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The economic impact of fuel consumption uncertainty for tankers

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Abstract

In this thesis, we evaluate how uncertainties in ship operation, particularly fuel consumption, impact speed optimization and profit maximization. By courtesy of SKS Tankers AS, three years of noon reports and the ship management history of ten sister ships are analysed. This data allows us to forecast and compare how factors such as ship speed, weather forces and hull fouling uncertainty impact fuel oil consumption.

We find that a proper assessment of the hull fouling condition is critical to avoid bias in other important variables' coefficients, yet finding a good proxy based on observable variables is found very difficult. Even though weather data in our noon report is limited, we show how wind, wave and swells drive up fuel oil consumption by specifying a detailed empirical model based on noon report data and assumptions based on naval architecture theory.

Empirical results show that optimal speed is very sensitive to bunker price rather than freight when subject to various weather and hull fouling conditions. In an era of expensive bunker price, the difference between theoretical optimal speed in idealized conditions and our empirical model is large.

To the best of our knowledge, the economic impact of uncertainty in weather and hull fouling conditions has not been empirically estimated on the basis of detailed noon report data. In this regard, we hope this thesis is useful as the first attempt to analyse how various factors in real-life ship operation change the decision making for profit maximization and speed optimization.

Keywords: Fuel Oil Consumption, Uncertainty in ship operation, Weather impact, Hull Fouling, Noon Report, Profit Maximization, Speed Optimization, Aframax Tanker

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Donggon Baik, Bergen Norway, June 2016

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1. Introduction

In the maritime industry, fuel oil consumption is frequently highlighted as an important issue for both economic and environmental reasons. The fuel cost is the decisive factor for freight rates and voyage costs, especially in an era of high oil prices. Most shipbuilding contracts include a fuel consumption level, and the contracted fuel consumption should be guaranteed and confirmed by a sea trial. However, the contracted/guaranteed fuel consumption level does not exactly represent real-life fuel consumption, even for mint condition ships.

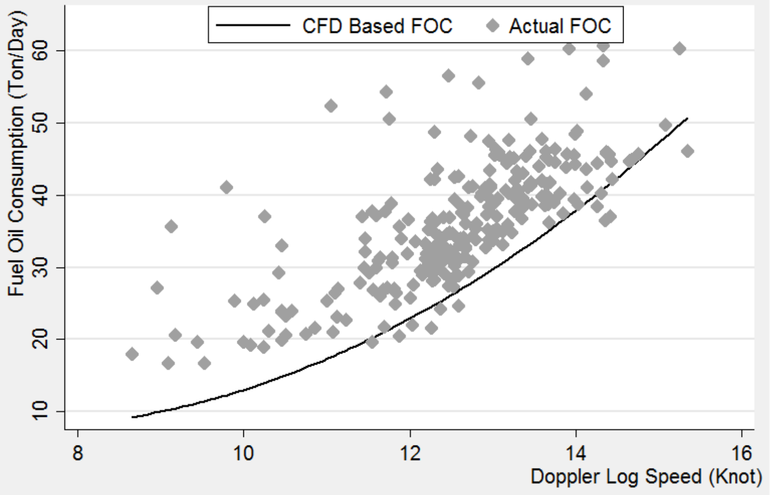

Figure 1, Theoretical (CFD based) and Actual fuel consumption at draft 12.5 m, SKS D-Series

This thesis evaluates the uncertainty in fuel oil consumption for tankers using data from Bergen-based ship owner SKS Tankers AS. The average age of a SKS D-Series Aframax[1] tanker is just around five years, but Figure 1 shows that, in service speed range, almost all of fuel consumption observations lie higher than the theoretical fuel oil consumption suggested by Computational Fluid Dynamic (CFD) models. There are multiple reasons for this gap. Once we exclude measurement errors of draft and speed, and assuming that the ship’s propulsion condition is well maintained and like new, then only ship resistance would matter. Heavy waves and ferocious wind generate considerable resistance and force a ship to burn more fuel to maintain the same speed. Moreover, hull condition of a ship just launched at sea is smooth and clean, but, as idling times get longer, slime or shells attach to the ship’s underwater area, and this adds more resistance. In certain areas where the ocean current is strong, a ship cannot but

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[1] AFRA of Aframax, the meaning of Average Freight Rate Assessment first used in 1954 by Shell, Oil to standardise shipping contract terms, represents 80,000 ~ 120,000 DWT tankers which mostly carry product oil or crude oil. The breadth of these vessels are about 41 ~ 44 meters and length overall is around 250 meters. Thanks to her wide breadth, the designed draught is relatively low, 15 meters deep, hence she can enter many of relatively shallow ports around the world.

use the rudder again and again, and this creates more resistance and higher fuel consumption. The weather, hull roughness and ocean current are continuously changing in uncertain real-life conditions. Thus, estimating the fuel consumption of a specific vessel based only on theory (CFD models) would not be aligned with actual results.

Until today, most papers about fuel oil consumption do not contain weather, ocean current and exact draft information and such omitted variables could bias the coefficients in the fuel oil consumption analysis.

Environmental compliance is increasingly important to ship owners. From July 2011, the Marine Environment Protection Committee (MEPC) of the IMO[2] mandates Energy Efficiency Design Index (EEDI) to be applied for new ships and Ship Energy Efficiency Management Plan (SEEMP) to be applied to all ships in service.[3] For the year 2012, total shipping emissions were approximately 938 million tonnes CO_2, accounting for 3.1% of global emission (IMO 2014). Heavy Fuel Oil (HFO) contains 3,114kg CO_2/tonne, and a higher consumption of this fuel would emit more green-house gases (GHG). The GHG emissions per tonne-mile are roughly proportional to the square of vessel speed, hence a speed increase would result in a rapid emission increase (IMO 2014). Therefore, environmental regulators have a keen interest in estimating accurate fuel consumption to study how pollution level could be effectively minimized. These CO_2 emission could grow by between 50% and 250% depending on the future economic growth and energy developments (IMO 2014). In the long term, managing GHG emission in the shipping industry is key to prevent increasing air pollution. The new IMO secretary-general Lim Ki-tack states that the IMO needs to adopt greater statistical analysis of safety and environmental issues (TradeWinds, 2015). In this regard, the empirical analysis of fuel oil consumption would assist in verifying the efficacy of rules and regulations for GHG emission control. Ultimately, it will help the shipping industry to become greener.

This thesis has been written in co-operation with Norwegian tanker owner SKS Tankers AS. Since 2012, SKS has accumulated credible noon reports of ten sister ships that form the SKS-D class. The noon report is sent to the fleet manager’s office at noon of each ship’s longitudinal position. It normally includes the ship’s position, sailing distance, RPM and speed. Additionally,

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[2] International Maritime Organization - United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships.

[3] EEDI and SEEMP regulations entered into force on 1st January 2013.

the SKS noon reports contain a detailed weather information, draft and trim. These identical ten sister ships were all delivered during a relatively short period, and this allows us to assume the same mechanical condition and little difference among sister ships.

Structure

The remainder of this thesis is organized as follows: In Chapter 2 – Theory and Literature Review, we discuss ship propulsion factors involved in fuel oil consumption changes. Next, we review how weather and hull fouling resistance are interacting with fuel oil consumption, and find possible uncertainties in our data. Lastly, we review how fuel oil consumption is related with optimum speed in the laden and ballast leg. In Chapter 3 – The Model, we introduce how we fit and add explanatory variables grounded on theory to properly reflect fuel oil consumption variation. We categorize explanatory variables as ship propulsion, weather, hull fouling condition, and dry-docking, and each transformation method is reviewed. In Chapter 4 – Data, we truncate the raw data to enhance its quality, and further adjustment is done based on theory. We check data quality using the final empirical model, and discuss observed methodological issues. In Chapter 5 – Analysis & Discussion, we perform methodological tests again with aggregated data of all sister ships, and more observations are filtered out based on test results to generate a final model. The empirical results section exemplifies an application of ship operating condition, and discusses values from examples. Using predicted fuel oil consumption values, the speed optimization section finds the functional relationship of each different ship operating condition in order to substitute the theoretical exponent in the gross profit formula. The limitation section looks through drawbacks. In Chapter 6 – Conclusion, we briefly summarize our findings.

2. Theory and Literature Review

2.1 Ship Propulsion

A ship's propulsion power is generated by a main engine, most of them are slow speed crosshead type two stroke diesel engines so as to maximize power output and minimize fuel consumption and maintenance work. As fuel oil explodes in a cylinder, a piston reciprocates. Then the crank shaft turns a vertical motion to rotational motion and the connected propeller shaft and blades rotates. The rotating propeller blades push a ship forward, and the ship sails. Since fuel oil consumption (FOC) corresponds directly with power, the most accurate way to measure FOC is to install a shaft power meter right on the propulsion shaft and monitor power output (ABS, 2015)[4]. However, shaft power is unobservable from noon reports, and the ultimate goal of this thesis is not to keep the most fuel efficient shaft power. In noon reports, only revolution per minute (RPM) and speed measures are related with ship propulsion. Intuitively, ship's RPM and speed would be highly correlated, and this implies high level of multi-collinearity and would result in opposite coefficient sign among these variables. In order to construct a proper model, we need to theoretically comprehend how theses variables interact together.

2.1.1 Shaft Power

The shaft power is the energy generated by a main engine to rotate a propeller shaft which is connected to propeller blades, though some of it is lost due to mechanical resistance. Therefore, propulsion power can be a reference to see how much shaft power is necessary to maintain a target speed and would be useful to monitor fuel consumption. Figure 2 depicts dramatic changes in propulsion power with increasing speed. This is mostly due to hull resistance, which will be discussed in the later section. In Figure 2, the design speed is 15 knots and a relatively gradual increase of propulsion power is needed until reaching to the design speed. However, the ship requires a doubling of propulsion power so as to speed up by 17.6 knots from 15 knots.

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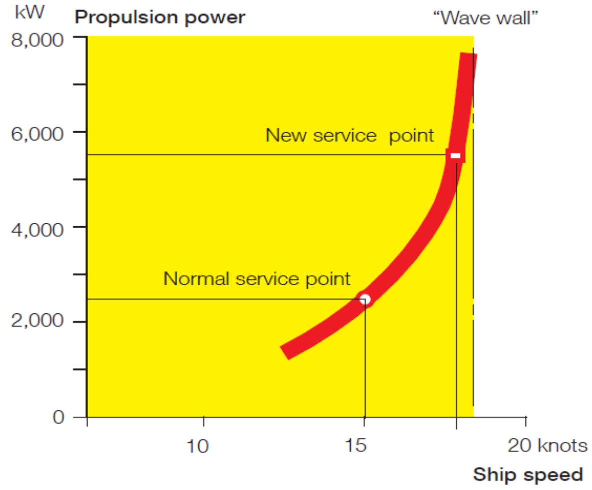
[4] American Bureau of Shipping (ABS) is a classification society, with a mission to promote the security of life, property and the natural environment, primarily through the development and verification of standards for the design, construction and operational maintenance of marine-related facilities. (Wikipedia)

A further increase of the propulsion power lifts only a minor ship speed, as most of the extra power will be offset by resistance (MAN B&W, 2013).

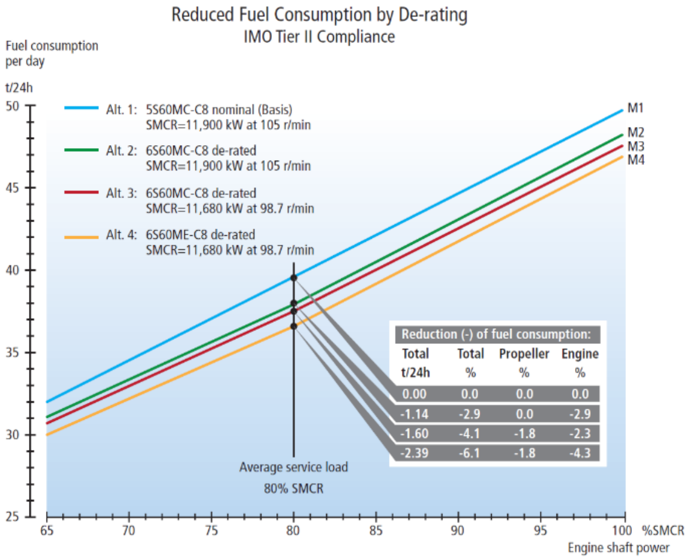


Power and speed relationship for a 600 TEU container ship

Figure 2, (MAN B&W, 2013)

2.1.2 Fuel Oil Consumption

The fuel oil consumption (FOC) has almost a linear relationship with engine shaft power. From the shaft power and speed graph of Figure 2, the exponential growth of FOC with increasing speed can be assumed. By applying the admiralty coefficient, the FOC formula can be derived. The admiralty coefficient A is a constant valid for a given hull design and is useful when we simply want to approximate FOC for a given draught and propulsion power.



Reduction (-) of fuel consumption:

Total t/24h	Total %	Propeller %	Engine %
0.00	0.0	0.0	0.0
-1.14	-2.9	0.0	-2.9
-1.60	-4.1	-1.8	-2.3
-2.39	-6.1	-1.8	-4.3

Figure 3, (ABS, 2015)

Let P: propulsion power

V: speed

D_{des}: displacement,

$$\mathrm{A} = \frac{D^{\frac{2}{3}} \times V^3}{P} = \frac{D_{des}^{\frac{2}{3}} \times V_{des}^3}{P_{des}} \tag{1.}$$

For equal propulsion power $\mathrm{P} = P_{des}$, we get the ship speed (MAN B&W, 2013) as:

$$\mathrm{V} = V_{des} \times (\frac{D_{des}}{D})^{\frac{2}{9}} \tag{2.}$$

For equal ship speed $\mathrm{V} = V_{des}$ we get the propulsion power as:

$$\mathrm{P} = P_{des} \times (\tfrac{D_{des}}{D})^{\frac{2}{3}} \tag{3.}$$

Given that fuel consumption is proportional to propulsion power, P, we must have that:

$$\mathrm{F} = F_{des} \times (\frac{D_{des}}{D})^{\frac{2}{3}} = \frac{\left(\frac{D_{des}^{\frac{2}{3}}}{D}\right)^{\frac{2}{3}} \times {V_{des}}^3}{A} \tag{4.}$$

Based on the above FOC formula, FOC has a non-linear relationship with displacement and speed when the admiralty coefficient is constant. Specifically, FOC is proportional to the speed V to the power of three and to the displacement D to the power of two-third. However, this relationship does not hold exactly for all ships as each hull design has its distinctive function which is estimated by making a scaled hull and testing it in a towing tank. The ship builder provides a FOC formula grounded on the experiment result. Since the displacement is not observable from noon reports, the draft can be a good proxy variable.

$$\text{Displacement} = \text{L} \times \text{B} \times d_1 \times \rho_1 \qquad 5.$$

Where L: length of a ship

B: beam of a ship

d_1: draft of ship

ρ_1: salinity

Assuming that the salinity is constant, the displacement is proportional to draft. However, this is true only for box shapes (Lester, 2013). In reality, Aframax tanker hull design has a slightly different ratio between a draft and displacement.

· **Fuel Efficiency and Specific Fuel Oil Consumption (SFOC)**

Fuel efficiency is the efficiency of a process that converts fuel into kinetic energy or work. The fuel efficiency of marine engine can be measured by the engine's specific fuel oil consumption (SFOC), which indicates the amount of fuel used to generate one horsepower for a period of one hour (Wärtsilä, 2015). The SFOC curve of SKS D-Series main engine (MAN B&W 6S70ME-C) is;

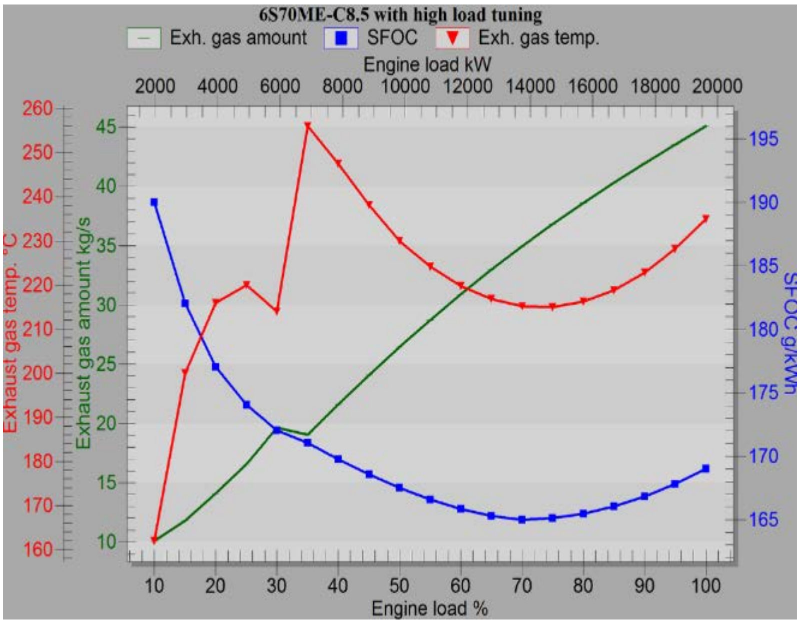


Figure 4, (MAN Disel & Turbo, 2013)

The SFOC curve goes down as the engine load increases from minimum load to 70% engine load, and it then increases until reaching the maximum continuous revolution (MCR). When it comes to the most fuel-efficient propulsion power, operating the main engine around 70% load would be the best. But even though the ship's service speed and hull form is optimized at 70% engine load, the complex relationship between speed, propulsion power, weather and SFOC cannot ensure fuel efficient ship operation. Moreover, engines are ideally designed near to the IMO NOx limit, hence a significant fuel saving pushes their engines outside of emission limits (Motor Ship, 2011).

In this section, the complex relationship between shaft power, speed and fuel consumption has been reviewed. The FOC model needs to reflect how speed and weather conditions interact with fuel consumption. Theoretically, FOC is proportional to the speed V to the power of three and proportional to the displacement to the power of two thirds depending on the hull shape. In noon reports, the reported draft can be a good proxy on behalf of unobservable displacement.

2.2 Ship Resistance

When a motor ship sails at a constant velocity, the resistance or drag[5] is equal to the propulsion power. If not, she would gain or lose speed until the propulsion power and drag is same. Ship's resistance is typically influenced by her speed, displacement and hull design. The total resistance can be categorized into three groups; frictional (viscous), residual (wave making) and air resistance.

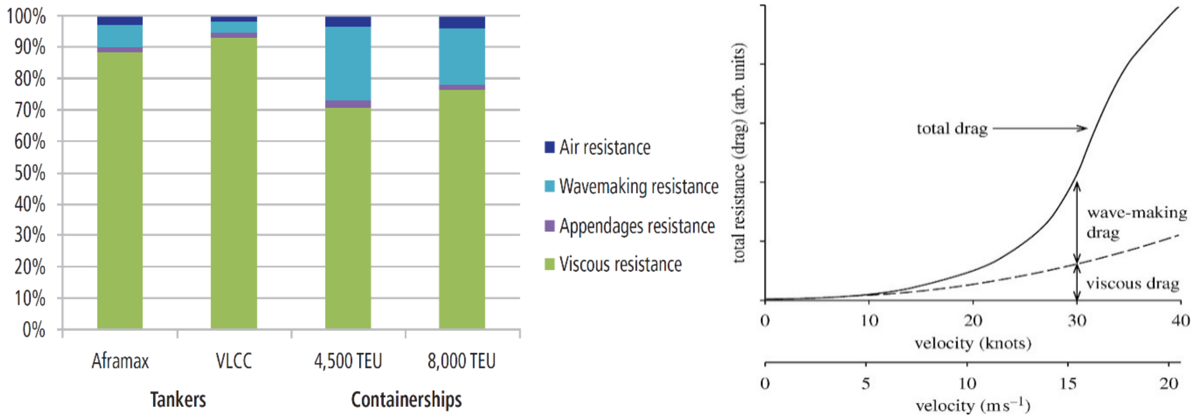


Figure 5, (ABS, 2015) & (Wood, 2010)

Their relative importance differs according to ship types and speed ranges. Referring to Figure 5, an Aframax tanker has a big proportion of viscous (frictional) resistance because the deck structure is simpler, and the underwater area is larger than a container ship. Figure 5 also shows that viscous drag accounts for most of total resistance until 17 knots, and that the wave-making

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[5] Drag is a force acting opposite to the relative motion of any object moving with respect to a surrounding fluid (Wikipedia).

resistance grows dramatically after 20 knots. Viewing that the service speed of a tanker is normally less than 18 knots, tankers have little air and wave resistance and large frictional resistance.

2.2.1 Frictional Resistance

. Hull Resistance

The frictional resistance is arising from the viscosity of water. Hence, the wetted hull surface is subject to frictional resistance on the wetted hull surface. Among all the sources of resistance, it comprises almost 90% of total resistance for Aframax tankers. According to International Towing Tank Conference (ITTC)[6], the frictional resistance can be written as;

$$R_F = \frac{1}{2} \times \rho \times S \times V_S^2 \times C_F \qquad 6.$$

Where

R_F: frictional resistance
ρ: water density
S: wetted surface area
V_S: speed
C_F: coefficient of frictional resistance, dimensionless

The frictional resistance is largely a function of the wetted surface area and the square of speed for a given hull or block coefficient[7] and slight enough density variations to ignore.

. Hull Fouling Resistance

The frictional resistance can differ despite the same wetted displacement and sailing speed because of hull fouling. Hull fouling means that the surface of the submerged hull is

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[6] The ITTC is a voluntary association of worldwide organizations that have the responsibility for the prediction of the hydrodynamic performance of ships and marine installations based on the results of physical and numerical experiments.

[7] The ratio between the displacement volume and the volume of a box with dimensions. $C_b = \frac{Volume}{L_{WL} \times B_{WL} \times D}$

contaminated by marine growth such as slime layers, sea weed and barnacles. Such marine growth is more active in the tropical regions.

Figure 6, World map of hull fouling risky area. (Hellio, 2009)

Ships are delivered with a very low surface roughness at about 75um, but the classification society ABS states that this value can increase to 250um by the time the ships enter dry dock. This means that the resistance can increas by 17%, driving FOC up by 3 to 4% or even 10% compare to the first launching at sea (fathom, 2013). The total resistance increase owing to the hull fouling resistance can differ depending on ship speed as the below graph shows.

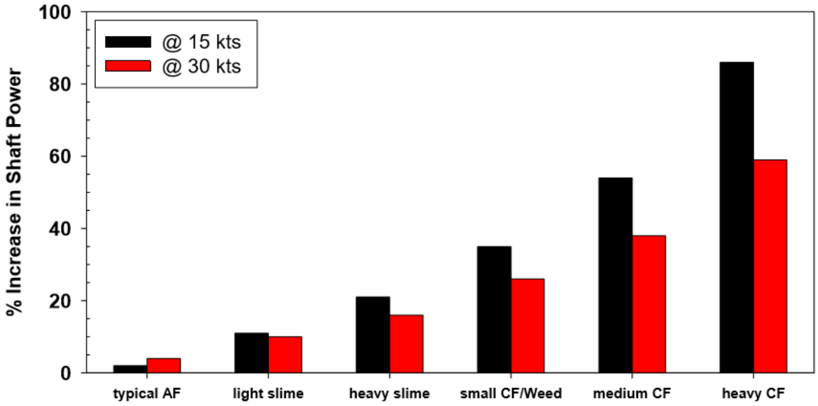

Figure 7, Increase in required shaft power for the FFG-7 class frigate (Schultz, 2007)

As the fouling condition deteriorates, the resulting shaft power increase at 15 knots is higher than at 30 knots, and this indicates that the hull fouling resistance is more significant at slower speeds. This is due to the less relative contribution of frictional resistance compared to the residual resistance at high speed (Schultz, 2007).

. Trim

Trim is a difference between the aft and forward draft and is adjusted by ballast water management. Trim can be divided to three categories: trim by the stern, trim by the head and even keel. Trim by the stern is that the draft aft is deeper than forward, and trim by the head is the opposite. At even keel the draft forward and aft is the same, and this condition is usually the basis for calculating how much cargo is on board. The slope of a hull changes the flow of water below a hull and propulsion direction from astern. In ballast condition, a ship usually keeps trim by the stern so as to minimize hull resistance and to optimize propulsion efficiency while a ship keeps even keel condition in laden passage. However, it has recently been claimed that the trim by the head condition can save fuel by 3% for containers and tankers (McKinsey, 2015).

. Salinity difference

Previously, we assumed that the density of sea water is invariable. However, the salinity of several ocean area is clearly less than for the tropical areas. This difference can make the SKS D-Series tanker submerges up to 28 cm deeper (Appendix A). Such a difference in draft can be significant for changes in the wetted area, and the resulting increase in frictional resistance. The wetted surface area equation for the present tankers is (Kristensen, 2013).

$$S = 0.99 \times (\frac{Displacement}{Draught} + 1.9 \times L_{wl} \times Draught) \qquad 7.$$

Where L_{wl}: the length of the water line

The Red Sea and the Mediterranean Sea have particularly high salinity level while the Black Sea and Baltic Sea is low level. Therefore, a ship in the Black and Baltic Sea is expected to consume more fuel oil than in other areas, and a ship in the Mediterranean and Red Sea would burn less fuel oil thanks to shallower draft.

. Implications

In order to capture variations in frictional resistance and the resulting FOC, vessel speed, draft, sailing area and idling day (anchoring or berthing) from noon reports and hull cleaning schedule and fleet performance history provided by technical managers are useful.

2.2.2 Residual Resistance

The residual resistance comprises of wave and eddy resistance. Wave resistance is literally caused by wave breaking on to a hull and the eddy resistance is due to the loss of energy caused by flow separation which creates eddies, particularly at the aft end of the ship (MAN B&W, 2013).

. Wave and Swell

The Douglas Sea Scale is a combination of wind wave and swell wave. A wind wave is generated by the local prevailing wind, and the vessel’s movement breaks the sea surface and makes wave resistance. A swell wave is made in a remote area such as an area of low pressure hundreds of miles away, and its length is usually longer and sometimes also the height. Predicting the swell waves impact is much more complex than wind waves since the ship rolls, heaves and yaws intensely depending on her GM[8] and block coefficient.

. The Wave Induced Motion

The Salvesen, Tuck and Faltinsen linear strip theory is commonly used to find the wave induced motion. The assumptions are that the ship has a slender hull form with lateral symmetry, and she is advancing at a constant mean forward speed U in sinusoidal waves with an arbitrary heading (Salvesen, 1970).

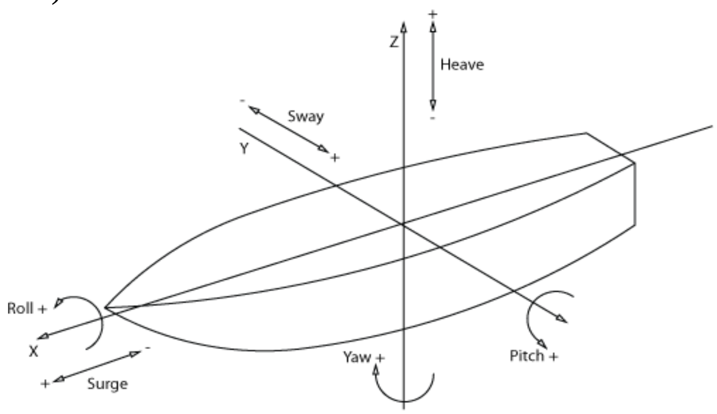

Figure 8, Ship motions

The translatory displacement in the x, y, and z directions are called surge, sway and heave. The angular displacement of rotational motion in x, y and z axes are roll, pitch and yaw respectively.

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[8] The metacentric height is the distance measured from the metacenter to the center of gravity: GM. If GM is large, then the vessel is considered to be stiff in roll – indicating that there will be a large righting moment as a result of small roll angles (A.H.Techet, 2004).

From Figure 8, it is easy to see that the ship would react in a variety of way against the wave direction, length and height.

. The Power Requirement Against Waves

The power requirement due to wave resistance is given (Lloyd, 1988);

$$P_w = \frac{C_w \times \rho \times g \times B^2 \times \omega \times \left(\frac{H_{\frac{1}{3}}}{2}\right)^2}{L} \times (v+u) \qquad 8.$$

Where

C_w : the drag coefficient for the added wave resistance

ρ : the density of water

g : vertical force

B : beam; width of a ship at water line

ω : wave circular frequency

$H_{\frac{1}{3}}$: significant wave height[9] (the amplitude is half the height)

v : the vessel speed

u : the speed of waves relative to that of the vessel

$u = v + \frac{\omega}{k} \times \cos\beta$, where k is number of waves

In addition, this formula can be adjusted further (Pinkster, 2002) & (Sorensen, 2006).

$$\frac{\omega}{k} = \frac{L}{T} = \sqrt{\frac{gL}{2\pi}} \ , \qquad L = \frac{gT^2}{2\pi} \ , \ \ \mathrm{w} = \sqrt{\frac{2\pi g}{L}}$$

Where L: wave length

T: wave period

g: gravitational acceleration

β : wave direction, 0 is head wave

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[9] The significant wave height is the mean or average wave height of the highest 1/3 of all the waves present in a given wave train (Bretschneider, 1964). Normally, the mean wave height is approximately equal to 2/3rds (64%) the value of significant wave heights (Ainsworth, 2006).

The drag coefficient for the added wave resistance (C_w) must be corrected for the position of the Longitudinal Center of Buoyancy (LCB), hull form, breadth-draft ratio and bulbous shape and size. In our case, the coefficients would be assumed to be constant as we are dealing with sister ships. The breadth-draft ratio could be different according to loading condition, but it is expected to be largely constant for each size of vessel (Kristensen, 2013). Equation (8) states that a ship against a head wave needs a bigger power to offset wave resistance, and a ship moving with a wave requires less power or negative power to offset it. Specifically, the square of the wave height is proportional to, and the wave length is an important factor to the power requirement. The longer wave would hit or push more than a short wave.

. The Wave Resistance Model

In addition to wave conditions and speed, the hull design is also a crucial factor to forecast how a ship reacts against waves. The added resistance in waves can be expressed as below (Havelock, 1942).

$$R_{aw} = -\frac{k}{2}\left[F_a Z_a \sin(\epsilon_z) + M_a \theta_a \sin(\epsilon_\theta)\right] \qquad 9.$$

Where

k : wave number

F_a : amplitude of heave force

Z_a : heave amplitude

M_a : amplitude of pitch moment

θ_a : pitch amplitude

ϵ_z & ϵ_θ: heave & pitch phase angle

Equation (9) is not precise but it shows that the added resistance in waves is partly due to the relative motion between waves and ship motions (Nordas, 2012). In this regard, ships in a ballast condition and laden condition would react differently against waves because the amplitude of pitch and heave forces are unlikely to follow the ship's loading condition. Specifically, the ullage[10] of the cargo tanks and ballast tank condition can change a GM[11] and this change would cause a different motion. Additionally, Equation (9) tells us that the wave resistance is heavier in a long swell compared to a short swell. The remaining residual

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[10] The height between the cargo surface in a tank and a ceiling, the main deck plate in a tanker ship.

[11] The metacentric height (GM) is a measurement of the initial static stability of a floating body. It is calculated as the distance between the centre of gravity of a ship and its metacentre (Wikipedia).

resistance is the eddy resistance due to a hull form. But discussing this is beyond the scope of this thesis.

Getting to grips with residual (wave) resistance is complex. It interacts with ship's speed, encountering angle, wave height, swell direction and swell height. It is usually analysed in a towing tank by ITTC methods with CFD (computational fluid dynamic) analysis. By doing so, the total resistance less frictional resistance is defined as a residual resistance coefficient. However, this is often not aligned with actual operation. Our empirical model will transform wave data in noon reports to account for wave making forces according to the theory.

2.2.3 Air Resistance

The air resistance comprises a relatively small proportion of the overall resistance experienced by a vessel, but it can be significant for containerships, ferries and other ships with large superstructures.[12] According to ITTC, the air resistance increase due to the effects of wind is (ITTC, 2014):

$$R_{AA} = \frac{1}{2}\rho_A V_{WR}^2 C_x(\varphi_{WR}) A_{XV} \qquad 10.$$

Where

A_{XV} : the area of maximum transverse section exposed to wind

C_x : the wind resistance coefficient

V_{WR} : relative wind speed

ρ_A : mass density of air

φ_{WR} : relative wind direction

The air resistance is proportional to the square of wind speed and linear to the wind-exposed area. Because the density of air (1.184kg/m^3) is much smaller than water (1,000kg/m^3), we can assume that the air resistance of a tanker is relatively small compared to frictional and residual resistance. On the other hand, container ships would face much stronger air resistance owing to faster speed and cargoes stacked high on deck. The wind speed is defined as the average velocity at ten meters above sea water level, and it can vary by twenty percent depending on observation height (National Data Buoy Center, 2008). As our data is aggregated

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[12] Structures on deck. Precisely, the structure stemmed from the outside hull plate.

from sister ships, such variation can be ignored. If the wind speed is faster than the ship's speed and the wind blows from the stern (negative relative wind speed) the resistance could be negative; air resistance can be positive for fuel oil saving.

The noon report data contains relative wind direction and true wind speed. The relative wind speed can be found with a transformation of ship speed and wind speed. The wind exposed area A_{XV}, could be reflected by the hull draft, but the draft cannot capture the change in wind exposure area for different wind encountering angles. The wind resistance coefficient C_x, depends on each relative wind direction, hence we here include binary dummy variables for each direction in an effort to capture this difference.

2.2.4 Other Resistance

. Squat Effect

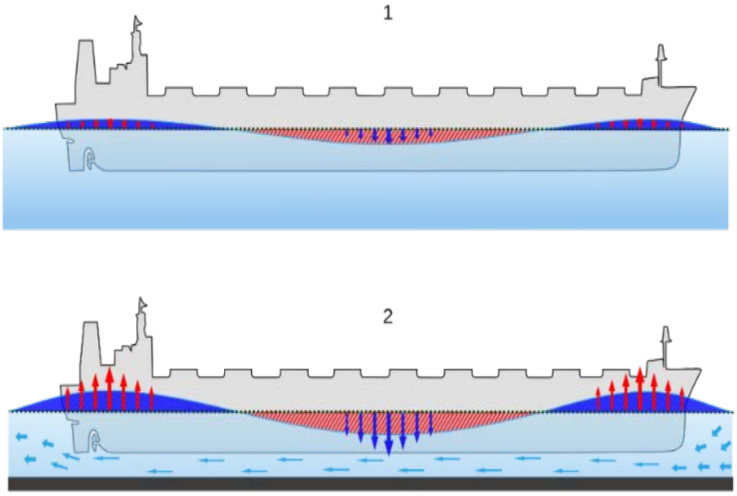

Figure 9, Illustration of squat effect

The Bernoulli's principle states that, in a thin and long pipe, the water density decreases when the water speed increases. Similarly, when a ship sails on shallow sea, the flowing water underneath of a ship goes faster as if it is pushed through a small pipe (ref. Figure 9). Consequently, the density of the water decreases and the ship immerses more. This effect can be ignored when the depth of water is at least twice of the draft. By filtering out noon report interval less than 24 hours would be helpful to exclude squat effect because these cases are expected to be common when a ship enters into a port or departures; sailing shallow areas.

. Ocean Current

Wind and salinity differences generate ocean currents around the world, and the gravitation of the moon makes tidal currents alongside coasts. The speed of an ocean current can be around 3 knots and the speed of tidal currents can be more than 10 knots. A ship's speed is measured in two ways: speed over ground[13] by the Global Positioning System (GPS), and speed through water[14] measured by the vessel's Doppler Log. As our noon reports include data on both GPS speed and Doppler log speed, we take the difference to represent the impact of the ocean current and use it as a variable to investigate how much the FOC is impacted by currents.

2.3 Uncertainty in Estimates

Generally, uncertainty is categorized into epistemic and aleatory uncertainty. The uncertainties that can be foreseen by a modeller is called epistemic uncertainty: a measurement error. The unknowable uncertainties are called aleatory uncertainty, and this uncertainty is omnipresent and any measured data may contain it (Trevelyan, 2004). The Noon Report (NR) has several sources of uncertainty in terms of data interval and accuracy. Each different duty officer measures weather information in noon reports and reports it, and the observation is usually done from a bridge, which is roughly 20 meters above the water line for Aframax tankers. Therefore, the measured wave values may not be very consistent. Particularly, as the Douglas Sea State scale comprises just 10 different of sea states and the Beaufort (BF) wind scale has a 0 to 12 phase to for wind velocity; it cannot represent exact wave and wind information. Moreover, the reported weather information can be noon observations, and it does not represent the variation for last 24 hours. Considering that the square of wave height and wind speed are proportional to ship resistance, the low resolution of Douglas sea state and BF scale might induce measurement error.

2.3.1 Measurement errors

To assess the magnitude of measurement errors in noon reports, Aldous et al (2013) depends on regression techniques. The starting point is that, if the explanatory variables of noon report

---

[13] The actual speed. It means how fast the ship moves from the certain ground point to point. Ex) the speed can be faster with flowing tide and slower with head tide.

[14] The speed on the water. The head tide or flowing tide do not affect speed change as far as she maintains same operational condition.

describe much of the variation in the dependent variable (FOC), it is a sign that the data is reliable. If the R-squared value is close to one and the standard error of coefficients are zero, this means that most of the dependent variable variation is explained by the independent variables, i.e. no omitted variables and zero errors. Since, there is no trusted benchmark to the noon report, we have no choice but to use the raw data which inherently contains uncertainties (Aldous, 2013). Aldous et al includes the explanatory variables of log RPM, log speed, Beaufort wind scale, ship age, loading condition, an interaction term between speed and BF and an interaction term between speed and ship age. Based on data for 89 vessels, they find that some vessels' data show low explanatory power, and the relative standard error for each ship as a percentage of the mean fuel consumption is between 1% and 8%. They assume that this might be due to an epistemic (measurement) error or aleatory error from the data inputs. Additionally, omitted variables like wave and swell data, might be a reason too.

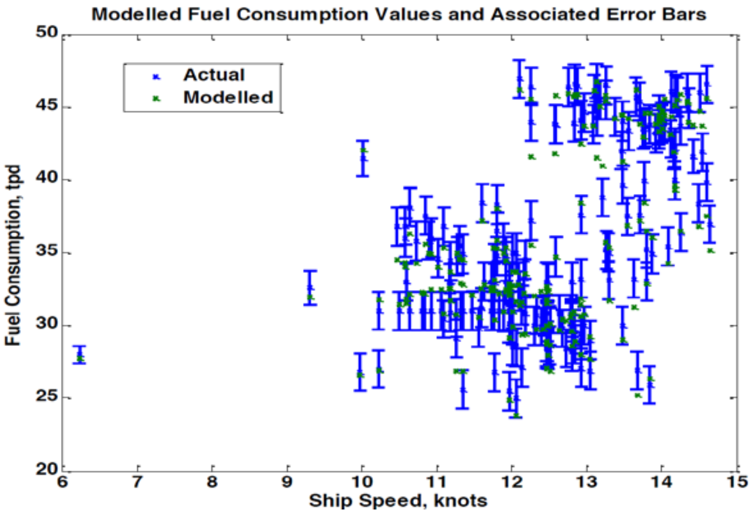

Figure 10, (Aldous, 2013)

Among noon report variables, fuel consumption, ship speed and wind speed and direction are measured by on-board equipment. Assuming that the equipment is well calibrated, the measurement error lies in duty officers' different standards or readings.

2.3.2 Continuously Monitoring

The ship sailing in busy traffic area or engaging in an arrival or departure operation adjusts RPM and changes course frequently, and it increases additional FOC. Given that FOC is very sensitive to changes in ship speed, the presence of frequent ship speed alterations for last 24 hours would bias coefficients. In this regard, the continuously monitoring (CM) is advantageous. Every five minutes or even one minute of data could enhance the possibility to get better coefficients, and tremendous data can be gathered for a short period. The Aldous et al (2013) found that the fuel consumption derived by theory is more similar to CM data rather than daily noon report by the comparison of CM and NR data over the same four months. It implicates that we need to exclude noon reports which are sent when a ship departs or enters into idling.

2.4 Optimum Speed of Ships

At the stage of basic design, a ship's scantling[15] is optimized for her particular market segment. The design speed is set to minimize the required freight rate when the ship is employed in the way intended (Evans&Marlow, 1990). However, the economically optimal speed should also take the prevailing bunker cost and freight rate into account, and would differ according to loading conditions. In the laden leg ship owners maximize profits, while in the ballast leg ship operators would balance the cost reduction by slow steaming and the alternative cost of time for the vessel.

2.4.1 Laden leg

. Without Cargo Inventory Cost

In a laden leg, it can be assumed that the two contracting parties have different reasoning behind the speed choice and associated profit maximization. Ship owners would typically be bound by contractual conditions, e.g. the specified minimum speed. Devanney (2009) claims that cargo owners would be indifferent to the speed choice in case there is plenty of stock and they have a flexible margin to operate their facilities. In this case, the incentives of both ship owners and cargo owner would be aligned; they do not consider cargo inventory cost but care about maximum profit and minimum transport cost. For optimal speed formula without a cargo inventory costs, a relatively simple equation can be derived from the daily profit formula (Evans&Marlow, 1990).

$$GS = \frac{RW}{d/s} - C_R - pks^3 \qquad 11.$$

---

[15] The scantling refers to the collective dimensions of the various parts, particularly the framing and structural supports (Wikipedia).

Where GS: gross profit or surplus per day

R: freight rate per ton of cargo

W: deadweight available for cargo

C_R: running costs / day

p: price of bunker fuel per ton

d: distance steamed, including ballast passage if applicable

s: speed in nautical miles / day

k: constant of proportionality

The last part of Equation (11), pks^3, is the daily fuel cost, where the fuel consumption per day is assumed to vary with the cube of speed. This relation would be different for each hull design and main engine specification and simply based on the fuel consumption function provided by the ship builder. However, it does not represent the actual fuel consumption well, and our main concern is to find better estimates for this real-life fuel consumption relationship which takes into account all influential variables. Thereby, we can apply this relationship to maximize gross profit and optimize sailing speed. By differentiating Equation (11) with respect to speed 's', we get the optimal speed formula (Evans&Marlow, 1990).

$$\frac{d}{ds}(GS) = \frac{RW}{d} - 3pks^2 = 0 \; for \; maximum \qquad 12.$$

$$3\text{pk}s^2 = \frac{RW}{d} \qquad 13.$$

$$s = \sqrt{\left(\frac{RW}{3pkd}\right)} \qquad 14.$$

As Equation (14) indicates, the optimal speed increases with the freight rate and decreases with fuel oil cost. The empirical version of this optimal speed formula for the laden leg would be different, in particular the denominator which represents fuel oil cost (i.e. the product of consumption and price).

. With Cargo Inventory Cost

The optimal speed formula which takes into account cargo inventory cost is a transformation of the cost minimizing model of Ronen (1982). Intuitively, for oil tanker, an oil price increase can become a motive to both accelerate for inventory cost savings and decelerate for fuel cost savings. Lindstad et al (2015) assume a fifteen percent and zero percent cargo inventory cost for Aframax tankers, and illustrate how the inventory cost influences the optimal speed. For speculators, the fifteen percent cargo inventory cost would be reasonable, and the zero percent cargo inventory cost would be applicable for those who do not care about inventory cost.

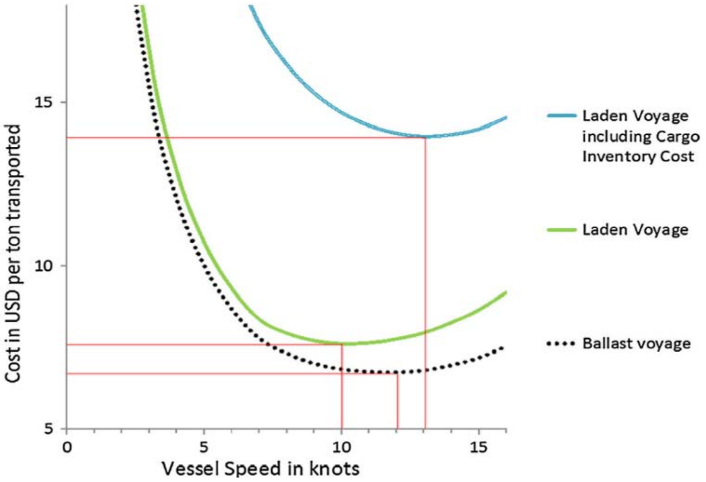

Figure 11, Optimal speed considering inventory cost (Lindstad, 2015)

Figure 11 is drawn based on Aframax tankers and reflects 15% cargo inventory cost and 600 USD per tonne fuel oil price. The optimized speed for zero inventory cost is about 10 knots, 3 knots slower than with cargo inventory cost. The magnitude of this change depends on the financing cost of the cargo, and how high the time charter equivalent (TCE) rate and fuel oil prices are.

2.4.2 Ballast leg

On the ballast leg, ship operators would minimize operating expenditures. Hence, the cost-minimizing model can be applied as per (Ronen, 1982)

$$min\left\{Z = \frac{L}{24V}C_a + \left(\left(\frac{V}{V_0}\right)^3 F_0 F_c\left(\frac{L}{24V}\right)\right)\right\} \qquad 15.$$

Subject to $0 < V_m < V < V_0$, $\frac{dZ}{dV} = 0$ gives an optimal speed V^*.

$$V^* = V_0\left(\frac{C_a}{2F_0F_c}\right)^{\frac{1}{3}} \qquad 16.$$

Where V_0: nominal (maximal) cruising speed
C_a: alternative daily value of the ship
F_0: daily fuel consumption (tons/day)
F_c: cost of bunker fuel ($/ton)
L: sailing distance (nautical mile)

From Equation (16), we observe that maximum speed can be an optimal speed when the alternative daily ship value is larger than the fuel cost. Conversely, the optimal speed would be less than design speed in case the fuel cost exceeds the ship’s value. Therefore, including freight rate and fuel oil price variables are expected to help explain fuel consumption variations.

3. The Model

We develop empirical models step by step with important explanatory variables for FOC variation, and we discuss how the data in noon reports and the data from fleet management history should be transformed and added. Using every transformed and added variables, we construct a complete model to estimate real-life fuel oil consumption.

3.1 Basic framework

The empirical model enables us to evaluate how the daily fuel oil consumption depends on all the aforementioned factors. Firstly, we can write a simple model based solely on the single most decisive factor, shaft power.

$$FOC = \beta_0 + \beta_1 \cdot ShaftPower + u \qquad 17.$$

However, the shaft power is unobservable from noon reports, hence we expand the model using noon report variables categorized into propulsion variables and resistance variables. Then, the model can be written;

$$FOC = \beta_0 + \beta_1 \cdot ShipPropulsion + \beta_2 \cdot ShipResistance + u \qquad 18.$$

The relevant factors of ship propulsion in noon reports are RPM and speed, and those of ship resistance in noon reports are wave and wind resistance and frictional resistance represented by a draft and trim.

$$FOC = \beta_0 + \beta_1 \cdot RPM + \beta_2 \cdot Speed + \beta_3 \cdot Wave + \beta_4 \cdot Wind + \beta_5 \cdot Draft + \beta_6 \cdot Trim + u \qquad 19.$$

This simple model assumes a simple linear relationship between the dependent variable and the independent variables. The detailed theoretical relationship will be applied later with added and fitted variables in the complete model.

3.2 Fitting and Adding Variables

3.2.1 Fitting Log Speed

All ships use a Doppler Log to measure speed through water. The speed through water is the actually moving speed on water. Therefore, speed through water should be applied to predict FOC variation rather than GPS speed. The Doppler Log does not always measure accurate speed through water especially when the Logs are not calibrated by the supplier. Moreover, hull fouling can hamper functioning of the Doppler Log. The SKS technical manager informed us that not all Doppler Logs are properly calibrated, hence, the Doppler Log speed needs to be adjusted accordingly. Assuming that the twenty-day average of GPS and Log speed is the same (i.e. the ocean current effect is equal to zero for the last twenty days of observations), the adjusted log speed (the ratio between average GPS speed and Log speed is multiplied with Log speed) would represent real Log speed.

3.2.2 Fitting Air and Residual Resistance

Equation (19) consists only of the available noon report variables and does not accommodate all important factors. Therefore, it would suffer from an omitted variable bias caused by missing data such as hull cleaning and ocean current speed. These variables can be generated by utilizing noon reports and fleet management history. In addition, the raw weather data should be transformed to account for relative wave and wind force to a ship; reflecting ship speed, wind/wave speed and wind/wave relative direction illustrated in Figure 12.

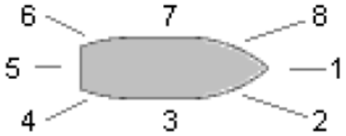

Figure 12, Relative directions of Wind, Wave and Swell in Noon Reports

. Air resistance

The raw wind data should be transformed before plugging into the model in order to see how wind speed interacts with ship speed. In the noon reports, we can find a true wind speed according to the Beaufort wind scale, and true and relative wind direction. Among them, relative wind direction and wind speed are selected since it is the apparent (relative) wind speed that would generate wind resistance. The velocity of the wind must be added or subtracted from the vessel’s velocity. For instance, when a ship sails aginst head wind, the apparent wind speed for a ship is simply the sum of wind speed and vessel speed. However, when the relative wind direction is diagonal to ship’s motion, the wind speed should be adjusted to relative speed.

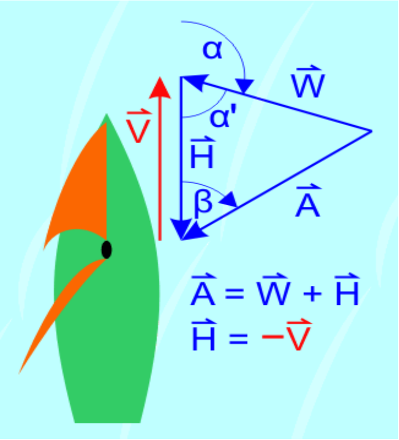

Figure 13, Apparent Wind

Where V: velocity (ship speed over ground)

W: True wind velocity

α: True pointing angle in degrees

A: Apparent wind velocity

From noon reports, we can find V (GPS speed), A (apparent wind velocity) and β (the angle of apparent wind). As a rule of thumb, if we assume that the wind velocity gradient looks like a cosine curve, the relative wind speed is;

$$u = v + (A \times \cos\beta) \tag{20.}$$

u : The relative wind speed

v : The GPS speed of the ship

β : $\frac{\frac{\pi}{180}}{\alpha}$

The air resistance increases with the square of the relative wind speed, thus u^2 should be applied. Referring to Figure 13, the wind exposure area needs to be considered lastly. The exact wind exposure area is not possible with noon report data. The wind exposure area depending on the draft is not proportional as the area of superstructure is fixed while the area on a hull differs. However, if we roughly assume that the area is proportionally changing with hull draft, we can use moulded depth[16] to account for changing wind exposure area. Given that our ship's moulded depth is 20.5 meters, the difference between the moulded depth and draft would be approximately proportional to the wind exposure area. Then, the air resistance can be written as;

$$air\ resistance = u^2 \cdot (20.5 - mean\ draft) \qquad 21.$$

The wind resistance variables are included as eight binary dummy variables; each relative direction variable contains the calculated value according to Equation (20) and (21) if matched with distributed relative direction, if not, the value of other relative direction variables are zero. This is to identify how the interaction between eight relative wind directions and the ship's exposed hull differs. The distribution of each direction is expected to be more accurate relative to a single wind resistance variable which contains transformed data of wind direction and speed information.

. Wave resistance

The sea surface is often very irregular, mixing the different heights, and irregular directions of waves and swells. To be able to observe how fast a wave and a ship meets, the wave and swell speed, and wave length data is necessary, however, we can use only wave height, wave direction, swell length and swell direction from noon reports. In spite of available swell length data, wave length is not assumable due to low correlation with a swell length. There are several studies about average wave speed and length according to wave height, but the wave and swell interacts together in a rough sea, and the higher wave does not always mean higher swell given the reasons of wave and swell generation. Consequently, it is too rough to assume that the wave speed solely depends on wave height. At first, we calculate total wave height, the combination of wave and swell height (Warren, 2003).

$$Total\ Wave\ Height = (WindWave^2 + SwellWave^2)^{\frac{1}{2}} \qquad 22.$$

---

[16] Moulded depth is the height between the upper deck plate and bottom of the keel

The next step is to relate the ship's speed, swell direction and wave speed. Similar to wind speed adjustment, the wave speed from eight relative directions are multiplied with cosine gradient values. Finally, the wave variables except swell length can be transformed as per Equation (23) and Equation (24) based on the previous assumptions about the encountering speed.

$$u = LS + (WS \times \cos\beta) \qquad 23.$$

$$Wave\ Resistance = TWH^2 \times u^2 \qquad 24.$$

Where LS : Adjusted Log Speed of a ship
WS : Wave Speed (Combined method or simple average speed)
TWH : Total Wave Height

Theory suggests, the multiplication of the square of wave height and relative wave speed (wave encountering speed on a hull), but we adjust it to the square of encountering speed (u^2) for our empirical model given that the square of speed is linearly related to resistance power. Last step is to apply the swell length. We here simply use the average swell length as input, accounting for relative direction but not speed. The average wave speed and additional explanation to calculate wave force is explained in Appendix B.

3.2.3 Add Frictional Resistance

. Hull Fouling Variables

Hull fouling condition gets worse over time due to dissolving anti-fouling coating, and particularly marine growth after long idling. Knowing that the noon report is not sent when a ship is at a berth, the number of missing noon reports can represent total berthing days. As the noon reports containing zero RPM, speed and distance let us assume that the vessel was at anchorage. The presence of these noon reports and missing gaps enable us to generate an idling day variable over the course of the observation periods. This can be combined with the ship's last reported position and date to check whether the vessel is in a high-fouling-risky area. In short, the number zero is assigned to the first reporting date of each ship, and the value increases by one for each idling time whenever a ship anchors or berths for longer than a week. Once a ship gets her hull cleaned, the number sets to zero again. Figure 7 shows us that the contaminated hull effect is relatively large when a ship speed is slow. Thus, speed divided by days after hull cleaning might indicate this relationship. The detailed hull fouling quantification method is explained thoroughly in Appendix C, and the binary dummies for idling regions are summarized in Appendix D.

. Sailing Region Variable

The salinity differences can change ship's draft by up to 28 centimeters for the Aframax in question (Appendix A). The noon reports contain the vessel's GPS position (latitude and longitude degrees), we could assign binary dummies to the Red Sea, Mediterranean Sea, Black Sea, Baltic Sea and the middle of Atlantic Ocean. It is expected that the Red Sea, Mediterranean Sea and Atlantic Ocean show slightly less fuel oil consumption thanks to its high salinity while the Baltic and Black sea are expected to show somewhat higher fuel oil consumption due to low salinity relative to the other regions. Each region is summarized in Appendix D.

. Mean Draft, Trim and Ocean Current

Mean draft is an average of forward and aft draft of a ship. A ship usually keeps constant ratio of aft and forward draft, hence using one of the drafts or both drafts might be fine. However, the average draft would better represent how much a ship is submerged, and the difference between aft and forward draft, trim, should also be a good indicator to estimate FOC. Making a trim variable is simple, subtracting the forward draft from aft draft.

The presence of an ocean current could push a vessel forward or backward. Finding a relative current speed and direction is impossible with noon reports data, but we can estimate how strong a current was by subtracting LOG speed from GPS speed. The unit of ocean current variable is knot.

3.2.4 Add Other Variables

. Fuel Consumption Formula

The FOC formula based on CFD test suggests tailor made speed and draft relationship for fuel consumption. It is presumably the best measure of the theoretical fuel consumption in idealized conditions for SKS-D Series Aframax tankers, but we should bear in mind that the experiment conditions for FOC formula are based on 12.8 meters of draft, 13.2 knots of ship speed, wind speed slower than 17 knots, wave height lower than 1.25 meters and smooth hull.

Though the empirical fuel consumption data comes from sister ships, everything is not exactly the same. For instance, Doda and Demini have a NOx Tier II compliant main engine which has a 3% higher SFOC at higher than 50% of engine load relative to the previously delivered sister ships. Considering that the average FOC of the other ships is roughly thirty tonnes per day, both ships are expected to consume at least one additional tonne of fuel oil a day. In this respect, adding a vessel specific variable would capture this distinction. Additionally, the level and growth rate of hull fouling would differ among ships. In this case, a single hull fouling variable cannot represent each ship’s hull condition, and these differences among sister ships will enter into to the vessel specific variables. Statistically, the Fixed Effects method would remove vessel specific variable, but the Random Effects method does not.

. Normal Wear and Tear

The SKS D-Series ships are young, four to six years old, but normal wear and tear is not same. The inclusion of a linear and squared term of age would enable us to see how aging affects FOC. Another candidate can be cumulative sailing distance since it is directly related to engine operating hours. Similarly, the square of cumulative distance to consider non-linear aging of the main engine. Alternatively, we can input a cumulative RPM multiplied with time since last report variable. Our empirical model includes only one of these candidate variables to avoid multicollinearity, and the optimal candidate will be selected by checking coefficient signs. The starting values of daily age and cumulative distances are summarized in Appendix E.

. Dry-docking

The dry-docking of the SKS-D series has taken place since December 2014, and the last of the initial dry-docking is scheduled to finish by the end of 2016. SKS informs us each vessel has been fitted with a fuel-saving (Mewis Duct) modification during the dry-docking period. According to CFD (computational fluid dynamic) test, these modifications save up to 3% of FOC. Dry-docking allows us for the removal of marine growth and renewal of the anti-fouling paint, resulting in a hull condition as good as new.

3.3 Complete Model

The final empirical fuel oil consumption model is given as below.

$$FOC_{it} = \beta_0 + \beta_1 \cdot Propulsion_{it} + \sum_{k=1}^{m} \theta_k \cdot Weather_{kt} + \sum_{j=1}^{m} \omega_j \cdot Added\,Vars_{jt} + a_{it} + u_{it} \qquad 25.$$

The propulsion variable includes either the cube of ship speed with the power of two thirds of draft or CFD-based fuel consumption formula that includes mean draft and ship speed. The weather variables contain eight relative directions of wind, wave and swell length. The added variables are trim, hull fouling, sailing region, current, vessel specific variables, dry-docking, and candidate variables for ship age. To recap, all the variables and the expected signs are summarized in next page Table 1.

Variables	Unit	Expected	Description
Dependent Variables			
Fuel Oil Consumption	Tonne/day		Volume measured based on 15 Degree Celsius
Independent Variables			
Propulsion			
Adjust Log Speed	Knot	+	The cube of ship speed measured by Doppler Log. The moving distance divide by 24 hours
Mean draft	Meters	+	The average of aft and forward draft
Fuel Consumption Formula	Tonne/day	+	Formula provided by shipbuilder (mean draft and adjusted log speed are input)
Weather			
Wind / 8 relative direction	Knot	+	Each direction has values when the direction matched, otherwise zero. Transformed to take account of ship speed and relative direction
Wave / 8 relative direction	Knot	+	
Swell / 8 relative direction	100 meters	+	Each direction has values when matched.
Added Variables			
Trim	Meters	-	The difference between aft and forward draft
Current	Knot	-	GPS speed minus adjusted doppler log speed
Ship specific effect / all ships		+/-	Binary dummies to indicate each ship
Age (cumulative distance/RPM)	Day (Nautical Mile)	+	Daily ship age (The sum of GPS distance)
Age Squared (square of cumulative distance/ RPM)	Day (Nautical Mile)	-	The square of daily ship age (The squared sum of GPS distance)
Hull fouling	Number	+	Accumulate whenever a ship idles longer than a week
Speed/Hull fouling	-	-	Adjusted speed divided by hull fouling
Idle fouling / 7 risky regions	Day	+	Idle days in fouling risky area
Idle other	Day	+	Idle days in other area
Dry-docking	Day	+	Days after dry-docking
Regions / 3 regions	0/1	+/-	Binary dummies to indicate sailing regions

Table 1: Overview of variables

4. Data

4.1 Scanning

The noon reports of ten sister ships are accumulated from January 2012 to March 2016, comprising 15,183 ship-day observations. There are 4,262 gaps in the reporting indicating port or idling days, hence 10,922 of noon reports are sent. All the noon reports contain reporting date, vessel name, reporting position, average GPS and Doppler Log speed, RPM, main engine FOC, distance by GPS and Doppler Log, wind and swell relative direction and time after last report. Since October 2012, the Beaufort wind scale and Douglas sea scale are added, and the daily draft of aft and forward are available from September 2014. In addition to noon reports, ship's hull cleaning history, dry-docking schedule and departure draft before September 2014 are provided by SKS technical manager.

4.2 Adjustment and Cleaning

4.2.1 Data Adjustment

1) Missing data filling

From January 2012 to October 2012, full reports of Beaufort wind scale and Douglas sea state are missing as only relative wind and swell direction are reported. Assuming that the wind speed and wave height values are normally distributed, filling these gaps with average values would enable us to use larger number of observations.

The daily draft data is available from September 2014, and only departure draft provided ship's technical manager is available before then. We fill out departure draft at first for ship's each voyage, and the draft is gradually decreasing little by little like a daily draft as a ship sails after departure. This is to reflect decreasing dead weight because of consuming fuel oil and fresh water on board.

2) 24-hour basis fuel oil consumption

Given that the reporting interval is between 23 to 25 hours, the FOC should be adjusted accordingly. Provided that the hourly fuel oil consumption is constant, the different reporting interval can be adjusted to 24-hour basis.

4.2.2 Data Cleaning

1) Removal of null or zero distance, fuel oil consumption and RPM

The vessel did not send a noon report when a ship was at berth or at anchor. Thus, this data is just utilized to generate ship's idling days (6,139 observations).

2) Removal of short distance, low fuel oil consumption and slow speed

A short reported distance, small fuel oil consumption or slow speed means that the ship didn't use her engine for last twenty-four hours. We find GPS/LOG speed of noon reports as GPS/LOG distance divided by 24. Thus, the GPS/LOG speed for a short distance is measured as lower than the actual operating speed. Seeing that the cube of speed is a key input to find FOC, this can bias coefficients severely. Observations with distance less than 170 nautical miles, GPS speed less than 7 knots and fuel consumption less than 10 tonnes are removed (546 observations).

3) Removal of short reporting interval

A short reporting interval implies that the vessel was engaged in a departure or arrival operation during which, frequent main engine adjustment is unavoidable. This causes the main engine to use more fuel oil. Most of reporting intervals in our sample are within 23 to 25 hours, as when a ship crosses each fifteen degrees of longitude, the ship's clock is advanced or retarded an hour respectively. We drop reporting intervals less than 23 hours (498 observations). The reasoning upon departure or arrival in port would be similar, and so we also find it necessary to delete observations when changing to/from a period of idleness (413 observations). This procedure is to align with the advantages of continuously monitoring.

4) Removal of unrealistic data and heavy weather

We additionally drop observations with reported draft below minimum safe operating draft of 6 meters (1 observations), estimated sea current speed outside +/- 3 knots (3 observations), wave height greater than 5 meters and wind speed faster than 35 knots (71 observations), and fuel consumption larger than 65 tonnes (7 observations). Last but not least, the Doppler Log of SKS Demini has been out of order since 24th Feb 2014. Since then only GPS speed is available (284 observations).

5) Cleaning Summary

Total 7,850 of observations are trimmed by the above procedures, and the remaining number of observations becomes 7,333.

Figure 14, Cleaning Summary

4.3 Data at a glance

After data cleaning and adjustment, the averages included in regression are graphed as below.

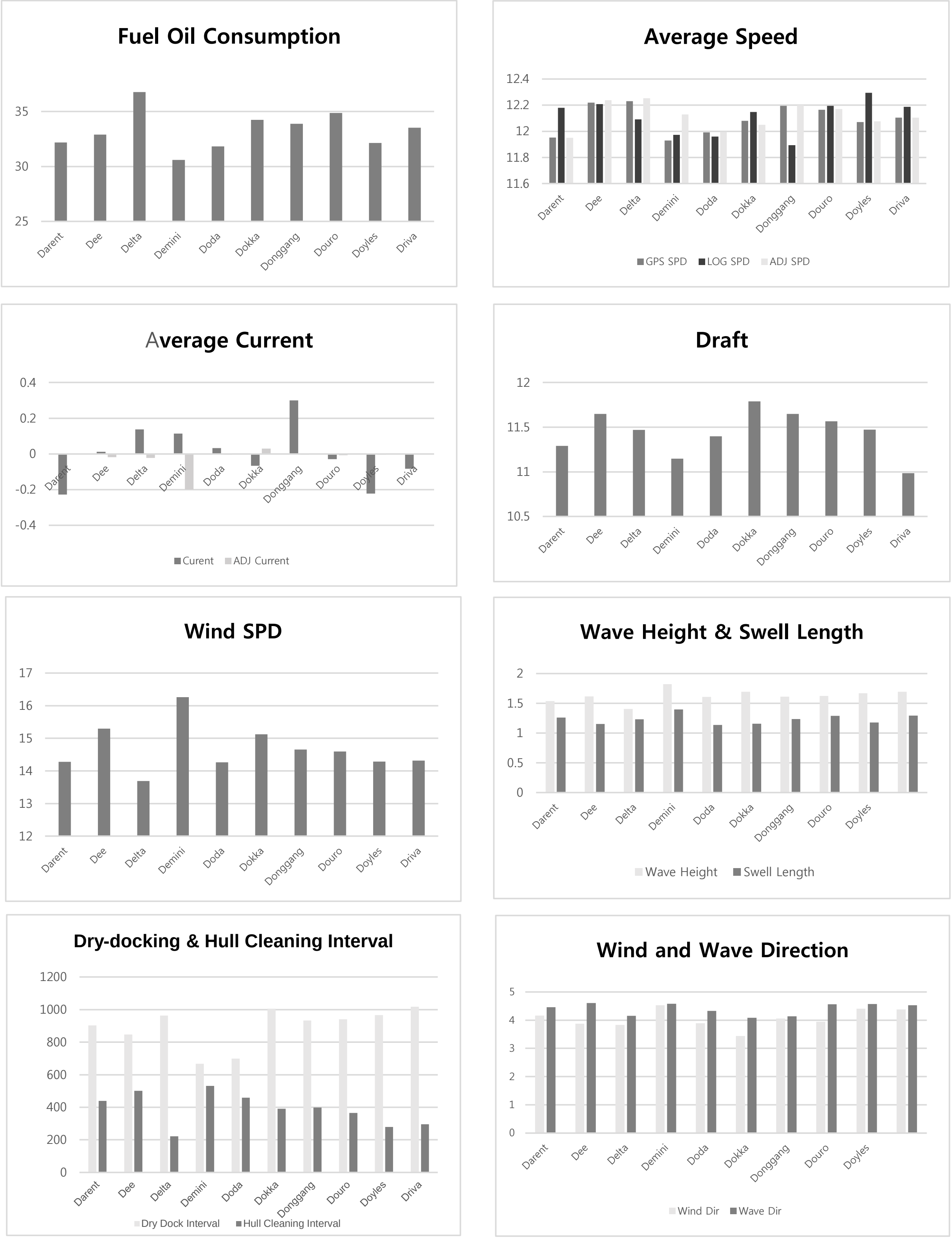

Figure 15, Averages of variables

Interestingly, the average fuel oil consumption of SKS Delta is roughly three tonnes higher than her sister ships even though the major explanatory variables such as speed, draft, and weather forces are similar to average levels. The average current speed of SKS Demini is significantly lower, and this is assumed to be caused by Doppler Log malfunction. The correlation between fuel consumption and explanatory variables are;

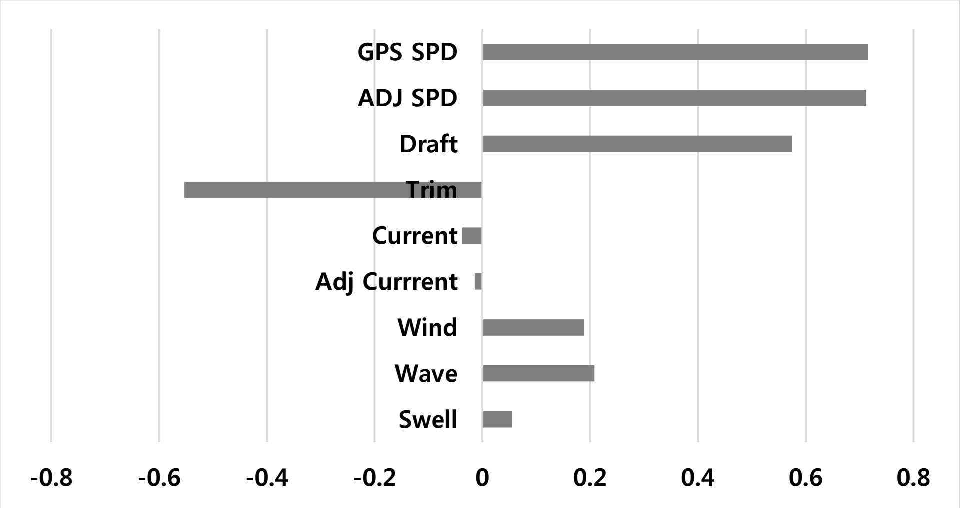

Figure 16, Correlations with FOC

All independent variables show expected sign.

	Fuel	GPS SPD	Adj. SPD	Draft	Trim	Current	Adj. Cur	Wind	Wave
Fuel	1								
GPS SPD	0.715	1							
Adj SPD	0.711	0.942	1						
Draft	0.575	0.365	0.334	1					
Trim	-0.553	-0.364	-0.332	-0.919	1				
Current	-0.038	0.136	-0.051	0.041	-0.044	1			
Adj Cur	-0.015	0.136	-0.205	0.076	-0.080	0.546	1		
Wind	0.188	-0.106	-0.105	0.111	-0.100	0.046	0.001	1	
Wave	0.208	-0.142	-0.134	0.102	-0.094	0.012	-0.020	0.845	1
Swell	0.054	-0.029	-0.022	0.012	-0.026	-0.008	-0.019	0.164	0.183

Table 2 Correlations between variables.

Wind speed, wave height, draft and trim show high correlation. This might imply high probability of multi-collinearity, and this can bias statistical significance among collinear variables. However, multi-collinearity is sometimes accepted as long as it is reasonable for the model to have collinear variables, when the result corresponds with expected signs.

4.4 Data Quality

The purpose of this section is to check data quality of each ship based on regressions in a manner similar to Aldous et al (2013), where the level of R-squared indicates how serious the measurement errors or misspecification are.

4.4.1 Used Model and Data

The used model to check data quality of each ship is;

$$FOC = \beta_0 + \beta_1 \cdot FOC\ Formula + \sum_{k=1}^{m} \theta_k \cdot Weather + hull\ fouling + dry\ dock + u \qquad 26.$$

This model is slightly different from the complete model discussed in Section 3.3. The differences are

1) It uses the FOC formula instead of cube of adjusted log speed and mean draft.
2) It omits age variables.
3) It omits binary dummy variables to assign sailing and idling regions.

The data is filtered out following the data cleaning and adjustment procedures in Section 4.2.2. In addition, we exclude missing wind speed and wave height observations. The first specification is regressed with the overall data while the second specification excludes wind faster than 17 knots and waves higher than 1.25 meters to avoid measurement errors in weather. This is helpful in order to judge the measurement errors in FOC and ship speed because measures are presumably quite precise in benign weather conditions relative to heavy weather conditions. The last specification excludes mean draft less than 10 meters, speed slower than 12 knots and FOC higher than 60 tonnes a day. This is recommended by the ships' technical manager because the FOC formula is derived with these conditions. The regression results of each ship are attached in Appendix G.

4.4.2 Quality Analysis

1) R-Squared and statistical significance of weather variables

The regression results tell us that the R-squared of the model including all weather conditions (1st Model) is less than the model excluding heavy weather observations (2nd Mode). The R-squared of the second model lies between 83.95% and 93.40%, and it indicates measurement errors in weather variables and lower measurement error in FOC and ship speed. Theoretically, the R-squared of the third model should be the largest among all models, but most of them are lower than the first and second model. This is assumed to be caused by low variation in variables and reduced number of observations. Even if the second model shows higher R-squared, we should not conclude that weather observations are inconsistent with reality because our model might not be good at explaining the influence of weather. However, the significant weather variables in both the first and second model could be taken as a good sign that weather variables are suitably transformed.

2) Coefficients of Fuel Oil Consumption formula

The coefficients of the first and second specification are around one; ship speed and mean draft are crucial factors for FOC. Overall the coefficients of the second model are larger than the first because of the larger weather coefficients of first model. Alternatively, it could be that inaccurate hull fouling quantification and, reduced variation in weather forces might exaggerate the coefficients of FOC formula.

3) Homoskedasticity, Functional Form and Residual Normality

Heteroskedastictiy does not result in biased estimators, but the Best Linear Unbiased Estimator (BLUE) result no longer holds (Wooldridge, 2012). The Breusch-Pagan test shows that six ships of the first model suffer from heteroscedasticity, and four ships in the second model. This might be an indication that the model is not correctly specified.

The Reset test checks models' misspecification of functional form, and here rejects the null hypothesis of no functional form misspecification. While we could explore further non-linear combinations of dependent variables, such specifications would lack theoretical support and so we do not pursue this approach.

The residual normality assumption is much stronger than any of Ordinary Least Square assumptions. Just two cases of the second model show statistically significant residual normality, though in our case, the lower bound of weather impact and fuel consumption for a given speed means, the non-normality is largely expected. The non-normality of the errors is not a serious problem with large sample size (Wooldridge, 2012), and the observation number of aggregated data of ten ships would be enough.

4) ***Dry-docking & Hull Fouling Quantification***

The FOC savings from dry-docking varies from 0.86 to 8 tonnes per day, with the bigger values related to serious hull fouling conditions. According to the reference fuel consumption history for SKS Driva and Douro, both had consumed more fuel oil than other sister ship, and come back to normal level after dry-docking. Hence the dry dock dummy coefficients are larger. The large apparent dry-docking effect tells us that the hull fouling quantification does not perform well.

5. Analysis & Discussion

In this chapter, we will analyse the regression results based on the cumulative data of all sister ships. Section 5.1 discusses methodologies. Section 5.2 finds better performing estimators, and explains how to interpret coefficients. Section 5.3 estimates FOC based on selected empirical results, and optimizes speed for real-life condition. Lastly, Section 5.4 reviews limitations in this thesis and further researches.

5.1 Test

5.1.1 Panel Data or Cross Sectional Data?

The time series data of ten sister ships constitutes a panel data set, also called longitudinal data; there is a cross sectional dimension and time-series dimension. However, the observation period of several ships is different, and some observations have missing cross sectional data, i.e. we have an unbalanced panel. Provided the missing data for some point in time is not correlated with the idiosyncratic errors, the unbalanced panel causes no problems (Wooldridge, 2012). Because the gaps among observations are caused by anchoring or port stays (when no fuel is consumed by the main engine), they have nothing to do with idiosyncratic error and so, our unbalanced data is expected to be fine. The panel data has several advantages relative to cross sectional data. It can control for unobservables which can be correlated with regressors and are time-invariant and individual-specific factors, α_i.

Assuming that every ship is maintained by the same procedures of SKS and that the age of ship does not matter for fuel consumption, there is not any individual-specific and time invariant unobservables. Then, the aggregated data accumulated from ten same ships can be treated as cross sectional data. In other words, we can use Ordinary Least Square (OLS) instead of panel data analysis methods such as Fixed Effects (FE) or Random Effects (RE). Statistically, the Breusch-Pagan Lagrange Multiplier (LM) test indicates appropriate method. In our case, the LM test shows that we fail to reject the null hypothesis, hence we can conclude RE is not appropriate. Interestingly, the estimates from OLS and RE are exactly same, and the OLS regression with ship-specific dummy variables results in the same coefficients as the FE coefficients. Consequently, we decide to treat the data as cross sectional and apply OLS.

5.1.2 Variables selection for Final Model

In Section 3.3, two candidates for the ship propulsion variable were suggested. One is to apply the cube of ship speed and power of two thirds of draft in accordance with FOC theory. The other is to use the CFD-based FOC formula provided by SKS. While the R-squared of the FOC theory model is slightly higher, by around 2%-points, the FOC formula is applied in the final empirical model as it is tailor made to the vessel in question.

The final model ignores draft for the calculation of wind variables given the lower R-squared. Furthermore, it drops regional variables. The signs of sailing region variables are counter-intuitive, and we find a low number of observation and generally slower speeds in these regions. In addition, we realize that draft values tend to decrease gradually throughout a voyage in spite of regional difference, and so we would not be able to reveal salinity differences anyway.

The final model drops age variables despite its significance. However, the ship’s supervisor informed us that there is little difference in FOC as long as the main engine is well maintained. In addition, the age variables can be collinear with the hull fouling condition.

The final model excludes an interacting variable; ship speed divided by hull fouling variable. Rough hull fouling quantification and similar reasons like age variables generate unreliable estimates.

We drop the trim variable as well. Trim by the stern condition is common for ballast voyage as it reduces frictional resistance, and most laden passage keeps even keel. Consequently, the low variation in both ballast and laden leg cannot explain fuel consumption.

Since we use adjusted log speed, the ocean current variable should be insignificant, but we keep it to capture out its effect on other coefficients. We exclude ship specific variables to get average estimates and apply our estimates to all sister ships. Our final can be written as:

$$\begin{aligned} FOC = \beta_0 + \beta_1 \cdot FOC\ Formula + \beta_2 \cdot Winds + \beta_3 \cdot Waves + \beta_4 \cdot Swell\ Lengths \\ + \beta_5 \cdot Dry\ Dock + \beta_6 \cdot Hull\ Fouling + \beta_7 \cdot Ocean\ Current + u \end{aligned} \qquad 27.$$

5.1.3 Homoskedasticity and Outliers

The Breusch-Pagan test result shows high level of heteroskedasticity in the combined vessel data. In order to manage heteroskedasticty, STATA provides the robust option to use Huber/White Sandwich estimator. The Huber/White Sandwich estimators do not result in different coefficients but merely adjusts the statistical significance of estimates. Most of our estimates are still statistically significant when Huber/White Sandwich estimator is used. The heteroscedasticity graph implies that the fitted FOC values for slow and fast speeds are relatively accurate compared to the middle range.

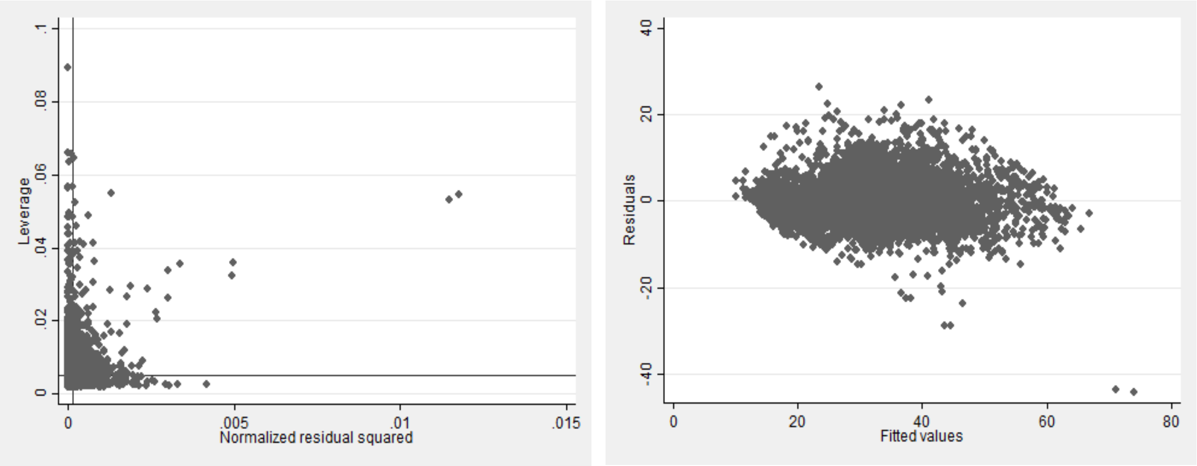

Figure 17, Outliers and Heteroskedasticity (regression result from OLS)

In order to deal with any remaining outliers, the robust regression, MM-estimator is used because OLS estimates are sensitive to outliers; it minimizes the sum of squared residuals. In recent years, MM-estimators is seen as the best suited estimation method, since they combine a high resistance to outliers and high efficiency for regression models with normal errors (Veradi, 2008). The final model is regressed using the MM-estimator (robust regression) without ship specific variables in order to account for outliers, and these estimates will be used to calculate predicted fuel oil consumption. However, we also present OLS-estimates (using Huber-White sandwich estimators to consider heteroscedasticity) so that we can track changes in explanatory power when we add independent variables. The MM-estimators and OLS-estimators including ship-specific variables are presented in Appendix H.

5.2 Empirical Results

	OLS	**OLS**	**OLS**	**OLS**	**OLS**	**OLS**	**MM**
Propulsion & Current							
FOC Formula	0.863^{***}	0.865^{***}	0.907^{***}	0.910^{***}	0.977^{***}	0.976^{***}	1.008^{***}
	(79.60)	(86.99)	(102.07)	(105.02)	(108.92)	(111.99)	(132.13)
Ocean Current	3.350^{***}	3.621^{***}	3.572^{***}	3.599^{***}	3.938^{***}	3.834^{***}	0.421^{*}
	(6.77)	(7.81)	(8.18)	(8.35)	(8.76)	(8.70)	(2.32)
Weather Forces							
Wind 1		0.00817^{***}	0.00439^{***}	0.00405^{***}	0.00427^{***}	0.00414^{***}	0.00521^{***}
		(32.92)	(14.67)	(13.36)	(14.66)	(15.05)	(15.59)
Wind 2		0.00837^{***}	0.00421^{***}	0.00381^{***}	0.00456^{***}	0.00410^{***}	0.00538^{***}
		(18.79)	(8.51)	(7.62)	(9.56)	(9.02)	(10.87)
Wind 3		0.0122^{***}	0.00371	0.00293	0.00340	0.00419^{*}	0.00613^{***}
		(6.02)	(1.87)	(1.46)	(1.82)	(2.44)	(3.73)
Wind 4		-0.00730	0.00920	0.0123^{*}	0.0122^{*}	0.0119^{*}	0.00168
		(-1.32)	(1.53)	(1.96)	(2.06)	(2.04)	(0.32)
Wind 5		-0.00157	0.00848^{***}	0.0112^{***}	0.0106^{***}	0.00906^{***}	0.00611^{*}
		(-0.65)	(3.39)	(4.35)	(4.18)	(3.76)	(2.40)
Wind 6		0.00222	0.0187^{**}	0.0229^{***}	0.0243^{***}	0.0223^{***}	0.0168^{**}
		(0.36)	(3.14)	(3.80)	(4.52)	(4.43)	(3.12)
Wind 7		0.0252^{***}	0.0133^{***}	0.0130^{***}	0.0122^{***}	0.0114^{***}	0.0111^{***}
		(11.46)	(6.86)	(6.85)	(6.93)	(6.86)	(6.15)
Wind 8		0.0108^{***}	0.00510^{***}	0.00470^{***}	0.00522^{***}	0.00516^{***}	0.00581^{***}
		(23.31)	(9.64)	(8.86)	(10.32)	(10.73)	(11.40)
Wave 1			0.00960^{***}	0.00949^{***}	0.00993^{***}	0.0100^{***}	0.000261^{***}
			(16.84)	(15.65)	(16.79)	(18.05)	(12.50)
Wave 2			0.0117^{***}	0.0120^{***}	0.0118^{***}	0.0117^{***}	0.000334^{***}
			(15.59)	(14.74)	(15.11)	(15.90)	(8.23)
Wave 3			0.0226^{***}	0.0219^{***}	0.0216^{***}	0.0184^{***}	0.00132^{***}
			(11.52)	(9.79)	(10.45)	(9.24)	(6.50)
Wave 4			-0.0580^{***}	-0.0607^{***}	-0.0608^{***}	-0.0542^{***}	-0.00511^{*}
			(-8.16)	(-6.72)	(-6.68)	(-6.02)	(-2.15)
Wave 5			-0.0146^{***}	-0.0172^{***}	-0.0165^{***}	-0.0150^{***}	-0.00123^{***}
			(-6.61)	(-6.94)	(-6.87)	(-7.07)	(-5.94)
Wave 6			-0.0373^{***}	-0.0426^{***}	-0.0455^{***}	-0.0453^{***}	-0.00797^{***}
			(-7.13)	(-7.61)	(-8.16)	(-8.10)	(-5.78)
Wave 7			0.0230^{***}	0.0262^{***}	0.0275^{***}	0.0284^{***}	0.00169^{***}
			(11.65)	(11.39)	(12.40)	(13.42)	(7.63)
Wave 8			0.0128^{***}	0.0129^{***}	0.0135^{***}	0.0136^{***}	0.000380^{***}
			(18.98)	(17.43)	(19.17)	(19.28)	(14.36)
Swell				1.201^{***}	1.106^{***}	0.876^{***}	0.351^{*}
Length 1				(7.40)	(7.10)	(6.05)	(2.37)
Swell				0.894^{***}	0.750^{***}	0.609^{***}	0.337^{*}
Length 2				(5.94)	(5.35)	(4.58)	(2.42)
Swell				0.988^{***}	0.914^{***}	0.897^{***}	0.570^{***}
Length 3				(5.16)	(5.27)	(5.83)	(3.44)
Swell				0.809^{***}	0.663^{***}	0.542^{**}	0.967^{***}
Length 4				(4.23)	(3.60)	(3.17)	(6.53)
Swell				0.626^{***}	0.602^{***}	0.501^{***}	0.261^{*}
Length 5				(3.49)	(3.67)	(3.50)	(2.11)
Swell				0.693^{***}	0.679^{***}	0.675^{***}	0.489^{***}
Length 6				(4.65)	(4.74)	(5.12)	(3.67)
Swell				0.314	0.328	0.183	0.0852
Length 7				(1.62)	(1.79)	(1.07)	(0.44)
Swell				0.958^{***}	0.920^{***}	0.842^{***}	0.490^{***}
Length 8				(6.17)	(6.21)	(5.95)	(3.94)
Dry-docking & Hull Fouling							
Dry-					-5.015^{***}	-4.035^{***}	-4.226^{***}
docking					(-29.68)	(-23.67)	(-26.54)
Hull						0.665^{***}	0.714^{***}
Fouling						(30.74)	(24.85)
Constant	12.19^{***}	8.934^{***}	6.863^{***}	5.801^{***}	4.982^{***}	3.962^{***}	3.288^{***}
	(42.51)	(34.61)	(29.70)	(23.52)	(21.23)	(17.73)	(16.08)
N	5938	5938	5938	5938	5938	5938	5938
R^2	0.6019	0.6927	0.7357	0.7413	0.7727	0.8048	N/A

Table 3; Estimates of aggregated data. *t* statistics in parentheses (* *p* < 0.05, ** *p* < 0.01, *** *p* < 0.001)

The MM-estimators is close to 1, 1.008, and the constant is the lowest among all estimated specifications.

The OLS-estimates of FOC formula without ship specific variables are almost one but not as close as the MM-estimator. The benchmark FOC formula and ocean current variables just explain 60% of total variation in our data. The R-squared rises to 74.13% when including wind, wave and swell variables and further to 80.48% when adding dry-docking and hull fouling variables. The R-squared rises to 88% once we exclude wind speeds faster than 17 knots and waves higher than 1.25 meters.

All the ocean current coefficients are significant and positive, which is counter-intuitive. If there is a designated speed to keep, a ship would decrease RPM when there is a positive current, and FOC would be less. Thus, if the model uses a GPS speed instead of Log speed, ocean current should be significant. However, the flow of ocean current does not impact vessel's movement significantly, and the Log speed merely indicate how fast a ship sails on water with propulsion power.

At first sight, the values of the wind coefficients also look unreasonable because wind that blows from port stern, direction 6, has the largest values. Moreover, the coefficient of direction 3, perpendicular of starboard, is higher than head side wind, direction 1, 2, and 8. However, we must keep in mind that the wind variables come from the transformation of true wind speed and the ship's sailing speed into the ship's wind encountering speed. Therefore, larger coefficients do not necessarily mean higher FOC. For example, when a ship sails at 10 knots (GPS speed) with 20 knots of head wind, the expected FOC increase is calculated as;

$$(10 + 20)^2 \times 0.00521 = 4.689\ ton/day$$

We can interpret that SKS-D tankers should burn more fuel oil by 4.689 ton/day to keep her speed when subject to such wind conditions, holding other variables fixed.

The values of the wave coefficients do not seem to be reasonable. The wave data is transformed to get the encountering power on a ship according to Appendix B and Section 3.2.2. Therefore, the coefficients cannot be directly interpreted like wind coefficients. For example, when a ship sails at 10 knots (adjusted log speed) in, 1.5 meters of wave, and 2 meters of swell from ahead (direction 1), the FOC increase is calculated as:

Total wave height: $(1.5^2 + 2^2)^{0.5} = 2.5\ meters$
Expected wave speed: 14.58 knots (Table 7 in Appendix B)
Wave encountering speed: $10 + 14.58 = 24.58\ knots$
FOC increase: $24.58^2 \times 2.5^2 \times 0.000261 = 0.9856\ tonnes/day$

Most of the swell length coefficients are statistically significant, but the values of the MM estimates look unexplainable. This might be caused by the low variation in swell length variable as there are just 4 phases of swell length such as 0, 0~100, 100~200, and 200~300 meters. Moreover, the observational error or standards to measure swell length could be different.

According to CFD test data used to validate FOC savings due to the propeller modification, the dry-docking procedure is expected to save 1 tonne/day. However, our empirical results show that dry-docking saves more than 4 tonnes/day. This might be the result of a combination of the propeller modification and new anti-fouling coating.

Referring to Appendix H, some ship specific variables are significant as well. The FOC of Demini and Doda which has NOx Tier II compliant engine should be larger than sister ships, but the empirical results are significant and counter-intuitive.

The coefficients of the hull fouling variables are statistically and economically significant, though we are not very confident about the approach and so leave a detailed assessment here to future research.

5.3 Discussion

Using our estimated propulsion, weather, and hull fouling coefficients, we can estimate FOC and optimize ship speed in real-life operating conditions. In order to arrive at consistent estimates, it is necessary to set a few conditions based on our main findings.

1. As discussed in Section 3.2.2, GPS ship speed should be used to get the wind effect, and Doppler Log Speed should be applied to find the wave effect on FOC. We assume that the ship's speed through water (Doppler Log speed) and true speed (GPS speed) is equal, and do not differentiate between the two measures of ship speed when we calculate weather forces. Similarly, the ocean current effect is assumed to be zero in the long run, hence we do not take it into account for optimal speed.
2. The weather condition is categorized into three phases: good, normal, and heavy weather. The good, normal, and heavy wind condition is assumed as wind speeds of 5, 20, and 35 knots, total wave height is 0.8, 2.5, and 4 meters, and swell length is 50, 150, and 250 meters respectively. The assumed wave speed is 7, 15, and 19 knots which are proportionally adjusted values using Table 7 in Appendix B.

5.3.1 Predicted Fuel Oil Consumption

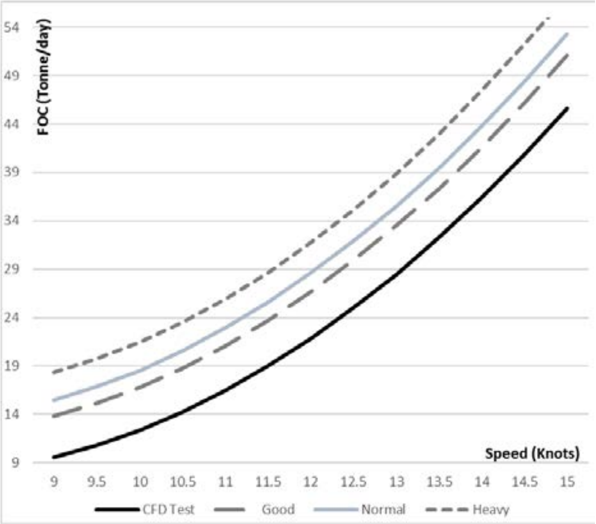

Figure 18, FOC of CFD based, Good weather, Normal Weather, and Heavy Weather at draft 11.34 meters

Figure 18 contains predicted FOC curves based on our model and shows that in speed ranges less than 10 knots, the FOC in heavy weather can be double of CFD-based FOC. As ship speed rises, the FOC gaps between real-life and the CFD simulation becomes a bit narrower because FOC increase due to speed is much higher than weather resistance increase.

	Rel. Dir.	**Sailing Speed**	**Good** (5 knots)	**Normal** (20 knots)	**Heavy** (35 knots)	**Sailing Speed**	**Good** (5 knots)	**Normal** (20 knots)	**Heavy** (35 knots)
Wind	**1**	9 knots	1.0212	4.3816	10.0866	14 knots	1.8808	6.0228	12.5092
	2		0.8454	2.8813	6.1276		1.6543	4.2608	8.0778
	3		0.4965	0.4965	0.4965		1.2015	1.2015	1.2015
	4		0.0490	-0.0434	-0.4067		0.1796	0.0000	-0.1895
	5		0.0978	-0.7393	-4.1304		0.4949	-0.2200	-2.6945
	6		0.5017	-0.4442	-4.1667		1.8397	-0.0003	-1.9409
	7		0.8991	0.8991	0.8991		2.1756	2.1756	2.1756
	8		0.9130	3.1116	6.6174		1.7865	4.6014	8.7234
Averages			0.6029	1.3179	1.9404		1.4016	2.2552	3.4828

Table 4; FOC (tonne/day) increase due to wind

Both 9 and 14 knots of sailing speed, the model suggests that head wind increases fuel consumption, and wind blowing from the stern helps a ship save a fuel as anticipated.

	Rel. Dir.	**Sailing Speed**	**Good** (0.8 m)	**Normal** (2.5 m)	**Heavy** (4 m)	**Sailing Speed**	**Good** (0.8 m)	**Normal** (2.5 m)	**Heavy** (4 m)
Wave	**1**	9 knots	0.0428	0.9396	3.2740	14 knots	0.0737	1.3719	4.5477
	2		0.0416	0.8025	2.6898		0.0768	1.2639	4.0223
	3		0.0684	0.6683	1.7107		0.1656	1.6170	4.1395
	4		-0.0537	0.0824	1.6081		-0.2679	-0.3678	-0.0261
	5		-0.0031	0.2768	1.9680		-0.0386	0.0077	0.4920
	6		0.0837	0.1286	2.5081		-0.4178	-0.5736	-0.0407
	7		0.0876	0.8556	2.1902		0.2120	2.0703	5.2998
	8		0.0473	0.9130	3.0602		0.0873	1.4380	4.5763
Averages			0.0393	0.5833	2.3761		-0.0136	0.8534	2.8763

Table 5; FOC (tonne/day) increase due to wave

Intuitively, when a ship runs at slow speed, waves coming from astern would help a vessel to gain additional speed; alternatively save more fuel at slower speed. However, our model results suggest that, at slow ship speed, heavy waves from astern force a ship to consume more fuel oil relative to high speed. This is assumed to be caused largely by imprecise wave speed assumptions.

	Rel. Dir.	**Good** (50 m)	**Normal** (150 m)	**Heavy** (250 m)
Swell Length	**1**	0.176	0.527	0.878
	2	0.169	0.506	0.843
	3	0.285	0.855	1.425
	4	0.484	1.451	2.418
	5	0.131	0.392	0.653
	6	0.245	0.734	1.223
	7	0.043	0.128	0.213
	8	0.245	0.735	1.225
Averages		0.2219	0.6657	1.1094

Table 6; FOC (tonne/day) increase due to long swell

Unlike wind and waves, FOC changes due to swell length do not depend on ship speed in our empirical model. This is due to lack of data, and we expect that much of the swell length effect is reflected in the wave and wind variables already.

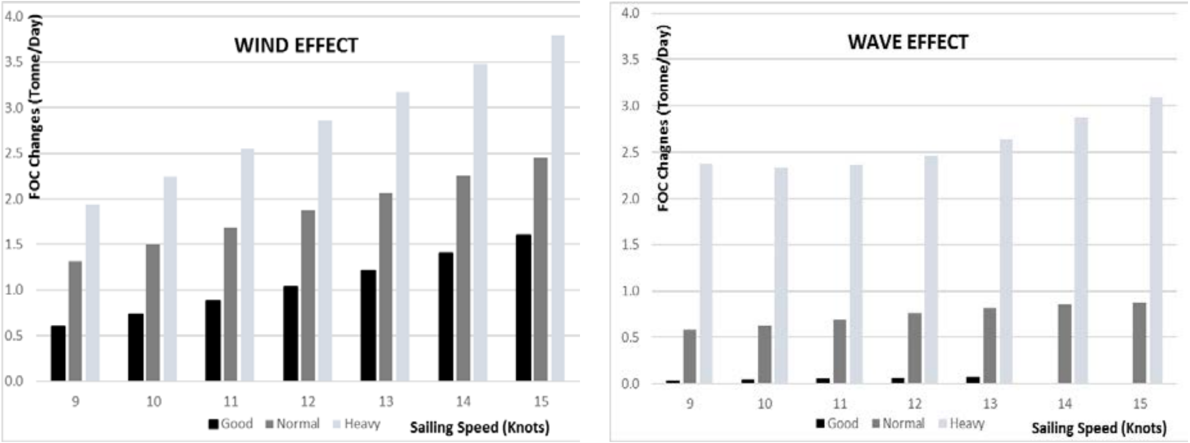

Figure 19; Averages of FOC changes (tonne/day) due to wind and wave

Figure 5 in Section 2.2 shows that wave making resistance is much larger than air resistance, but the result from our model is not in line. This might be simply due to the definition level of good, normal, and heavy wind speed and wave heights, or the empirical model puts more weights on wind resistance relative to wave forces owing to high level of collinearity or misspecification of wave resistance transformation. It could also be that wave resistance might be absorbed into frictional resistance and that draft and ship speed variables represent wave resistance already. To account for this problem, we decide to use the sum of average weather conditions defined as good, normal, and heavy weather.

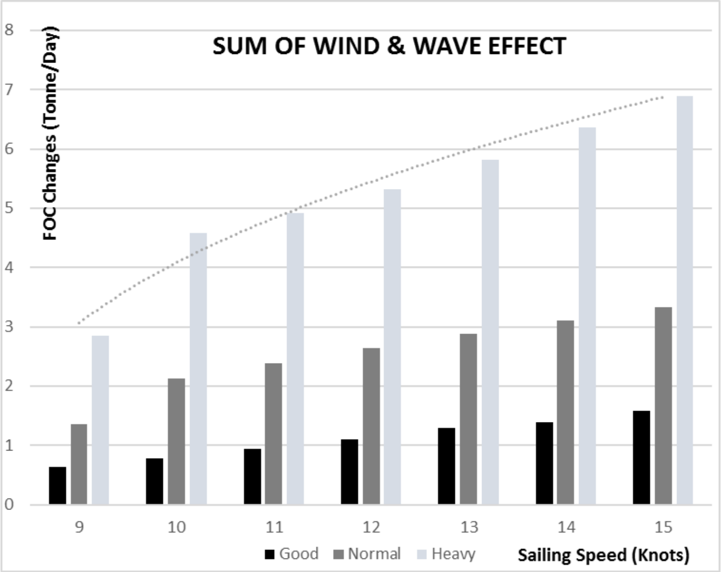

Figure 20; Sum of FOC changes (tonne/day) due to wind and wave

5.3.2 Speed Optimization

In order to optimize sailing speed for tramp vessels, Equation (11) in Section 2.4.1 can be used. However, the theoretical fuel oil consumption is substituted with predicted FOC based on our model. Then, our formula to maximize daily profit can be written as;

$$\mathrm{GS} = \frac{RW}{d/s} - C_R - p \times predicted\ FOC \qquad 29.$$

Then we can modify Equation (29) to get optimal speed as;

$$\mathrm{GS} = \frac{RW}{d/s} - C_R - pks^c \qquad 31.$$

$$\mathrm{cpk}s^{c-1} = \frac{RW}{d} \qquad 32.$$

$$s = \left(\frac{RW}{cpkd}\right)^{\frac{1}{c-1}} \qquad 33.$$

Where GS: gross profit or surplus per day

R: freight rate per tonne of cargo

W: the cargo size

p: price of bunker fuel per tonne

d: distance of each trading route

s: the speed (knots)

c: real-life exponent

k: constant of proportionality

Using historical flat rates[17] and World-scale spot rate of Aframax route TD 7[18] from Jan 2012 to May 2016, the freight rate, R, is calculated. Regarding the cargo on board, W, we assume that SKS tankers carry 80,000 tonnes of cargo for each voyage, and the draft is assumed to be 11.34 meters keeping in mind that the TPC[19] of SKS D-Series is 101.67 metric tonnes, and the summer dead weight tonnage is 119,456 metric tonnes at her summer draft, 15.22 meters (SKS, 2016). We use 380cst bunker price (Clarkson, 2016) for Rotterdam. The constant of

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[17] The flat rate is the $/tonne rate for a defined standard ship that gives a TCE of $12,000/day on any global tanker route. Flat rates are adjusted every 1st Jan based on changes in voyage costs the previous year. (ÅdlandRoar, 2015)

[18] TD7 route is between North Sea (Sullom Voe, UK) and Europe Continent (Wilhelmnshaven, Germany). The distance is around 600 nautical miles, and is a common route for Aframax tankers with 80,000 metric tonnes of cargo. (Clarkson, 2016)

[19] Represents ‘tonnes per centimeter’ of immersion. It is the weight that must be loaded or discharged in order to change the ships mean draught by one centimeter (UK P & I, 2008)

proportionality (*k*) and exponent (c) under the different weather and hull fouling condition is estimated from Figure 18 using MS Excel trend line function. We find that the estimated exponent, *c*, is less than the exponent (3.0) suggested by theory, and that the constant of proportionality, *k*, increases as weather condition deteriorates.

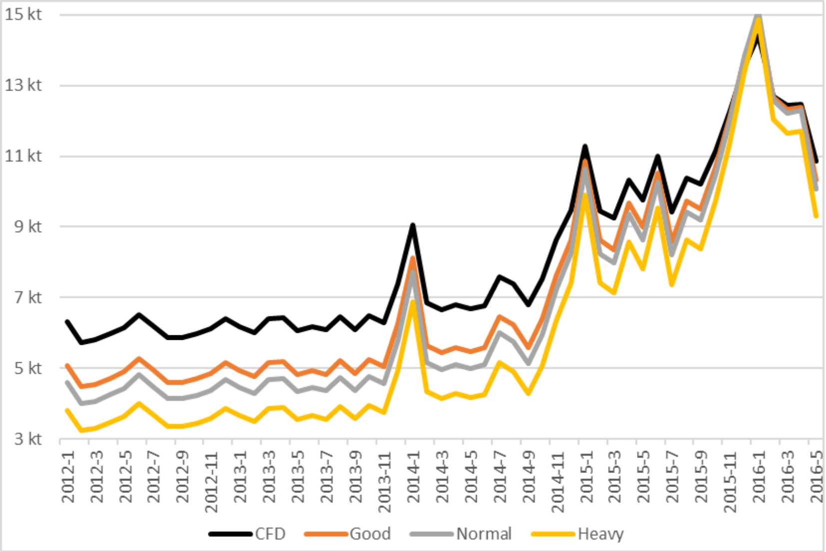

Figure 21, Optimal speeds for TD 7

For the TD 7 route, we derive an optimal speed based on theoretical CFD condition, good, normal, and heavy weather based on our empirical analysis results. The calculated optimal speed values are far below actual operating speeds, and more importantly, real-life operating conditions generate optimal speeds that are substantially below the theoretical speed.

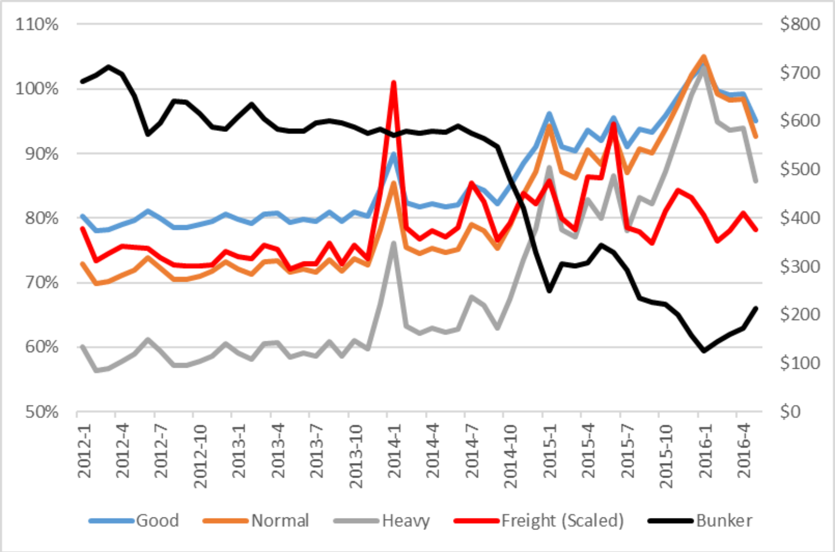

Figure 22, Optimal speed ratios among different weather condition for TD 7

To better illustrate this, we also graph the ratio between the CFD-based optimal speed and equivalent for each weather. The right axis is bunker price ($/tonne), and the left axis is optimal speed ratio of each weather condition to CFD-based optimal speed. The freight rate is scaled just to demonstrate how optimal speed of each weather condition reacts. The optimal speed of weather condition is more sensitive to bunker price than freight rate. In Jan 2014, the skyrocketing freight rate increases optimal speed ratio in normal weather by 10% at best. While in Jan 2015, the inexpensive bunker price makes optimal speed ratios jump almost close to 1; optimal speed under different weather condition is same with CFD-based optimal speed.

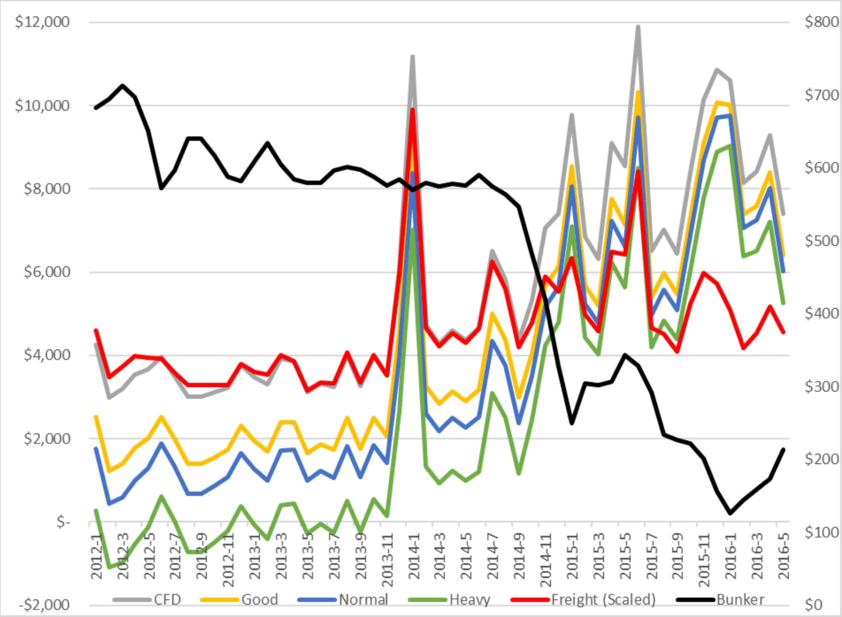

Figure 23, Daily gross profit movement according to each weather condition for TD 7

In order to analyse how weather condition impacts ship owner's profitability, we graph gross profit variation using the calculated optimal speed for each weather condition. Knowing that the minimum service speed is 7 knot because of course keeping and engine fouling, we apply ship's minimum service speed in case optimal speed is less than 7 knot. The right axis is bunker price ($/tonne), and the left axis is a daily gross profit. The freight rate is scaled to illustrate how gross profit of each weather condition responds. When the freight rate is low and the bunker price is high, the CFD-based speeds generate profit while heavy weather condition barely makes it. When either freight rates soar or bunker prices plunge, daily profits go up. In a time of expensive bunker price, the gross profit difference in heavy weather and CFD-based condition is clear, and this is same when the freight rate rises. In times of inexpensive bunkers, the optimal speed difference among weather conditions is small, and gross profit difference decreases as well.

5.4 Limitations

The major drawback of this thesis is the method to capture hull fouling condition. Suitable hull fouling quantification is important since it impacts the magnitude of other key coefficients. An alternative could be analysis of performance using shaft power meter and actual log speed, as a seriously contaminated hull would increase shaft power to maintain the same log speed.

The other critical limitation of this thesis is specification and proper measurement of weather variables. The predicted FOC increase due to waves at slow speed, and waves coming from perpendicularly from the ship (both starboard and port side) at fast speed, increases more fuel oil consumption relative to ahead waves. This doesn’t make sense. There are several important assumptions behind the transformation of wave data. Among them the wave speed assumption is the roughest. The assumed wave speed which is found by the relationship between height and frequency would not be the real speed in a complicated hydrodynamics model. Also, our model does not account for weather force differences due to draft changes. A linearly specified swell length is not accurate as well. A long swell is particularly critical for the ship’s roll and pitch, yet cargo sloshing and ballast tanks condition would make the ship’s movement unpredictable due to dynamically changing center of gravity.

Another limit of this thesis is the speed measure accuracy, which in part depends on the proper calibration of a vessel’s Doppler log.

6. Conclusion

In this thesis, we analyse noon reports, fleet management and performance history of ten SKS-D Series Aframax tankers to estimate how uncertainties in ship operation conditions impacts fuel oil consumption, and thereby speed optimization and profit maximization.

We discover that different hull fouling condition and data quality of each ship cause distinctly large and different coefficients. We strive to capture hull fouling condition as much as possible in order to minimize its effect on other explanatory variables.

The empirical fuel oil consumption model applies transformed weather variables to reflect dynamically interacting weather force based on naval architecture theory and assumptions. The data is truncated to take away extraordinary observations (outliers), and we use MM-estimators to manage the remaining outliers and heteroscedasticity. Using the estimated FOC in defined weather conditions, we replace the theoretical fuel consumption-speed relationship with the ship's real-life exponent and constant of proportionality to maximize gross profit. The real-life exponent to calculate FOC is generally less than what theory suggests (3.0), and the constant of proportionality also increases as the weather condition gets worse.

The maximum gross profit difference between heavy weather and CFD-based condition is clear when the bunker price is expensive, and it reduces sharply for low bunker prices.

The IMO's reinforced air pollution regulations such as emission control areas act like expensive bunker prices. In other words, the gross profit difference depends more on uncertainties in ship operating condition. In this regard, better ship management - sometimes named smart shipping (Stopford, 2016) - would be a solution in order to tackle these issues. This would help the world's maritime industry to meet greener shipping standards, and ultimately make ship owners maximize their profits in challenging environment.

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8. Appendix

Appendix A – Draft Change

Displacement: The weight of the ship, equivalently the underwater volume multiplied by the water density. In the majority of cases the standard density used is 1.025tonnes per cubic metre. To obtain the volume the displacement is divided by whichever density has been used to compile the data. SKS D-class displacement at 98% total is 134645.14m^3.

TPC: Represents tonnes per centimetre of immersion, i.e. the weight that should be loaded or discharged to change the ship’s mean draft by one centimetre. SKS D-class TPC is 101.67MT.

When calculating the displacement tonnes from draft and salinity, the salinity is input at the last step.

$$\text{True Displacement} = \frac{\text{Measured displacement in salt water} \times \text{port salinity}}{Standard\ salinity\ (1.025)}$$ (UK P & I, 2008)

For example, if the salinity in the loading port is 1.015, and the vessel then sails in the Red Sea where the salinity is high, roughly 1.036, the displacement is 135870.70m^3, and 133116.57m^3, respectively.

Hence, the SKS D-series tankers would immerse more by

$$\frac{(135870.70m^3 - 133116.57m^3)}{101.67\text{MT/cm}} = 28cm$$

Appendix B – Wave Variable Generation

As the noon reports do not contain any information about wave speed and period, the average wave speed is assumed as Table 7 using deep water theory.

Wave Height	**Wave Speed**
Less than 0.05 meter	2.92 knots
0.05 ~ 0.3 meter	6.80 knots
0.3 ~ 0.875 meter	7.78 knots
0.875 ~ 1.88 meter	11.66 knots
1.88 ~ 3.25 meter	14.58 knots
3.25 ~ 5 meter	18.47 knots
5 ~ 7.5 meter	21.38 knots
Higher than 7.5 meter	25.27 knots

Table 7: Wave speed assumption. Source: https://en.wikipedia.org/wiki/Wind_wave

The cosine gradient is multiplied in accordance with Equation (8) in order to correct wave encountering speed depending on different encountering angle.

Appendix C – Hull Fouling Quantification

Since the hull fouling condition is continuously changing, the quantification process to catch hull fouling is tricky. The marine growth activity is expected to be slow in cold water; high latitude areas or during the winter season of sub-tropical region. While it is very active in tropical regions specifically when a ship idles more than a week in a shallow anchorage or berthing dolphins. In addition, the quantification process should consider attached barnacles or slimes drop away in fresh water ports Due to limit of port data, we visually conclude fresh water ports where is located in the middle of river or edge of river. The fresh water ports where all SKS tankers visit are found as below using port information sites (FleetMon, 2016). Most such ports are located in the USA.

- Houston, Nerdeland (Texas), Brooklyn, Beaumont, Delaware, Lake Charles, Portland

To begin with, for each ship, hull fouling values are accumulated one by one whenever a ship idles longer than a week in tropical and sub-tropical regions. Once a ship idles at fresh water ports or a ship gets her hull cleaned, the number is set to zero. Next, we exclude observations which contains wind speed faster than 17 knots per hour and wave height higher than 1.25 meters in order to match with the CFD experimental condition which is used to derive fuel consumption formula. Otherwise, the weather forces might distort quantification process. The regression model is;

$$FOC = \beta_0 + \beta_1 \cdot FOC\ Formula + \sum_{k=1}^{m} \theta_k \cdot Weather + hull\ fouling + dry\ dock + u$$

After OLS regression, we plot estimated residuals with time. It is our belief that there should not be any time trend in residuals; it should be randomly distributed as time changes. In addition, except SKS Demini and SKS Doda (Nox Tier II compliant engine), the coefficient of FOC formula should be around one. That is to say, actual FOC observation is well explained by theoretical FOC, and hull fouling quantification captures FOC abnormality well. Otherwise it is an evidence that there is abnormal FOC which is highly likely caused by hull fouling. Using fresh water port information and historical fuel consumption curves of fleet, we compare time trend with fleet fuel consumption history. We find that most of estimated residuals show similar trends with a fuel consumption abnormal curve provided by technical manager. Until residual time trends disappear as much as possible, and the coefficient of fuel consumption formula come close to 1, the quantification is edited; assign larger values when residual trend for some period is distinctly positive and vice versa. Each ship's hull fouling quantification is combined in one data sheet to generalize quantified values. We note that the coefficients of hull fouling variables are ship specific and vary between 0.5 and 2, i.e. each long idling period adds to fuel consumption by 0.5 to 2 tonnes per day. Until statistically significant ship specific variables disappears, hull fouling variable of each ship is multiplied or divided. However, we could not make some of ship specific variables (Demini, Doda, Delta) insignificant.

Appendix D – Idling & Sailing Regions

When a ship sails in specific regions, it is expected that fuel oil consumption varies due to draft changes caused by salinity differences. The binary dummies for high salinity areas such as the Mediterranean Sea and Atlantic Ocean, and the salinity areas such as Black Sea, North Sea and Baltic Sea are distributed by matching the ship's reported position with the below defined regions. In order to distribute idling region dummies, the last reported position is assumed to be the position where a ship idles. Likewise, the binary dummies are assigned by matching the last reported position and the below defined geographical regions.

Regions	**Idling / Sailing**	**Latitude**		**Longitude**		**Expected Sign**
		Max	**Min**	**Max**	**Min**	
Mediterranean Sea	Sailing	N31	N41	E28	E37	- (high salinity)
		N29	N45	W5	E28	
Atlantic Ocean	Sailing	S2	N27	W57	W26	- (high salinity)
Black Sea	Sailing	N40	N47	E27	E42	+ (low salinity)
North & Baltic Sea	Sailing	N54	N61	E1	E24	+ (low salinity)
West Africa	Idling	S33	N6	W14	E17	+ (fouling risky)
American Gulf	Idling	S5	N29	W37	W97	+ (fouling risky)
Red Sea & Middle East	Idling	N15	N30	E32	E74	+ (fouling risky)
South East Asian Sea	Idling	S7	N22	E97	E121	+ (fouling risky)
Australia	Idling	S38	S11	E110	E156	+ (fouling risky)

Table 8: Geographic position distribution for Sailing and Idling regions.

Appendix E – Ship Age & Cumulative Distance

Since the delivery date and cumulative sailing distance of all ships are different, the ship age variable needs to reflect these distinctions. As the noon reports are accumulated from January 2012, the ship's daily age variable should start with ship's actual daily age which can be found by the delivery date of each ship. Though it is unavailable to find exact moving distance of each ship until the January 2012, the starting cumulative distance is estimated by the multiplication between average daily sailing distance and days after delivery to January 2012. For whole period, the average daily sailing distance of all ships is 165 nautical miles. The results are summarized in Table 9.

Vessel Name	Days	Cumulative Distance
SKS Darent	325	53,742 NM
SKS Dee	535	88,275 NM
SKS Delta	716	118,140 NM
SKS Demini	0	0
SKS Doda	0	0
SKS Dokka	412	67,980 NM
SKS Donggang	261	43,065 NM
SKS Douro	596	98,340 NM
SKS Doyles	473	78,045 NM
SKS Driva	657	108,405 NM

Table 9: Days and Cumulative distance

Appendix F – Estimated FOC increase depending on Weather

All values are based on 11.34 meters of SKS D-Series' mean draft of SKS tankers.

	Speed	**Good**	**Normal**	**Heavy**	**Speed**	**Good**	**Normal**	**Heavy**
Wind	8 knot	0.4868	1.1372	1.6388	9 knot	0.6029	1.3179	1.9404
Wave		0.0317	0.5680	2.4923		0.0393	0.5833	2.3761
Swell		0.2219	0.6657	1.1094		0.2219	0.6657	1.1094
Sum		0.7405	2.3709	5.2405		0.8642	2.5669	5.4260
	Speed	**Good**	**Normal**	**Heavy**	**Speed**	**Good**	**Normal**	**Heavy**
Wind	10 knot	0.7336	1.5008	2.2444	11 knot	0.8788	1.6860	2.5506
Wave		0.0478	0.6272	2.3332		0.0572	0.6966	2.3634
Swell		0.2219	0.6657	1.1094		0.2219	0.6657	1.1094
Sum		1.0033	2.7937	5.6870		1.1579	3.0483	6.0234
	Speed	**Good**	**Normal**	**Heavy**	**Speed**	**Good**	**Normal**	**Heavy**
Wind	12 knot	1.0385	1.8735	2.8591	13 knot	1.2128	2.0632	3.1698
Wave		0.0675	0.7612	2.4667		0.0787	0.8134	2.6433
Swell		0.2219	0.6657	1.1094		0.2219	0.6657	1.1094
Sum		1.3279	3.3003	6.4352		1.5134	3.5423	6.9225
	Speed	**Good**	**Normal**	**Heavy**	**Speed**	**Good**	**Normal**	**Heavy**
Wind	14 knot	1.4016	2.2552	3.4828	15 knot	1.6050	2.4529	3.7981
Wave		-0.0136	0.8534	2.8763		-0.0250	0.8811	3.0878
Swell		0.2219	0.6657	1.1094		0.2219	0.6657	1.1094
Sum		1.6099	3.7743	7.4686		1.8019	3.9997	7.9954

Table 10 Estimated FOC increase depending on each weather condition and ship speed

Appendix G – Data Quality of Each Ship (Regression Results)

	R-SQ Adj (%)	Coeff. Theory	Jarque Bera	Breusch Pagan	Reset	Dock Ton/day	VIF	Obs	Exclude
Darent	81.85	1.02	0.01	0.10	0.00	-3.94	1.60	633	-
	86.40	1.04	0.39	0.68	0.00	-3.55	1.41	376	Heavy Weather
	73.00	0.90	0.56	0.22	0.00	-2.22	1.61	176	Draft, Speed, Fuel Limit
Dee	83.97	0.91	0.00	0.00	0.00	-2.96	1.70	592	-
	92.02	0.95	0.00	0.65	0.00	-4.80	1.48	330	Heavy Weather
	83.11	0.84	0.14	0.44	0.40	-3.13	1.77	170	Draft, Speed, Fuel Limit
Delta	89.10	1.08	0.00	0.26	0.00	-4.01	1.65	631	-
	92.80	1.08	0.00	0.66	0.00	-3.88	1.54	406	Heavy Weather
	78.40	0.80	0.18	0.00	0.15	-2.98	1.75	231	Draft, Speed, Fuel Limit
Demini	73.17	0.92	0.00	0.00	0.01	-	1.87	629	-
	84.54	0.96	0.13	0.00	0.05	-	1.57	198	Heavy Weather
	87.25	1.03	0.35	0.10	0.32	-	32.15	92	Draft, Speed, Fuel Limit
Doda	87.15	1.10	0.00	0.00	0.88	-	1.70	614	-
	93.40	1.07	0.00	0.00	0.43	-	1.38	340	Heavy Weather
	90.47	0.94	0.00	0.00	0.00	-	1.55	204	Draft, Speed, Fuel Limit
Dokka	84.67	0.98	0.00	0.73	0.01	-1.87	1.53	631	-
	90.63	0.98	0.00	0.25	0.01	-3.14	1.41	318	Heavy Weather
	86.63	0.87	0.07	0.39	0.31	-3.04	1.75	162	Draft, Speed, Fuel Limit
Donggang	87.83	1.01	0.00	0.01	0.00	-0.86	1.58	644	-
	92.69	1.06	0.00	0.01	0.00	-1.54	1.36	357	Heavy Weather
	82.85	0.84	0.34	0.09	0.33	-0.29	1.43	239	Draft, Speed, Fuel Limit
Douro	77.82	1.02	0.00	0.74	0.00	-8.00	1.89	590	-
	83.95	1.05	0.00	0.19	0.00	-8.00	1.76	300	Heavy Weather
	71.45	0.83	0.00	0.00	0.00	-5.93	2.09	156	Draft, Speed, Fuel Limit
Doyles	79.47	1.01	0.00	0.00	0.00	-2.65	1.70	676	-
	86.54	1.03	0.00	0.00	0.00	-3.33	1.55	348	Heavy Weather
	70.91	0.94	0.00	0.00	0.49	-3.18	1.85	185	Draft, Speed, Fuel Limit
Driva	80.52	1.09	0.00	0.00	0.00	-8.00	1.69	716	-
	85.20	1.09	0.00	0.44	0.02	-7.20	1.56	347	Heavy Weather
	68.51	0.80	0.07	0.00	0.69	-4.22	1.85	172	Draft, Speed, Fuel Limit

Table 11 Regression results of each ship for data quality analysis. Source; SKS D-Series Noon reports

Appendix H – MM & OLS-Estimators Including & Excluding Ship Specific Variables

	MM-Inc	MM-Exc	OLS-Inc	OLS-Exc
	Propulsion Variables			
FOC Formula	1.009***	1.008***	0.963***	0.960***
	(132.60)	(132.13)	(111.03)	(109.14)
Ocean Current	0.494**	0.421*	3.641***	3.928***
	(2.75)	(2.32)	(8.80)	(8.66)
	Weather Variables			
Wind 1	0.00527***	0.00521***	0.00426***	0.00411***
	(15.90)	(15.59)	(15.56)	(14.70)
Wind 2	0.00525***	0.00538***	0.00398***	0.00397***
	(10.62)	(10.87)	(8.69)	(8.47)
Wind 3	0.00653***	0.00613***	0.00518**	0.00421*
	(4.13)	(3.73)	(3.03)	(2.38)
Wind 4	-0.000308	0.00168	0.000677	0.00219
	(-0.06)	(0.32)	(0.12)	(0.38)
Wind 5	0.00505*	0.00611*	0.00465	0.00550*
	(2.02)	(2.40)	(1.89)	(2.19)
Wind 6	0.0154**	0.0168**	0.0146**	0.0155**
	(2.76)	(3.12)	(2.91)	(3.02)
Wind 7	0.0111***	0.0111***	0.0121***	0.0113***
	(6.46)	(6.15)	(7.38)	(6.70)
Wind 8	0.00628***	0.00581***	0.00546***	0.00511***
	(12.77)	(11.40)	(11.25)	(10.30)
Wave 1	0.000252***	0.000261***	0.000287***	0.000291***
	(11.93)	(12.50)	(16.73)	(16.85)
Wave 2	0.000341***	0.000334***	0.000420***	0.000414***
	(9.09)	(8.23)	(15.09)	(14.76)
Wave 3	0.00138***	0.00132***	0.00140***	0.00131***
	(7.29)	(6.50)	(8.16)	(7.20)
Wave 4	-0.00518	-0.00511*	-0.00569*	-0.00553*
	(-1.82)	(-2.15)	(-2.55)	(-2.47)
Wave 5	-0.00134***	-0.00123***	-0.00125***	-0.00117***
	(-6.14)	(-5.94)	(-5.42)	(-5.09)
Wave 6	-0.00754***	-0.00797***	-0.00590***	-0.00601***
	(-6.07)	(-5.78)	(-4.45)	(-4.38)
Wave 7	0.00166***	0.00169***	0.00221***	0.00219***
	(8.25)	(7.63)	(12.98)	(12.09)
Wave 8	0.000379***	0.000380***	0.000482***	0.000486***
	(13.63)	(14.36)	(17.85)	(17.92)
Swell Length 1	0.362*	0.351*	0.748***	0.726***
Swell Length 2	0.469***	0.337*	0.629***	0.482***
Swell Length 3	0.627***	0.570***	0.867***	0.838***
Swell Length 4	1.046***	0.967***	0.948***	0.840***
Swell Length 5	0.226	0.261*	0.414**	0.429**
Swell Length 6	0.558***	0.489***	0.798***	0.765***
Swell Length 7	0.191	0.0852	0.260	0.124
Swell Length 8	0.516***	0.490***	0.790***	0.714***
	Ship specific Variables			
Dee	-0.295		-0.0671	
Delta	1.386***		1.597***	
Demini	-3.272***		-4.809***	
Doda	-1.081***		-0.506	
Dokka	-0.151		-0.0561	
Donggang	-0.506		-0.164	
Douro	0.171		-0.456	
Doyles	-0.599*		-0.224	
Driva	-0.0662		0.226	
	Dry-docking and Hull Fouling			
Dry-docking	-4.874***	-4.226***	-4.742***	-4.041***
	(-29.54)	(-26.54)	(-26.71)	(-23.33)
Hull Fouling	0.557***	0.714***	0.538***	0.668***
	(18.06)	(24.85)	(20.76)	(30.77)
Constant	3.749***	3.288***	5.039***	4.783***
	(13.25)	(16.08)	(17.87)	(20.79)
N	5938	5938	5938	5938
R^2	N/A	N/A	0.8083	0.7983

Table 12 Regression results of final data, *t* statistics in parentheses, * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$