EFFECTS OF MARINE CONDITION ON THE SPEED AND FUEL CONSUMPTION OF A FULLY – LOADED VLCC

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SUMMARY

Minimizing fuel consumption is a priority for ship-owners seeking to reduce their vessel costs due to sea conditions. One of the most reliable methods used to estimate fuel consumption is to identify field investigations for future voyages. The VLCC Salina was used based on daily field data collected over a proper period and year of 2014 was identified as a period of optimal performance after its periodic dry dock repair. According to verified results for Beaufort scales of 2, 3 and 4, the vessel exhibited an average speed loss of 2.2% due to wind and wave effects for a Froude number of 0.15 while its greatest speed loss was observed at angles of 30–60° relative to its longitudinal axis. The results were finally used to develop a methodology for estimating fuel consumption of Salina and 3 other sister-ships, during future voyages, in the fleet of the National Iranian tanker company.

1. INTRODUCTION

Discrepancies between measured and estimated values of fuel consumed by a vessel lead to delays in its scheduled voyages. Moreover, failure to obtain proper estimates of fuel consumption entails unpredicted additional costs. This study was implemented to improve upon the methods of estimating vessel fuel consumption. A second objective of the study was to estimate fuel consumption on future voyages by taking into account the relevant marine conditions and their effects on the vessel. Included among the scientific approaches employed by the maritime industry to protect the environment, to reduce vessel propulsive power requirements and, thereby, to reduce fuel consumption are those that aim at controlling fuel consumption during slow steaming or while sailing in weather routing.

Townsin et al. collected and categorized the Beaufort scale route frequency distributions for twelve 210,000-ton tankers on their routes from the Persian Gulf to Europe (Townsin, *et al*, 1975b). Aertssen used an empirical method to estimate speed loss due to seaway conditions (Aerstssen, 1998a), while Pershin (Pershin & Voznesenskii, 1957), Nakamura (Nakamura & Fujii, 1977) and Van Berlekom (1981) developed theoretical models for the same purpose. Nilsson showed that the fastest drop in ship speed occurred with headwinds (Nilsson, 1977). Gould (1967), Wagner (1967), Tsuji et al. (1970), Aage (1971), and Ishrewood investigated the effects of wind resistance and ship speed loss due to wind stress (Nilson, 1977). Finally, Byrne calculated ship speed loss due to hull roughness and encrustation (Byrne, 1980). It has been established that added resistance due to wind and waves, contributes to enhancements in total drag force (Bertram, 2017b). Enhanced effects of the physical conditions of the seaway, such as wind stress, wave direction, and currents during a ship's voyage, increase total drag force, reduce ship speed, and increase fuel consumption. Thus, ship speed is considered as a factor of great importance in most methods used to optimize fuel consumption by a vessel. This is clearly reflected in the literatures cited in the latest version of ISO 19030 of 2017 (Bertram, 2017b), in which ship performance indices are still deemed to depend heavily on ship "speed". The method most appropriate for analyzing ship performance in response to marine conditions is to obtain the speed over ground (SOG) while sailing through water using direct measurements and continuous records of such relevant environmental parameters as sea surface currents. Because the added drag force is highly dependent on ship speed, the difference between speed loss averages is used for monitoring ship performance. Nikolas Bialystocki and Dimitris Konovessis (2016) studied a newly-operated ship that had been in service for only three years. Despite their objectives and because of the short service life of the vessel, these workers failed to set up appropriate time steps for monitoring variations in performance over an adequately large number of intervals to identify the corresponding variations in the fuel consumption of the vessel with ageing.

The present study was conducted on the M.T. Salina (Figure.1) (sister ship of recent collided tanker in china sea, M.T. Sanchi), as a case study using long-term environmental data and reasonable time intervals under the diverse geographical and marine environment conditions navigated by the ship along its routes (Figure. 2). For this purpose, 417 daily noon reports on the ship's cruises during the period from mid-2013 to February 2017 were used to investigate the effects of sea conditions on speed-power curves and fuel consumption of the ship in laden condition.

Another advantage of the present study over previous ones is the greater angular resolutions used in determination of speed losses under the influence of wind direction and sea force.

The rest of the paper is organized as follows. Section 2 describes the evaluation method as well as data

Figure. 1. M.T. Salina (Ex. M.T. Sarv)

Figure. 2. Routes paved by the M.T. Salina from the loading point at Kharg Island to its unloading port of destination in Turkey

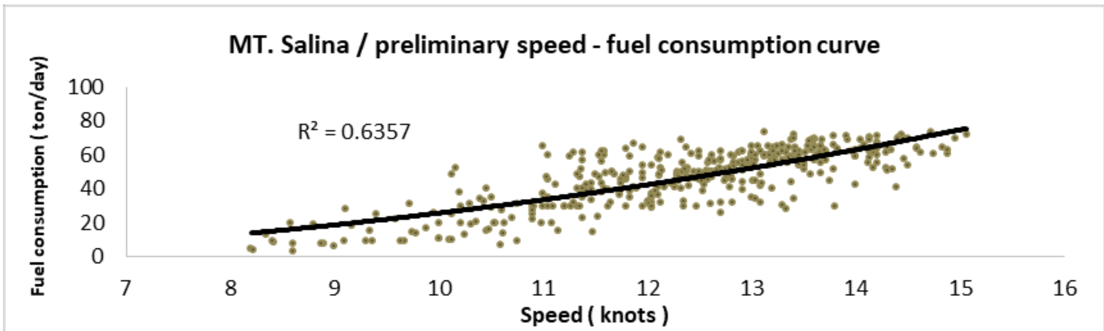

Figure.3 Preliminary speed-fuel consumption curve of the M.T. Salina after correction for draft

collection and refinement. The effects of current, wave, and wind on the ship are also explained in this Section. Finally, the method used to validate the findings is presented. Section 3 presents the results obtained in this study and further explores the achievements and findings of the study toward its objectives. Finally, general conclusions are presented in Section 4.

Table 1: Main Specifications of M.T. Salina

Build Year	2009
Length overall	274.18 m
Vessel beam	50 m
Design draft	17.023 m
Cargo carrying capacity	164040 MT.
Displacement at summer draft	189187 MT.
Service speed	15.40 Knots

2. MATERIALS AND METHODS

2.1 FIELD DATA PROCESSING

For the purposes of this study, field data were collected during the period from mid-2013 to February 2017 on current and wind speed and directions, sea conditions, draft conditions, displacement, engine power, steamed distance in 24 hours, vessel speed, and fuel consumption, all reported as daily averages. The reference values including service speed, design summer draft, Beaufort scales, and wind direction were also used to normalize the data collected. The ship made a total number of 34 voyages, all departing from Kharg Island in Iran to their ports of destination in Turkey (24 voyages) and India (10 voyages). Passing through such areas as the Persian Gulf, the Oman Sea, the Arabian Sea, the Red Sea, and the Mediterranean Sea, the voyages from the port of loading to that of discharge had taken a minimum of five and a maximum of 16 days. As a first step, field data collected for the laden condition were separated from those collected on the ballast condition. In a second step, any incomplete daily data were removed from the aggregated reports. This made a total of 417 daily reports available for processing to evaluate the effects of environmental factors on the speed-fuel curves of the M.T. Salina.

2.1 (a) Relationship between ship log speed and current speed

Based on water depth, current speed and direction have different effects on the ship's speed over ground. Given the Salina average draft of 16.5 m in her previous voyages and also because of the effect of sea surface current on SOG, in the initial estimation of fuel consumption, the impact of surface current speed and direction on SOG were corrected. Rather, daily SOG was calculated based on the vessel's routes taking into account current directions and speeds.

Average SOG is calculated by dividing the steamed distance by the steamed hours; similarly, the average fuel consumed is determined based on SOG and the steamed distance in 24 hours.

2.1(b) Effect of correction for draft (tonnage performance) on fuel consumption

Operational performance is related to tonnage performance under different environmental conditions (Bertram 2017a). In other words, ship friction resistance increases with increasing cargo and ship's draft, which will ultimately lead to increased fuel consumption. In this study, the daily fuel consumption records and the differences in displacement and draft conditions over the past 34 voyages were exploited to accomplish the second correction in fuel consumption for each voyage based on the design displacement and draft. For this purpose, Eq. (1) was used:

$$\frac{F.C._{Corr.toDes.}}{F.C._{in\,24hrs.}} = \left(\frac{\nabla_{Des.}}{\nabla_{Voy.}}\right)^{2/3} \quad (1)$$

where, the dividend term represents fuel consumption corrected for the design draft and the divisor term represents fuel consumption over the preceding 24 hours. The dividend and the divisor on the left-hand side of the equality sign represent constant displacement volume in the summer draft and displacement volume in each voyage, respectively.

Figure. 4 shows the preliminary speed-fuel curve of the Salina. The fuel consumption of the vessel in each voyage is initially corrected for the design draft. This yields the speed-fuel curve presented in Figure.3. Clearly, this figure cannot be practically employed to estimate the ship's fuel consumption in its future voyages as it will contain too many errors due to the dispersion and gaps in the data. Hence, it must be corrected for the effects of other environmental factors.

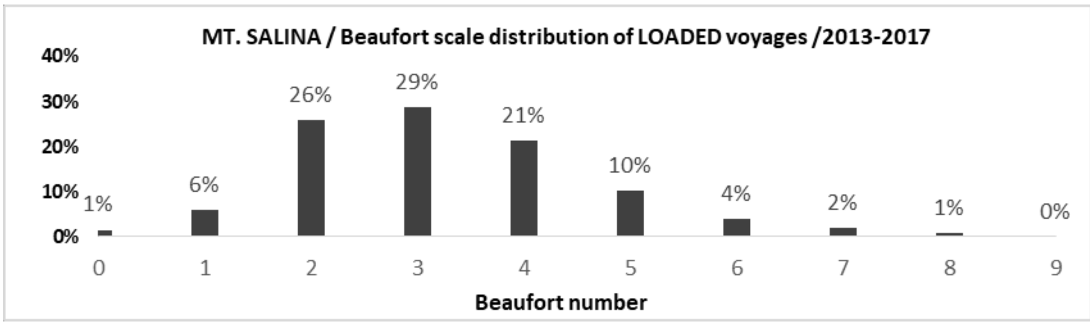

Figure. 4. Frequency distribution chart of Beaufort scales during Salina's voyages

2.1(c) Seaway effects on vessel performance

The direction and severity of sea state as indicated by Beaufort scales have different effects on the speed and fuel consumption of a ship. Beaufort scales of 0 to 3 are considered as good weather conditions for ocean-going vessels. Higher Beaufort scales of, say, 5 or more have significantly enhanced effects on vessel performance

Figure. 4 presents the frequency distribution of Beaufort scales during the voyages made by M.T. Salina. Clearly, Beaufort scales of 2, 3, and 4 accounted for the dominant conditions of the sea in 76% of the cases, with the highest share of 29% belonging to a Beaufort scale of 3 followed by 26% and 21% belonging to scales 2 and 4, respectively. Using Eq. (2) below, fuel consumption rates for Beaufort scales of 2 and 4 were normalized relative to that of Beaufort scale of 3:

$$\frac{F.C._{Corr.to\ F3}}{Fuel\ cons._{Corr.to\ Des.}} = \frac{F.C._{AV.F3}}{F.C._{AV.F3}\,OR\ F.C._{AV.F4}} \tag{2}$$

where, the dividend represents fuel consumption corrected for a Beaufort scale of 3 and the divisor is obtained from Eq. (1) above. The dividend and the divisor terms on the left-hand side of the equality sign represent fuel consumption at a Beaufort scale of 3 and average fuel consumption rates at Beaufort scales of 2 or 4, respectively. The formula compares fuel consumption at a Beaufort scale of 3 with those at scales of 2 and 4 so that it can now be used to estimate the increase in fuel consumption of M.T. Salina when sea forces during its voyage change from a Beaufort scale of 2 to one of 3. Similarly, reductions in fuel consumption can be estimated using this Equation when the sea force turns from a scale of 4 to one of 3.

Figure.5 depicts the changes in the speed-fuel curve of the M.T. Salina after correction for sea conditions. As expected, the highest average fuel consumption belonged to a Beaufort scale of 4 and the lowest values belonged to Beaufort scales of 2 and 3. Moreover, it is seen that sea conditions had almost similar effects on fuel consumption at Beaufort scales of 2 and 3.

2.1(d) Effect of wind-induced drag on fuel consumption

The effect of wind force on the drag force of a ship is a function of the projected windage area of the ship. Although the decelerating effect of wind power on oil tankers is less than that on container or passenger ships, oil tankers offer a greater viscose drag due to their larger draft. In this research, the effect of drag force due to wind stress on variations in fuel consumption by the M.T. Salina was determined with respect to the wind direction relative to the ship. Wind angles relative to the longitudinal axis of the hull are taken to range from zero to 180°. Due to the importance of the effect of wind angle on the drag force of a ship and its fuel consumption, the following distinctions are made in the wind angles to the vessel direction:

- Head wind, defined as the wind striking either the port or starboard side along the longitudinal axis of the ship at a relative angle of 0 to 60°. (For more accurate calculation of ship's speed loss due to wind effect, the headwind will be further divided into one with a relative angle of zero to 30 and one with a relative angle of 30–60°).
- Side wind: Winds striking the port or starboard side of the ship's longitudinal axis at relative angles of 60–150°.
- Tail wind: Winds striking the port or starboard side of the ship's longitudinal axis at angles of 150–180°.

Based on the data obtained, head and tail winds recorded the most and least frequent winds. The objective was to determine Salina's fuel consumption rates while sailing along the direction of the tail wind but suddenly facing a head or side wind; and, similarly, when she left the impact region of an opposite wind while the tail wind would help reduce her fuel consumption. It was then necessary to assume that the dominant wind was the side one. Fuel consumption would be then determined for other wind types by correcting it for the side wind using Eq. (3):

$$\frac{F.C._{Corr.to\ Beam\ wind}}{Fuel\ cons._{Corr.to\ F3}} = \frac{F.C._{AV.Beamwind}}{F.C._{AV.Head\ wind}\,OR\ F.C._{AV.Tail\ wind}} \tag{3}$$

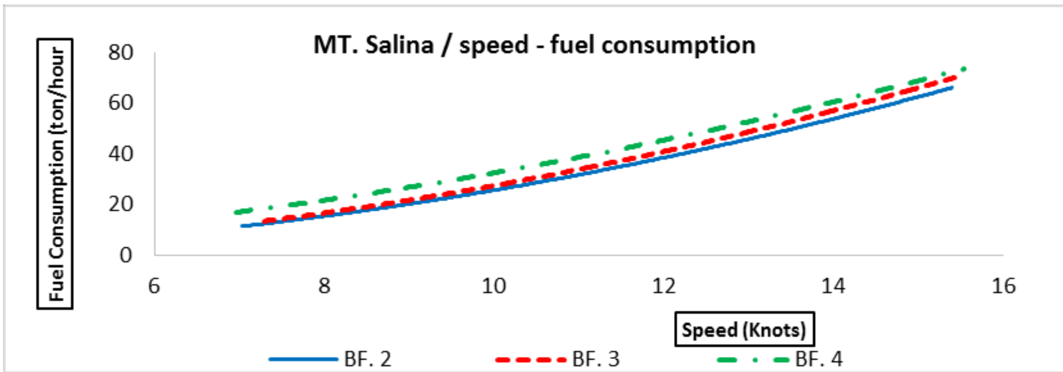

Figure. 5: Speed-fuel consumption curve of the M.T. Salina after correction for sea conditions

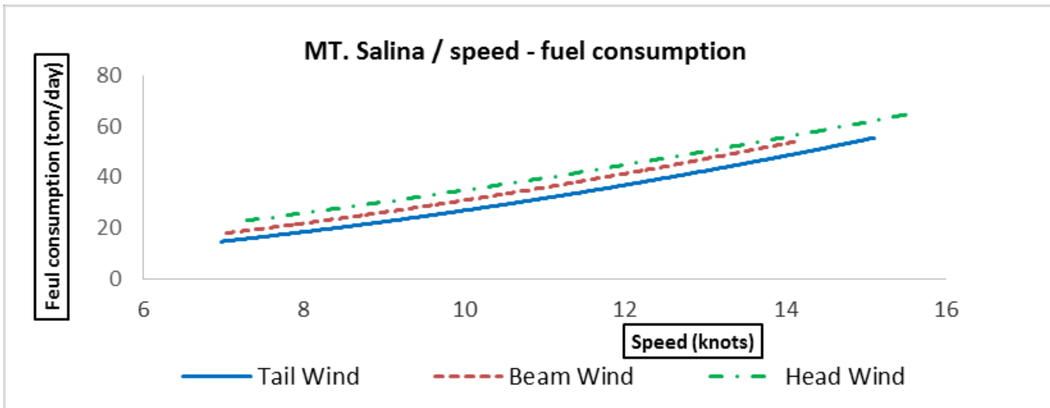

Figure. 6: Speed-fuel consumption curve of the M.T. Salina after correction for wind effect

where, the dividend term represents fuel consumption corrected for the side wind and the divisor is obtained from Eq. (2). The dividend and the divisor terms on the left-hand side of the equality sign, respectively, represent average fuel consumption when facing a side wind and average fuel consumption when facing a head or tail wind.

Figure. 6 depicts the effects of wind direction on the speed and fuel consumption of the M.T. Salina. Clearly, a relative wind in the opposite direction (i.e., 0–30 and 30–60°) increased the drag force and, consequently, fuel consumption. Tail and side winds had lower, and almost the same, effects on fuel consumption.

2.2 EFFECTS OF SERVICE LIFE AND HULL ENCRUSTATION ON FUEL CONSUMPTIONE

It is difficult, or even impossible, to make observations of the fouling and encrustation on the hull as the vessel is constantly on the move across different geographical regions since the process heavily depends on a variety of factors such as speed and hull coating paint of the vessel as well as sea temperature and salinity (Dückert, *et al*, 2016). Although modern self-polishing coatings prevent fouling and encrustation, it was found necessary to investigate the effects of hull paint coating and fouling on fuel consumption by the M.T. Salina for the reasons outlined below:

- The vessel sailed through such varied passages and areas as the Persian Gulf, the Oman Sea, the Arabian Sea, the Red Sea, and the Mediterranean Sea.
- The vessel is already ageing and the probability of hull fouling and encrustation increases with service life.

2.2 (a) Overall assessment of fuel consumption by M.T. Salina

Encrustation and fouling on the hull increases the drag force, which entails increasing engine power required to maintain given speeds throughout the voyage. For this reason, services-life monitoring has been proposed as a method of assessing the effects of hull roughness and fouling. To employ the proposed method in the present study, the data available on Salina's performance were used to plot her speed-fuel consumption curves for the years shown in Figure. 8. The average fuel consumption by Salina in these years were 54.83, 59.86, and 59.38 tons per day, respectively, for her loaded condition, with a 3-year average of around 58 tons per day. Based on the above considerations, it may be concluded that there is now a greater probability for service life to affect Salina's fuel consumption.

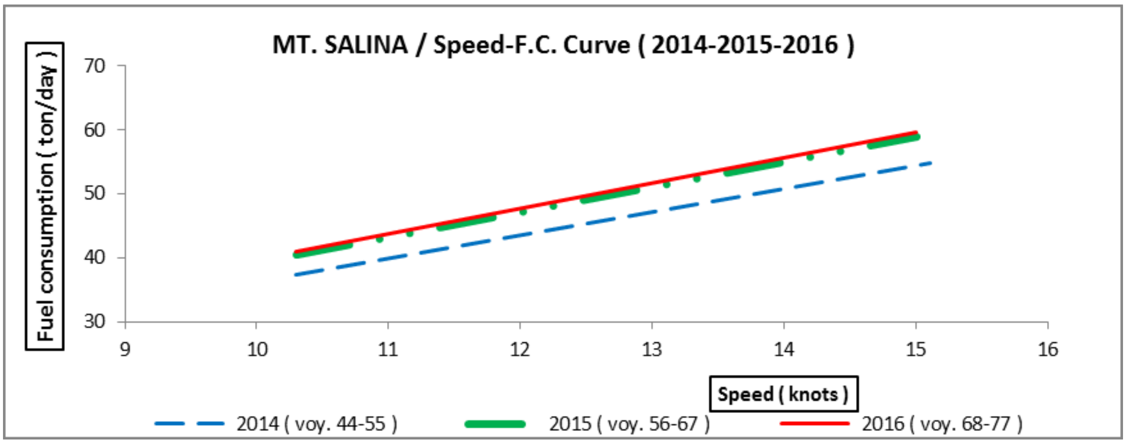

Figure. 7: Salina's speed-fuel consumption curve under laden conditions during the years 2014, 2015, and 2016

It is clear from Figure 7 that Salina recorded its lowest average fuel consumption during her voyages in 2014 after its periodic maintenance and its highest averages in 2015 and 2016, indicating 2014 as Salina's best performance period.

2.2 (b) Correlation of admiralty coefficient, wetted surface area, and vessel's drag force with fuel consumption

In Step 2 of our calculations, the admiralty constant was used to investigate the relationship of propulsive power with displacement and speed. The relationship between variations in the overall vessel drag force and variations in vessel speed that underlies the Admiralty Equation was exploited to provide a better estimate of the effect of service life on vessel fuel consumption. This is reflected in Eq. (4) below:

$$R = \rho S V^{n} \quad (4)$$

where, R is the vessel's drag force; S is the wetted surface area of the hull, which is a function of displacement; and n is a constant for low-speed commercial vessels considered to be equal to 2 in the present calculations. For a constant water density, we have:

$$R_t = \Delta^{2/3}.V^2 \quad (5)$$

Using Eq. (5), the relationship between propulsive power (P), on the one hand, and total drag force (Rt), speed (V), and displacement, on the other, are captured by (6) below:

$$P = R_T.V = \Delta^{2/3}.V^3 \quad (6)$$

This relation may be reduced to a coefficient called 'admiralty constant' expressed by (7):

$$A_C = \frac{\Delta^{2/3}.V^3}{P} \quad (7)$$

This Relation was used to determine variations in Salina's propulsive power and fuel consumption as a function of service life over the study period. Reduction in values of admiralty coefficient lead to increases in fuel consumption such that fuel consumption varies in a linear manner with changes in propulsive power. A non-varying value of this coefficient indicates the non-linear relationship of fuel consumption with displacement and vessel speed.

2.2 (c) Effect of maintenance and hull cleaning on fuel consumption

More accurate estimations of service life effects on vessel speed and fuel consumption were obtained in the third stage of our computations in which four different time steps in the period from mid-2013 to early 2017 were selected for study. The first time step included the period up to the first dry dock of March 2014; the second extended over the vessel's performance period after the dry dock in 2014; the third involved the period before hull cleaning, which was associated with the greatest drag force due to encrustation and fouling on hull and, thereby, increased fuel consumption; and the fourth time step started immediately after the latest hull cleaning of 2016. Figure.8 depicts Salina's fuel consumptions over the above four time steps.

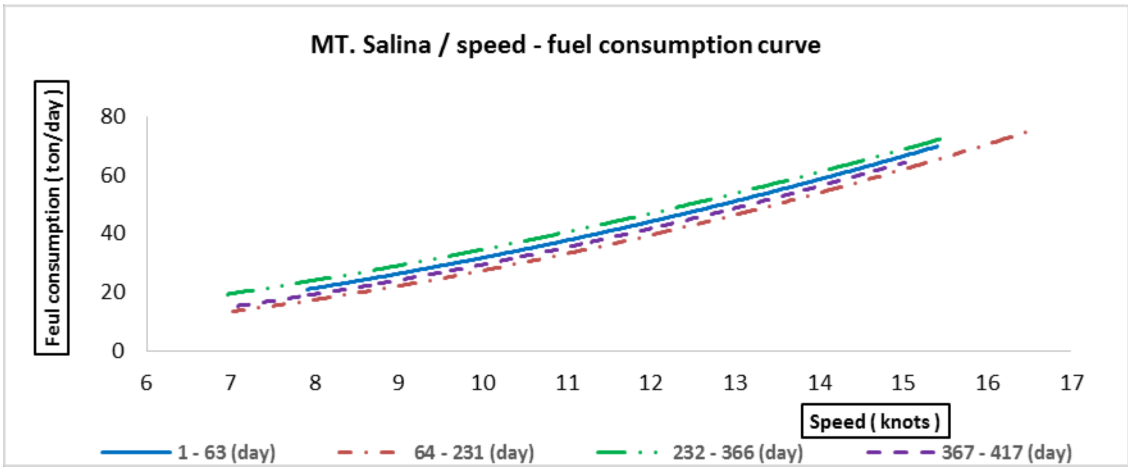

Figure. 8: Salina's speed-fuel consumption curves over the four periods

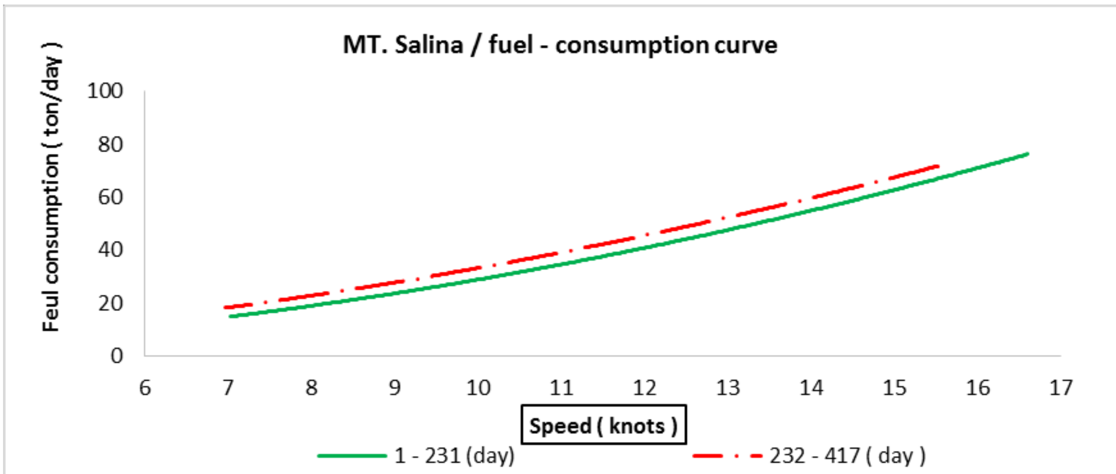

Figure. 9: Comparison of Salina's speed-fuel consumption curves during the first and second halves of the monitoring period

Clearly, the period characterized by the highest fuel consumption is the period just before the hull and propeller cleaning. Moreover, the second time step in the above classification was the one characterized by the most optimal fuel consumption when the periodic overhaul of 2014 was conducted. Clearly, dry dock maintenance and hull cleaning activities had decisive impacts on reducing fuel consumption.

Figure. 9 is complementary to Figure. 8, giving a more general comparison of the average fuel consumption rates by the vessel in the first and second halves of the monitoring period. It is seen that Salina's fuel consumption increased compared with that in the first half of the performance monitoring period. According to Figure. 10, fuel consumption increased with service life from 2013 to 2017.

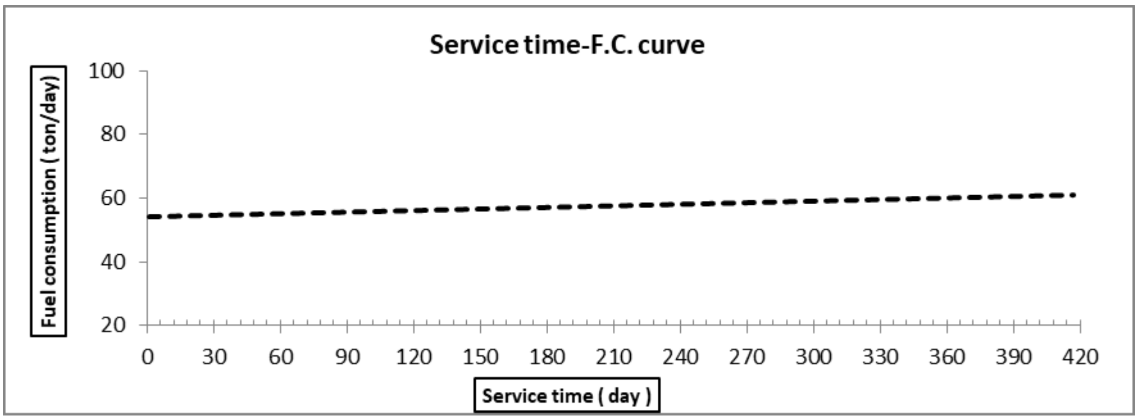

Figure. 10: Relationship between Salina's service life and its fuel consumption

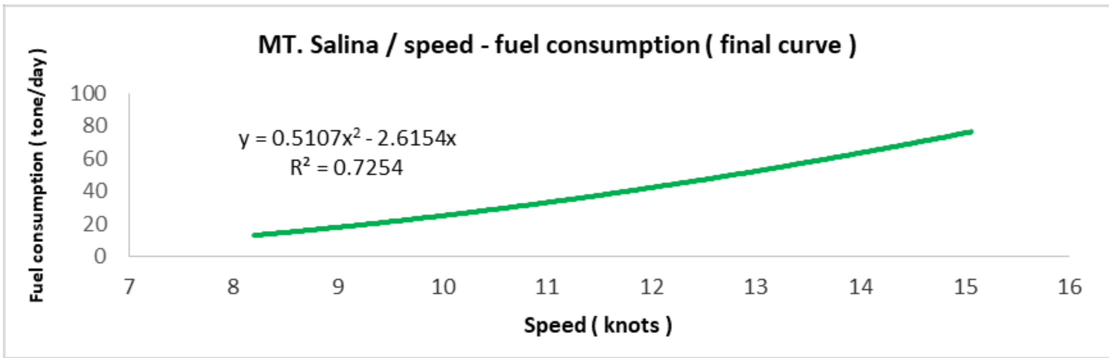

Figure. 11: Salina's Full load ultimate speed-fuel consumption curve over the period from 2013 to 2017

Having studied the effects of environmental factors on Salina's fuel consumption, changes and corrections were made in the relevant equations to introduce these effects into the estimation of fuel consumption by the vessel. These led to the most accurate speed-fuel curves for M.T. Salina as reported in Table 3. Thus, Figure. 11 presents a practical speed-fuel consumption curve for the ship as updated and corrected with regard to the variations during her service life and on the basis of the effects of sea currents, design draft, a Beaufort scale of 3 and side winds.

Figure. 11 is the combines Figures 9 and 10 to present Salina's full-load ultimate speed-fuel consumption curve over the period from mid-2013 to early 2017.

In the next Section, the curves thus far obtained along with the corrections effected in them will be sequenced and exploited to estimate Salina's fuel consumption on its future voyages.

2.3 A METHODOLOGY FOR THE ESTIMATION OF SALINA'S FUEL CONSUMPTION ON ITS FUTURE VOYAGES

Although environmental factors such as reduced seawater depths and sailing in shallow waters or the less severe factors such as adverse water temperatures and salinity have effects on speed-fuel consumption curve, the present study mainly addresses the major environmental factors of wind and waves. As per the objective of the study, a methodology has been developed for estimating Salina's fuel consumption at desirable speeds on its future voyages based on past records of environmental indices as outlined below:

- Using the ultimate–speed-fuel consumption curve (Figure. 11) and considering the specified speed for an upcoming voyage, an initial fuel consumption estimate is obtained.
- Using the weather forecasts for the upcoming days and the speed-fuel curve corrected for wind (Figure. 6), expected increases or decreases in the values of fuel consumption are determined to update the values obtained in Step 1 above.
- Using the weather forecasts based on the examined Beaufort scales for the upcoming days and the speed-fuel consumption curve corrected for sea state (Figure. 7), increases or decreases in the values of fuel consumption are determined to update the values obtained in Step 2 above.

The admiralty coefficient is used to determine Salina's fuel consumption taking into account the corrected draft values. The resulting changes in fuel consumption are then effected in the values obtained in Step 3. The corrections thus made will yield the ultimate estimate of fuel to be consumed on the vessel's upcoming voyage from load port to discharge port.

2.4 SPEED LOSS DUE TO WIND AND WAVES

Wind and waves account for the major factors leading to involuntary speed losses and increased fuel consumption (Herradón de Grado & Bertram, 2016). Due to the importance of the concept of "speed loss" as an index in the ISO. 19030, efforts were made in this study to determine speed losses due to wind and waves for Salina as a case study. The true drag force of a vessel depends on its real speed over water (Dückert, *et al*, 2016). Reduced speed due to waves, in turn, depends on the angle of impact, speed, and displacement. Towson and Won (Young-Joong, 1981) proposed a relatively straightforward relation (Eq. 7) for estimating speed loss due to additional drag imposed by wind and waves. Using this relation, Salina's speed losses were calculated and reported in percentage for Beaufort scales of 2 and 4.

$$\Delta V = C_{\mu}.C_{ship}.V\% \qquad (8)$$

where, ΔV is the speed loss due to wind and wave, V is service speed, and C_{μ} is a coefficient for wind and wave impact angles (Bertram, 2012).

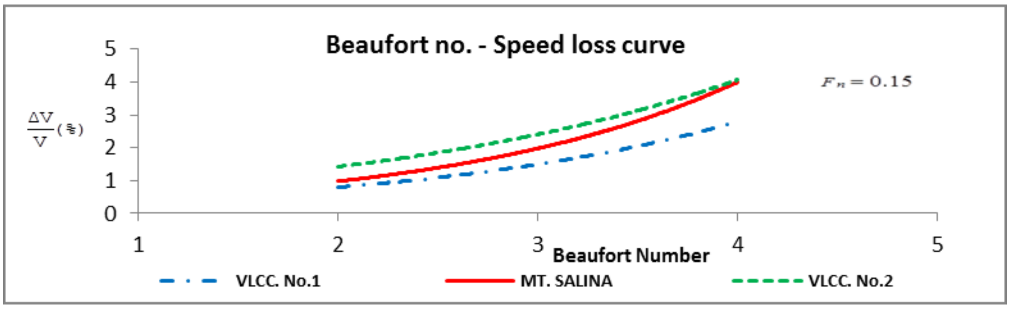

Figure. 12: Comparison of speed losses recorded for Salina and those for two VLCC oil tankers reported by Towson and Won

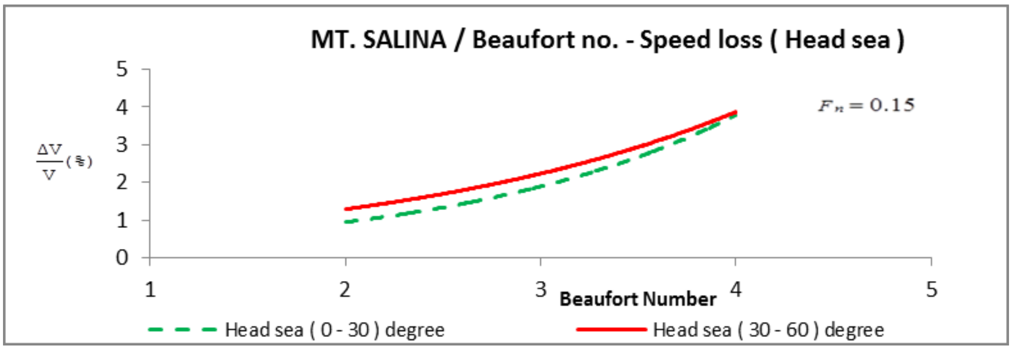

Figure. 13: Comparison of Salina's speed losses when hitting into wind and waves at impact angles of 0–30 and 30–60°

2.5 VALIDATION

The estimated values of Salina's speed loss for an average displacement of 179,000 cubic meters at Beaufort scales of 2 to 4 were verified following Won (Young-Joong, 1981). He compared the speeds of two tankers with displacements of 156,000 and 350,000 cubic meters for a Froude number of 0.15 at different Beaufort scales. He then compared the results with those estimated by Townson and Won's Relation (Nilson, 1977). The lowest speed loss of 0.8% for a Beaufort scale of 2 was recorded for the heavier vessel and the highest of 4% for a Beaufort scale of 4 was recorded for the lighter one. In the case of M.T. Salina, only slight differences were observed in the speed losses for Froude Nos. in the range of 0.13–0.16 and Beaufort scales of 2 to 4 due to changes in the wind and wave impact angles. The lowest average speed loss for a Beaufort scale of 2 was only 1.02% and the highest average for a Beaufort scale of 4 was 4.17%. An average speed loss of 1.83% was also recorded for a Beaufort scale of 3. Clearly, a good agreement is observed between the speed loss results obtained for Salina in the present study and those reported by Towson and Won (Young-Joong, 1981). Figure. (12) compares Salina's speed loss ratios for Beaufort scales 2, 3, and 4 at a Froude No. of 0.15 with those obtained for the two tankers in Towson and Won (Young-Joong, 1981). Figure. (13) compares Salina's speed loss ratios when facing wind and waves at impact angles of 0–30° and 30–60° relative to the longitudinal axis. Clearly, impact angles of 30–60° exhibit slightly greater effects on speed loss than those of 0–30° at Beaufort scales of 2, 3, and 4. More specifically, a greater difference is observed between the speed loss at impact angles of 30–60°than that at impact angles of 0–30° at a Beaufort scale of 2 while this difference is negligibly small between the same impact angles at a Beaufort scale of 4. It seems that, under more severe marine conditions with higher Beaufort scales, the impact angles of head, or even side, winds and waves yield different results in terms of involuntary speed losses.

3. RESULTS

Initial assessment of daily data revealed that wind and waves were unidirectional on 332 days but impacted the vessel from different directions on 85 days. Over 76% of the same period, the dominant sea conditions could be described by Beaufort scales of 2, 3, or 4, with the Beaufort scale of 3 dominating 29% of the whole period followed by scales of 2 and 3 accounting for 26% and 21% of the period, respectively. Beaufort scales of 2, 3 and 4 were the dominant conditions over 317 days of the study period; the average speed loss due to wind and waves during this period reached 2.2%. Average speed losses due to wind and waves were found to be 2.3%, 2.5%, 2.1% and 1.8% at relative impact angles of 0–30°, 30–60°, 60–150°, and 150–180°, respectively. Clearly, the highest speed loss occurred at a Beaufort scale of 4 and the lowest at a scale of 2. The highest and lowest average fuel consumption rates, respectively, were recorded to be 57.2 tons.day^{-1} at an impact angle of 0–60° and 51.8 ton.day^{-1} at an angle of 150–180°. This is while the average speed over ground (SOG) was 12 Knots and the average surface current speed was 0.5 Kn. Analysis of the daily data revealed that the average surface current speed was in the direction of the vessel's route so that it increased the vessel's speed. The maximum surface current speed was 3.2 Knots and its lowest was 0.1 Kn. Segmentation of the service life of the vessel in this study was indirectly used in the determination of speed and fuel consumption as a result of hull fouling and encrustation. Comparison of vessel performance before and after the dry dock and hull cleaning indicated a drastically reduced fuel consumption immediately after the dry dock of 2014 to rise again in the course of time by mid-2015. The maintenance evidently led to increased number of voyages as nine voyages were made by the vessel during the last 7 months of 2014 (immediately after the dry dock) but only 10 voyages were made throughout the whole year of 2015. This clearly indicates the reduced number of voyages during the first and third service periods and the significant contribution of periodic maintenance of dry dock and hull and propeller cleaning in the number of voyages by the vessel. The records of ship's repairs indicate that the first dry dock of March 2014 was accomplished between the segmented time steps of 3 and 4 and hull cleaning were carried out in June 2016. Obviously, the minimum drag force belonged to this period and led to increased speed and reduced fuel consumption. In other words, the vessel had its optimal performance during the segmented time steps of 2 and 4 of the total 42-month performance monitoring period after the dry dock maintenance of 2014 and after hull cleaning of 2016. Moreover, the voyage time of the vessel from the load port to the discharged port increased. The overall assessment of ship performance in the monitoring period from mid-2013 to early 2017 shows a steady decline in admiralty coefficient. Moreover, the results of this study indicate a direct relationship holding between service life and increased fuel consumption and speed loss.

4. CONCLUSION

Examination of M.T. Salina's trading pattern over the years indicates her reduced time lag for the next voyage. Compared to other vessels with time lag of months for their next lay day, Salina's hull had less fouling and encrustation due to its more frequent voyages. Measuring hull roughness and fouling is a difficult task due to the small size of the surface roughness compared to the ship's hull dimensions. Due to the limited variations in the vessel's draft on different voyages, such estimations are not sufficient to determine the definitive effect of displacement on fuel consumption; rather, combined assessments need to be made of the vessel in her laden and ballast conditions. The segmentation of the vessel's service life based on Beaufort scales led to improved estimations of Salina's fuel consumption. Further verifications for low Beaufort scales revealed that the greatest speed loss due to wind and wave occurred with headwinds and head seas. It was also found that the average speed loss was slightly higher with impact angles of 30–60° than with 0–30°. As Salina did not encounter adverse sea conditions of high Beaufort scales during its voyages, towing tank experiments might be required to obtain more reliable results. The results obtained from examination of Salina's performance over the past three years indicate that dry dock maintenance had slightly greater effects on her reduced fuel consumption than her hull cleaning and propeller polishing did. Moreover, investigations of Salina's performance over the past four years indicate that the differences in her fuel consumption rates between 2015 and 2016 increased to some extent with increasing service life. The methodology proposed in this study paves the way toward more accurate estimations of fuel consumption by Salina and 3 other sister ships on their future voyages. Depending on the scenario provisioned for each vessel, the proposed method may be recommended for using prior to each voyage to develop a fuel consumption estimation table for Beaufort scales of 2, 3 and 4 at the desired speeds. The information obtained might be usefully exploited during each voyage. For future study, the less severe marine factors of water temperature and salinity or the effects of more severe marine conditions of higher Beaufort scales on speed and fuel consumption may be suggested for detailed investigation.

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