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Prediction of Ship Fuel Consumption and Speed Curve by Using Statistical Method

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Abstract: Vessel fuel consumption has emerged as one of the key contributors to environmental deterioration and rising operational cost to the maritime industry. In practice, fuel efficiency can be achieved by design or operational approaches in newly designed or in-service vessels. In this paper, multiple linear regression (MLR) method is used to construct the fuel efficiency profile of working tugboats. Performance curves are derived to analyze and monitor the performance of on-cruising vessel. A Fuel Consumption Analysis System is developed for vessel operators to monitor fuel consumption in real-time and operate the vessel at economy speed for optimum fuel efficiency. Practicality and usability of the software are demonstrated using two sets of real operational data for a vessel in ballast and laden voyages. The proposed system has been verified using historical operational data revealing that up to 37.1% fuel saving can be achieved.

Keywords: energy efficiency, vessel fuel consumption, statistical analysis, multiple linear regression.

1. Introduction

The maritime industry is responsible for the carriage of about 90% of world trade and is vital to the functioning of the global economy. Based on the statistical data by International Chamber of Shipping (ICS), the world seaborne trade is projected to grow exponentially from 10 billion to 20 billion tonnes a year by 2030 [1].

Vessel fuel consumption has emerged as one of the key contributors to environmental deterioration. For instance, shipping industry has contributed 4% of world carbon dioxide (CO_2) emissions in 2007 leading to increasing greenhouse gases in the atmosphere [2]. The need for environmental preservation has led the International Maritime Organization (IMO) to take concerted effort towards limiting the environmental footprint of sea vessel significantly. Since January 2013, IMO, through the Maritime Environmental Protection Committee (MEPC), has been imposing requirements to shipping companies to significantly improve fleet energy efficiency during the design and operation phases through the Energy Efficiency Design Index (EEDI) [3] and the Ship Energy Efficiency Management Plan (SEEMP) [4] respectively, to regulate CO_2 emissions. EEDI facilitates implementation of technical measures through design of new ships to meet energy efficiency and carbon emission limits whereas SEEMP aims to improve the energy efficiency of a ship during its operation lifecycle through operational methods, including crew awareness and training on energy efficiency. Ship fuel efficiency can be optimized and accomplished by several designs and operational approaches in newly designed or in-service vessels, as summarized in Figure 1 [5].

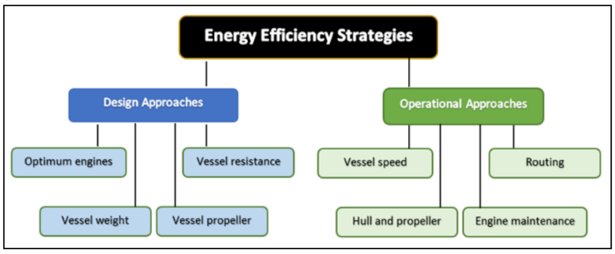

Figure 1. The summary of energy efficiency methods of an ocean vessel in design and operational approaches

Apart from that abovementioned, fuel consumption efficiency has been the subject of intense research due to rising fuel cost. The fuel cost is typically ranked the highest cost item of shipping operational expenses, i.e. about 50 ~ 60% of vessel operating voyage cost [6, 7]. In this regard, fuel saving has become paramount important for ship energy efficiency.

As such, various theories and estimation methods of the influential factors on ship performance are studied [8]. Ship fuel consumption can be affected by the speed, draft, displacement, weather, hull and propeller roughness [9]. Conventionally, ship performance is analyzed via speed-power curve of the specific vessel derived from a series of experimental tests of sea trials. Unfortunately, as far as fuel efficiency is concerned, the key concern is on ship fuel consumption, not on engine power derived from the speed-power curve. The theoretical-oriented single curve derived from sea trials is insufficient to analyze fuel consumption of the entire, constantly changing vessel lifespan. All of these give rise to inaccurate estimation. For instance, a typical ship voyage charter has 280 yearly running days at 50 tonnes/day. The 5% error in fuel consumption estimation may give rise to a loss of 280,000 USD/year. As such, vessel operators are indeed in need of a more precise and novel model that can derive a realistic and accurate performance curve for aged ships.

In this paper, a statistical analysis on ship operational performance is presented. The work aims at overcoming the speed-power curve deficiency, where fuel consumption is only predicted through the relation between power/consumption and speed [10]. Our proposed performance curve, derived statistically from actual operational data, is more accurate, realistic and contemporary for ship performance analysis [11]. A more accurate model is important to the shipping industry for cost saving and revenue. In addition to the analysis model, an in-service ship fuel management system is developed to support real-time monitoring and decision-making for the ship operators and owners for fuel efficiency operation.

The rest of this paper is organized as follows. Firstly, the conceptual model of our work is presented. Secondly, a Ship Fuel Consumption Prediction Model based on multiple linear regression (MLR) is formulated. It is followed by discussion on a case study for predicting optimum speed of operational tugboats from the performance curves. Finally, the practicality and usability of a Fuel Consumption Analysis System which enables analysis and optimization of vessel performance is demonstrated.

2. Conceptual Model

2.1 Ship Propulsion System

The propulsion system of a ship is described as follows. The primary source of the propeller power is the main engine where the fuel is transformed into brake power, P_B. It is then transmitted to the propulsion shaft whereby the shaft power is subsequently transformed through the propellers, into thrust delivered to the water that is known as effective power. Figure 2 illustrates how the power is propagated through the propulsion system.

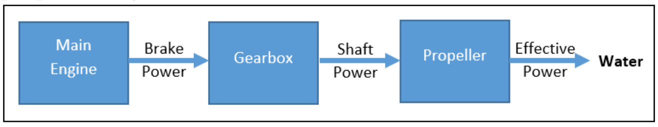

Figure 2. The propulsion system for twin-motored tugboat

The relationship between the fuel consumption with the specific fuel consumption (SFC), and the brake power is

$$Fuel\ consumption = \int P_B . SFC(P_B). dt \quad (1)$$

The brake power, P_B, is transmitted to the propulsion shaft on the one hand and to the electrical generator on the other, through the gear:

$$P_B = \eta_B (P_s + P_{el}) \quad (2)$$

where P_S is the shaft power, P_{el} is the power transmitted to the electrical generator and P_B is the efficiency factor of the gear which is considered to be constant.

Subsequently, the shaft power is transmitted to the propellers.

$$P_S = \eta_S P_D \quad (3)$$

where P_D is the power delivered to the propellers and η_s is the efficiency factor of the shaft which is considered to be constant.

The propeller power is transformed into thrust delivered to the water

$$P_E = \eta_P P_D \quad (4)$$

where η_P is the efficiency factor of the propeller which is dependent on the speed and the rotational velocity of the shaft.

2.2 Performance Metric

Fuel consumption of ships depends on the vessel speed and the resistance obtained from the ship during free running. However, it varies with many parameters such as engine power, engine revolution per minute (RPM), vessel speed, hull resistance condition in sea and vessel displacement [12]. In order to analyze the performance of free running vessel, a performance metric i.e. fuel consumption per unit of distance travelled (l/nm) is defined as:

$$\frac{litres\ (l)}{natical\ miles\ (nm)} = \left(\frac{litres\ (l)}{hour\ (h)}\right) \div \left(\frac{natical\ miles\ (nm)}{hour\ (h)}\right) \quad (5)$$

2.3 Fuel Consumption vs. Speed

It is known that a vessel's fuel consumption generally increases with the square of the speed. As far as vessel propulsion is concerned, the performance metric, l/nm is a function of square of vessel speed [13].

$$\frac{litres\ (l)}{natical\ miles\ (nm)} \propto (vessel\ speed)^2 \quad (6)$$

An empirical study of optimal speed of ship has demonstrated the conformity of relationship of the performance metric (l/nm) and ship speed squared based on the sea trial measured at 20 nautical miles at different speed) [14]. The derived performance curve can be approximated as polynomial order-2 equation whereby the most economic vessel speed can be obtained at the curve's minimum point (lowest fuel consumption at economy (ECO) speed).

Furthermore, fuel consumption of a ship is dependent on the voyage type (laden or ballast) [15]. The performance curves (l/nm versus knots) of free running vessel for two distinct operational voyages are illustrated in Figure 3. The different lowest points on both curves give rise to different optimal vessel speed with v_1 (laden) < v_2 (ballast).

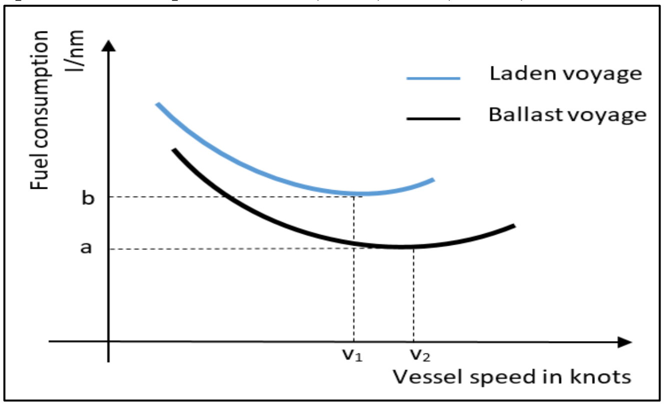

Figure 3. Fuel consumption of laden and ballast voyage as a function of vessel speed squared

3. MLR Fuel Consumption Prediction Model

Historical data of vessel operation are collected from two sister ships, namely JinHwa 40 and JinHwa 43, properties of GimHawk Shipping Sdn Bhd. Both ships are used on a commercial route to link different destination ports in Peninsular Malaysia of the West Malaysia and Sarawak in the East Malaysia. The ships are instrumented with a data acquisition device capable of acquiring signals coming from sensors such as GPS points, Course Over Ground, Speed Over

Ground, balance of the vessel, wind direction, depth, vessel inclination, acceleration, shaft power and so on. Besides, vessel crews also manually fill the "noon report" about time, starting and arrival port, nautical miles, time of sailing, fuel consumption rate, main engine rotation, power and wind speed.

The experiment procedure starts with the collection of historical vessel operational data stored in cloud server together with the noon report. The data is pre-processed to remove the outliers. The amount of ship fuel consumed (in litres) is designated as the output dependent variable while factors such as the travelled distance in Nautical Mile (nm), travelled hours (HRS), Speed of Ship (V), Deadweight in metric tonnes (DWT) and Wind Speed (W) are designated as the input (independent) variables.

In this paper, we take into consideration only the variables such as shown in Table 1 which have the key influences on the fuel consumption *Y* (in litres) from the technology point of view. Operational data of vessels on laden and ballast voyage conditions between two specific destinations (Melaka and Langkawi Island) are collected for analysis. Raw data is filtered to remove undesirable noises and outliers.

Table 1. The main influence factor of ship fuel consumption

Variable	Symbol	Unit
Travelled distance in nautical miles	NM	Nm
Travelled hours	HRS	Hours
Speed of vessel	V	Knots
Deadweight in metric tonnes	DWT	Mt
Wind Speed	W	Beaufort scale

A prediction model of the vessel's fuel consumption is established based on the historical operational data. The model is then used to develop an accurate ship fuel performance curve for analysis and optimization purposes.

A mathematical model is developed to predict the relationship between input variables and ship fuel consumption. The multiple linear regression (MLR) was used to establish the relationship between variables using the least-squares method. The MLR takes the following form:

$$Y = a + b_1X_1 + b_2X_2 \ldots\ldots + b_kX_k \quad (7)$$

where Y is the dependent variable, which is to be predicted; X_1, X_2, … X_k are the k independent variables on which the prediction is based; a_1, b_1, b_2 … b_k are the coefficients.

ANOVA analysis was performed on the input dataset from the collected operational data to analyze the relationship between the designated variables for their correlation.

The derived prediction model is validated with coefficient of determination, R^2 for goodness of fit. The coefficient of determination, R^2 result at 0.9085 indicates the good fitness of regression, as shown in Figure 4. The resultant MLR model is shown as follows:

$$FC = 2192.20 + 15.37\ NM + 26.90\ HRS - 1722.61\ DWT \quad (8)$$

where FC = fuel consumption (in litres); NM is the travelled distance (in nautical miles); HRS is the travelled hours; DWT is the deadweight (in Mt).

The influencing factors are designated as the input variables and divided according to laden and ballast conditions. A performance metric of fuel consumption as litres/nautical miles travelled (l/nm) is designated as the output independent variable.

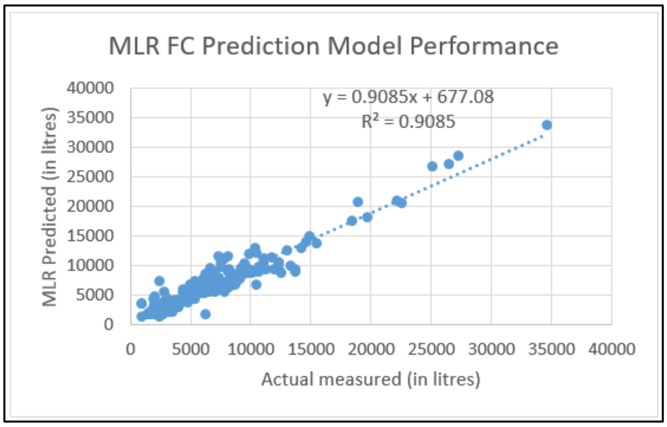

Figure 4. The relationship between measured and predicted data for fuel consumption of MLR model

4. Results and Discussion

4.1 Case Study: Predicting Optimum Speed from the Performance Curves

An analytical study of ship performance was conducted on the working tugboats operational along the Rejang River and the Straits of Malacca, Malaysia. The tugboats were used for cargo transportation by towing a barge with 3000MT (in average) of cargo for laden voyage mode. Figure 5 shows the typical operational scene of the tugboat towing a barge of cargo.

The twin-motored tugboat generates the propulsion power from two main diesel engines (M/E) coupled to the shaft and gearbox (GB) to drive the propellers. Furthermore, there are two auxiliary diesel generators (D/G) to support the on-board electricity load whereby one of them is designated for standby or emergency use. Figure 5 shows the conceptual representation of the case study tugboat's propulsion plant. The operational profile of the vessel is listed in Table 2.

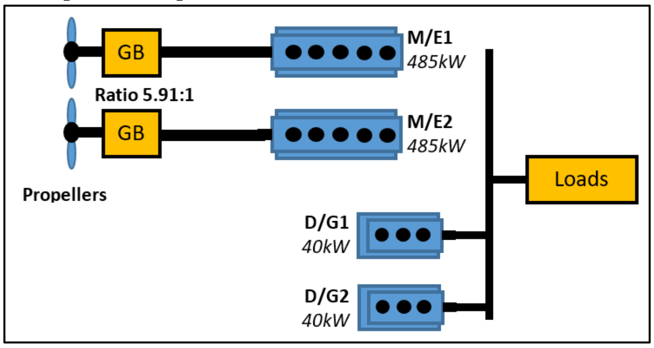

Figure 5. The conceptual representation of tugboat propulsion plant

Table 2. Specifications of vessel under case study

Feature	Value	Unit
Deadweight	5000	Mt
Installed power (main Engines)	485kW @ 1900 RPM × 2	kW
Installed power (auxiliary engines)	40kW/415V × 2	kW
Gearbox ratio	5.91:1	-
Register length	21.97	m
Designed draft	2.7000	m
Designed speed	10	knot

The performance curves (l/nm versus knots), the trend lines of ballast and the laden voyages are plotted as polynomial order-2 equations, shown in Figure 6 and Figure 7 respectively.

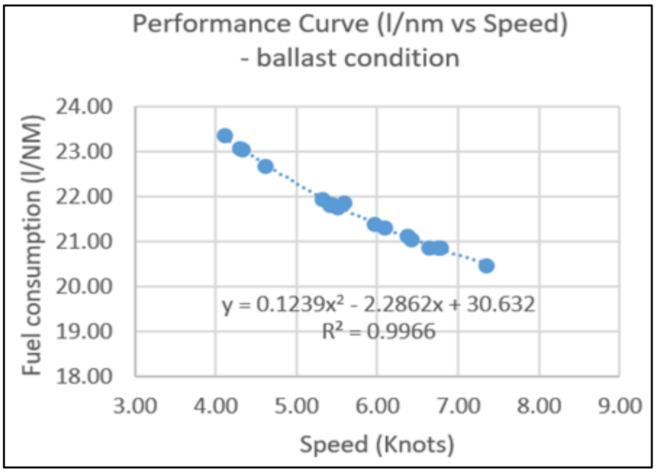

Figure 6. Performance curve (ballast voyage)

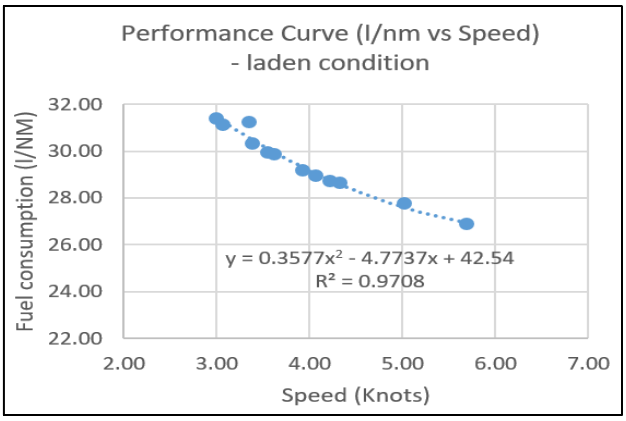

Figure 7. Performance curve (laden voyage)

In Figure 8, it is shown that the optimum speed for ballast condition is 9.23 Knots with the minimum fuel consumption is 20.09 l/nm while the optimum speed for laden condition is 6.67 Knots with the minimum fuel consumption is 26.61 l/nm. Hence, the optimum operating speed of the vessels under ballast and laden voyages can be predicted using the model.

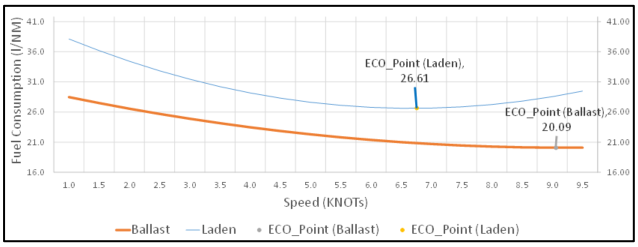

Figure 8. The performance curves and the minimum points are defined as optimal (ECO) speeds for both laden and ballast voyages

5. Fuel Consumption Analysis System

With the formulation of the prediction model, a Fuel Consumption Analysis System is developed to analyze and optimize vessel operation. Figure 9 shows a snapshot of the graphical user interface of the developed software.

The Fuel Consumption Analysis System enables analysis and optimization of vessel performance based on parameters such as vessel speed. We demonstrate the practicality and usability of the software using two sets of real operational data for ballast and laden voyages for a vessel which took the laden voyage (DWT of 3000 Mt) from Malacca to Langkawi Island.

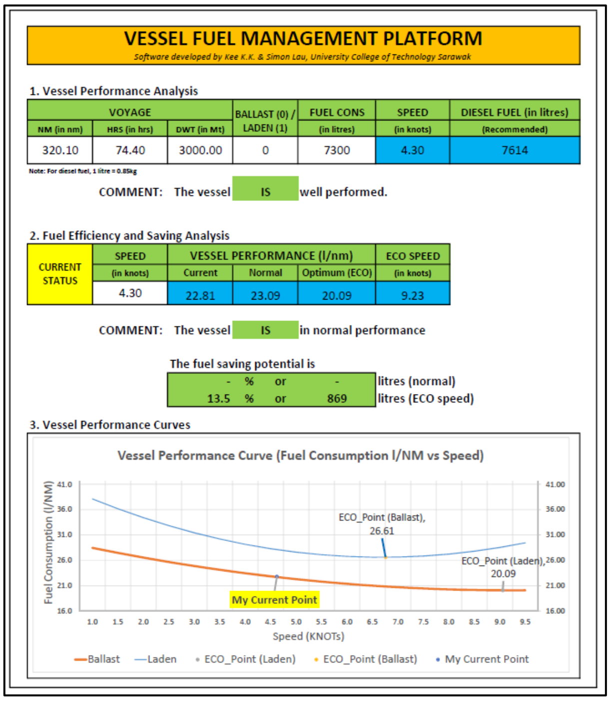

Figure 9. Visualization of ship performance curves for laden and ballast voyages (with minimum points for ECO speed)

Voyage 1 is 323.0 nm voyage on 24 June 2015 took 116.12 hours at the speed of 2.78 knots. The recorded fuel consumption was 10000 litres with good weather and calm sea condition. The operational data and results are illustrated in Figure 9. Meanwhile, voyage 2 with 323.0 nm on 25 August 2016, spent 80.5 hours at the speed of 3.85 knots. The recorded fuel consumption was 11300 litres with poor weather and sea condition. The operational data and results are illustrated in Figure 10 and 12 respectively. The performance profile of voyage 1 is illustrated in Figure 11.

1. Vessel Performance Analysis

VOYAGE NM (in nm)	HRS (in hrs)	DWT (in Mt)	BALLAST (0) / LADEN (1)	FUEL CONS (in litres)	SPEED (in knots)	DIESEL FUEL (in litres) (Recommended)
323.00	116.12	3000.00	1	10000	2.78	10629

Note: For diesel fuel, 1 litre = 0.85kg

COMMENT: The vessel IS well performed.

2. Fuel Efficiency and Saving Analysis

CURRENT STATUS	SPEED (in knots)	VESSEL PERFORMANCE (l/nm) Current	Normal	Optimum (ECO)	ECO SPEED (in knots)
	2.78	30.96	32.03	26.61	6.67

COMMENT: The vessel IS in normal performance

The fuel saving potential is

-	%	or	-	litres (normal)
16.3	%	or	1405	litres (ECO speed)

Figure 10. Voyage 1 operational information

3. Vessel Performance Curves

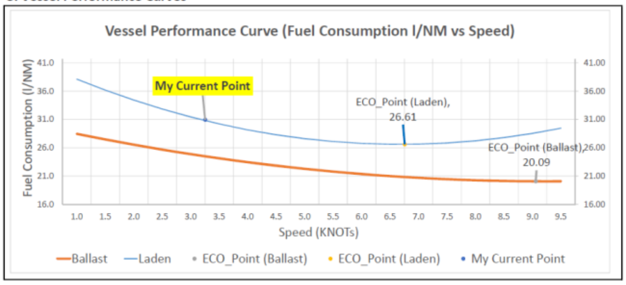

Figure 11. Performance profile of voyage 1

According to Figure 10, voyage 1 is well performed where the fuel consumption of 10,000 litres is less than the normal or reference value derived from the predictive model, i.e. 10,629 litres. The speed of 2.78 knots is not at optimal or economy (ECO) speed, i.e. 6.67 knots. It implies that the vessel is not operated in fuel efficient mode. At 2.78 knots, the vessel is operated at 30.96 l/nm which is higher than 26.61 l/nm at optimal economy speed. Hence, the vessel has the potential of further fuel saving of 16.3% or 1,405 litres, as compared to the current operational condition. The performance profile of voyage 2 is depicted in Figure 13.

1. Vessel Performance Analysis

VOYAGE NM (in nm)	HRS (in hrs)	DWT (in Mt)	BALLAST (0) / LADEN (1)	FUEL CONS (in litres)	SPEED (in knots)	DIESEL FUEL (in litres) (Recommended)
309.80	80.50	3000.00	1	11300	3.85	9361

Note: For diesel fuel, 1 litre = 0.85kg

COMMENT: The vessel IS NOT well performed.

2. Fuel Efficiency and Saving Analysis

CURRENT STATUS	SPEED (in knots)	VESSEL PERFORMANCE (l/nm) Current	Normal	Optimum (ECO)	ECO SPEED (in knots)
	3.85	36.48	29.47	26.61	6.67

COMMENT: The vessel IS NOT in normal performance

The fuel saving potential is

23.8	%	or	2171	litres (normal)
37.1	%	or	3056	litres (ECO speed)

Figure 12. Voyage 2 operational information

According to Figure 12, Voyage 2 consumed 11,300 litres of diesel fuel which is higher than the normal or reference value. The system implied that the vessel has consumed about 20.7% more than the normal. At 3.85 knots, the vessel is operated at 36.48 l/nm which is higher than the normal operation condition which may be attributable to operational, technical or/and environmental factors. According to the system, vessel has fuel saving potential of 23.8% or 2,171 litres of diesel fuel. In the meantime, if the current vessel is operated at optimal (ECO) speed of 6.67 knots, it can achieve optimum performance of 26.61 l/nm with potential fuel saving of 37.1% or 3,056 litres. As illustrated in Figure 13, there is a significant big gap between the current operating point, the normal performance curve and optimum point.

3. Vessel Performance Curves

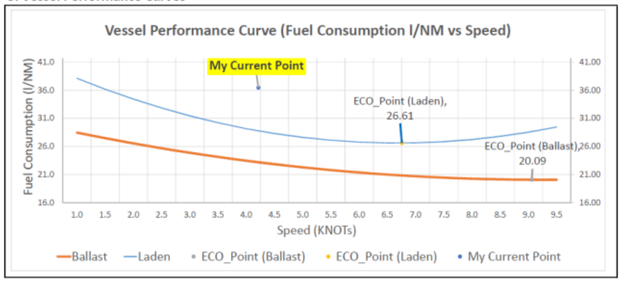

Figure 13. Performance profile of voyage 2

From the results shown above, the Fuel Consumption Analysis System facilitates visual indication of current operation point of the vessel and the deviations from the normal and optimum (ECO) conditions. Further developments can been carried out to provide additional information such as difference in time of arrival, percentage of additional fuel used if the vessel speed differs from ECO speed and CO2 emission.

6. Conclusions and Future Work

Vessel fuel consumption efficiency which can be affected by speed, draft, displacement, weather, hull and propeller roughness etc. has been a subject of intense research due to rising fuel cost and environmental issue. In this paper, a Fuel Consumption Prediction Model based on multiple linear regression (MLR) is proposed. The performance curves (l/nm versus knots) are derived to predict optimum speed for the best ship fuel consumption performance. A Fuel Consumption Analysis System is built to validate the model. Using the system, a case study of ship performance is conducted on the working tugboats operational in the laden and ballast voyages. From the study, it is shown that the Fuel Consumption Analysis System enables analysis and optimization of vessel performance based on parameters such as vessel speed.

Moving forward, the prediction model can be further refined for better accuracy using methods such as artificial neural network (ANN). Apart from the operational approach shown in this paper, advanced design approach of ship namely hybrid propulsion also plays important role in fuel efficiency. Hence, more factors are to be considered in further investigations.

Acknowledgements

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References

[1] International Chamber of Shipping (ICS), Shipping, World Trade and The Reduction of CO_2 Emissions - United Nations Framework Convention on Climate Change (UNFCCC), 2014.

[2] J. S. Carlton, *Marine Propellers and Propulsion (2nd Edition)*. Oxford: Elsevier, 2007.

[3] International Maritime Organization (IMO), *Guidelines for calculation of reference lines for use with the energy efficiency design index (EEDI), annex 11 resolution MEPC.215 (63)*, 2012.

[4] Lloyd's Register, *Guidance for the development of a vessel energy efficiency management plan (SEEMP)*, 2009.

[5] Det Norsk Veritas, Hovik, "Assessment of measures to reduce future CO2 emission from shipping", *Position Paper*, 2010.

[6] M. Stopford, *Maritime Economics*, Routledge, 2009.

[7] M. M. Golias, G. K. Saharidis, M. Boile, S. Theofanis , M. G. Ierapetritou, "The berth allocation problem: optimizing vessel arrival time", *Maritime Economics Logistics*, vol. 11, no. 4, pp. 358–377, 2009.

[8] V. Bertram, *Practical Ship Hydrodynamics*, Butterworth-Heinemann, Oxford: Elsevier, 2002.

[9] P. Andersen, A. S. Borrod, H. Blanchot, "Evaluation of the Service Performance of Ships", *Maritime Technology*, vol. 42, no. 4, pp. 177-183, 2005.

[10] J. D. Van Manen, P. Van Oossanen, *Principles of naval architecture, Chapter 5 – Resistance*, Jersey City, NJ: The Society of Naval Architects and Marine Engineers, 1989.

[11] A. F. Molland, S. R. Turnock, D. A. Hudson, *Ship Resistance and Propulsion, Practical Estimation of Propulsive Power*. New York: Cambridge University Press, 2011.

[12] O. Gulbrandsen, Fuel savings for small fishing vessels – a manual, in *Food and Agriculture Organization of the United Nations*, Rome, pp. 56-58, 2012.

[13] IMO, *Train the trainer (TTT) course on Energy Efficient Ship Operation, Module 3 – From Management to Operation, P37 – 38*, International Maritime Organisation, 2016.

[14] I. Zaman, K. Pazouki, R. A. Norman, S. Younessi, S. Coleman, "Utilising real-time ship data to save fuel consumption and reduce carbon emission", in *Proc. Shipping in Changing Climates Conference*, Newcastle upon Tyne, 2016.

[15] H. Lindstad, G. S. Eskeland, "Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution", Transportation *Research Part D: Transport and Environment*, vol. 41, pp. 244-256, 2015.