increase in propeller efficiency of about 6%. There may be some increase in resistance with an inclined keel, but the indications are that the gains to be made from the increased propeller diameter are greater than the losses due to the increase in resistance. These findings would suggest that the concept deserves further consideration.

Propeller – hull interaction

As propeller-hull interaction is dependent on many features, there is often scope for improvements in overall hull-propeller efficiency. The propeller performance will depend on the inflow which is dependent on the hullform, and there will be cases where increases in hull resistance due to changes in hullform will be balanced against potential greater improvements in propeller efficiency. Fundamental features are aft end hull shape and propeller-hull clearances, which should be optimised. Fundamental also is propeller rudder-interaction, having an influence on thrust deduction and some recovery of propeller induced rotation of the flow. A further basic change would be the use of a 'bulbous' stern, with or without asymmetry. Beyond these fundamental aspects are detailed devices that can contribute to improvements in efficiency. These include vortex generators which are claimed to have led to 4-6% reduction in fuel consumption, Anon (2008c), and a duct upstream of the propeller which is claimed to save up to 4% of power for large full form vessels, Anon (2008d). Savings of between 2-4% might be expected from the application of pre and/or post swirl stators. An integrated twisted rudder, bulb and propeller hubcap is described in Anon (2008e), and it is suggested that savings in power of up to 10% might be achieved with careful integrated design of hull, propeller and rudder.

Alternative propulsors

Alternatives to the simple solid fixed-pitch propeller may be summarised as ducted, controllable pitch, contra-rotating, cycloidal and podded units. Generally, these are employed for specific applications where improvements in propulsive efficiency can be made, noting that for ocean-going merchant ships such units must be robust, reliable and safe. There are also a number of detailed modifications that can be made to the simple propeller, including the use of tip fins and tip

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rake. Based on the need for robustness and reliability, the alternative propulsors discussed are unlikely to have a significant impact on overall emissions reduction for large tankers, bulk carriers and container ships.

Alternative fuels

A number of alternative fuels are under consideration which would reduce the emission of greenhouse gases and reduce the dependence on oil, ECSA (2008). These include bio fuels, nuclear power, LNG and fuel cells. Bio fuel does not contain sulphur and reduces the emission of CO_2. It does, however, have a high price and may not be available in suitable quantities for shipping. Nuclear power has a proven track record for naval ships, but is likely to have too many restrictions for practical application to merchant ships. The use of LNG would reduce CO_2 emissions. The large volume of stowage required for LNG tends to make it non-viable for large ocean-going ships, although it has several suitable applications for small ships. Fuel cells may become viable in the future, but at present energy efficiency levels are not suitable for the propulsion of large ships.

Auxiliary power

A number of devices are available that are driven by renewable energy sources, including wind, wave and solar. These were summarised in an earlier Section. All the devices will provide a propulsion power input, but not necessarily economically. It is the lack of economic justification that has generally held back their development. Solid wing sails and Flettner rotors have, for example, proved to be technically but not economically viable. With the rise in oil prices, such devices may become economically viable. At the same time, if savings in power and hence greenhouse gas emissions are the main driver, and some form of carbon offset subsidy is provided, then the application for propulsive power of some auxiliary devices with proven robustness and reliability should be investigated in more depth. It was noted earlier that some of the devices, such as wind turbines and solar panels, can be usefully employed to provide supplementary power to the auxiliary electrical generators, thus leading to a reduction in overall power and a reduction in emitted greenhouse gases.

Design metrics

It is clear from the earlier Sections that metrics for quantifying the impact of greenhouse gas emissions need to be incorporated in the ship design process. This could, for example, entail the incorporation of the CO_2 index (Equation [1])

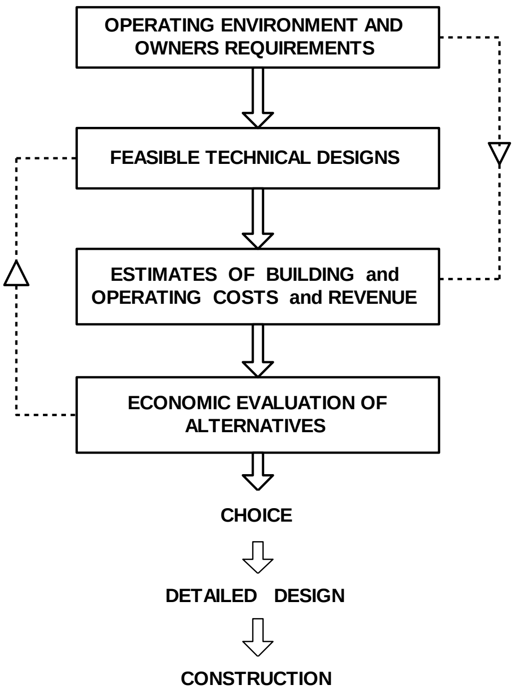

Figure 7 Overall flow path

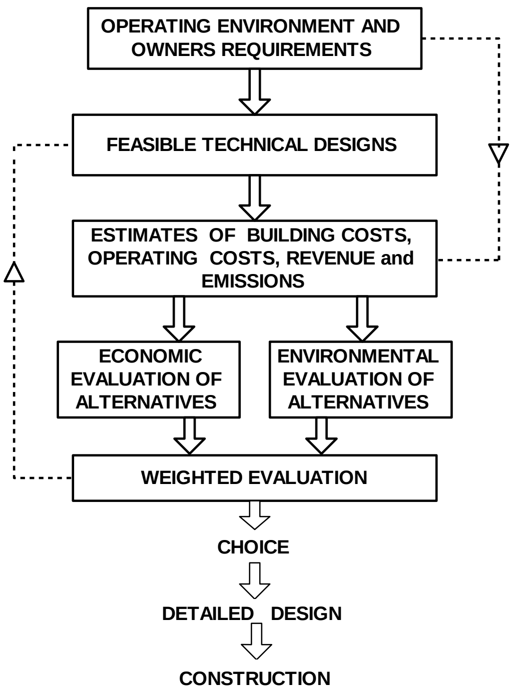

Figure 8 Overall flow path incorporating environmental effects

as an objective function. Figure 7 shows a traditional ship design approach where the objective function is some economic criterion such as NPV or RFR, Molland (2008), Schneekluth and Bertram (1998).

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Figure 8 indicates how the environmental effects may be incorporated in the ship design process. The use of such an approach allows design changes, technical innovation and auxiliary power devices to be incorporated in the feasible technical design, and a cost benefit analysis of these changes carried out in the usual way, Schneekluth and Bertram (1998). Thus the objective function for optimising on an economic basis might be NPV or RFR, whilst the environmental 'optimum' might be to achieve the lowest CO_2 index. Earlier examples have indicated that the economic and environmental optima may not coincide. This is illustrated in Figures 9 and 10, where the CO_2 index is based on the calm water propulsive power. Figure 9, based on the same ship as in Figure 4, indicates that increases in speed lead to an increase in the CO_2 index, approximately as the square of the speed. Reductions in speed ultimately lead to an increase in RFR, although useful reductions in the CO_2 index are achieved. Decisions on levels of speed reduction may well depend on the overall operation of a number of ships to move a certain amount of cargo, as discussed earlier.

Figure 10 illustrates the effect of L/B on the RFR and the CO_2 index. It is based on the same ship as in Figure 5. It is seen in Figure 5 that as fuel prices rise, there is a need for a higher L/B (with a decrease in specific power). Figure 10 illustrates how higher L/B leads to a lower CO_2 index. Thus the combined influences of fuel costs *and* CO_2 emissions are likely to take a more important role in the choice of the overall hull parameters for future tonnage.

As the design path now becomes a multiple criteria problem, see for example Sen (1992) and Schneekluth and Bertram (1998), weightings will have to be applied depending on what financial incentives might be given, directly or indirectly, to arrive at an environmental optimum which is not necessarily the economic optimum. The weightings are likely to depend on fuel cost levels and incentives in carbon trading schemes.

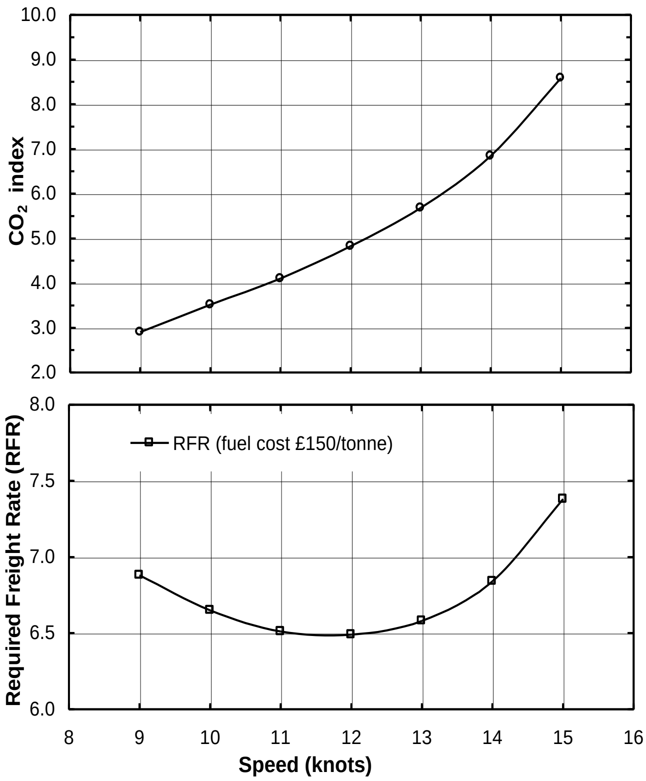

Figure 9 Influence of speed on Required freight rate and CO_2 index

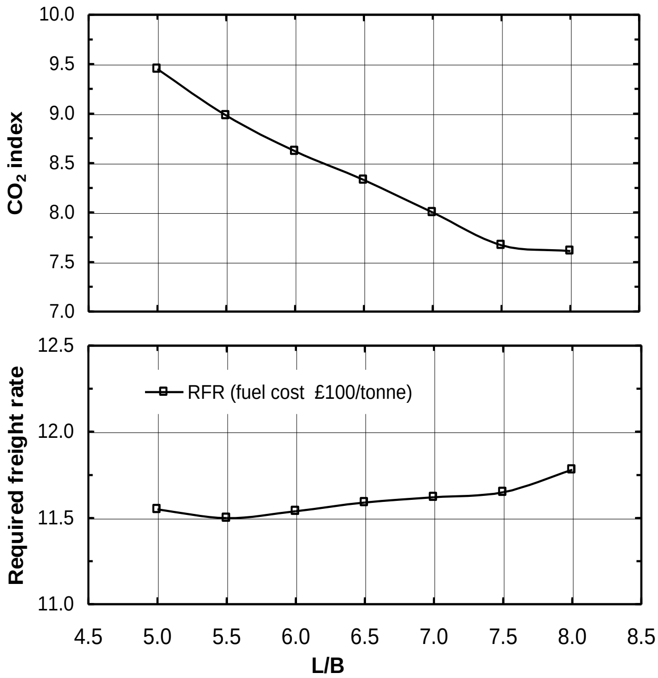

Figure 10 Influence of L/B on Required freight rate and CO_2 index

Some potential savings in fuel and CO_2 emissions due to a 1% saving in power are summarised in Table 3 for a range of ship types. As discussed earlier, improvements in overall efficiency of propulsion and reduction in power might be achieved with changes in main hull parameters, correct use of bulbous bows, increased propeller diameter, good hull surface finish and use of auxiliary power. It is seen that with only 1% reduction in power and fuel, savings can be substantial, with savings in annual fuel costs ranging from £13,000 to £140,000 (based on fuel at £150/tonne) and annual CO_2 savings of the order of 300 – 3000 tonnes.

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Table 3 Potential savings in fuel and CO_2 emissions

Ship type	Deadweight (tonnes) or TEU	Speed (knots)	Length of round voyage (nm)	Round voyages/ year	Annual fuel (tonnes)	Annual CO_2 (tonnes)	1% saving in fuel consumption	
							Annual fuel saving (£)	Annual CO_2 saving (tonnes)
Bulk carrier	45,000	14	5,000	17	8,400	26,700	12,600	270
Tanker	250,000	15	10,000	10	30,700	97,000	46,000	970
Container	10,000 TEU	26	20,000	10	90,600	287,000	136,000	2870

CONCLUSIONS

General: A number of areas have been identified where initial design changes and investment at the construction stage can lead to significant savings in fuel consumption and emission of greenhouse gases. Changes may be made at the design/construction stage, or modifications carried out whilst the ship is in service. Whatever changes are made, these must be robust, reliable and safe.

Greenhouse gases: CO_2 emissions control for ships is likely to be introduced in the future, putting further pressure on the need to improve the efficiency of propulsion of existing and new ships.

Resistance: Several areas have been identified where overall propulsive efficiency may be improved. In terms of resistance, optimisation of overall hull shape parameters should be investigated, together with attention to the fore end in terms of bulbous bows and local section shape, and to the aft end in terms of section shape and the interaction of the wake with the propeller. CFD may be usefully employed to develop suitable shapes of the bulbous bow for particular operational conditions.

Propeller efficiency: Propulsive efficiency offers a number of areas for improvement. Maximising and optimising propeller diameter is fundamental and there are some opportunities for doing this. Attention to local detail can be productive, including the hull to propeller and propeller to rudder interactions where efficiency gains can be made. These include asymmetric and bulbous sterns. CFD should be used to further complement model tests for hull-propeller-rudder interaction effects, where worthwhile improvements in overall efficiency of the propulsion unit might be achievable. At a greater level of detail, boss cap fins, upstream ducts, pre and post swirl devices and twisted rudders can be used to advantage.

Savings: In reacting to the pressure to reduce propulsive power, the designer will need to investigate every feasible possibility. This might entail deriving small improvements from a number of the component parts which, collectively, will provide worthwhile savings in overall power and a reduction in the emission of greenhouse gases.

Economic viability: With the increased pressure from the environmental point of view and with the possible future introduction of emissions trading schemes, reductions in power and emissions might be achieved with design changes and fuel saving devices which are not necessarily the best economic solution.

Design metrics: The design process should be adapted to take account of the changing emphasis between economic viability and environmental factors such as greenhouse gas emissions. The process will include some economic objective function, such as NPV or RFR, and an environmental objective function which could be the CO_2 index. A multiple criteria approach will be necessary, with weightings between the criteria depending on what financial incentives might arise in order to persuade ship operators to reduce emissions.

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