Quantitative Comparison of Different Key Performance Indicators

Søren Hattel, FORCE Technology, Kgs. Lyngby/Denmark, shl@force.dk
Giannis P. S. Papageorgiou, FORCE Technology, Kgs. Lyngby/Denmark, gpp@force.dk
Vivien Rieu, FORCE Technology, Kgs. Lyngby/Denmark, vr@force.dk

Abstract

Based on data from a simple low-cost plug and play device for automatic logging of performance data we analyse the statistical properties of different performance indicators. Data originate from several ships from time periods of between one and twelve months of recorded data. We study correlations between the performance indicators and autologged signals in attempt to reveal shortcomings in the underlying model used for normalisation of the performance indicators. Furthermore, auto correlations of the performance indicators are studied in attempt to characterise completeness of the underlying model for normalisation of performance indicators.

1. Introduction

In this work we study the quality of different vessel performance indicators and their objective ability to describe the performance parameter they were designed for. The purpose of performance indicators is to as clearly as possible characterize a certain performance parameter. For instance, a performance indicator may be designed for studying the roughness of the hull and propeller surfaces and particularly the time evolution of the roughness. By monitoring the performance indicator over time, ideally it can be used for making decisions regarding hull and propeller treatments in order to optimize the performance in order keep the fuel consumption and emissions to a minimum. Since hull and propeller treatments are expensive and may require withdrawing the ship from service the reliability of the performance indicator is imperative. If the performance indicator is not reliable, the risk of making bad decisions is high and the potential for loss is correspondingly high.

The ship dynamics and propulsion system is influenced by many parameters for instance speed through water, draught and trim, wind and waves, water depth, water temperature, water salinity, rudder movements, ships motions and ship loading. These parameters influence the power demand to the propulsion system and to study only the effect of hull and propeller roughness the performance indicator has to deal with the influence of these parameters. Otherwise, the change in the performance indicator may simply be due to a change in one of these parameters. For instance, the increase in power demand may equally well be caused by an increase in speed through water as from an increased hull and propeller roughness, and if the performance indicator is not able to separate the effect of speed through water from the effect of hull and propeller roughness then we may not be able to make decisions about hull and propeller treatments.

In statistical terms the inability to differentiate two different effects on the conclusion is known as "confounding". One way of studying confounding for a performance indicator is to study the statistical correlations between different parameters and the performance indicator. A good performance indicator should exhibit strong correlation to the effect we wish to observe – say the hull and propeller roughness – while the correlation between other parameters and the performance indicator should be low.

Due to the complexity and nonlinearity of ship dynamics and ship propulsion systems it is not trivial to avoid confounding. Hence, different approaches to defining performance indicators have been proposed, *Pedersen (2014)* and references therein. Performance indicators are based on some underlying model of the ship dynamics and ship propulsion system. In some approaches, the performance indicator has been defined without explicit reference to an underlying model, but implicitly the performance indicator is always based on a model even if the creators of the performance indicator were not aware of the model. In these approaches the performance indicator may accidentally be confounded with other parameters leading to a poor performance indicator.

In other cases, the performance indicator is defined with a clear and explicit reference to a model explicitly including the effect that the performance indicator is designed to monitor. In the following section, we will discuss three different performance indicators. Two are based on implicit models and one is based on an explicit model. In the following sections, we study the correlations and auto-correlations of these performance indicators calculated from real world data collected by a simple and affordable autologging device, *Hattel et al. (2017),* onboard several ships.

We think the quest for defining the best performance indicators for ship performance as the holy grail in ship performance monitoring. This study is but a small contribution to our quest for the holy grail.

2. Definition of performance indicators

In this section, we introduce three performance indicators designed for monitoring hull and propeller fouling, and discuss their characteristics and properties. In the following sections, we will report our experience with the performance indicators from real world data.

2.1 Speed loss

A common performance indicator is known as "speed loss" in marine lingo. In this study, we apply the definition from the ISO19030 standard:

$$V_{loss} = \frac{V_m - V_e}{V_e}\ 100\% \tag{1}$$

where V_m is the measured speed through water and V_e is the calculated expected speed through water. The procedure for calculating V_e from the measured parameters – shaft power, wind, draught, trim etc – are described in the ISO19030 and were applied in this study. (Note that the expected speed is not corrected for wave effects. Also, the v_g(speed over ground) appearing in formula G.2 of the ISO19030 standard was replaced with v_{tw} (speed through water) as we believe the presence of v_g in G.2 is a typo.)

Note that $V_{loss} < 0$ when the measured speed is below expectations which suggest that the proper name is a speed gain. In any case, V_{loss} should be very close to zero for a well performing ship and negative values indicate poor performance.

The speed loss concept is widespread and very easy to understand: If the ship sails slower than expected, then it is evidently not performing optimally. However, the speed loss definition is not derived from an explicit model attempting to address the nature of the performance loss. Hence, the underlying model must be inferred from the definition (Eq.(1)).

The first assumption is that V_{loss} is indeed a good performance indicator which is independent of the actual speed V_m . Then the speed loss measured at one speed will represent the speed loss at all speeds. From the definition of V_e we got a reference speed-power curve $P_{cond}(v_{tw})$ for each relevant condition – draught, trim, wind and waves. (Wind corrections are included in $P_{cond}(v_{tw})$ instead of correcting the measured power for wind effects. The two approaches are completely equivalent.) Assuming V_{loss} is small we can derive the approximate speed power curve for the implicit performance model at each set of conditions:

$$P_{speedloss}(V_m) = P_{cond}(V_e) = P_{cond}\left(\frac{V_m}{1 + \frac{V_{loss}}{100\%}}\right)$$

$$\approx\ P_{cond}\left(V_m(1 - \frac{V_{loss}}{100\%})\right)$$

$$\approx P_{cond}(V_m) - \frac{\partial P_{cond}}{\partial V_e}(V_m)\frac{V_m\, V_{loss}}{100\%} \quad (2)$$

where the first power identity is based on the definition of V_e and the approximation is to first order in V_{loss}.

Eq.(2) is the implicit model description of the ship dynamics and propulsion at varying speeds for a certain condition assuming that Eq.(1) defines a speed independent performance indicator, V_{loss}. By inspection of Eq.(2) we observe this model predicts that the speed power curve is shifted upwards at reduced performances ($V_{loss} < 0$). The shift is proportional to both V_{loss}, V_m and the slope of the reference shaft power curve, $\frac{\partial P_{cond}}{\partial V_e}(V_m)$. Roughly estimating the speed power curve as $P_{cond}(V) \sim k\, V^{\epsilon}$ (with the exponent $\epsilon \gtrsim 3$) the model roughly estimates the shift to be proportional to V_{loss} and V^{ϵ}:

$$\Delta P_{speedloss}(V_m) \propto -V_{loss}\, V_m^{\epsilon}$$

Hence, this model roughly predicts that the upward speed power curve shift at 12 knots is $2^{\epsilon} \gtrsim 8$ times higher than the shift at 6 knots.

2.2 Excess resistance

A common performance indicator is defined in terms of an extra resistance that is observed when comparing the nominal provided thrust from the propeller compared to a reference hull resistance at the specified speed and conditions. The extra resistance is sometimes referred to as "added resistance due to fouling" but to avoid confusion with the often used phrases "added resistance due to waves/wind/shallow water" we will refer to this as the "excess resistance" indicating that the origin of the resistance is not addressed.

We define excess resistance as:

$$R_x = \frac{T - R_{cond}(V_m)}{½\left(T + R_{cond}(V_m)\right)} 100\% \quad (3)$$

T is the effective thrust $T = (1-t)T_{prop}$. T_{prop} is the thrust provided by the propeller and t is the thrust deduction due to increased suction on the hull. $R_{cond}(v_{tw})$ is the reference speed-resistance curve at specified condition – draught, trim, wind and waves.

The definition of R_x is not derived from an explicit model and we wish to derive the model equivalent to the procedure for the speed loss. Assuming that R_x is a robust performance indicator then it should be independent of the actual speed V_m. In static conditions T will balance the actual hull resistance, $R_{actual}(V_m)$. Using this identity and assuming that R_x is small we can perform a derivation equivalent to the derivation for speed loss:

$$R_{actual}(V_m) \approx \left(1 + \frac{R_x}{100\%}\right) R_{cond}(V_m) = R_{cond}(V_m) + \frac{R_x R_{cond}(V_m)}{100\%} \quad (4)$$

This model predicts a shift of the speed-resistance curve proportional to excess resistance, R_x, and the reference speed-resistance curve. In order to compare with Eq.(2) we convert to the power domain by multiplying Eq.(4) with V_m/η_T:

$$P_{actual}(V_m) \approx P_{cond}(V_m) + \frac{R_x P_{cond}(V_m)}{100\%} \quad (5)$$

Comparing to Eq.(4) we observe that this model predicts the shift of the speed-power curve to be proportional to R_x and $P_{cond}(V_m)$ rather than $\frac{\partial P_{cond}}{\partial V_e}(V_m)V_m$ in Eq.(4). Again, using the rough estimate

$P_{cond}(V) \sim k\, V^{\epsilon}$ we observe that this model predicts the same shift:

$$\Delta P_{actual}(V_m) \propto R_x\, V_m^{\epsilon}$$

Hence, except for a scaling factor and a sign convention the speed loss and the excess resistance are essentially based upon the same implicit model. Consequently, a priori we may expect the two performance indicators to show similar correlations and autocorrelations. However, $R_{cond}(V_m)$ includes added resistance due to waves whereas the speed loss calculation does not correct for waves. Hence, we may expect some differences between the two performance indicators.

2.3 Speed index

The third performance indicator is the speed index. The definition of the speed index is based on a complete explicit steady state model of the hydro- and aerodynamics and propulsion system of the ship, *ITTC (2011)*, including hull surface roughness and propeller roughness. The influence of hull surface roughness is modeled by an increase, ΔC_F of the viscous coefficient and the influence of propeller roughness is modeled by an increase, ΔK_Q, of the propeller torque coefficient and a decrease, ΔK_T, of the propeller thrust coefficient. The model includes an effect of the hull fouling on the wake fraction and consequently on the hull efficiency.

For an observed speed, draught, propeller speed, propeller torque, wind, waves, water depth, etc., the three parameters ΔC_F, ΔK_Q and ΔK_T are estimated as the values providing the best consistency between the measured data and the model. The speed index is defined as:

$$V_{idx} = \frac{V_{norm}}{V_{ref}} 100\%$$

Here V_{norm} is the speed which the model predicts from the calculated values of ΔC_F, ΔK_Q and ΔK_T at a certain reference torque in calm sea and deep water. V_{ref} is the speed which the model predicts if ΔC_F, ΔK_Q and ΔK_T are zero.

In this model, the estimated parameters are required to calculate the shift of the speed power curves. The estimation of the three parameters depends differently for the three parameters. Since the speed index is the consequence of this shift it is not possible to quantify the shift only in terms of the speed index. This contrasts with the previous performance indicators where we could write the speed dependency in terms of the performance indicators themselves.

Essentially, the three parameters are the proper performance indicators in this model, and the speed index describes an aggregate of the three.

2.4 Discussion

The three performance indicators defined here reflect different approaches. Speed loss and excess resistance have very simple definitions. Our calculations show that the simple definitions implicitly assume models where the speed power curves are shifted upwards with a shift described directly by the performance indicator.

The speed index on the other hand attempts to model the actual effect of hull and propeller roughness from established hydrodynamic principles including the effect of speed according to the physical laws of the system. The observation that the model for the speed index cannot be formulated as a simple shift of the speed power curves suggests that the two simpler performance indicators may be incomplete for the description of the performance. For instance, it may turn out that their prediction of the speed dependency of the speed power curve shift is not properly describing underlying physics. Hence, we may expect the three performance indicators to show different correlations to the measured speed.

In the ISO19030 standard the key performance indicators are formulated as averages of the speed loss over substantial time spans. One may argue that this will compensate for the possible speed dependency of the speed loss provided the distribution of speeds over the different timespans are the same. However, in many cases the distribution of speeds will not be the same for two different timespans and even if the average speed for two timespans are the same then the distribution of speeds may be very different. Due to nonlinearities of the system the average speed loss may not be equal even if the average speeds are the same, *Hattel et al. (2017)*.

Apart from the understanding of the different models response to varying speeds it is also interesting to understand the models response to variations in draught and trim. We may explore this question in a future project.

3. Procedure

In the following sections, we present statistical observations of the behavior of the three performance indicators when applied to data recorded from ships in operation. We emphasize that all three performance indicators are calculated based on the same reference curves established from the same external data. Hence, the differences are not due to differences in the quality of the external data.

We have used data from fifteen tankers and bulk carriers in operation. All vessels have recorded the same complete set of signals – shaft power, propeller RPM, speed through water, rudder angle, wind angle and direction, water depth – and reported the draught and trim via noon reports. The vessels have recorded in varying time spans ranging from a few weeks to more than a year. The quality of the reference data for the fifteen ships varies.

All data were batched into datasets of one hour periods. Datasets were filtered for invalid data and outliers. Datasets were decimated by removing the least stable datasets as described in *Hattel et al. (2017)*. A total of 9874 datasets representing 9874 hours of collected data remained for use in the final analysis.

For the remaining datasets, the three performance indicators for speed loss, excess resistance and speed index were calculated. Datasets were grouped into laden condition and ballast condition. For ships with data series spanning more than three months' data were separated into groups spanning less than three months. The separation was made between two voyages. For each dataset for each vessel the correlations between the performance indicators and the different measured parameters were calculated. For each vessel, the autocorrelations of each performance indicator were calculated for one hour of lag. I.e. the correlation between a performance indicator value at one time and the performance indicator one hour later (if it exists and is not excluded by filtering):

$$\hat{\rho}_{1hour} = \frac{E[(y_{t+1} - \bar{y})(y_t - \bar{y})]}{E[(y_t - \bar{y})^2]}$$

where y_t is one of the performance indicators at time t.

4. Results

Fig.1 shows the calculated correlation coefficients between speed through water and the three performance indicators. Correlation between speed through water and speed index is plotted along x-axis. Correlations between speed through water and excess resistance (triangles) and speed loss (circles) are plotted on y-axis. Correlations for speed index ranges from -0.83 to 0.85 with the average at 0.18. Excess resistance ranges from -0.7 to 0.73 with the average at -0.16. Speed loss ranges from -0,48 to 0.82 with the average at 0.37. The general picture is that there are substantial correlations between speed through water and all the performance indicators. Hence, none of the performance indicators are clearly superior or inferior to the others.

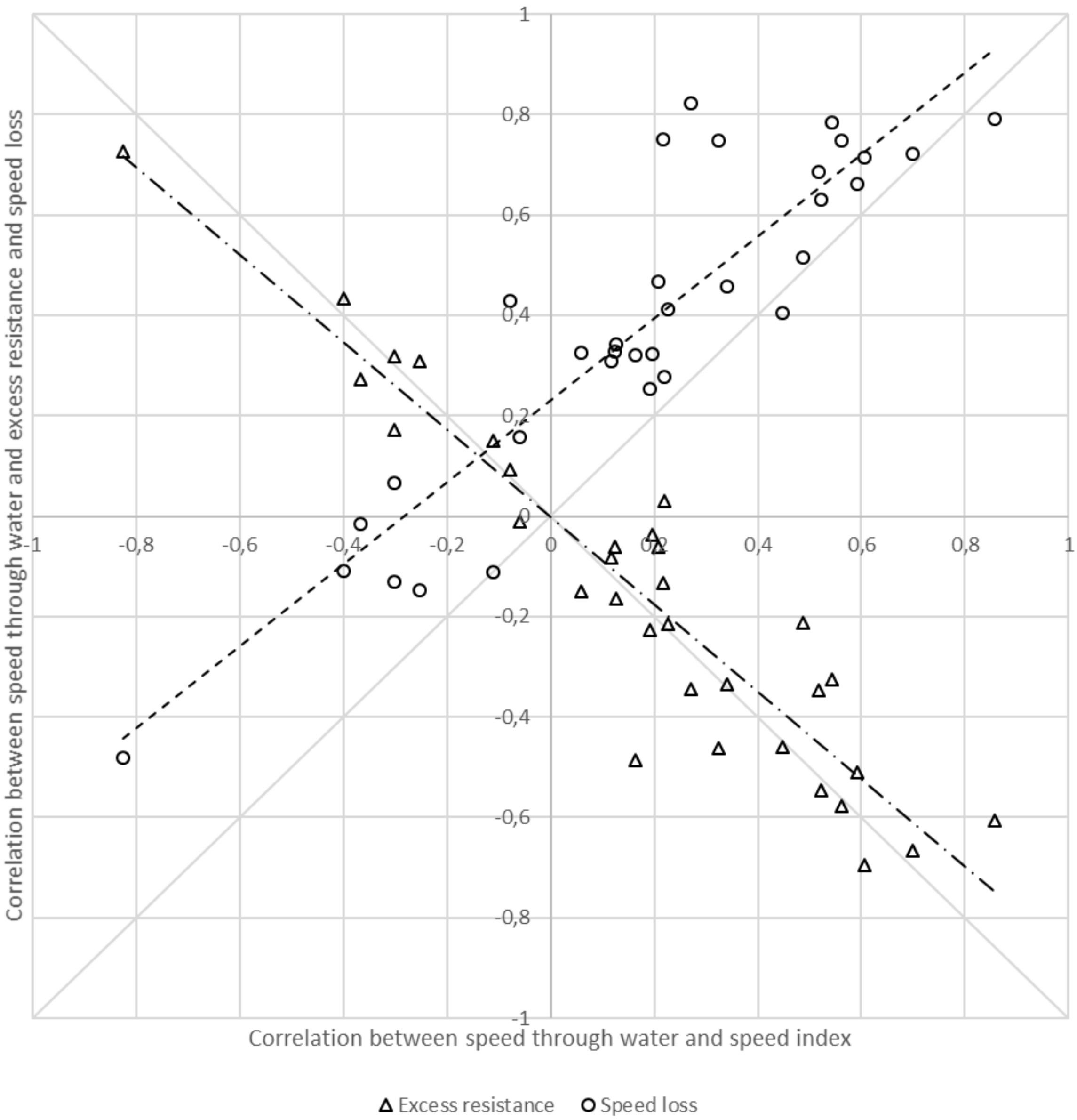

Fig.1: Correlation coefficients between speed through water and the three performance indicators: Speed index (x-axis), excess resistance (triangles, y-axis) and speed loss (circles, y-axis)

We observe a clear tendency that the speed index correlations and the speed loss correlations have the same sign whereas the speed index correlations and the excess resistance correlations have opposite signs. This reflects the fact that good performance corresponds both to higher speed index and higher speed loss (due to the confusing sign convention in Eq.(1)) whereas it corresponds to lower excess resistance.

The correlations for speed index and excess resistance are quite similar except for the opposite signs with points falling almost equally on each side of $y = -x$ line. In contrast, we observe that correlation coefficients for speed loss are generally falling on the high side of the $y = x$ line indicating generally higher correlations for speed loss than for speed index. Thus, the correlation coefficients for speed loss are between 0 and 0.55 higher than the correlation coefficients for speed index.

The observation of correlations generally does not proof a causality. Hence, the correlations we observe in Fig.1 do not suffice to say that the performance indicators depend on speed. In our dataset, we observed that most ships were sailing in a "fixed propeller RPM" mode. Hence, whenever wind and waves build up then the speed through water tend to fall. In other words, we observe some correlation between the wind and the speed through water. To at least to some extend the variations in speed are due to variations in wind and waves. This causality between weather conditions and speed through water may suggest that the observed correlations are describing a correlation between weather and performance indicators.

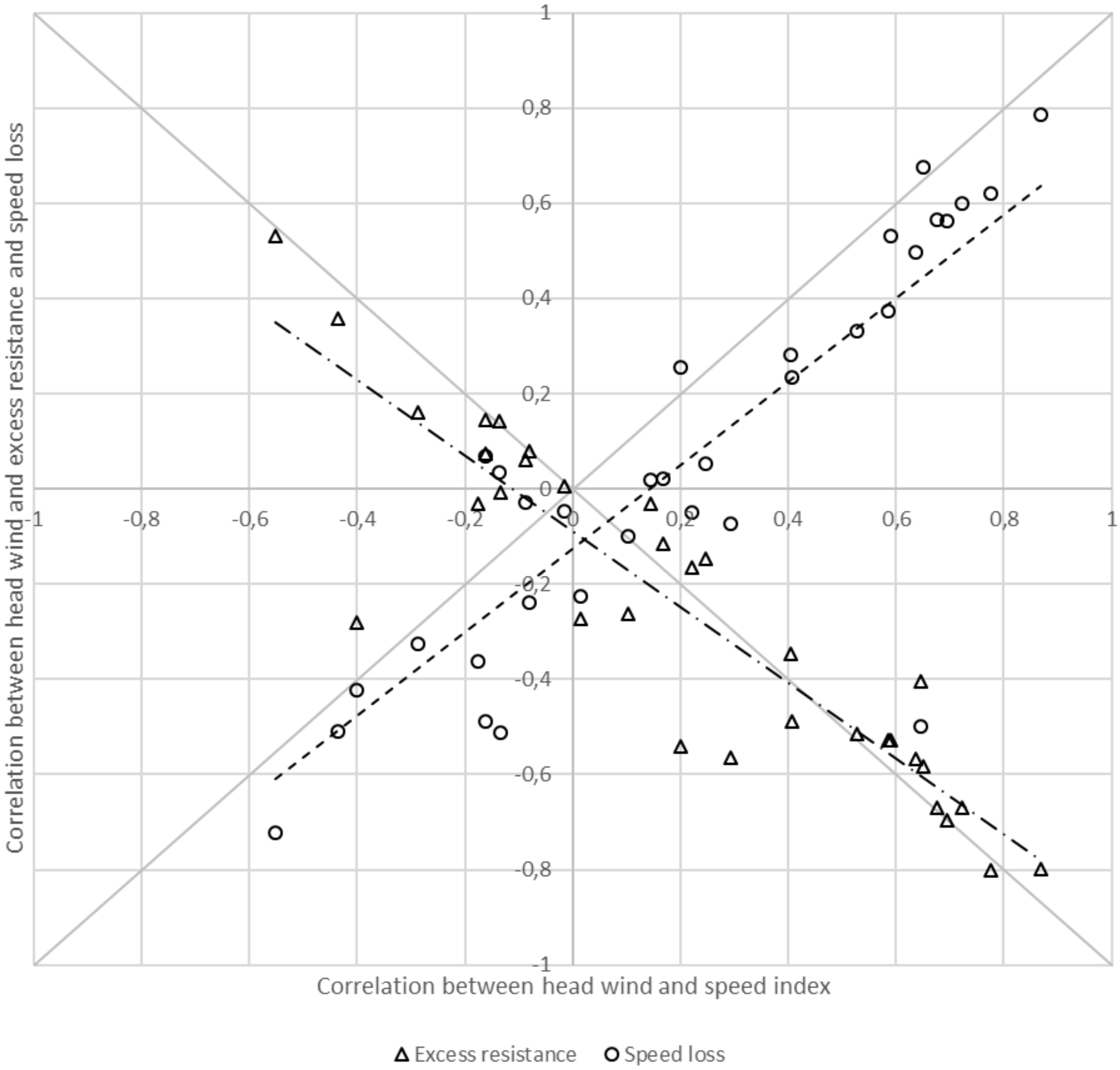

Fig.2: Correlation coefficients between head wind component and the three performance indicators: Speed index (x-axis), excess resistance (triangles, y-axis) and speed loss (circles, y-axis)

Fig.2 shows the correlation coefficients between the head wind component (relative wind vector projected onto ships heading) and the performance indicators. The general picture resembles that of Fig.1 except that the speed loss correlations are generally below the $y = x$ line and not above. This is probably the consequence of the speed loss not accounting for waves which are highly correlated to wind making the speed loss less dependent on weather conditions.

Fig.3 presents calculated autocorrelation coefficients for each performance indicator. All performance indicators show strong autocorrelations and there is no noticeable trends or differences between them.

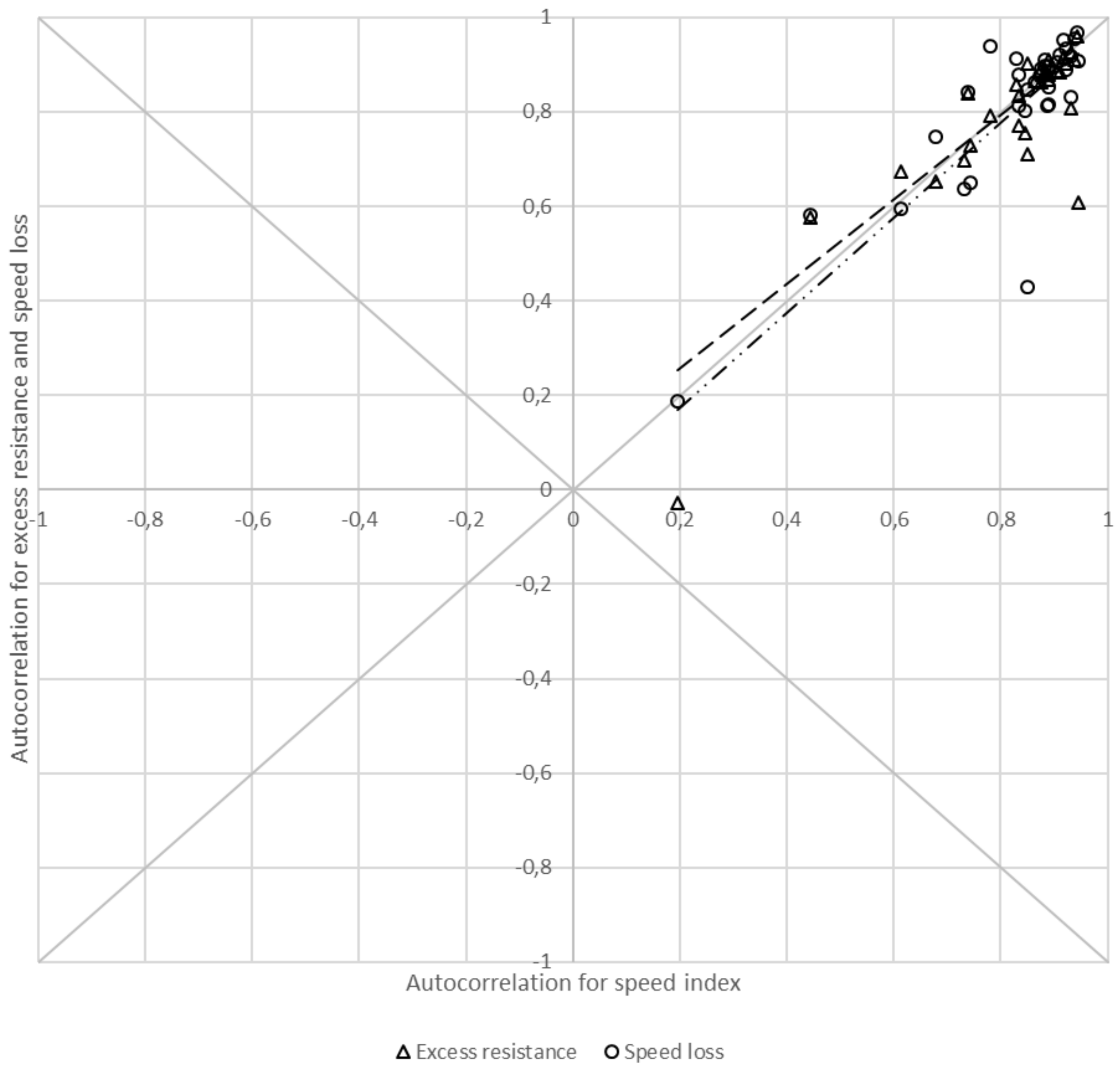

Fig.3: Autocorrelations for one hour lag for each performance indicator. Autocorrelation for speed index on the x-axis. Autocorrelation for excess resistance (triangles, y-axis) and autocorrelation coefficients for speed loss (circles, y-axis).

5. Discussion

The three performance indicators studied aim to characterize the state of the hull and propeller surfaces. Hence, ideally – if the underlying models adequately describe the physics of the ships - the performance indicators should not show any significant correlations to the input parameters and only show strong correlation to the hull and propeller surface states.

However, we observe substantial correlations between speed through water and the performance indicators as well as between the head wind and the performance indicators. In this study the variation in speed is linked to the variation in weather conditions due to the "fixed propeller RPM" mode used by the ships, and speed through water is partially a proxy for measuring the weather conditions. Hence, the effect of weather and speed through water are more or less confounded in our datasets.

All the performance indicators are defined in a way that should account for and subtract the effect of weather, but the correlations suggest that this effort fails to some extent. Our hypothesis is that the models for wind resistance and wave resistance are inadequate.

This hypothesis may be supported by the observed substantial autocorrelations. Strong autocorrelations are a sign that the underlying model is inadequately describing the actual system, since an adequate model would only leave uncorrelated random noise. Autocorrelations originate from some underlying mechanisms that are in themselves autocorrelated. In this system, the weather conditions are the most likely causes for the autocorrelation, as it is well known that the odds for the weather to be the same as the present within the next hour are quite high. The weather conditions are not to be considered a stochastic uncorrelated parameter.

With a more detailed view, we observe that the speed index and the excess resistance performance indicators behave very much the same with regards to the correlations except for the trivial sign convention. On the other hand, the speed loss correlations behave slightly but noticeably different.

The derivations in section 2 of the models that represent the performance indicators we expected that speed loss and excess resistance would be very similar whereas it was suspected that the speed index would behave differently. This contrasts with the observations.

Recall however, that the speed loss does not correct for waves whereas both speed index and excess resistance corrects for waves. This may explain why speed loss is behaving slightly differently from the two others. If all three performance indicators applied the same procedure to correct for weather conditions, we may observe higher agreement between all three performance indicators.

6. Conclusion

We have formulated a framework for studying the underlying models for different performance indicators. We derived the implicit models for speed loss and excess resistance and they turn out to be equivalent except for a sign convention and for a difference in the procedure for correction for weather conditions.

We calculated selected correlations and autocorrelations for the performance indicators from observed autologged data from fifteen ships. For all three performance indicators, substantial correlations and autocorrelations were observed and they showed remarkable agreement between them despite their different formulations especially considering the differences in the procedure for weather corrections.

The three performance indicators are equally poor as performance indicators. This is good news if you prefer one performance indicator for another as it really does not make any difference. The bad news is, of course, that the observed correlations to weather and speed may lead to false conclusions regarding the actual performance of hull and propeller. The correlations may hide or even reverse the effect of the hull and propeller performance on the performance indicators.

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