Analysis techniques for evaluating the fuel savings associated with wind assistance

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Abstract

Before steam and diesel engines, all cargo merchant ships were propelled by wind power. The arrival of cheap, high-density energy sources such as coal and oil and the economic benefits of the service speed and reliability that this enabled removed wind as a form of propulsion for much of the 20th century. However, higher prices for these energy commodities and environmental regulation, has led some to speculate that wind could return once again as a source of at least some share of a modern merchant ship's propulsion energy requirement. A number of proposals for the technology that could enable this exist (e.g. soft-sails, wingsails and flettners), all share in common difficulties in their fair assessment, both relative to each other and relative to a conventionally powered ship. A moderately sized rig can supply anywhere between 0-100% of a merchant ship's propulsion requirements, but this varies as a function of wind speed and direction, which in turn could vary several times a day over the course of multiple-day voyage. The weather, its variability and the specifics of a ship's route are therefore all key components that render simpler 'generic' energy savings assessments meaningless. Furthermore, whilst conventional ships might sail a shortest distance route that avoids extreme weather, a wind-assisted ship might undertake more extreme variation in route and speed over the course of the voyage to maximize benefit obtained from the wind, and this in turn therefore needs to be taken into account in a fair comparison.

This paper describes an analysis process that can be applied to any ship design and wind-assistance technology, to fairly evaluate the performance over a range of conditions, and then simulate the performance on a specific voyage using historical records of metocean parameters. The process is applied to an example design to illustrate the method.

Keywords: Apportionment, GHG emissions,

1 Introduction and state of the art

The 'modern' implementation of wind assistance technologies on merchant ships, as a method for reducing fuel consumption, can be traced back to at least the oil shocks of the 1970's. The Japanese designs Shin Aitoku Maru and Usuki Pioneer were sailing in the 1980's demonstrating the potential of solid wingsail devices. Developments in materials and design have progressed a number of different rig concepts, including the Dyna rig, which following its successful implementation on the Maltese Falcon, has been configured for implementation on both a container ship and a bulk carrier shown in Figure 1.

Figure 1: The Ecoliner and the B9 concept, Dyna rig assisted merchant ship designs

A number of assessments have been carried out to quantify the benefits of wind assistance technologies. Early work by Schenzle (1985), has been built on more recently e.g. Naaijen et al. (2006) and Fujiwara et al. (2005a). This has been further underpinned by detailed analysis of some of the components that contribute towards performance e.g Fujiwara et al. (2005b).

Traut et al. (2014) present one of the most complete studies carried out to date, simulating a voyage and calculating the power generated by both a kite and a Flettner rotor assisted ship on representative routes. The wind power variability is taken into account and produces a variability of power generated by the wind devices over the routes. Examples of specific vessels travelling at slow steaming speeds found savings of 20-45% (depending on route direction). However, the study did not consider the integration of the kite and the conventional propulsion machinery (which can be important depending on the off-design efficiency of the ship's machinery i.e. how the fuel consumption varies with propulsion power output). The study also did not consider variations in the ship's route or speed over the course of the voyage. Given the sensitivity of wind devices' power outputs to wind speed and direction, these voyage and route operational specifics have the potential to create a significant impact on power generated and therefore fuel consumption savings.

2 Statement of the problem

Due to the variability of wind both in time (day, season) and space (route), as well as the aerodynamic and hydrodynamic interactions that need to be carefully managed through ship operation in order to produce a performance benefit, wind assistance technologies suffer from being complex to analyse.

Existing analysis has quantified some components of the performance, however has simplified other important components (e.g. ship operation), which can have a significant impact on the quantification of benefits. Furthermore, the consideration of a cost-benefit is often disregarded altogether. The complexity in analyzing wind can lead to a lack of transparency and comparability in the way that technology's benefits (in terms of fuel savings) are assessed and presented, which in turn can lead to a range of common misunderstandings. This paper demonstrates a suite of techniques that can be coherently assembled in order to produce rigorous analysis of wind-assistance technologies, and provide the inputs to a cost-benefit assessment that can be used as a basis for investment appraisal.

3 Description of the method and approach

It is proposed that there are three important stages in assessing the performance of a wind-assisted ship:

- Characterizing the physics of a wind-assisted ship (its hull, rig and machinery) and the performance of a wind-assisted ship in a given environmental (weather) and operational state (speed, loading condition)
- Characterising the performance of a wind-assisted ship on a voyage, taking into account the variability in the weather and the ship's operation on a voyage
- Aggregating the performance over a number of voyages and characterizing the techno-economics of the ship's operation (the interaction between speed and fuel savings) and the cost-benefit of the investment (the compensation of any changes in capital and operating expenditure through fuel savings and other benefits).

The following sub-sections of this paper outline some of the detail behind each of the stages listed above.

3.1 Characterising the ship system

For an implementation of a wind-assistance technology, the power supplied to propel a ship through the water comes from a combination of the rig and the ship's machinery (engine and propeller). In steady-state (constant speed conditions), both the lateral forces (causing heeling and leeway) and the longitudinal forces (thrust and drag) must be in equilibrium. The thrust force can be supplied by any combination of aerodynamic forces from the rig and the conventional thrust produced by the ship's propeller. Figure 2 depicts the forces acting on a sailing ship, to which the propeller thrust force must be added in order to consider the case of motorsailing (part wind, part engine propulsion).

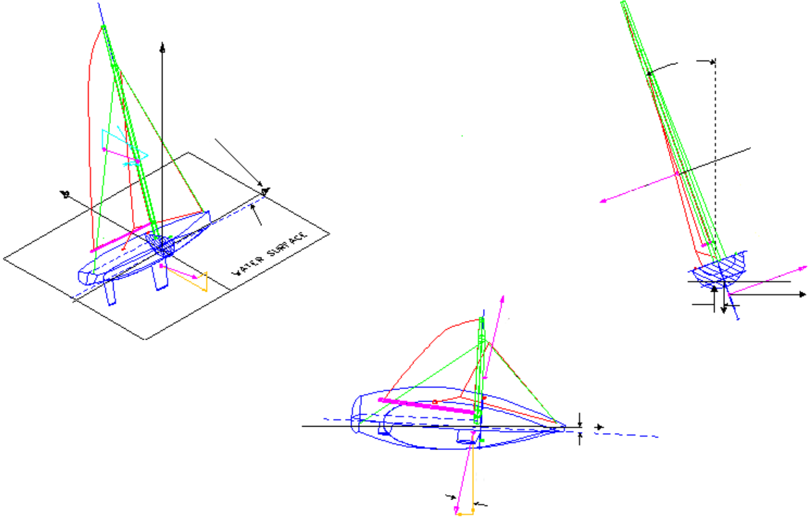


Figure 2:Free body diagram of forces acting on a sailing ship

In addition to models of the machinery and propeller performance, the aerodynamics of the rig and hydrodynamics of the hull and their variation over a wide range of conditions (ship speeds, leeway, heel, wind speed and direction) are required. Inputs to the quantification of aerodynamic and hydrodynamic characteristics can come from a variety of sources (first principles theory, non-dimensional extrapolation, computational fluid dynamics (CFD), tank and tunnel testing etc), each with relative merits in terms of cost (computational and time) and benefit (accuracy).

The source of the data used to describe the approach in this paper is ongoing collaboration between UCL-Energy, B9 and Rolls-Royce. This has provided insight into the concept design, performance analysis and evaluation of a 3,000 dwt Dyna rig assisted merchant ship. Over the course of 2011/2012, the following steps were undertaken by partners in the B9 consortium including Humphreys Yacht Design, Wolfson Unit and UCL:

- specification of a requirement (merchant sailing ship to carry 3,000 tonnes of bulk cargo)
- development of a design for hull and rig (hull lines plan and rig geometry specification)
- construction of scale models for testing in a towing tank
- testing of rig to estimate rig configurations and corresponding lift and drag coefficients over a range of reynolds numbers and wind directions
- testing of the hull over a range of Froude numbers, static angles of heel and yaw, to estimate the hullform's resistance characteristics
- combination of hull and rig measurement data in order to estimate the sailing and motorsailing performance of the concept design

3.1.1 Characterizing the performance of the sailing rig

Data for the aerodynamic performance of a Dyna rig was obtained from the B9 tunnel test in a private communication from Wolfson Unit – described in Grech La Rosa 2012. The wind tunnel tests were carried out for an assembled hull and multi-masted rig, and included the effects of multiple rig interaction (e.g. flow over a downwind rig is modified by the presence of an upwind rig). At each angle of attack of the wind relative to the centre line of the hull (an indicator of the ship's heading relative to the wind direction), the sails are adjusted to achieve an estimate of the balance of total lift and drag that results in the maximum net forward thrust. Figure 3 describes this variation in the lift and drag, expressed as coefficients of the combined rig and hull, between head winds (0 degrees) and stern winds (180 degrees). The performance of the rig is symmetrical about the centreline of the hull hence the representation over just 180 degrees.

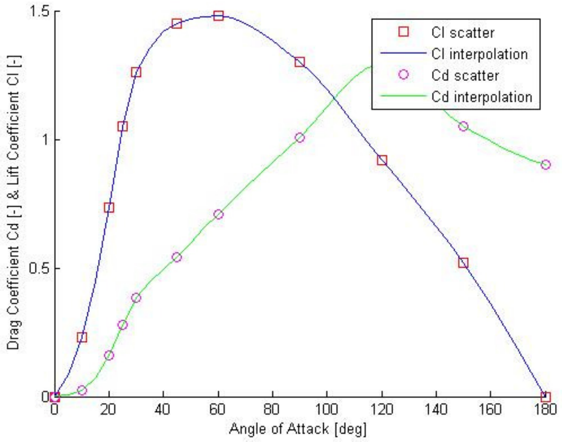


Figure 3: Lift and drag coefficient data, both measured (wind tunnel testing) and interpolated (cubic spline) for use in the analysis methodology

In addition to this information on the gross aerodynamic performance of the rig, it is also necessary to estimate the location of the rig's centre of effort (which can vary with the wind direction) and in the case of a fletter rig, the aerodynamic moment coefficient, C_m, which informs the estimation of the power input required of the flettner (a formula for which can be found in Traut et al. 2014).

Lift and drag coefficients are Reynolds number dependent, and so will vary as a function of wind speed. In particular, the boundary layer behavior (turbulent or laminar boundary layer) can create discrepancies between results obtained at scale and the performance of a rig at full scale. Similarly, CFD can produce erroneous results if the mesh is not applied appropriately or an inappropriate selection or application of a turbulence model. These are some explanations for the wide range across the literature for the estimates of these fundamental parameters e.g. Traut et al. 2014.

3.1.2 Characterising the performance of a hull

Both hydrostatic and hydrodynamic data is required to characterize a wind assisted ship's hull.

Hydrostatic data includes the force couple resisting heeling moments generated by the aerodynamic forces acting on the rig. As a hull heels, the shape of the hull and the relative immersion and emmersion resulting from the asymmetry of the heeled hull cause the centre of buoyancy to move towards the immersing side which creates a righting moment. The relationship is commonly characterised as a GZ curve, a description of how the magnitude of the heeling lever changes with angle of heel. The GZ curve is therefore an important component in calculating the angle of heel that results from the aerodynamic forces acting on the rig. This angle of heel then has implications both to safety (safety of the crew moving about the ship), the stability of the ship (cargo stowage and ultimately, loss of transverse stability and capsize), and the ship's performance (hydrodynamic drag varies as a function of angle of heel).

Hydrodynamic data includes the characterisation of resistance of the the hull in calm water, and the modification of this resistance as a result of the side force and heeling caused by the lateral forces from the rig. The bare hull resistance is obtained from standard analysis techniques (e.g. Holtrop (1984), or resistance calculation tools such as ShipX (www.sintef.no). These tools do not also feature the ability to calculate the additional resistance due to side force and heeling, and so these need to be calculated separately using CFD or towing tank experiments. Alternatively, approximations can be obtained by non-dimensionalising and applying the data measured in the towing tank analysis of a geosim parent hull. The significance of the impact of side force (SF) and heel (Phi) on drag force (resistance) can be seen for a range of conditions in Figure 4.

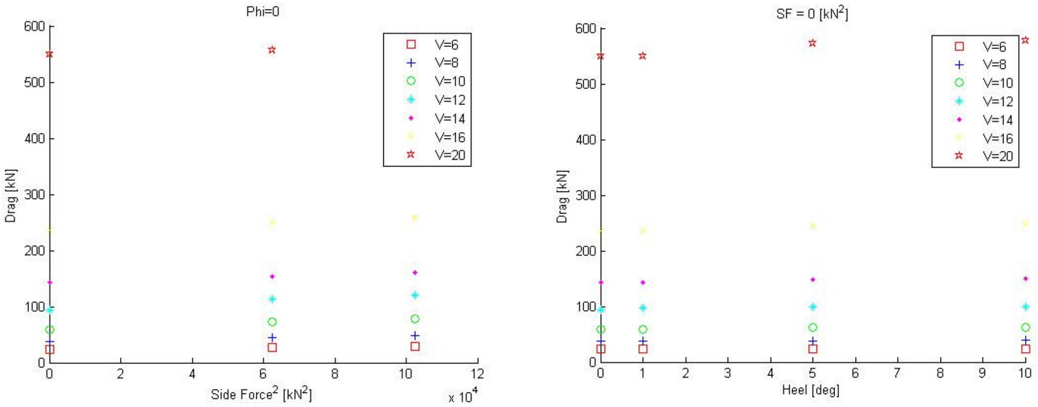


Figure 4: Characterisation of the added resistance due to angle of heel

In addition to modification to ship performance due to wind, there is also the effect of waves that needs to be taken into account, particularly as the wind conditions that generate favourable aerodynamic performance are often coincident with waves heights that can have a significant impact on ship performance (although there may be a lag between the onset of high winds and the fully developed accompanying sea state). The added resistance of a ship in waves (at a given speed, wave height and direction) can be calculated using naval architecture tools (e.g. ShipX) that incorporate theoretical approximations (e.g. Gerritsma and Beukelman (1972)). The resulting added resistance can then be added to the power required to propel a ship at a given speed in given wind conditions (speed and direction). It is an approximation that the wind and wave impacts on ship performance can be superposed, because in practice they are coupled (the angle of heel created when the vessel is sailing modifies the hydrodynamics of the hull form and the added resistance). Similarly forces in the sail might create damping effects that interaction with the ship's motions, dynamics and therefore added resistance. However, it is assumed that the modification to the added resistance due to these coupled effects is negligible relative to the overall resistance impacts of added resistance. In rough conditions (e.g. sea state 7 and above) both the linear theory based analysis techniques for added resistance and the assumption that coupled aero-hydro interactions can be ignored will create departures from actual performance achieved, which may be significant in the evaluation of the overall ship performance depending on the specifics of the ship's voyage.

3.1.3 Characterising the machinery

Combining all of these considerations (the resolved forces from the rig and hull, the added resistance from waves and the power input requirements (for example if a flettner is fitted), the total fuel consumption FC_{me} can be calculated as:

$$FC_{me} = sfc\left(\frac{P_{flett}}{\eta_{conv}} + \frac{(P_{wind} + P_{wave})}{PC\eta_c\eta_{dt}}\right) \quad (1)$$

Where:

- sfc is the specific fuel consumption of the main engine
- P_{flett} is the input power requirement of a flettner (if fitted), and can be calculated
- η_{conv} is the conversion efficiency associated with power generated for the flettner
- P_{wind} is the effective propulsion power required in addition to the thrust from the rig
- P_{wave} is the effective propulsion power to overcome the added resistance in waves
- PC is the propulsion coefficient
- η_c is the condition efficiency of the hull, allowing for hull deterioriation due to fouling
- η_{dt} is the drivetrain efficiency (losses in the shaft/gearbox)

For all rigs, the following assumptions and constants were applied for the calculation of fuel consumption, with the intention to revisit these assumptions in the future as required:

- sfc = 190 g/kWhr (this value represents a typical 4-stroke engine, but will vary depending on machinery used. It can also vary as a function of the engine's operating point %MCR, with increases at low levels of power output, which are important to include if these commonly occur on the voyages analysed)

- η_{conv} = 0.85 (this is a typical value for power assumed to be taken through a power take off device fitted to the shaft, but could vary depending on the power system architecture of the ship)
- PC = 0.7 (this incorporates a number of physical interactions: a propeller's open water efficiency, the relative-rotative efficiency and the thrust deduction factor []. Each of these vary as a function of ship speed and propeller power output, and so whilst a constant value of propulsion coefficient is the simplest to implement, the "off-design" characteristics and any limits to propeller performance need to be captured in cases where significant departures from ship design speed and large wind-assistance power inputs are present)
- η_c = 0.9 (ships in operation attract biofouling from marine organisms on the surface of the hull and propeller. The consequence of the fouling is to increase resistance, which in turn can increase fuel consumption. As a proxy, an estimated 10% penalty is applied in this formulation, but a more sophisticated implementation may be required depending on the Froude number of the hull at design and operating speeds and the relative importance of frictional and wavemaking resistance)
- η_{dt} = 0.975 (in a conventional single shaft propulsion system this represents the mechanical losses, but if a hybrid of full electrical propulsion system is used, this could also include the losses in the mechanical to electrical power conversions stages. This value is an approximate representation for a single-stage gearbox with power take off).

3.1.4 Representing rig, hull and machinery interaction across a range of conditions

The purpose of this stage of the analysis is to resolve these forces and their interaction, for each possible condition in a concept design's performance range. Four independent variables are considered:

- Wind speed and direction
- Wave height and direction
- Ship heading
- Demanded ship speed

The demanded ship speed is achieved by some combination of forward thrust from the rig and the propulsor. The amount of supplementary propulsor thrust being a function of all four independent variables. The analysis of sailing performance is mature in literature and so the details of the method used are derived from standard texts on the subject (see Philpott et al. (1993) and Larsson and Eliasson (2007)), however, some modification of these methods is made to account for the need to represent motorsailing and the added interaction between the aerodynamics, hydrodynamics and propulsor dynamics. The modifications are described in Grech La Rosa (2012).

The core output from the analysis can be seen in Figure 5. The polar plots show examples of the characterisation of propulsor power as a function of heading relative to the wind direction. The rig in this example is a flettner rig. For headings 0 to 30 degrees, the flettner is turned off, as it is not possible to generate useful lift when sailing into the wind. The drag of the flettner is taken into consideration (approximated as a bluff body) in this condition. From 30 degrees, in both cases, the fletter's useful performance increases to a maximum at a wind direction of 90 degrees (consistent with the rig's lift force being most closely aligned with the direction of the ship's velocity). At 90 degree's heading, in the case where the demanded ship speed is 12 knots (LH figure), the entire propulsion power required is provided by the flettner, and so Peff = 0. At the higher demanded ship speed (RH figure), a moderate supplement to the rig's propulsive power is required from the engine.

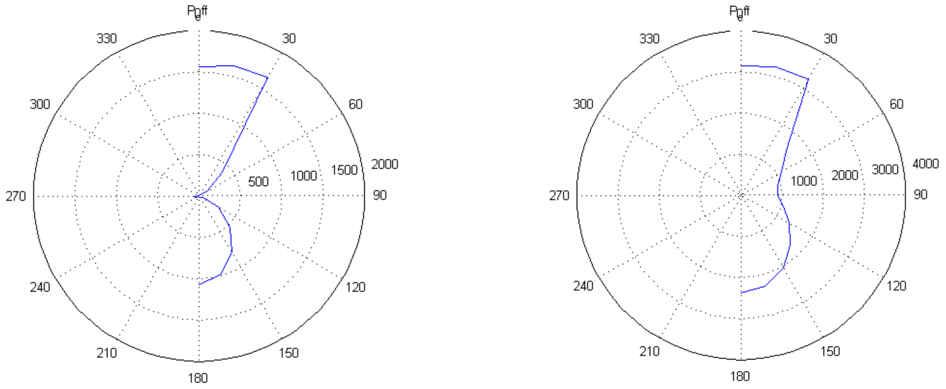
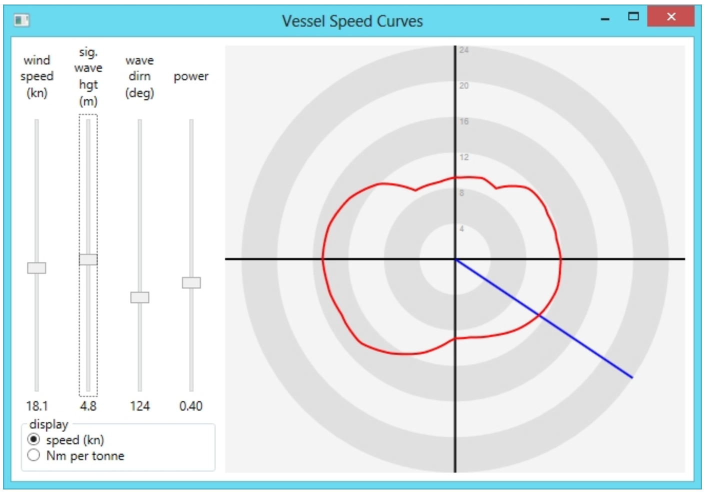


Figure 5: Calculations for an example ship of the effective power (Peff) in kW required from the propulsor in a wind strength of 12knots, in order to achieve a ship speed of 12 knots (Left hand polar) and 14 knots (Right hand polar)

For application in an algorithm describing ship operation, the data shown in Figure 5 needs to be prepared as a set of continuous performance ’curves’ combining the impacts of ship speed of any wind, wave and main propulsion engine combination. Some smoothing of discontinuities in the data is carried out, and Figure 6 demonstrates the ”Vessel Speed Curves” tool that is used to check the coherency of the combined, smoothed data. The tool produces polar plots showing the input data derived ship speed (red line) as a function of a specified wind speed, wave height and direction and propulsion engine power. The wind direction is set as ship heading directly into the wind at the ”12 o’clock” position and ship sailing downwind at ”6 o’clock”. The wave direction in this example is shown relative to that wind heading direction as the blue line. If the wind and wave directions are not aligned or in perfectly opposing directions, the shape of the curves will be asymmetric – as is shown in this example.



wind speed (kn) 18.1
sig. wave hgt (m) 4.8
wave dirn (deg) 124
power 0.40

display
● speed (kn)
○ Nm per tonne

Figure 6: superposition of wind, wave and conventional propulsion

3.2 Analysing performance on a voyage

The statistics of the wind strength and direction vary significantly depending on the area of the oceans of interest, due to the interactions of the continental and polar weather systems and metocean systems (e.g. circulating currents). Figure 7 displays some of the dominant wind patterns globally, although clearly these are variable in both time and space, demonstrating how variable the performance of a wind assisted ship might be as a function of its route.

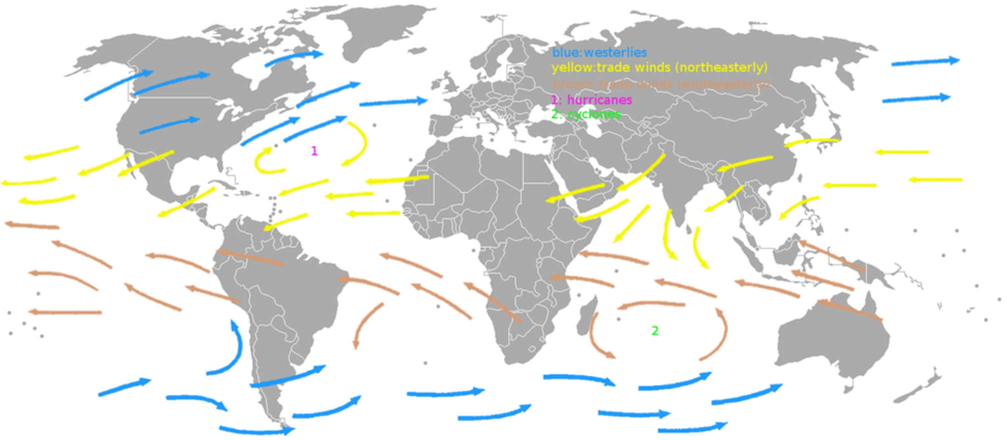


Figure 7: Dominant wind patterns globally (from [wikipedia]

When operating a conventionally powered ship, the preferred route is normally the shortest distance between the origin and the destination (or rhum line). Typically, only if there are significant currents/tides or storms would this be deivated from. However, with wind assisted ships, there can be an advantage of making deviations from the shortest distance between two points in order to ’catch’ the most favourable wind conditions (in terms of both speed and direction). Furthermore, as the performance calculated in Figure 5 shows, using devices which enable the ship to achieve between zero and speeds above the ship’s design speeds depending on the wind conditions, there can be a benefit in varying the ship’s speed along the course of the voyage in order to maximise progress when conditions are favourable and minimise engine use when the conditions are less favourable.

Both the specifics of the wind conditions on a route and the operational characterstics for a given wind assisted ship’s design (the benefits of route deviations and speed deviations) need to be taken into account in order to provide a rigorous and fair assessment of the overall performance benefits of a wind-assisted ship. Therefore, the aim of this element of the analysis process is to produce simulations of a ship’s actual voyage, including course and speed variation, and to calculate for the voyage, its fuel consumption.

The approach uses a voyage optimization algorithm to select the most favourable route and voyage speed profile from an infinite range of candidate routes. The objective function seeks a minimum fuel consumption given a demanded overall duration for the voyage between an origin and a destination location. This assumes that the operator of a ship has perfect foresight of the metocean parameters (wind and wave conditions) over the course of the whole voyage, which is in practice not the case – there is uncertainty in the forecast weather conditions, particularly for long (e.g. greater than 5 day) voyages. If this approximation is considered significant, the same method could be used to represent imperfect foresight, by optimizing performance along a series of waypoints representing stages of the voyage along which the weather forecast was known with low uncertainty.

3.2.1 Area of operation

A coarse differentiation can be applied between the liner trade ships which make regular calls on a predefined route, and the tramp trade ships which are engaged one voyage at a time, and follow more of a ‘random walk’ around the globe Stopford (2009). Although random, depending on the cargo and the size of the ship, certain patterns can be observed. Figure 8 and **Error! Reference source not found.**Figure 9 depict all voyages performed by two size ranges of tankers during a two month period in 2011. They show clear patterns and ‘trade routes’, clearer for the larger ships than the smaller ships. The figures show a subset of data, including Satellite AIS data, that has been analysed in order to estimate a range of parameters for ships trading the globe Smith et al. (2013a).

The data enables a degree of route ‘genericisation’ to be achieved and average trading patterns identified for a number of ship types. Whilst these trade patterns may vary as transport demand evolves over time, they can be viewed as representative or indicative. Alternatively, if a ship is being designed for a specific trade route and therefore the area of the voyages is known in advance, this data can be used to specify area of operation.

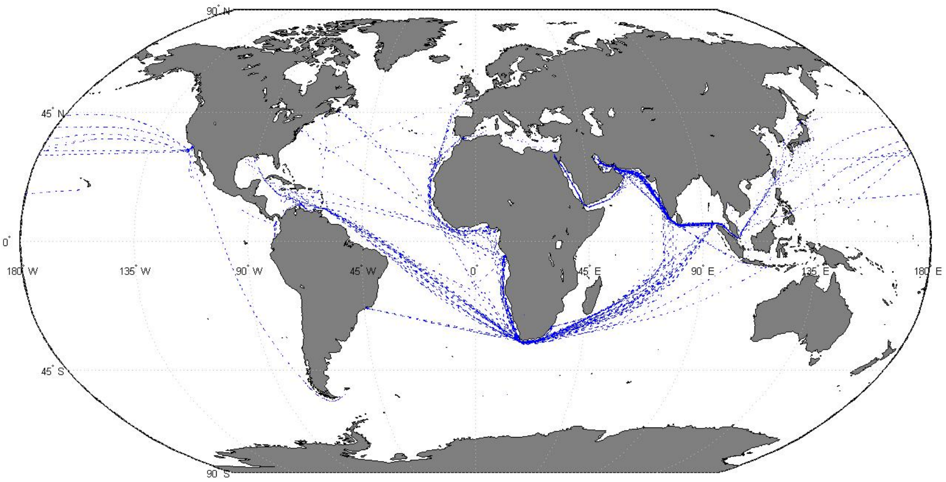


Figure 8: Ship movements for tankers > 200,000 tonnes deadweight

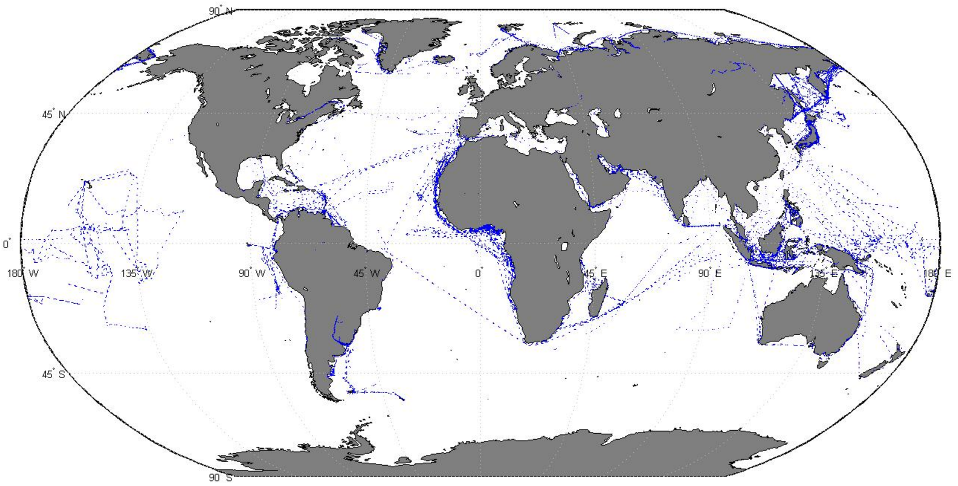


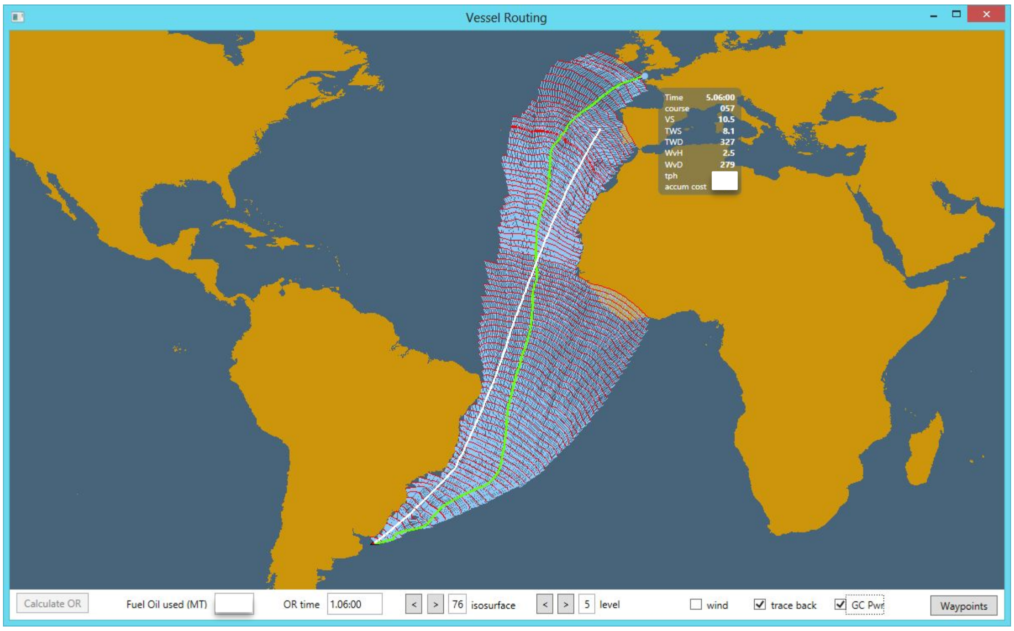
Figure 9: Ship movements for tankers < 10,000 tonnes deadweight

3.2.2 Weather specific to the area of operation

Data files are taken from NOAA archives describing the ocean wind and wave metocean parameters during the period 1980 to 2009. The data is sourced both from observations (satellite, wave buoys metocean facilities on fixed platforms) and from models (hindcast). The resolution of the data is 3 hourly (temporally) and at least 1 degree x 1 degree (spatially). Weather can vary year on year due to long-term variability from metocean influences such as El Nino, as well as day-by-day. The long time-period of the weather data available for analysis ensures that a number of random samples can be used for the analysis from across three decades, controlling for this variability and prepared as specific input files. The voyage simulation can then be undertaken for as many simulations is required in order to produce a mean performance a characterization of the performance's standard deviation which are statistically significant.

3.2.3 Example voyage

Example results from the calculation are shown in Figure 10. The voyage is a simulation of the route from Argentina to UK in a 10,000dwt chemical tanker with flettner rotors. The white line is the great circle route (shortest distance) between the origin and destination, taking into account the land masses. The green line is the route calculated for this ship in the specific wind and wave conditions experienced during the simulated voyage that would result in the lowest fuel consumption. There is a significant deviation between the two lines demonstrating the importance of using simulations of a voyage (the differential between the fuel consumption when free to vary route or whilst constrained to the Great Circle vary, but are typically of the range 5-10%).



Time 5.06:00
course 057
VS 10.5
TWS 8.1
TWD 327
WvH 2.5
WvD 279
tph
accum cost

Fuel Oil used (MT)
OR time 1.06:00
< > 76 isosurface
< > 5 level
☐ wind
☑ trace back
☑ GC Pwr

Figure 10: route simulation results for the voyage between Buenos Aries and the Western Approaches

Due to the variability in the wind conditions, the simulation needs to be repeated many times to provide a convergence on a statistically representative trend for the voyage's specifics. This is carried out both in different seasons (to reflect seasonal metocean variability) and for different average voyage speeds. The results ffrom a number of simulations carried out in samples of metocean data for winters between 1980 and 2009 in the direction Argentina to UK and the direction UK to Argentina can be seen in Figure 11. The results are for three rig types, flettner, dyna and wingsail with different assumptions used to characterize each rig (total sail area, profile and aerodynamic characteristics etc) specific to the installation. These specifics prevent a straight-forward comparison of the devices so the differences between the rigs should not be viewed as a performance ranking. In the case of the flettner, the power consumption of the device is included in the total calculation. For confidentiality reasons, the fuel consumption data is anonymised, however a linear scale is used, so the magnitude differences and the significance of the variability can be assessed.

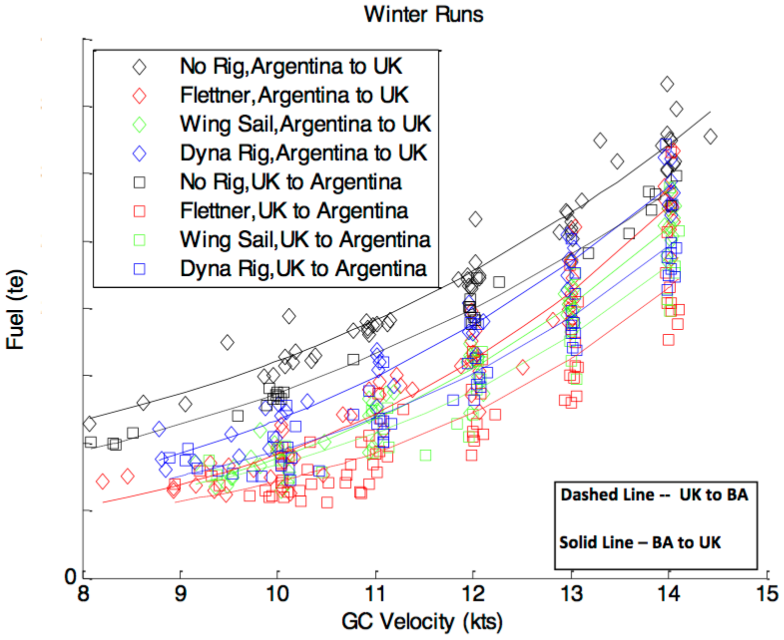


Figure 11: route simulation results for the voyage between Buenos Aries and the Western Approaches, fuel consumption

In any characterization of a benefit (in this instance fuel saving), it is important to reference to a credible baseline. For this reason, as well as undertaking the simulation for the ship with a number of different rigs, the simulation is carried out for the same hullform in the same metocean conditions (including wind and wave resistance effects) but without any rigs (the 'no rig' data included in Figure 11). Taking the fuel savings as the difference in the fuel consumption with and without the rig for these equivalent simulations, Figure 12 presents the results as a percentage benefit.

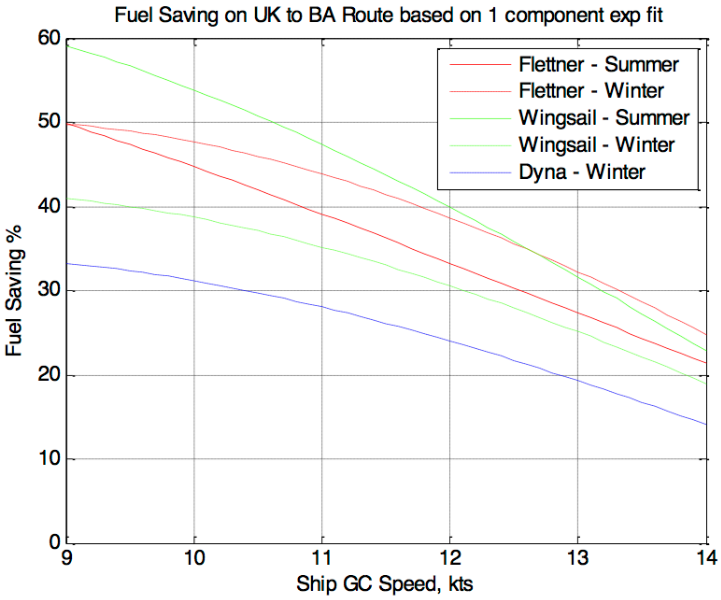


Figure 12: route simulation results presented as % fuel savings relative to a 'no rig' voyage simulation

These figures demonstrate the significance of ship speed in determining the % of fuel saving, which is immediately apparent when looking at polar analyses of a ship's performance for different demanded speeds (Figure 5), but hard to quantify as a 'voyage' impact until route analysis and simulation has been undertaken. Figure 12 also demonstrates the significance of seasonality (e.g. winter vs summer) in terms of the savings.

3.3 Analysing the commercial viability of wind-assistance

The principle benefits of wind assistance technologies are that they reduce the fuel consumption, which in turn reduces fuel costs. However, they also represent an increase in the capital cost of a ship and operational cost (e.g. crew costs, maintenance costs, consumables etc). As demonstrated in Figure 12, savings a re function of ship speed, and given that ship speed influences both fuel consumption (with or without wind) and revenue, can modify the profitability of ship operation in a number of ways. For an assessment of commercial viability all of these components need to be fairly assessed and considered.

3.3.1 Standalone

A number of models can be used for investment appraisal purposes. One commonly used example is NPV (net present value), incorporating estimations of the cost of the technology C_0, the revenue R of the ship owner/operator, the costs C of the ship owner/operator, a time period for the investment T and a cost of capital d.

$$NPV = C_0 - \frac{\sum_{t=0}^{T}(R-C)}{(1+d)^T} \tag{2}$$

The simplist implementation of the investment appraisal is for an owner/operator who would pay both the costs associated with installation and owner ship of the wind assistance technology, and also the but can be refined to suit specific charter arrangements (e.g. short term time charter, long term time charter, bareboat or voyage charter), see Smith et al. 2013b. Components that need to be considered are:

- marine fuel prices (HFO/MDO) and forecast, if required carbon prices

- revenues (earnings), volatility and trends, particularly the relationship between revenue and ship speed
- capital and operating costs for the wind assistance technology
- discount rates/cost of capital
- time period over which the investment is expected to create a return

Projection of commercial viability across a range of scenarios (e.g. future fuel price, regulation, transport demand growth etc) can be used to test the robustness of the investment case, and identify the market conditions in which the technology will or will not be commercially viable.

3.3.2 Relative to competitor technologies

NPV analysis is useful for estimating the benefit for conventional technology. However, with regulation and fuel prices stimulating technology development in a range of fields (energy efficient hydrodynamic devices, engine and propulsor developments, alternative fuels and machinery), it can also be useful to evaluate the commercial viability of wind assistance technology relative to a number of different future technologies, which will compete with wind assistance for commercial viability. This also enables the conditions in which there are positive interactions (other technologies benefit or enable wind assistance's commercial viability) and negative interactions to be evaluated.

The outputs from all the analysis stages listed above can be incorporated in the analysis tool GloTraM, which enables scenarios of future fuel price and regulation to be applied to the shipping industry along with a suite of technical and operational ship specifications. The profit maximizing ship specification in a given year, which could include a combination of technologies, is identified by the model and used in calculations of fleet growth and turnover. This enables both market penetration and market size to be evaluated, as well as the emissions reduction potential of wind assistance to be considered across the shipping industry.

4 Concluding remarks

Wind assistance technologies present an exciting opportunity for cost savings and low carbon propulsion solutions for the shipping industry. They also present an analysis challenge that requires rigorous analysis to be under taken in a number of disciplines including (at least): physics, naval architecture, marine engineering, meteorology, logistics, trade, statistics and economics. This paper presents a multi-step process that is coherent through its transfer of the key parameters from one analysis stage to the next. The method allows consideration of the impact on performance of the variability in the wind strength and direction specific to trade routes associated with a given ship type, and the inclusion of the likely ship operational response (in terms of ship speed and voyage planning) in order to maximize the fuel cost savings for a given voyage.

The results demonstrate that, for the example ship and trade route considered (a 10,000 dwt chemical tanker operating a liner trade from Argentina to the UK (and back)), when incorporating all of the key interactions that determine performance, fuel savings can be achieved in the range 10-50%. A more specific fuel saving can be estimated from the identification of the actual ship speed and a selection of a particular rig configuration.

Due to confidentiality constraints, no results are presented for the cost-benefit of the rigs analysed, and therefore the commercial viability. However, two approaches that can be applied in order to assess commercial viability are identified and their inputs discussed.

5 Acknowledgments

This paper combines work carried out by four individuals, in a number of different research programmes and activities, including Low Carbon Shipping – A Systems Approach, a project funeded by RCUK Energy and four industry partners (Rolls Royce, Shell, Lloyd's Register and BMT), and the Energy Technology Institute's Heavy Duty Vehicle transport programme.

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