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Speed Optimisation for Liquefied Natural Gas Carriers: A Techno-Economic Model

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Abstract
The effect of a ship's speed on its propulsion power requirements is of importance primarily due to their well-known cubic relationship. The ship's speed also plays a fundamental role in its profitability; higher speeds are attractive to shipping's customers but costly to the owner, both in capex and opex. Revenue and costs are dynamic and largely influenced by freight rates and bunker prices which fluctuate according to market conditions. This is further complicated in the LNG carrier sector where chemical and thermodynamic interactions contribute to the rate of LNG boil-off in the tanks. This affects revenue either directly at the LNG import terminal, or indirectly through on board re-liquefaction plant power requirements. This paper investigates the 'optimum speed' problem in the LNG carrier fleet from a technical perspective that describes boil off, fuel consumption and CO_2 emissions as a function of vessel speed, and from an economic angle whereby revenue and costs are evaluated with respect to speed by means of a profit optimisation and cost minimisation function.

Keywords: LNG carrier, speed optimisation, efficiency, emissions

1. Introduction
Historically, LNG carriers have been installed with steam turbines which required low maintenance and have the fuel flexibility to use either boil-off LNG or HFO. With the advent of on board re-liquefaction plants, an improvement in reliability of 2-stroke diesel engines and less boil off gas due to more effective tank insulation, more options for LNG carrier propulsion power have materialised. Figure 1 summarises the changing face of the LNG carrier fleet which is moving away from steam turbine propulsion to medium-speed dual-fuel diesel-electric (DFDE) and slow speed direct drive diesel engines.

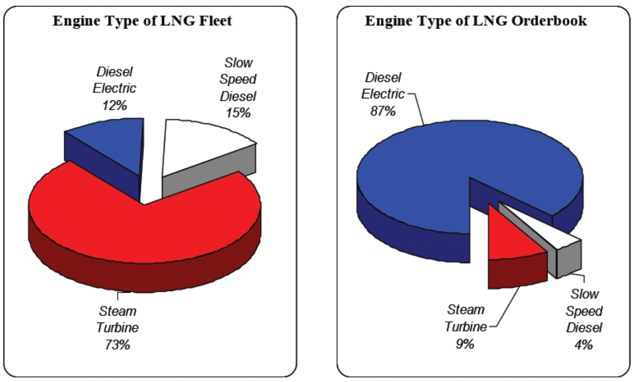

Figure 1: Engine configurations employed in LNG fleet and on order
Source: Clarksons Fleet Data, Limited (2011)

The traditional optimum speed question with regards to emissions and profit has largely been applied to the container and oil tanker fleet, for example, Ronen (1982), (Lindstad et al.2011) and Corbett, Wang et al. (2009) have investigated this issue. Ronen separates the loaded and ballast legs due to the nature of tramp and industrial shipping operations and maximizes daily profit or minimises per leg costs to each, respectively. This is from the perspective of the ship owner and alternate costs are included which amount to the market charter rate. Lindstad et. al follow a cost minimisation approach and expand their model to include sea state and emissions of the shipbuilding process to study the effect of speed on the direct emissions and costs of maritime transport, they assume a constant transport volume is maintained by representative roro and container vessels and expand this to the world fleet. Corbett et. al use a profit maximization function and extrapolate to an annual profit from a known service frequency to meet demand. Two scenarios demonstrate the optimum speed if a) the service frequency is fixed or b) if the vessel size increases to meet demand.

The optimum speed decision matrix is complicated for the LNG carrier fleet given the economic ramifications when the LNG cargo also becomes the fuel for propulsion; the revenue is reduced as fuel consumption is increased (due to faster vessel speed), simultaneously the voyage costs apportioned to HFO bunker fuel are reduced. The relative price of LNG to HFO at import and export terminals is of consequence and there is an important speed-time trade off. This is further affected by the rate of boil-off of the LNG within the cargo tanks which affects revenue either directly or indirectly through on board re-liquefaction plant power requirements. This rate is dynamic and involves multiple variables; vessel speed, initial gas composition and quantity, tank material insulation characteristics and geometry, sloshing, ambient temperature (George G. Dimopoulos and Frangopoulos 2008). The rate of boil off during the ballast voyage impacts the percentage heel to remain in the tank and this effects the shipper's profit either directly through the revenue received at the import terminal or indirectly through flash boil off that may occur at the export terminal. The ballast voyage optimum speed has therefore to be considered separately. This paper describes the model developed to provide insight into this problem, followed by the presentation of results from two vessels representative of dual fuel diesel electric and 2-stroke direct drive LNG carriers.

2. Model Description and Assumptions

The described model (Figure 2) investigates the relationship between speed, fuel consumption and revenue/costs in LNG carriers; vessel speed is the independent variable. This model assumes the ship is operating long term between the same two ports a specified distance apart. The optimum speed is found on a per day basis by discretizing the vessel speed range and iterating over this range to yield the optimum speed to maximise profit for the loaded voyage and the optimum speed on a per voyage basis to minimise costs for the ballast leg. Total round trip time and the number of trips per year, the annual profit, costs and emissions are then extrapolated.

2.1. Estimating Detailed Ship Characteristics

From the ship's geometrical parameters the resistance is calculated using the Holtrop and Mennen (1982) approach, the resistance is assumed to be described wholly by the wave, correlation, bulbous bow and frictional resistances. The bulbous bow transverse sectional area is calculated as a function of the ships beam and draught and the ship's block coefficient is estimated according to the regression analysis presented by Chadzynski (2010) in which dwt is the independent variable. The total ship's resistance gives rise to the effective (towing) power required at each vessel speed. For the purposes of the level of complexity it is wished to achieve in this model, the loaded and ballast trips are assumed to incur the same resistance although in reality this is not the case.

In the first iteration the model calculates the optimum propeller pitch at the design vessel speed for propeller efficiency using the regression analysis of the open water characteristics of the Wageningen B-Series propellers as investigated by Oosterveld and Oossanen (1975). The thrust required at the vessel's design speed and maximum engine rpm and the propeller blade cavitation limitations for the blade area ratio are both limitations. A pitch/diameter ratio limit is fixed at 0.4 to 1.5. The diameter is fixed at 0.76 x Draught for large conventional carriers and 8.6m for Q-flex vessels.

Once the optimum pitch is determined at the vessel design speed (all LNG carriers have fixed pitch propellers) the propeller efficiency, η_o over the range of vessel speeds is obtained in order to construct the propeller curve on the shaft rpm-power diagram. The minimum propeller shaft power required to deliver the thrust corresponding to each vessel speed is evaluated over a range of advance coefficient values, again using the open water characteristics of the Wageningen propellers. The propeller efficiency and corresponding shaft power is therefore found for each vessel speed, see Figure 4.

The vessel design speed and the engine specifications are fixed but a wide range of operational speeds are considered, when the investigated operational speed exceeds the design speed considerably the results are merely to explore sensitivities and understand the overall trends since, in reality, a greatly increased design speed would require redesign of the whole ship.

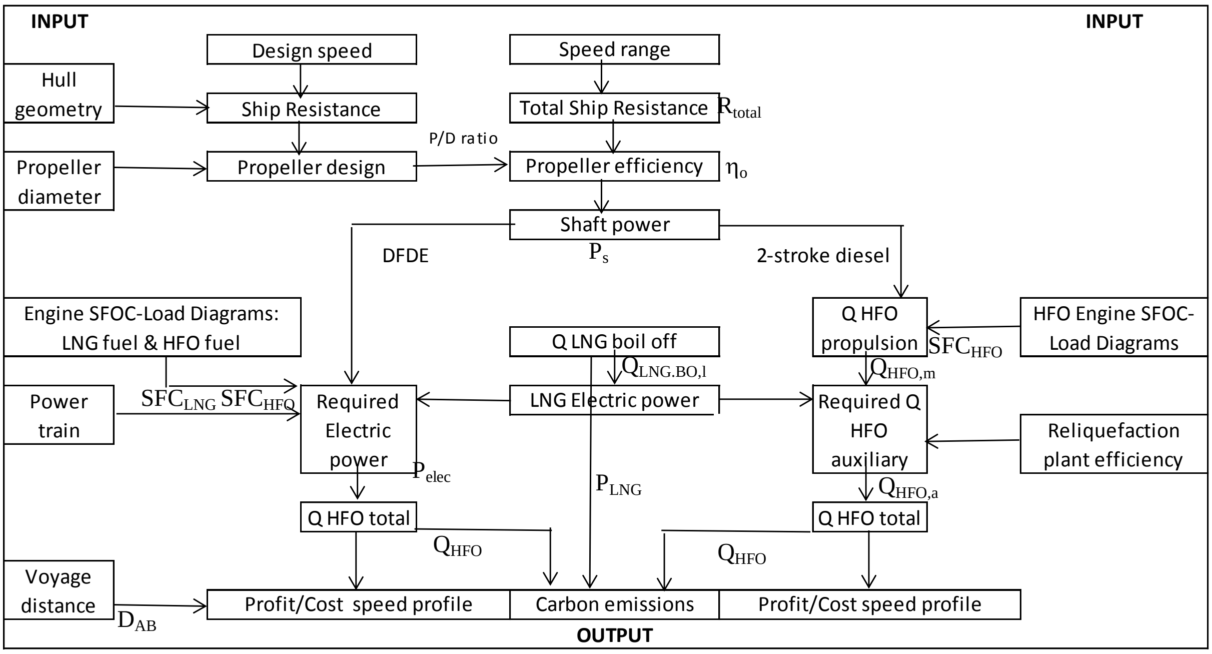

Figure 2: Mode Description

Nomenclature and Assumed Values

R_{total}	Total ship resistance, N	P_{elec}	Electric power required for propulsion, kW $P_{elec} = P_s / 0.908$
P_e	Effective (towing) power $P_e = R_{total}.V$,kW	ρ_{CH4}	Density of methane = 470kg/m^3 (the boil off gas is assumed to be 100% methane)
P/D	Pitch:Diameter ratio	MCR	Engine MCR
D	Diameter, m	LCV_{CH4}	lower calorific value of methane = 50 000kJ/kg
η_s	Shaft efficiency, 0.98	D_{ab}	Distance export-import terminal=5500km (=D_{ba})
η_h	Hull efficiency, from thrust and wake	V_l, V_b	Vessel speed loaded/ballast voyage
η_r	Relative-rotative efficiency	SFC_{LNG}	Specific fuel consumption, kJ/kWh
η_o	Propeller open water efficiency	SFC_{HFO}	Specific fuel consumption, kg/kWh
P_s	Shaft power, $P_s = P_e$ / ($\eta_r\ \eta_o\ \eta_s\ \eta_h$,kW	P_{LNG}	Power from boil off, DFDE, kW
$T_{S,l}$	Time at sea, loaded, days =$D_{AB}/24.V_l$	$Q_{LNG,BO,l}$	Quantity LNG boiled off, m^3/leg
$Q_{LNG,l}$	Quantity LNG loaded at export , m^3	BOR_L	Boil off rate loaded, 0.12%/day[2]
H_v	Heel volume, 5% $Q_{LNG,l}$	BOR_b	Boil off rate ballast, 0.06%/day
$Q_{HFO(m/a)}$	Quantity of HFO, (main/aux) t/leg	N_{HFO}	Number of HFO engines
η_{gs}	Genset electric conversion efficiency=96%	P_{RLP}	Re-liquefaction plant specific power consumption = 0.920 kW/kg/h (D&T 2003)
$c_{f,lng}$	Carbon factor = 0.75 for LNG	c_{CO2}	Molecular weight CO_2 = 44kg/mol
$c_{f,hfo}$	Carbon factor = 0.8645 for HFO	c_C	Molecular weight C = 12kg/mol
$E_{l/b}$	Emissions loaded/ballast, kg/leg		

[2]Méndez Díaz and Maté Maté (2003)

2.2. Dual Fuel Diesel Electric Engines (DFDE)

For the DFDE engine the electric power to meet the shaft power required is formed considering assumed efficiencies of the components ; generator 0.974, switchboard 0.999, transformer 0.985, frequency converter 0.986, electric motor 0.98, gear box 0.98 (Harsema-Mensonides (2007)).

In the first instance all available boil off gas is used for the vessel's propulsion and the remainder of the required electric power is provided by HFO. It is assumed that boil off gas is first burnt in the main engines and make-up HFO is burnt in the auxiliary engine or the auxiliary plus a main engine as required. In the model the engines do not operate at loads of less than 30% for practical reasons due to potential engine damage (turbocharger fouling/soot build up). If the engine loading is found to be less than 30% it is assumed that the excess gas is burnt in a gas combustion unit and the HFO makes up the resulting extra required power. Therefore the HFO and LNG fuel quantity calculation begins at the available energy from the boil off which is converted to power generated on a per trip basis, P_{LNG} (kW) according to:

$$P_{LNG} = Q_{LNG,BO,l}\frac{\rho_{CH_4} LCV_{CH_4}}{SFC_{LNG}\left(\frac{D_{AB}}{V_l}\right)} \qquad (1)$$

This is an iterative process; initially the engine loading is assumed to be 100% and the power from boil off gas is split equally among the minimum possible number of available engines known to be on board. Given the resultant power per engine a new engine load is established and the power from LNG recalculated by interpolation between data points.

$$Q_{LNG,BO,l} = Q_{LNG,l}\left(1 - \left(1 - \left(\frac{BOR_l}{24}\right)\right)^{\frac{D_{AB}}{V_l}}\right) \qquad (1)$$

For the current required level of complexity, boil off rate is taken to be constant throughout the voyage and constant whether the LNG cargo is forced to vaporize to match the propulsion requirements (FBOG) or if natural boil off gas only is used in the engine (NBOG). The boil off is assumed to be comprised of 100% CH_4. A dynamic model for LNG evaporation involving greater detail by George G. Dimopoulos and Frangopoulos (2008) has shown variations in boil off rates both during the voyage and when the LNG is vaporized forcibly. The remaining electric power required is provided by HFO, the correct quantity of which, Q_{HFO} (tons/leg) is calculated as follows:

$$Q_{HFO} = \frac{N_{HFO} . SFC_{HFO} EL . D_{AB} . P_{max}}{V_l . 1E6} \qquad (2)$$

A similar procedure is undertaken for the ballast leg with vessel speed, V_b directly replacing V_l as the independent variable subject to optimisation. $Q_{LNG,l}$ is then the heel volume left in the tanks after discharging and BOR_l becomes BOR_b. In port the power for propulsion is zero and replaced instead by the cargo pump operations, fixed at 4 000kW and 7 500kW for loading and unloading, respectively. This is assumed to be met by natural boil off for unloading and HFO while loading. Since hotel load is included a nominal SFC is used. The MDO used as a pilot fuel (~1%) is not included in the model.

2.3. 2-Stroke Direct Drive Engines

The Clarksons World Fleet Register was used to assess the make and model of the main engines installed on each ship therefore the maximum power output of the engine is known and the specific fuel consumption can be found by interpolating between points for engine load as a % of the MCR and SFC (g/kWh) data provided by the manufacturer. The quantity of HFO required for propulsion, $Q_{HFO,m}$ is then obtained:

$$Q_{HFO,m} = T_{S,l} . SFC_{HFO} . EL . MCR . 24/1x10^6 \qquad (3)$$

For engine power requirements at the higher operational speeds it is assumed that the SFC is the same as for when EL equals 100% and that engine size increases according to the power requirements. In Q-flex and Q-max ships 2-stroke, direct drive, HFO-fuelled engines provide the propulsion power while the boil off natural gas is re-liquefied and returned to the cargo tanks, auxiliary power demands are met by means of diesel-electric gensets. The auxiliary hotel load is assumed to be negligible however the on board re-liquefaction plants required for handling the boil off gas when it is not utilised in a dual fuel engine for propulsion are intense power consumers and therefore worthy of inclusion. The calculation for the re-liquefaction plant power consumption is as follows:

$$Q_{HFO,a} = \frac{1}{\eta_{gs}} SFOC_{HFO} . Q_{LNG,BO,l} \frac{D_{AB}}{1E6 . V_l} \rho_{CH_4} \quad (4)$$

$$Q_{LNG,BO,l} = \frac{Q_{LNG,L}}{24 . T_{S,l}} \left(1 - \left(1 - \frac{BOR_L}{24}\right)^{\frac{D_{AB}}{V_L}}\right) P_{RLP} \quad (5)$$

2.4. Emission calculation

This is calculated on a per voyage basis once the quantity of HFO is fixed according to the optimum speed calculation for maximum profit. Emissions from LNG is defined by the total boil off.

$$E_L = 1x10^3 . (c_{CO2} / c_C) . (Q_{HFO,B,L} . c_{f,hfo} + Q_{LNG,BO,L} . c_{f,lng}) \quad (7)$$

2.5. Profit and Costs

The economic model considers the ship owner and the charterer as a single entity in order to gain a holistic perspective of interactions between parameters. For the loaded leg the profit maximisation function is established (π_L):

π_L = Revenue – Costs ($/day)

$$\pi_L = \left\{\frac{(Q_{LNG,D} . CIF_{LNG} - Q_{LNG,L} . FOB_{LNG}) 24 V_L}{D_{AB}}\right\} - \{C_O + C_B + C_I + C_S\} \quad (8)$$

CIF_{LNG}: Price of LNG at the import terminal =$320/ton, (2001-2011 average) (BP 2012)
FOB_{LNG}: Price of LNG at loading terminal = $250/ton
FOB_{HFO}: Bunker fuel price of HFO =$575/ton (2001-2011 average, bunkerworld.com)
$Q_{LNG,L/D}$: Quantity of LNG loaded/delivered at the export/import terminal, (tons) (section 2.2.1)
C_O = Operating Costs, $12 000/day for all ships types[1], this covers the cost of crew, stores, insurance, repairs and maintenance, and lubrication oil, the variation between ships is assumed to be negligible.
D_{AB} (D_{BA}): Distance between ports A and B (or, B and A for the ballast leg, here $D_{AB} = D_{BA}$)

$$C_B = \frac{Q_{HFO} FOB_{HFO} 24 V_L}{D_{AB}} \quad \text{Bunker costs (\$/day)} \quad (9)$$

$$C_I = \frac{CIF_{LNG} Q_{LNG,D} \rho CH_4 ir}{(365) 1E3.} \quad \text{Inventory Costs (\$/day)} \quad (10)$$

$$C_S = \frac{Capex\left(\frac{4}{5}\right) CC}{365(1-(1+CC)^{-10})} \quad \text{Ship capital costs (\$/day)} \quad (11)$$

Capex is the cost of the ship which is bought at a fixed 4:1 debt to equity ratio and cc is the weighted average for the cost of capital; 7.8%[2]. ir is the interest rate fixed at 10%.

[1] http://www.lngoneworld.com/lngv1.nsf/Main.html?OpenPage&p=2M5x0Cxx1x25x
[2] http://www.petroleum-economist.com/Article/2801286/LNG-shipping-economics-on-the-rebound.html

For the ballast leg, the costs are found on a per voyage basis:

$$C_b = \frac{(C_O + C_B + C_I + C_S)D_{BA}}{24.V_b} + C_A \tag{12}$$

C_A is the 'opportunity cost' which is incurred for everyday extra that the ballast voyage takes as a result of slow steaming, 'extra days' being relative to the optimum loaded speed previously calculated.

$$C_A = \pi_L\left(\frac{D_{BA}}{24.V_b} - \frac{D_{BA}}{24.V_l}\right) \tag{13}$$

The per leg cost is minimized with respect to speed (V_b) using the same speed range discretization procedure as for the loaded leg. To avoid double accounting, the opportunity cost is omitted when the costs are extrapolated annually.

For port operations, the costs are attributed only to ship capital costs and bunker costs which are evaluated for 48hours; 2 days are spent in port per trip (1day for loading, 1 day for unloading). The quantity of HFO that is attributed to bunker costs is determined from the cargo pump power consumption. Port and passage fees are fixed for each trip.

3. Input Data and Representative Vessels

The two vessels investigated and other fixed input parameters are summarised in Table 1

Main power machinery	Dual fuel diesel electric	2-Stroke direct drive HFO
Capacity, m^3	157 610	217 000
Dwt, tons	84 455	109 503
Length between perpendiculars, m	275	302
Draught, m	12.2	12
Beam, m	44.2	50
Design speed, knots	19.5	19.5
Main engine, kW	2 x 11 707	2 x 19620
Auxiliary engine, kW	2 x 8 780	15 200

Table 1: Representative ship geometrical parameters and engine specifications

4. Results

The towing power and propeller efficiency for the range of vessel speeds for the dual fuel diesel electric ship are displayed in Figure 3 and Figure 4 to graphically represent the model outputs.

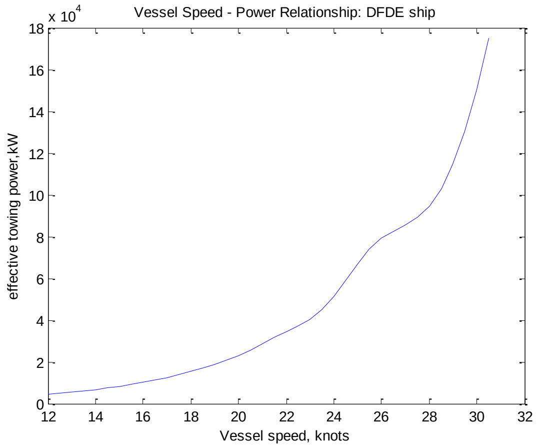

Figure 3

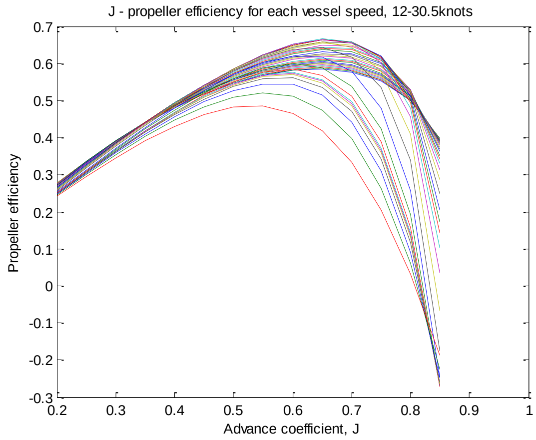

Figure 4

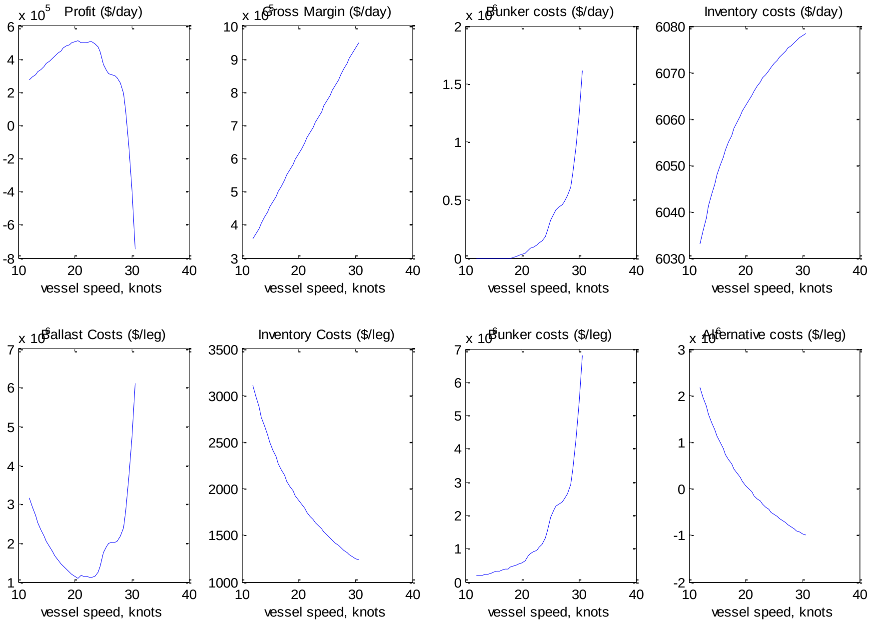

Figure 5: Top: Profit per day curves. Bottom: Cost per voyage curves, dual fuel diesel electric, large conventional ships

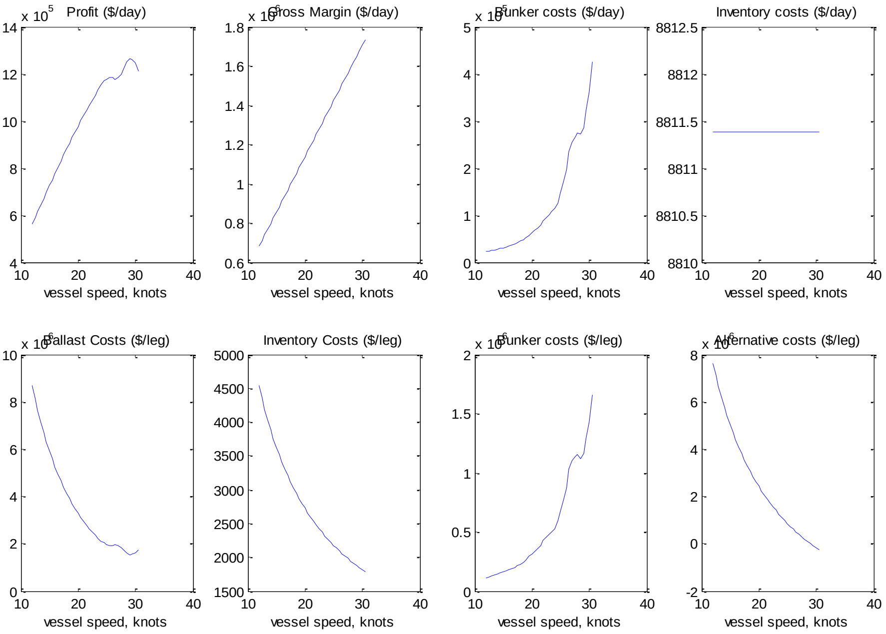

Figure 6: Top: Profit per day curves. Bottom: Cost per voyage curves, 2-stroke diesel, Q-flex ships

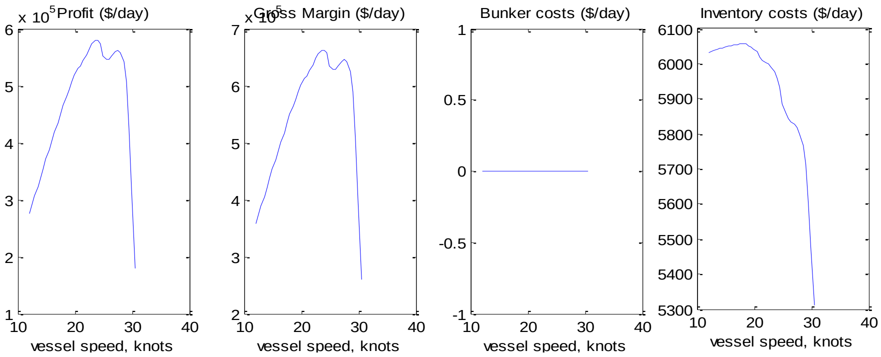

Figure 7 Top: Profit per day curves. DFDE, *forced* boil off

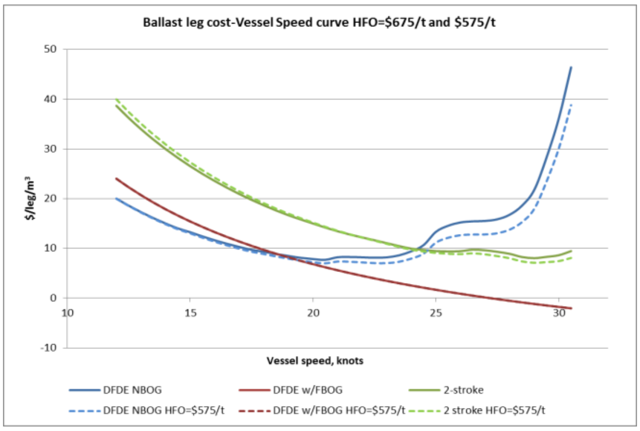

Figure 8

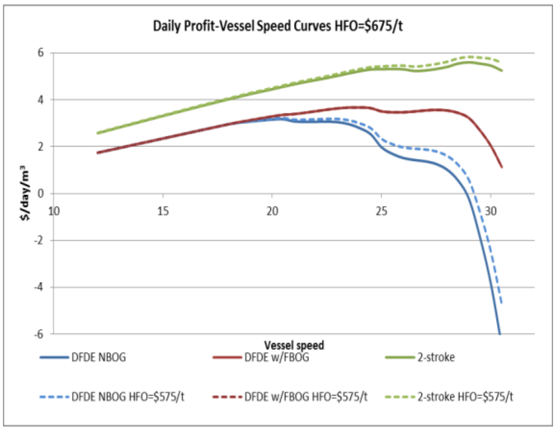

Figure 9

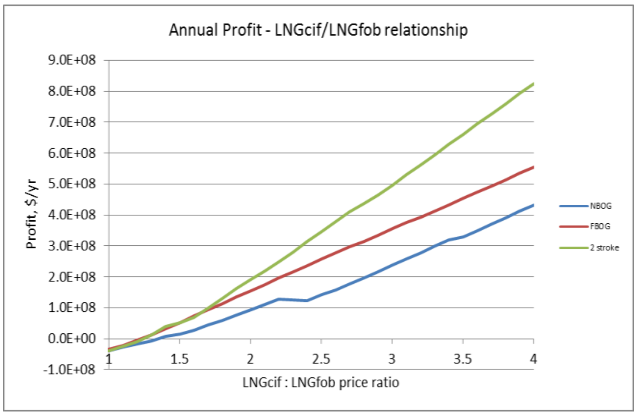

Figure 10

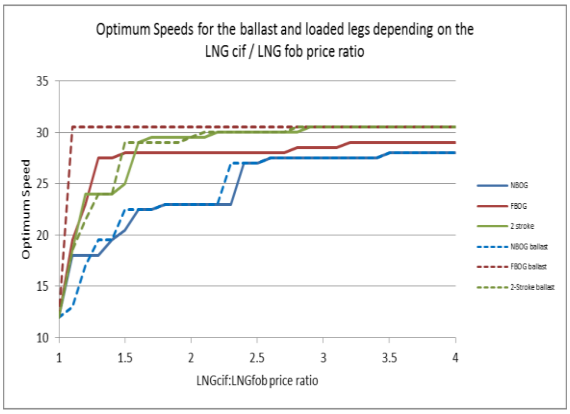

Figure 11

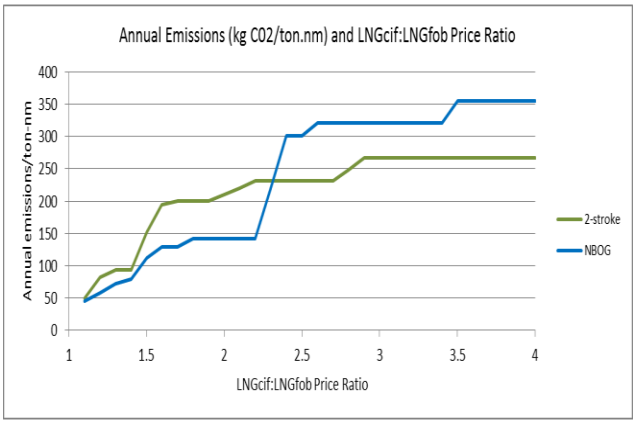

Figure 12

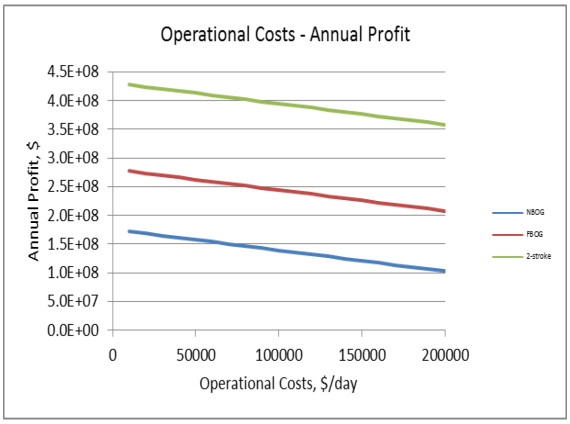

Figure 13

Figure 5 and Figure 6 graphically represent the profit and cost relationships with vessel speed for the DFDE and Q-flex ships respectively. Figure 7 represents the profit-speed relationship when the LNG cargo is forced to vaporize to match the propulsion requirements (FBOG). Figure 8 and Figure 9 show the profit/cost curves normalised by the vessel's capacity, DFDE and Q-flex displayed on the same axis. The resultant difference when the LNG is forced to boil off to meet the propulsion power requirements is shown and the effect of increasing HFO price from $575/t to $675/t. Figure 10, Figure 11 and Figure 12 show the relationship between the CIF_{LNG}:FOB_{LNG} price ratio and annual profit, optimum speed (loaded and ballast legs) and emissions (kg CO_2/t.nm), respectively. The HFO price is fixed at $575/t and the FOB_{LNG} was also fixed ($90/t) but the same results would have been shown if a more general price ratio was chosen. Figure 13 is to represent the 'operational costs' as a proxy for a voyage charter. Ship capital and operating costs were combined and increased in steps of $10 000 per day from $10 000 to $200 000/day in order to simulate the effect of an increasing charter rate in situations of high vessel utilization when demand exceeds supply.

5. Discussion

The effective towing power/speed relationship shown in Figure 3 shows the prismatic and main 'humps' of the wave making resistance owing to the interactions between bow and stern wave systems. In reality the naval architect would aim for the ships service speed and length to be such that it was operating in a hollow on the speed-power curve rather than a hump. The effect of the wave resistance as detailed in Figure 3 is shown to propagate through the model and is represented in the bunker costs and ultimately as a double peak in the final profit-vessel speed curve.

Figure 5 shows the resultant economic-speed characteristics for the dual fuel diesel engine (NBOG). At speeds lower than the optimum, the gross margin drives the increase in profit with vessel speed until the speed is such that the boil off gas from the LNG is insufficient for propulsion. The cost of the supplementary HFO and its approximately cubic relationship with vessel speed rapidly causes the daily profit reduction that is seen above 20.5knots. The boil off rate of the LNG therefore appears to be an important parameter in the vessel's optimum speed selection (all other things being equal). Increasing vessel speed causes the inventory cost increase as a result of less LNG boiled off and therefore larger cargo volume, this is of the order of $10/day and its effect is therefore negligible. Cost curves show the alternative daily costs work to reduce costs at slower speeds before the effect of bunker costs force an optimum as vessel speed continues to increase. For the 2-stroke, Q-flex ship the trends are similar (Figure 6), in general the optimum speed is faster since the larger capacity of these ships cause gross profit margin gains to predominate over increased bunker fuel prices for a wider range of vessel speeds.

Figure 7 gives a picture of the loaded leg profits when the LNG is forced to boil off to meet the required propulsion power for the vessel's speed. The bunker costs (attributable to HFO) are therefore nil and the peak profit is forced by the gross margin which decreases as the cargo is burnt as fuel. In general when the LNG is forced to boil off then optimum vessel speeds are faster because there are no HFO bunker cost increases introduced that have the effect of reducing the vessel speed.

The leg cost and daily profit are aligned for each vessel in Figure 8 and Figure 9 highlighting that the forced boil off scenario exhibits a higher daily profit and lower ballast leg cost at the higher end of the vessel speed spectrum owing to their isolation from bunker fuel costs when natural boil off gas is insufficient for propulsion demand. An increased fuel price (dashed to solid line) increases the ballast leg costs and reduces daily profit across the board except when boil off gas is forced. This demonstrates the resilience of dual fuel engines to HFO price fluctuations.

Given the sensitivity of the optimum speed to gross margin the CIF_{LNG}:FOB_{LNG} price ratio was explored (Figure 10, Figure 11 and Figure 12). Forcing boil off gas and its ability to increase annual profit is particularly significant (relative to the natural boil off gas scenario) when the price ratio increases. This is perhaps not intuitive since forcing boil off gas reduces the LNG quantity delivered and therefore the potential gross margin, but materializes due to the higher optimum speed that is obtained when HFO is not used for bunker fuel; the CIF_{LNG} price is still less than that of HFO. Figure 11 shows clearly the variation in optimum speeds over the range of LNG CIF:FOB price ratio (and also demonstrates that the optimum speed for the ballast leg is not always the same as for the loaded leg) which leaves a question for the designer as to what is the appropriate LNG carrier design speed? The FOB_{LNG} price is significant for the ship owner who may be able to pass on savings (in the form of reduced charter rates) to the charterer if the optimum design speed for efficiency is known, however it is also ambiguous especially for a ship owner operating within short term voyage contracts between various ports. Added to this is the value of any environmental premium that LNG has; this CO_2 emission reduction is shown in Figure 12 which is scaled to allow for the 2-stroke/DFDE ship comparison. The dual fuel engine using NBOG at low price ratio has lower emissions however as the optimum speeds increase as a result of the increased ratio then dual fuel engines require more supplementary HFO. The 2-stroke engines then become preferable in terms of annual CO_2 emissions on a per ton-nm basis. So, the environmental premium may also be difficult to quantify, and variable, depending on the time a ship spends in ECAs for example. A gas producer chartering vessels under long term contracts may determine FOB_{LNG} from the cost of production plus re-liquefaction. Even so, the CIF_{LNG} price will be vulnerable to fluctuations (the effect of seasonal demand cycles and the recent demand increases in Japan are obvious examples) and highly dependent on the geographical location in which the ship is operating.

An increase in fixed costs, such as operating costs attributable to the ship owner (ship capital and operating costs) causes an upwards shift in the profit curve without changing the optimum speed. There is a consequent increase in the alternative daily cost/voyage and increase in overall ballast costs as shown by Figure 13.

6. Conclusions

A speed optimization model for LNG carriers is described in this paper which considers a ship's geometric parameters, propeller characteristics and installed engine specifications to determine the power requirements over a range of speeds. The effect of various economic input parameters on the optimum speed for profit maximization and cost minimization are explored, in particular the gross margin from LNG revenue and bunker costs are explored. This is with respect to dual fuel diesel electric and 2-stroke HFO engines where the advantages of dual fuel engines and their resilience to HFO fluctuations are seen. When the LNG cargo is forced to vaporize to meet the demands of propulsion then its ability to increase profits (relative to using natural boil off plus HFO) at the higher end of the LNG CIF:FOB price ratio spectrum is demonstrated. There follows a discussion on the difficulties of the correct ship speed to design for, particularly for ship owners' operating vessels on short term contracts owing to the range of optimum speeds that are found as gas prices fluctuate. Discussed also are the problems of correctly valuing LNG, particularly at the export terminal but also the CIF value at import owing to regional and seasonal fluctuations.

7. Acknowledgements

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