

# VOYAGE OPTIMISATION: PREDICTION OF SHIP SPECIFIC FUEL CONSUMPTION FOR ENERGY EFFICIENT SHIPPING

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## Abstract

Voyage optimization is a technology to predict the ship performance in various sea states and current conditions, and based on the performance of the ship to assist ship masters in route selection. The targets of increasing energy efficiency and reducing Green House Gas (GHG) emission in the shipping industry can be achieved by voyage optimization. However, the practical and accurate prediction of ship operational performance is the prerequisite to achieve targets. In this paper, empirical fuel consumption prediction approach based on Kwon's added resistance modeling (Kwon, Y.J. 2008) with a specific application to Suez-Max oil tanker is proposed. By using this approach, an operational performance model can be created for each loading condition, speed and relative wave heading on each Suez-Max oil tanker. The accuracy of operational performance prediction for sea-going vessels can be further enhanced by utilizing noon report data of a specific vessel. The operational performance model enables the user to investigate the relation between fuel consumption and the various sea states that the ship may encounter in its voyage. The potential results of operational performance model are collected in the ship operational performance database. Based on the database and real time climatological information, the ships' various courses can be evaluated according to a number of objectives including minimization of voyage time, maximization of safety, and minimization of fuel consumption using single or multi-objective methodologies. By utilizing a decision support tool, the ship's crew may now select the optimum course according to their preference.

Energy Efficiency of Operation (EEO) is defined as an indicator to illustrate the main engine fuel consumption efficiency in the study. The results of the two case studies indicate that the modified empirical approach for the Suez-Max oil tanker can predict the fuel consumption reasonably well considering the uncertainty factors in the ship actual onboard data recording process. In future work, the modified empirical approach will be applied to other vessel sizes, and extended to various other commercial ship categories.

*Keywords:* Voyage optimization, Energy efficient shipping, Ship operation, Fuel saving,  $CO_2$  emission reduction

## 1. INTRODUCTION

Energy efficient shipping is required in reducing Green House Gas (GHG) emission. The continuous growth of the world population and of its standard of living, together with depletion of local resources, increases the dependency of the world economy on international trade. Ship transport accounts for 90% of world trade, and it is predicted that the cargo transported by ships will triple by the year 2020. For 2007, it is estimated that shipping emitted 1,046 million tonnes of  $CO_2$ , which accounts for 3.3% of the global  $CO_2$  emission during that year. International shipping  $CO_2$  emission is estimated to account for 2.7% of the global  $CO_2$  emission in 2007 (IMO, 2009).

In addition to  $CO_2$  reductions, energy efficient shipping is also required in fierce shipping competition. Although the commercial ship engines burn the cheapest 'bunker fuel', the cost of IFO 180 has risen sharply with other petroleum products, increasing by more than 250% (from \$170/ton) since 2002 and 160% (from \$230/ton) since 2005, to nearly \$700/ton today. In general cost classification, the fuel

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consumption accounts for 76% of voyage costs, and voyage costs account for 40% of the total cost of running ships (Stopford, M. 2009). Currently, for some ships fuel cost is around 60% of the running costs. The competition between shipping companies is becoming fiercer with the increasing fuel price.

Voyage optimization is a procedure where an optimal route is selected based on weather forecast, seas, currents, and the ship performance characteristics with respect to the safety, energy consumption and environment. For a commercial ship, the high energy efficiency is the primary target in voyage optimization.

In general, voyage optimization can be divided into fleet planning level and specific ship planning level. Specifically, the shipping category can be concluded into industrial, tramp, and liner shipping (Christiansen, M., Fagerholt, K., & Ronen, D. 2004). The characteristics of these modes of operations are described in the following:

- Industrial shipping

In industrial shipping, the cargo owner or shipper also controls the ships. Industrial operators try to ship all their cargoes at minimal cost. The target in industrial shipping is to minimize costs while servicing all cargo transportation requests.

- Tramp shipping

Tramp ships follow the available cargoes, like a taxi. A tramp shipping company may have a certain quantity of contract cargoes that it is committed to carry, and tries to maximize the profit from optional cargoes. The objective of tramp shipping is normally to maximize profit per time unit.

- Liner shipping

Liners operate according to a published itinerary and schedule similar to a bus line. Liner shipping has a significant difference compared to the other two types of shipping operations: industrial and tramp shipping. The differences can be shown with regards to four aspects: route and schedule design; fleet size and mix; fleet deployment and Cargo booking.

It is important to realize that operating efficiency cannot be only measured in terms of fuel consumption. Normally, the voyage optimization has multiple objectives, consists of a few attributes, such as minimizing costs regardless of arriving time; punctual time of arrival; safety and passenger comfort or a combination of the criteria. In most cases, improving efficiency in one attribute may degrade efficiency in other. Each attribute requires a weighting of importance. For example, for one shipping company's business model, they prefer to have on time arrival, shorter transit time than reduced fuel consumption; for another company's business model, they pay more attention to 'green service'- low carbon shipping.

The accuracy of selecting optimum route in voyage optimization depends on the following three points.

- The accuracy of the ship operational performance prediction
- The accuracy of weather forecasts
- The capability of optimization algorithm applied

This paper will focus on the development of accurate and practical ship operational performance prediction methodology to optimize voyage route and achieve energy efficient shipping whilst adhering to the safety of the ships. The reasonable and practical ship added resistance modeling is the most important basis of providing good ship operational performance prediction. A modified empirical method based on Kwon's added resistance modeling (Kwon, Y.J. 2008) is proposed to estimate the added resistance of Suez-max oil tanker. The accuracy of ship operational performance can be further enhanced based on the recorded ship operational performance from noon report data. The effective range of this modified empirical method can further be extended to other tanker size and various commercial ship categories.

After the development of the fuel consumption prediction model which also include the ship added resistance modeling, a self-refined ship performance database system can be built up. The database includes the fuel consumption rate under each sea state, speed, ship heading direction, draught, etc. This database also involves the feedback from captains and fleet managers, and the ship operational performance database can be updated by the user based on the real-time ship performance. Alternatively, condition monitoring and added resistance study system can be utilized to update the database and refine the method. Based on the characteristics of each specific ship, the database could provide more accurate and realistic ship performance data to enhance the users' confidence in using the voyage optimization system. A decision support tool can be installed on board and the optimum course can be selected according to the users' preference. The users of the voyage optimization system could decide the best route to go by weighting the attributes (e.g. passage time, fuel consumption, etc.) based on the suggestions shown on chart.

## 2. VOYAGE FUEL CONSUMPTION PREDICTION IN ACTUAL OPERATIONAL CONDITIONS

An empirical voyage fuel consumption prediction model is proposed in this paper by using a ship's characteristics for a specific ship type. The model can be adjusted to other type of ships. The modified empirical method for added resistance modeling for Suez-Max oil tanker is proposed as part of the ship operational performance prediction. It is developed to enhance the accuracy of added resistance prediction by modifying the Kwon's added resistance modeling method (Kwon, Y.J. 2008) to focus on the specific ship category by taking into account more details of the specific ship's characteristics. The proposed model for specific in generic form can be seen in Figure 1. The dashed boxes on the left dedicate the general inputs of the modified empirical method.

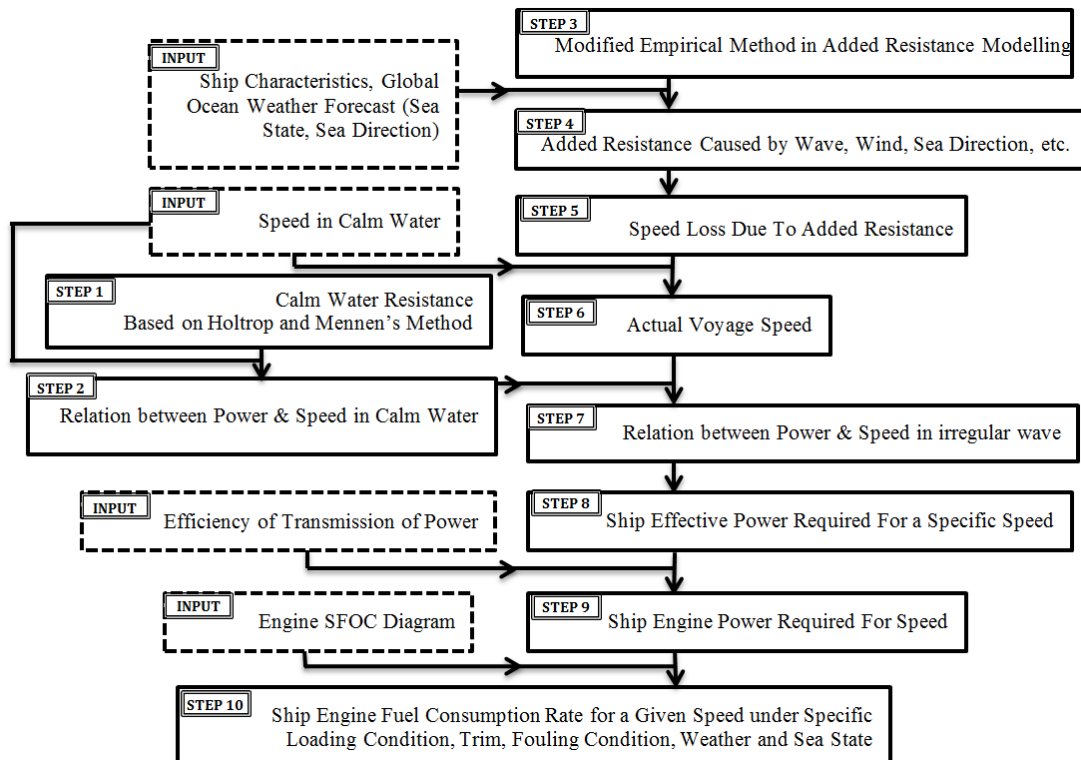


Figure 1. Flow Diagram of voyage fuel consumption prediction in actual operational conditions

### 2.1 CALM WATER RESISTANCE MODELLING

The well-known Holtrop and Mennen's method is used to estimate the resistance of the ship. (Holtrop and Mennen, 1982). It provides a prediction of the total resistance of a wide variety of ship sizes,

hullforms and range of Froude numbers. In our work, the method is used to estimate the ship's total resistance in calm water.

$$R_{total} = R_F(1 + k_1) + R_{APP} + R_w + R_B + R_{TR} + R_A \quad (1)$$

Where:

$R_{total}$  ship total resistance in calm water  
 $R_F$  frictional resistance according to the ITTC-1957 friction formula

$$R_F = 0.5\rho V^2 S C_F \quad (2)$$

$$C_F = 0.075 / (\log_{10} Re - 2)^2 \quad (3)$$

$$Re = \text{Reynold's No.} = \rho V L / \mu \quad (4)$$

$1 + k_1$  form factor describing the viscous resistance of the hull form in relation to  $R_F$   
 $R_{APP}$  resistance of appendages

The appendage resistance can be determined from:

$$R_{APP} = 0.5\rho V^2 S_{APP}(1 + k_2)_{eq} C_F \quad (5)$$

Where  $\rho$  is the water density,  $V$  the speed of the ship,  $S_{APP}$  the wetted area of the appendages,  $1 + k_2$  the appendage resistance factor and  $C_F$  the coefficient of frictional resistance of the ship according to the ITTC-1957 formula.

$R_w$  wave-making and wave-breaking resistance

$$R_w = c_1 c_2 c_5 \nabla \rho g \exp\{m_1 F_n^d + m_2 \cos(\lambda F_n^{-2})\} \quad (6)$$

$R_B$  additional pressure resistance of bulbous bow near the water surface

$$R_B = 0.11 \exp(-3P_B^{-2}) F_{ni}^3 A_{BT}^{1.5} \rho g / (1 + F_{ni}^2) \quad (7)$$

$R_{TR}$  additional pressure resistance of immersed transom stern

$$R_{TR} = 0.5\rho V^2 A_T c_6 \quad (8)$$

$R_A$  model-ship correlation resistance

$$R_A = 0.5 \rho V^2 S C_A \quad (9)$$

$$C_A = 0.006L + 100^{-0.16} - 0.00205 + 0.003\sqrt{L/7.5} C_B^4 c_2 (0.04 - c_4) \quad (10)$$

Based on Holtrop and Mennen's method, the calm water resistance / displacement of the specific vessel under each Froude number can be estimated. In calm water, the relation between total resistance / displacement and Froude number is shown in Figure 2.

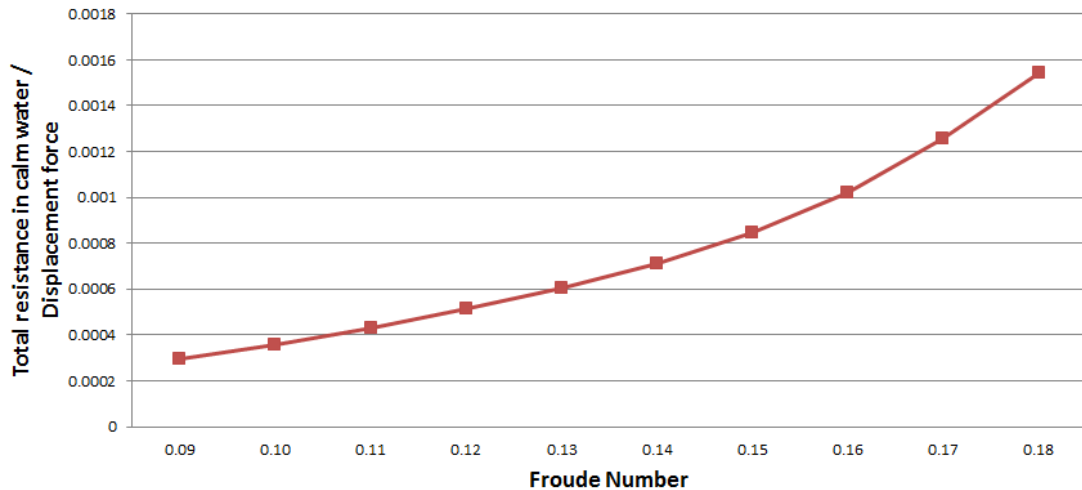


Figure 2. Relation between Total Resistance in Calm Water / Displacement and Froude Number

Then the total resistance in calm water can be converted to effective power by using Equation 11.

$$P_E = R_{total} * V \tag{11}$$

The next step is to calculate and evaluate the relation between engine power and speed based on the propulsion coefficient from engine power to effective power. The propulsion coefficient includes the power transmission efficiency and the propeller efficiency, an example of propulsion coefficient is shown in Figure 3. The propulsion coefficient can be concluded based on the specific ship operational performance conditions and sea trial data.

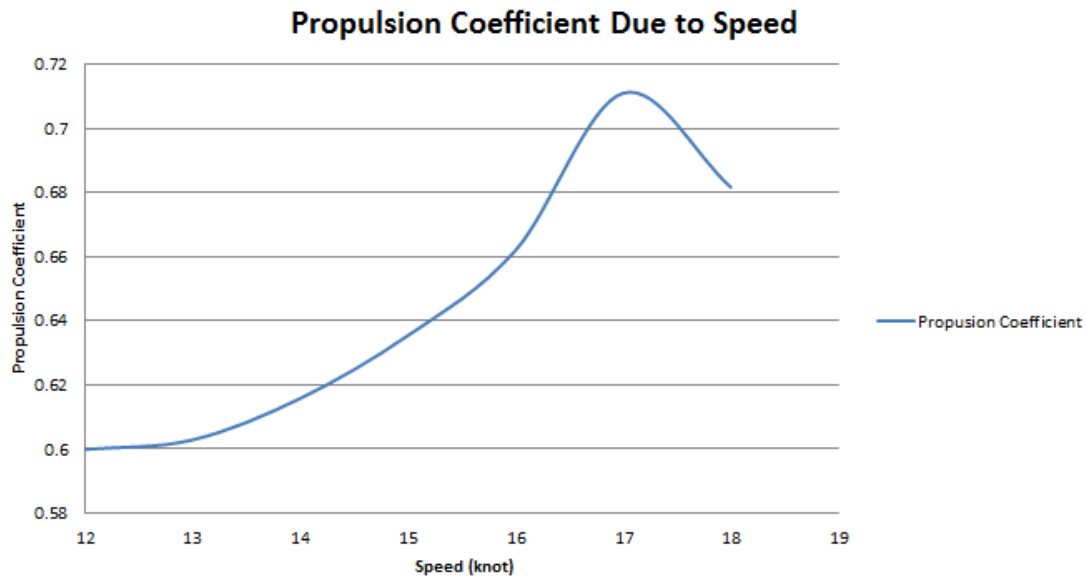


Figure 3. Propulsion Coefficient

The final step is to obtain the relation between engine fuel consumption and ship speed in calm water under specific loading condition. Based on the sea trial data, the specific fuel oil consumption (SFOC) of the installed main engine can be computed. The output of engine power is converted to load percentage of specified Maximum Continuous Rating (MCR). Then the relation between engine output power and fuel consumption can be built up by calculating 'Power required \* SFOC'. Up to this step, the relationship between power and speed in calm water can be clearly illustrated.

2.2 ESTIMATING ADDED RESISTANCE IN SHIP OPERATIONAL PERFORMANCE PREDICTION MODEL

Kwon’s added resistance modeling (Kwon, Y.J. 2008) is an approximate method for the prediction of loss of speed due to added resistance in rough weather condition (irregular waves and wind). The advantage of this method is the practical prediction of the involuntary loss of speed due to the effect of weather loading on an advancing displacement type of ship.

The weather effect is converted to the speed loss from ship speed in calm water; the percentage of speed loss for Suez-Max oil tanker is shown in equation 11 and 12. The formulas of modified empirical method are shown in Table1, 2 and 3

$$\frac{\Delta V}{V_1} 100\% = C_{\beta} C_U C_{Form} \tag{11}$$

$$V_2 = V_1 - \left(\frac{\Delta V}{V_1} 100\%\right) \frac{1}{100\%} V_1 = V_1 - (C_{\beta} C_U C_{Form}) \frac{1}{100\%} V_1 \tag{12}$$

Where,

$V_1$  Design (nominal) operating ship speed in calm water conditions (no wind, no waves), Given in m/s.

$V_2$  Ship speed in the selected weather (wind and irregular waves) conditions, given in m/s. Note:  $V_2 < V_1$ .

$\Delta V = V_1 - V_2$  Speed difference, given in m/s.

$C_{\beta}$  Direction reduction coefficient, dependent on the weather direction angle (with respect To the ship’s bow) and the Beaufort number BN (Bft), as shown in Table 1.

$C_U$  Speed reduction coefficient, dependent on the ship’s block coefficient  $C_B$ . The loading condition and the Froude number  $F_n$ , as shown in Table 2.

$C_{form}$  Ship form coefficient  $C_{form}$ , as shown in Table 3.

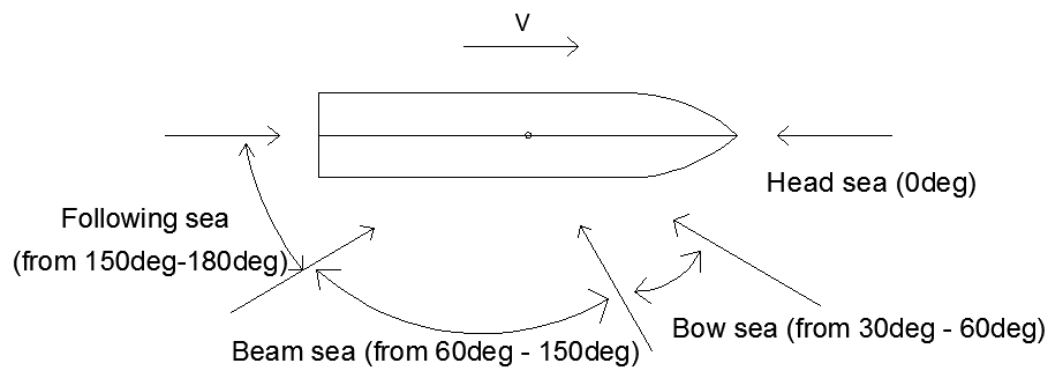


Figure 4. Ship heading directions

Table 1: Direction reduction coefficient  $C_{\beta}$  due to weather direction

Weather direction	Direction angle (with respect to the ship's bow) (deg)	Direction reduction coefficient $C_{\beta}$
Head sea (irregular waves) and wind	0	$2C_{\beta}=3.0$
Bow sea (irregular waves) and wind	30-60	$2C_{\beta}=2.3-0.03*((BN-4)^2)$
Beam sea (irregular waves) and wind	60-150	$2C_{\beta}=1.5-0.06*((BN-6)^2)$

Table 2: Speed reduction coefficient  $C_U$  due to Block coefficient  $C_b$

Block coefficient $C_b$	Ship loading conditions	Speed reduction coefficient $C_u$
0.8	loaded or normal	$2.6-13.1*Fn-15.1*(Fn^2)$
0.85	loaded or normal	$3.1-18.7*Fn+28.0*(Fn^2)$
0.8	ballast	$3.0-16.3*Fn-21.6*(Fn^2)$
0.85	ballast	$3.4-20.9*Fn+31.8*(Fn^2)$

Table 3: Ship form coefficient  $C_{form}$  due to ship categories and loading condition

Type of (displacement) ship	Ship form coefficient $C_{form}$
Suez-Max oil tanker in loaded loading condition	$0.6BN+(BN^6.5)/(2.7*(\nabla^{2/3}))$
Suez-Max oil tanker in ballast loading condition	$0.8BN+(BN^6.5)/(2.7*(\nabla^{2/3}))$

Ocean weather forecast is an important input in voyage optimization, especially in added resistance modeling. The routes selection in voyage optimization is based on the evaluation of ship operational performance in each alternative route, the accuracy of the ocean weather forecast and the frequency of updating the forecast have a significant impact on the quality of voyage optimization. Therefore, the program of ocean weather forecast input and update in voyage optimization is important. Based on the 'GRIB2' - ocean weather forecast file from NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION (NOAA), the decode program has been written by the authors to read and output the global ocean weather forecast, as shown in Figure 5, which includes significant wave height, wave direction and frequency, swell, wind speed and directions

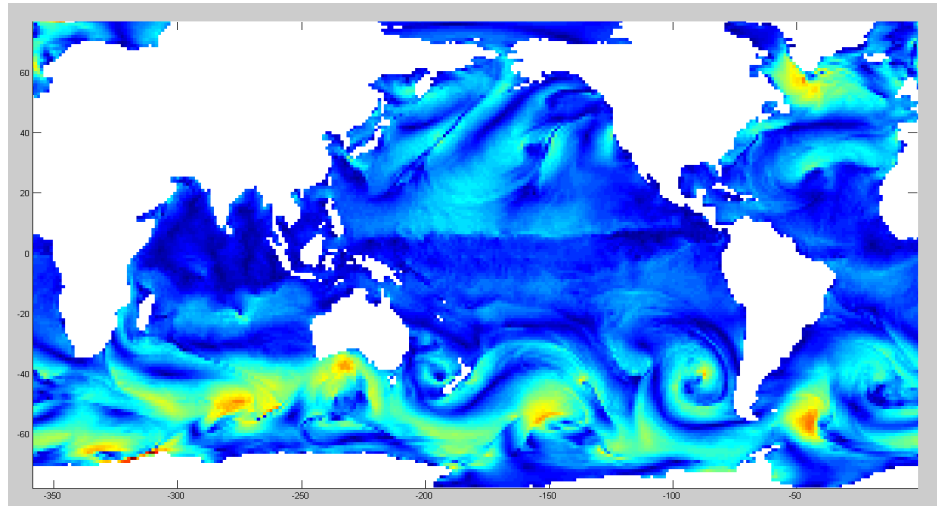


Figure 5. Screenshot from decode program, Graph of Global Ocean Weather Forecast

Noon report is an actual on board record of operational performance of the ship. The parameters, as shown in Table 4, provide a dedicated description of the ship performance. The ship operational performance can be compared between the recorded noon data and the predicted value from modified empirical method as shown in case studies 1 and 2. The modified empirical method in added resistance modeling can be further refined to adapt to the recorded noon report data for each specific ship, which contributes to enhance the accuracy of ship operational performance prediction.

Table 4: Parameters in noon report

Date and time	Achieved speed	Beaufort number (strongest and average)
Port or position	Order speed	Wind direction (strongest and average)
Destination	Loading condition	Main engine fuel consumption
Observed distance	Mean draught	Shaft power
Distance to go		etc.

In an overview, the modified empirical method in added resistance modeling is proposed to generate the ship operational performance model for Suez-Max oil tanker. The accuracy of the model can be further refined by utilizing the recorded ship operational performance from noon report. For each specific ship, the refined ship operational model can provide the most accurate and practical ship fuel consumption rate under the relevant sea states, propulsion efficiency, loading conditions, trim, fouling condition, and currents. In future work, the modified empirical approach can be applied to predict the ship operational performance for other types of tanker ships, and can be extended to other commercial ship categories, such as bulk carrier and container ships.

### 3. CASE STUDY AND COMPARISON

The ‘Energy Efficiency of Operation’ (EEO) is defined as an indicator to illustrate the main engine fuel consumption efficiency in this study.

$$EEO = \frac{\text{Fuel consumption (t - fuel)}}{\text{Voyage distance (nautical mile) * Cargo onboard (t - cargo)}}$$

The unit of EEO is tonne of heavy fuel consumption per tonne of cargo and per nautical mile.

EEO attributes to the calculation of EEOI, which is the key parameter in Ship Energy Efficiency Management Plan (SEEMP)

In order to enhance the accuracy of ship operational performance prediction, the predicted EEO based on the modified model and the recorded EEO from noon report data were compared and analyzed in two case studies.

The uncertainty factors affecting the accuracy of ship operational performance prediction model include:

- The sea state and weather condition may change considerably during each 24 hours (24 hours are the normal recorded period in noon report)
- Errors exist in recording of wave height, wind speed, valid average speed and power
- Lack of well completed noon data record

#### 4.1 CASE STUDY 1 – ‘SUEZ-MAX OIL TANKER A’



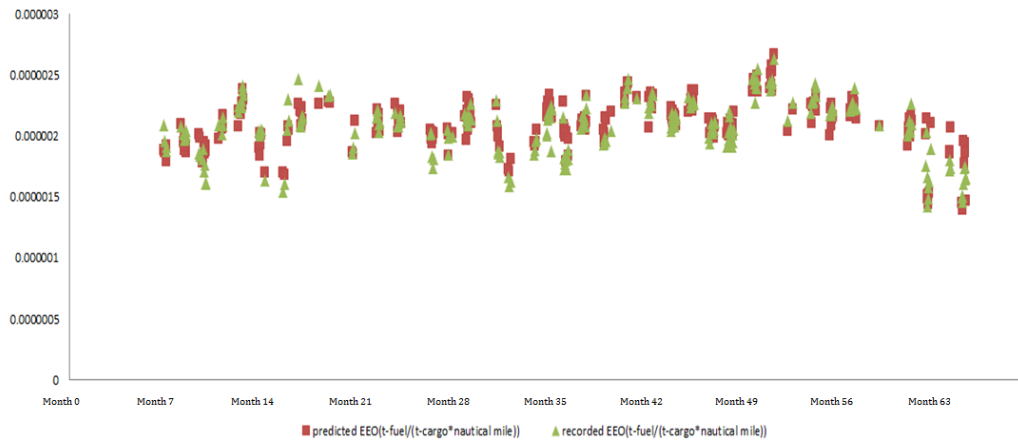


Figure 6. Comparison between predicted EEO and recorded EEO of ‘Suez-Max oil tanker A’

The average difference between predicted EEO using the proposed method and recorded EEO of ‘Suez-Max oil tanker A’ is 5.12%. On the other hand using the original Kwon’s ship added resistance model the average difference between predicted EEO and recorded EEO of Suez-Max oil tanker A was 14.7%. Certainly, the modified model improves the accuracy significantly.

Under each sea state (sorted by Beaufort number), the predicted EEO and recorded EEO with each weather direction were compared, as shown in Figure 7, for BN = 3 as an example. EEO results for ship operational performance by using the proposed method is compared to the actual noon data recorded on board.

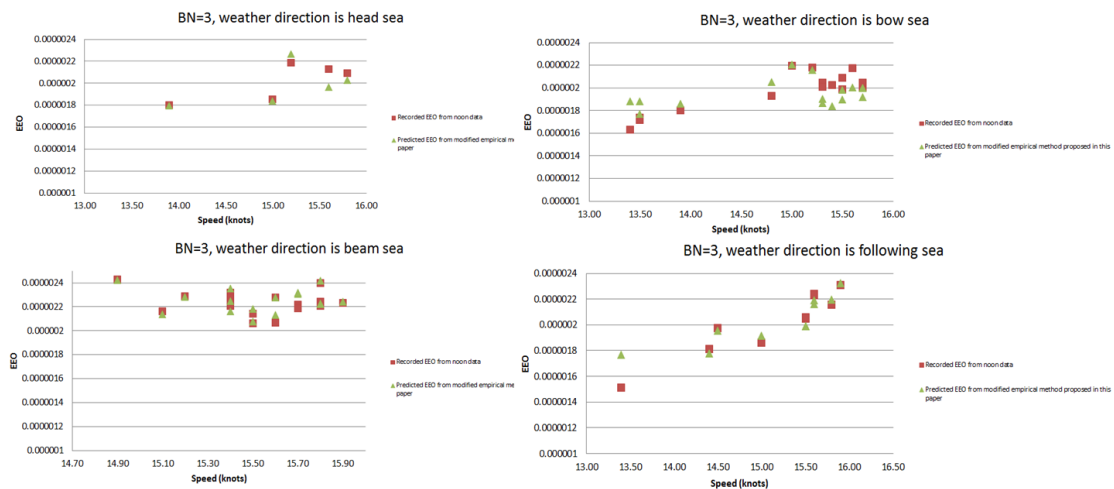


Figure 7. Comparison between predicted EEO and recorded EEO of ‘Suez-Max oil tanker A’ with each weather direction under the BN = 3.

### 3.1 CASE STUDY 2 – ‘SUEZ-MAX OIL TANKER B’

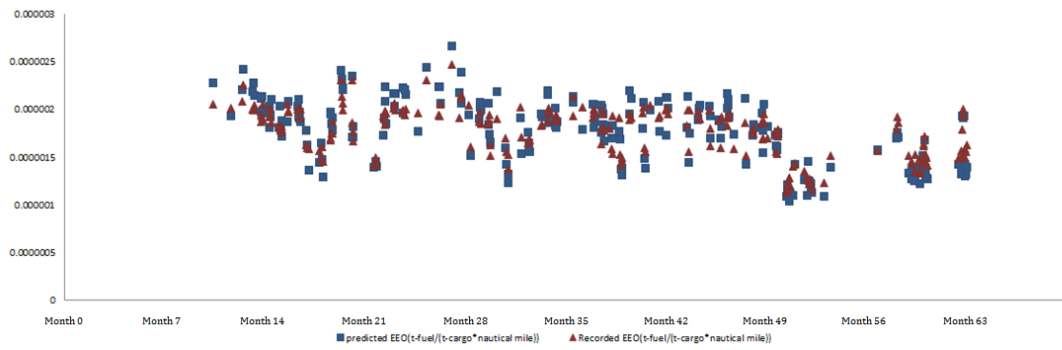


Figure 8. Comparison between predicted EEO and recorded EEO of ‘Suez-Max oil tanker B’

The average difference between predicted EEO using the proposed method and recorded EEO of ‘Suez-Max oil tanker B’ is 7.15%. Whereas, using the original Kwon’s ship added resistance model the average difference between predicted EEO and recorded EEO of ‘Suez-Max oil tanker B’ was 21.6%. Similar to the Case study 1, the modified model improves the accuracy significantly.

Under each sea state (sorted by Beaufort number), the predicted EEO and recorded EEO with each weather direction were compared, as shown in Figure 8, for BN = 4 as an example. EEO results for ship operational performance by using the proposed method is compared to the actual noon data recorded on board.

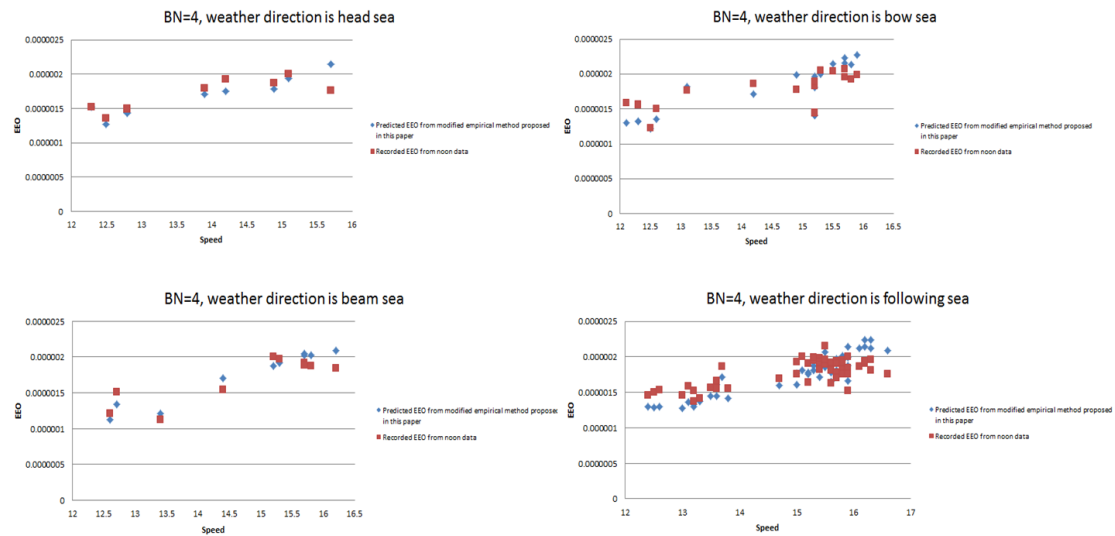


Figure 9. Comparison between predicted EEO and recorded EEO of ‘Suez-Max oil tanker B’ with each wind direction under the BN = 4.

#### 4. CONCLUSION

As the Ship Energy Efficiency Management Plan (SEEMP) has been made mandatory for all ships by the International Maritime Organization (IMO) since 1<sup>st</sup> January 2013, as well as fierce competition in the shipping market, it is necessary and wise to develop methods/tools for voyage optimization. This is not only to comply with relevant regulations but also to save vessel operational cost by reducing fuel consumption and decreasing carbon dioxide emissions.

In this paper, the modified empirical method for added resistance modeling for Suez-Max oil tanker was developed and this new proposed method for added resistance modeling has been tested through two case studies. By comparing the original Kwon’s added resistance method against the modified

empirical added resistance model, the difference between predicted EEO and recorded EEO for ‘Suez-Max oil tanker A’ is reduced from 14.7% to 5.2%; ‘Suez-Max oil tanker B’ reduced from 21.6% to 7.15%. The results prove that the modified ship operational performance prediction modeling is more accurate considering the uncertainty and unpredictable factors in ship operational performance prediction procedure.

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