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Prediction of ships' speed-power relationship at speed intervals below the design speed

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ABSTRACT

This study investigates the speed-power relationship of ships, and is based on a combined econometric and naval architectural data-driven model fed with operational data from more than 50,000 noon reports obtained from 88 tankers. It is shown that the speed-power exponent is significantly lower than 3 at speed intervals below the design speed. This finding, including the study itself, affects the environmental discussions related to slow steaming, since it implies that slow steaming will not be as good as often stated. As such, the study imparts attention to speed optimisation, rather than reduction, in the political and environmental debate focused on the reduction of carbon emissions from shipping.

1. Introduction

1.1. Background and motivation

In the shipping industry, the focus on fuel consumption and vessel performance – driven by the present green and sustainable mindset – has lead to many initiatives in order to minimise emissions. One of them is *slow steaming*; in simple terms achieved by reducing the speed of the vessel, thus leading to a reduction of the main engine demand, even down to 10–20% maximum continuous rating (MCR) according to MAN Energy Solutions (2012) and Psaraftis and Kontovas (2014). As there is a simple linear relationship between fuel consumption and emissions as well as a nonlinear relationship between power and fuel consumption through the specific fuel oil consumption (SFOC) curve, there is a direct relationship between power and emissions; that is, reduced power leads to reduced emissions. Due to the nonlinear relationship between speed and power, a relatively small reduction in speed will lead to a significant reduction in power. The relationship between power P and speed V is often described with $P \approx V^c$ where c is a constant exponent with a value of at least 3 (MAN Energy Solutions, 2018), noticing that the relationship generally is applicable to relative high speed intervals around the design speed (Psaraftis and Kontovas, 2014). On the other hand, it has been argued that at lower speed intervals, the relationship will underestimate the power and thus fuel consumption, which means that the effect of slow steaming is overestimated, as reported by Adland et al. (2020), Taskar and Andersen (2020), Tillig et al. (2018) among others.

In the past, the reduction of speed has been considered as a low-hanging fruit towards lower emission levels (Eide et al., 2009; Corbett et al., 2009; Fagerholt et al., 2010; Lindstad et al., 2011; Faber et al., 2012; Lindstad et al., 2013; Norlund and Gribkovskaia,

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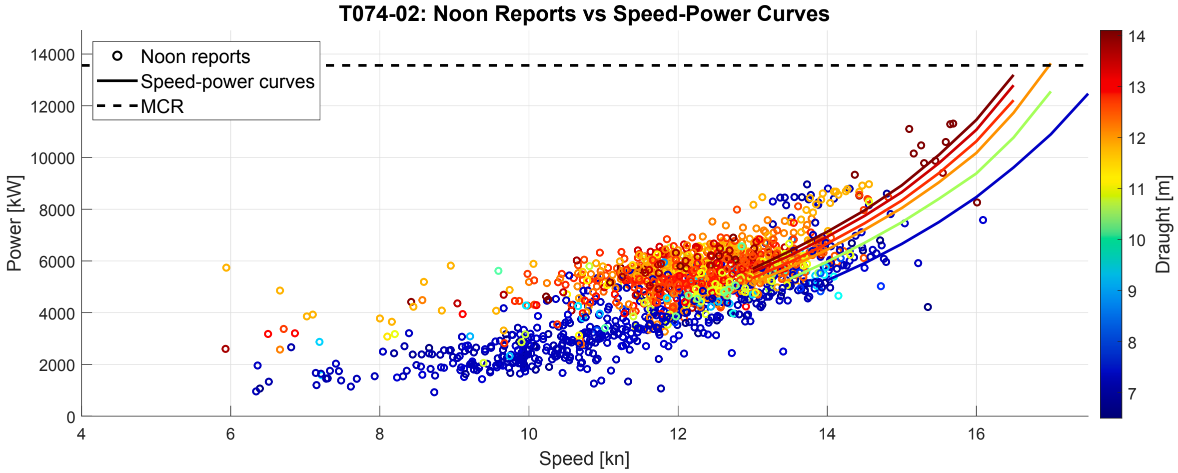

Fig. 1. Illustration of the operational profile of a group of sister ships with respect to corrected speed, corrected power and draught compared to the associated model test curves for different but given draughts. This is data for two tankers of 74,000 DWT. Note that the colour scale (draughts) is the same for noon report data and model test curves.

2013; Woo and Moon, 2014), primarily focused on CO_2 but also affecting other emissions (NOx, SOx, etc.). On a policy-level, the effect of speed reduction has called for the use of operational measures as well as market-based measures assuming that an increase in bunker price through tax will lead operators to reduce speed. However, it is clear that if the cubic law does not hold, it impacts one of the main policy recommendations by the International Maritime Organization (IMO) to reduce carbon emission through speed reduction. Nevertheless, it is a fact that the environmental discussions in IMO are based on the assumption that ships' main engine power is proportional to the speed cubed (IMO, 2014, 2020); although the assumption is not necessarily accepted as the universal truth by all members of the IMO.

It is beyond doubt that the amount of CO_2 reduces, as measured for the single transported unit, when ships slow steam. However, as reported by Kristensen (2018), if the total amount of transported units should remain constant, the effect of slow steaming is degraded, as more ships are needed. This point is as important to consider as that of the physics related to speed-power modelling, introduced above and being the main research topic of the present study, when discussing the future environmental policies and regulations for ships and shipping.

Sea trials and ship resistance model testing, typically used as benchmark in ship power performance monitoring, are often done around the design speed and therefore at fairly high speed intervals, not necessarily matching the actual operational speed of the ships. The problem can be seen in Fig. 1 where real operational noon report (NR) data is plotted together with speed-power curves derived from resistance model tests. In the figure, the reported NR power has been corrected for added resistance due to wind and waves and the speed is corrected for current. In order to do vessel performance monitoring, a benchmark that covers the whole speed interval is needed; while it can be appreciated that the results from model test curves only extend down to the higher speeds of the NR-reported speeds. This problem is often encountered by shipping companies, or by third party vessel performance companies monitoring the performance and providing voyage optimization as a combined service. One specific example of the latter is the company COACH Solutions[1] that has provided the data for the present study, see Section 3. The problem with traditional extrapolation of model test data is also discussed by, e.g., Kauffeldt and Hansen (2018).

1.2. Objective and novelty

The main objective of this study is to investigate ship's speed-power relationship at speed intervals below the design speed. Due to the physical nature of the problem at hand, as indicated above, this boils basically down to investigating the speed-power exponent, also denoted the elasticity in the literature (Adland et al., 2020). In the study, this is done by analysing operational data consisting of noon reports from tankers through a data-driven approach combining principles from naval architecture and an econometric framework. The speed-power exponent is itself dependent on speed; hence, speed *intervals* are introduced (for practical reasons) in such a way that the speed-power exponent is constant within a given limited interval, noticing that in reality the speed-power exponent is expected to vary continuously with speed.

The paper brings emphasis to the slow steaming debate in shipping (Maloni et al., 2013; Psaraftis and Kontovas, 2015; Psaraftis, 2019a). Notably it questions the often imposed assumption (”misconception”) about a constant power exponent equal to 3 (IMO, 2014, 2020); potentially leading to an overestimation of the positive effects of slow steaming with respect to fuel consumption and associated emissions. Next to this, the paper documents the problem often faced in vessel performance monitoring; namely that the observed

[1] https://coachsolutions.com/.

speeds in operational data do not match the model test curves upon which the monitoring and benchmarking are based.

The novelty of the study compared to the existing literature (Adland et al., 2020) is the consistent use of methods from naval architecture in combination with econometric models, while Adland et al. (2020) rely on an econometric framework exclusively. The introduction of naval architectural models, especially for the correction of measured power with respect to wind and waves, in accordance with reports by the International Towing Tank Conference (ITTC) and ISO 19030 (ISO, 2016a,b,c), is considered a means for reducing uncertainties related to manual choices and decisions necessary in the pure econometric framework. Furthermore, the present study puts the findings in a context of practical vessel performance monitoring by comparing all data and modelled outcome with available resistance model test curves. This can be considered a way to emphasise the credibility of the present study; and to some extent also the previous similar study (Adland et al., 2020) which did not include such a comparison.

1.3. Literature review

There is a wide and increasing literature dealing with modelling and evaluation of the performance of ships sailing at sea, e.g. Kristensen (2010), Pedersen (2014), Lu et al. (2015), Trodden et al. (2015), Tsujimoto and Orihara (2018), Coraddu et al. (2019), Karagiannidis and Themelis (2021), Hüffmeier and Johanson (2021), Spandonidis et al. (2021) to mention just a few earlier and more recent ones. The increasing set of studies is largely explained because of ease of data access; thus, most of today's ships are monitored with sensor systems, either relying on the ship-board crew to read data on a daily basis in terms of noon reports, or the data is continuously logged and stored on local hard disks, and subsequently sent to shore manually or via internet. Three noteworthy references about general use of ship performance data are Bazari (2007), Aldous et al. (2015), Dalheim and Steen (2020). The specific literature about slow steaming is also large, with both older existing studies and newer ones coming in, e.g. Corbett et al. (2009), Cariou (2011), Meyer et al. (2012), Woo and Moon (2014), Ferrari et al. (2015), Tillig et al. (2020), Degiuli et al. (2021) to add on what has already been mentioned in the beginning of the introduction (Kristensen, 2018; Tillig et al., 2018; Taskar and Andersen, 2020). The background literature for the econometric framework of the present study has been mentioned (Adland et al., 2020). The particular framework has itself been applied previously to other interesting, similar problems; mentioning that, on a general level, the framework has been developed to study the local effects of an innovation (Gobillon and Wolff, 2017; Gobillon and Wolff, 2020), while Adland et al. (2018) used the framework to study the effect of periodic ship hull cleanings. The combined naval architectural framework used in the present study is based on the ISO standards: ISO (2016a,b,c). In addition, detailed readings about the correction of wind and waves (Liu et al., 2020; Nielsen et al., 2021) as well as readings about the use of hindcast wave data (Copernicus Climate Change Service (C3S), 2018; Hersbach et al., 2020; Hersbach et al., 2021; Nielsen, 2021) could be worth to consult.

1.4. Article structure

The article contains six sections. Section 2 presents the fundamentals and basic concepts of the study. Section 3 describes the data used in the study. Section 4 presents the results from the study, and Section 5 discusses the results and brings forward their relevance to the slow steaming debate. Finally, Section 6 concludes on the study.

2. Fundamentals and basic concepts

The basis for ship power prediction is from the International Towing Tank Conference (ITTC) *1978 ITTC Performance Prediction Method* (ITTC, 2017a), upon which the standard ISO 19030 (ISO, 2016a,b,c) is based. The fundamentals of the linear regression models are taken from Pardoe et al. (2021) and Neter et al. (2003).

2.1. Speed-power exponent

The speed-power relationship of a sailing ship can be approximated with $P \approx V^3$ as described in Section 1.1. In fact, the relation is based on the still water resistance, dependent on the density of (sea) water ρ_w, the wetted surface area S_w, and the total resistance coefficient C_t. In this case, the effective power P_e is modelled with,

$$P_e = \frac{1}{2}\rho_w S_w C_t V^3 \tag{1}$$

where $(1/2\rho_w S_w C_t)$ often is assumed to be constant which, however, is not true. This term is both speed, draught and temperature dependent. The speed is included through the Reynolds number in, respectively, the frictional resistance coefficient, the roughness allowance and correlation allowance. The draught is included through the wetted surface area, and temperature is included through the density of water but also through the viscosity in the Reynolds number, and through the density of air in connection with the air resistance coefficient.

It is important to note that, in this study, the speed-*power* relationship is modelled, instead of modelling the relationship between speed and fuel consumption, like studied by Adland et al. (2020). The present study is thus independent of the engine type which is considered an advantage compared to the models in Adland et al. (2020) that require the nonlinear SFOC curve to be modelled into the problem.

In the following, two models are given for the relationship between speed and power. First, a simple model is introduced to define the problem and, subsequently, an extended model is developed.

2.2. Simple model

The starting point for the model generation is the most simple power law model describing the relationship between power P and speed V reported in the noon reports:

$$P = x_1 V^{x_2} \tag{2}$$

where x_1 and x_2 are the unknown variables. Here x_2 is the speed-power exponent that is the focal point of this study, and it is emphasised that both variables, x_1 and x_2, must be determined from the analysis of data. The nonlinear model is made linear by taking the logarithm:

$$\ln(P) = \ln(x_1) + x_2 \ln(V) \tag{3}$$

As shown subsequently, the model can be extended in order to take other relevant variables into account. First, however, note that in practice, the model is given by:

$$\begin{bmatrix} \ln(P_1) \\ \ln(P_2) \\ \ln(P_3) \\ \vdots \\ \ln(P_n) \end{bmatrix} = \begin{bmatrix} 1 & \ln(V_1) \\ 1 & \ln(V_2) \\ 1 & \ln(V_3) \\ \vdots & \vdots \\ 1 & \ln(V_n) \end{bmatrix} \begin{bmatrix} \ln(x_1) \\ x_2 \end{bmatrix} \tag{4}$$

when a set of corresponding observations $\{P_i, V_i\},\ i = 1, 2, \cdots, n$ exist from n noon reports. This means that the unknown coefficients x_1, x_2 can be easily determined by formulating a least-squares problem.

2.3. Extended model

The simple model is the basis for an extended model that take the draught and speed intervals into account. The simple model is therefore gradually extended.

2.3.1. Draught

One of the most important parameters regarding the speed-power relationship is the draught. As realised from speed-power curves, e.g. Fig. 1, the ballast curve (smallest draught) and scantling curve (largest draught) will differ relatively much. It is therefore necessary to introduce the draught as an independent parameter in the model:

$$\ln(P) = \ln(x_1) + x_2 \ln(V) + x_3 T \tag{5}$$

noticing that T is the mean of the reported fore and aft draughts. This extended model, with draught as a parameter, implies that speed-power curves at different draughts will be parallel but shifted when studied in a log-log plot. Qualitatively speaking, draught is thus an additive effect. In order to take into account that the resistance model test curves are not parallel in log-log domain, an interaction term is introduced since the exponent x_2 must be dependent on the draught when studying speed-power curves from model tests:

$$\ln(P) = \ln(x_1) + x_2 \ln(V) + x_3 T + x_4 \ln(V) T \tag{6}$$

Hereby the slope of the linear equation becomes dependent on the draught:

$$\ln(P) = \ln(x_1) + (x_2 + x_4 T) \ln(V) + x_3 T \tag{7}$$

When transformed back into the nonlinear form the speed-power relationship becomes:

$$P = x_1 V^{(x_2 + x_4 T)} \exp(x_3 T) \tag{8}$$

2.3.2. Speed

A speed dependent exponent is introduced through piecewise linear regression. This is done by introducing a dummy variable assigning the noon reports to different speed intervals, hence introducing a ”breakpoint” separating different speed intervals. As an example, the speed-power regression model with one breakpoint B_p reads:

$$\ln(P) = \ln(x_1) + x_2 \ln(V) + x_3 T + x_4 \ln(V) T + x_5 (\ln(V) - B_p) V_d \tag{9}$$

In practice, the MATLAB function `findchangepts` (MathWorks, 2016) is used as a simple implementation to find breakpoints. The function is used by sorting the noon reports after speed, and use the function on the power in the speed-sorted noon reports. The implementation then finds where the mean slope changes the most abruptly according to the specified minimum threshold. Hereby the index is found and the speed from the associated noon report is then the breakpoint B_p.

Table 1
Vessel parameters for the MR1 segment which includes 2 vessel groups and 9 vessels in total.

Vessel Group	L_{pp} [m]	B [m]	T_b [m]	T_d [m]	T_s [m]	∇_s [m^3]	MCR [kW]	Year
T035-03	162	27.42	6.5/6.5	9.75	11.8	42659	7150	2005
T039-06	176	27.4	7.0/6.4	9.8	11.9	47137	7290	2015

Table 2
Vessel parameters for the MR2 segment which includes 5 vessel groups and 48 vessels in total.

Vessel Group	L_{pp} [m]	B [m]	T_b [m]	T_d [m]	T_s [m]	∇_s [m^3]	MCR [kW]	Year
T050-04	175	32.2	7.3/6.3	11	13.1	59619	8310	2019
T050-09	178.5	32.26	6.9/6.5	11	12.9	59706	7628	2015
T050-10	174	32.2	7.3/7.2	11	13.29	59280	7660	2014
T050-12	174	32.2	7.5/6.5	11	13.29	59197	7240	2013
T053-13	176	32.2	7.7/6.7	11	12.6	56608	9480	2009

Table 3
Vessel parameters for the LR1 segment which includes 6 vessel groups and 23 vessels in total (only 2 vessels in T075-04).

Vessel Group	L_{pp} [m]	B [m]	T_b [m]	T_d [m]	T_s [m]	∇_s [m^3]	MCR [kW]	Year
T074-02	218	32.2	8.1/5.9	13.2	14.37	85273	13560	2006
T074-04	219	32.24	8.2/6.2	12.2	14.35	86450	11230	2017
T075-02	219	32.24	8.1/6.3	12.2	14.45	87113	10215	2016
T075-04	218.9	32.2	8.1/5.9	13.2	14.37	88972	12270	2006
T075-05	224.5	38	8.5/5.5	11	12.9	86651	10850	2019
T075-08	219	32.26	7.7/5.2	12	14.55	88945	12240	2007

2.3.3. Other predictor variables

It could be relevant to include *time* as a variable since the vessel performance will decrease over time when the hull gets fouled. To implement this it would be necessary to distinguish between different vessels as the performance over time would be individual for each vessel. By distinguishing between vessels the model would thereby capture vessel specific variations which can be caused by different crew, variations in hull construction and more. This could be implemented with a categorical predictor similar to the dummy variables introduced in the piecewise linear regression with speed. The current study does however not include time as a predictor variable, partly justified by the fact that the vessels undergo periodic hull cleanings. Besides, the study by Adland et al. (2020) left little evidence about the importance of time as a predictor variable. Similarly, it is left as a future work to consider other parameters such as trim, water salinity, water temperature and water depth as predictor variables.

As already mentioned, this study relies fundamentally on principles from naval architecture (ITTC, 2017a,b; ISO, 2016a; ISO, 2016b; ISO, 2016c) in combination with econometric models. Inclusion of knowledge from naval architecture makes it possible to correct the studied data (i.e., the noon reports) for wind and waves *before* introducing the econometric framework in terms of Eq. (9). As introduced, this is the central difference compared to the study by Adland et al. (2020). Thus, were it not for the introduction of the correction procedure outlined by ISO (2016a,b,c), it would be necessary to include the information about wind and waves directly in the (extended) econometric model. This can be done, as shown by Adland et al. (2020), by introducing the wind and sea state variables as a lot of categorical parameters. Ultimately, this leads to an extended econometric model where manual choices become important. The present approach, on the other hand, is not affected by such manual choices and selections, which is considered a means to reduce uncertainty in the modelled output/ results.

3. Data

Data for this study was kindly provided by COACH Solutions. The dataset contains noon reports, vessel data and speed-power curves from model tests for 88 ships divided into 15 vessel groups. All the ships are tankers, and all the data is from the same shipping company. Roughly, the noon reports cover a five year period (2016–2020) with vessels operating worldwide. In total, 51,826 noon reports are available after filtering, cf. Section 3.4.1.

3.1. Vessels

Data from 15 vessel groups are considered, with each group consisting of between 2 and 13 sister vessels. In order to work with these vessels and vessel groups and keep them anonymous, a naming convention has been introduced, e.g. T*XXX*-*YY* where *XXX* indicates the deadweight and *YY* indicates the number of vessels in each vessel group. This means that T035-03 is a 35,000 DWT vessel group consisting of 3 vessels.

Table 4
Vessel parameters for the LR2 segment which includes 2 vessel groups and 8 vessels in total.

Vessel Group	L_{pp} [m]	B [m]	T_b [m]	T_d [m]	T_s [m]	∇_s [m^3]	MCR [kW]	Year
T105-02	234	42	7.3/6.3	14	14.56	120243	13560	2009
T110-06	242	44	8.5/6	13.6	15.2	112812	13450	2019

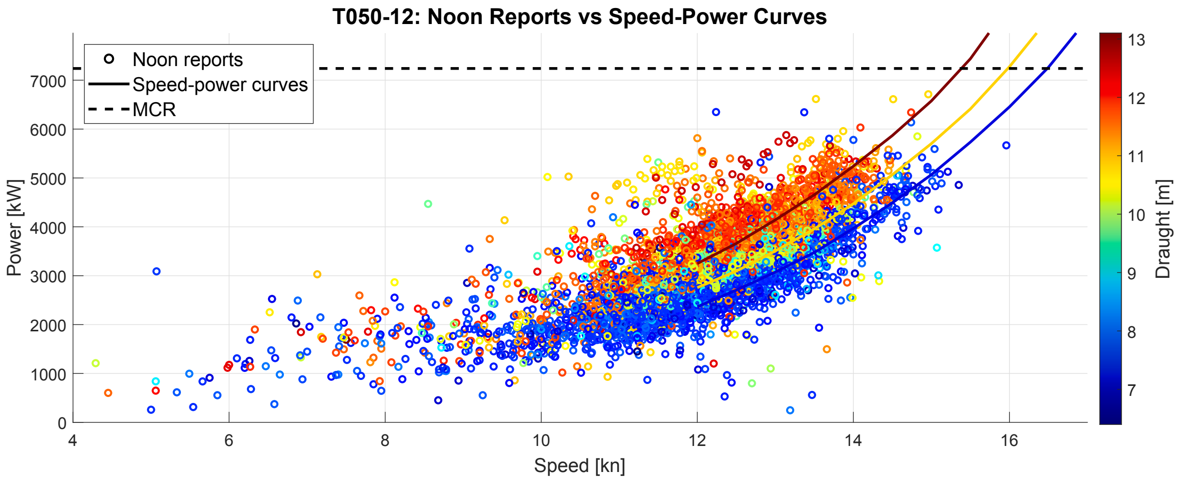

Fig. 2. Illustration of the operational profile of a group of sister ships with respect to corrected speed, corrected power and draught compared to the associated model test curves for different but given draughts. This is data for T050-12, i.e. twelve tankers of 50,000 DWT. Note that the colour scale (draughts) is the same for noon report data and model test curves.

The 15 vessel groups can be seen in Tables 1–4 where the vessel groups are divided into MR1, MR2, LR1 and LR2 deadweight groups.[2] There are 9 MR1, 48 MR2, 23 LR1 and 8 LR2 vessels. As a reference (Adland et al., 2020) analyses 10 aframax tankers and 6 suezmax tankers, making it 16 vessels in total, compared to 88 in this study. In the present work the LR2 segment would correspond to aframax tankers and suezmax tankers would be even larger than LR2. So this study is working with relatively smaller tankers than Adland et al. (2020).

In Tables 1–4 the length between perpendiculars L_{pp}, breadth B, ballast draught T_b (written as $T_{b,aft}/T_{b,for}$), design draught T_d, scantling draught T_s, volume displacement at scantling draught ∇_s, MCR of the engine and year of construction are given. The design draughts and scantling draughts are from the general arrangements for the vessels and these draughts are mostly also corresponding to the draught for the model test curves. The ballast draughts are here describing the lowest draught with a corresponding model test curve. Therefore the vessels can in reality operate at a lower draught than the ballast draught indicated, but it does not happen that often. Onwards, the aft and for draught for ballast will not be stated but the mean of these two will be used instead as T_b.

3.2. Speed-power benchmark curves (model test curves)

For each vessel group, COACH Solutions has provided speed-power curves at minimum three draught conditions (ballast, design and scantling). This applies for 11 of the vessel groups, and for some of the groups there are speed-power curves at five draughts. The curves are derived from towing tank tests. As introduced in the following subsection, the model test curves are included in plots with NR data in the appendix.

3.3. Noon reports

The noon reports from the ships are reported and sent to COACH Solutions via the reporting programme COACH Onboard.[3] The ship master reports the fuel consumption, logged speed, weather etc. This set of data is then validated in COACH Onboard before being sent to shore in order to secure high data quality and prevent faulty entries. The noon reports are then populated with hindcast data describing current, wind and wave conditions. Specifically, the hindcast data assigned to the noon reports is a weighted average of how the weather has been during the duration of the noon report by use of AIS-data.

The noon reports and speed-power curves for one vessel group can be seen in Fig. 2, which is similar to Fig. 1 but for another vessel

[2] MR = medium range and LR = large range.
[3] https://coachsolutions.com/noon-reporting/.

Table 5
Number of noon reports for each vessel group when filtered as described in Section 3.4.1. Total number of filtered noon reports is 51,826.

Vessel Group	No. of NR
T035-03	1813
T039-06	6753
T050-04	1076
T050-09	6759
T050-10	4126
T050-12	5359
T053-13	10233
T074-02	1570
T074-04	1932
T075-02	1149
T075-04	2173
T075-05	1667
T075-08	4571
T105-02	327
T110-06	2318

group. The figure clearly shows that all the vessels, most of the time, sail relatively slow compared to the model test curves which are used as benchmark for performance analysis. For completeness, the noon reports, including model test curves, for all vessel groups are presented in Appendix D.

3.4. Preprocessing

3.4.1. Filtering

The data has been filtered to remove outliers that makes no physical sense. The applied filters are:

- Mean draught $> T_b - 1$ [m] where T_b is mean of $T_{b,aft}$ and $T_{b,for}$ in Tables 1–4.
- Mean draught $< T_s + 1$ [m].
- Corrected speed > 0 [kn].
- Power corrected > 0 [kW].
- Power corrected $< 1.1 \cdot \mathrm{MCR}$ [kW].
- Hindcast data: Data is considered only if hindcasts (waves and wind) are available.

3.4.2. Speed corrections

The noon reports contain information about the speed over ground (SOG), calculated from the GPS position, and the speed through water (STW), obtained from the speed log onboard the vessels. In addition, a corrected speed is included. The corrected speed is the speed over ground from GPS corrected for current obtained from hindcast current data (Oikonomakis et al., 2019; Oikonomakis et al., 2021). This study makes use of the corrected speed.

3.4.3. Power corrections

As introduced previously, the measured power is corrected for added resistance due to wind and waves. The procedure is fairly technical and contains many details, but it is a standardised method (ITTC, 2017a,b) and it will be beyond the scope to report the procedure here.

4. Results

4.1. Descriptive statistics

In order to give an overview of all the noon report data, descriptive statistics have been prepared. As the data set is comprehensive, with many vessel groups with many single vessels within, the presented statistics will just be a glimpse of the larger picture. In Table 5, the number of noon reports (NR) after filtering can be seen for each vessel group. The total number of filtered noon reports is 51,826, while the number of unfiltered noon reports is 53,017 which means around 2.5% of the noon reports are filtered out from the provided noon reports. The focus will be on speed, power, and draught, as these parameters are considered the most important factors in power prediction. The vessel group T050-09 is considered somewhat representative and will be covered in the following subsection, while a summary of the descriptive statistics for all vessels and vessel groups is given in Section 4.1.2. It is noteworthy that the vessel group T050-12 is almost similar to T050-09, and further remarks about the similarity are given later.

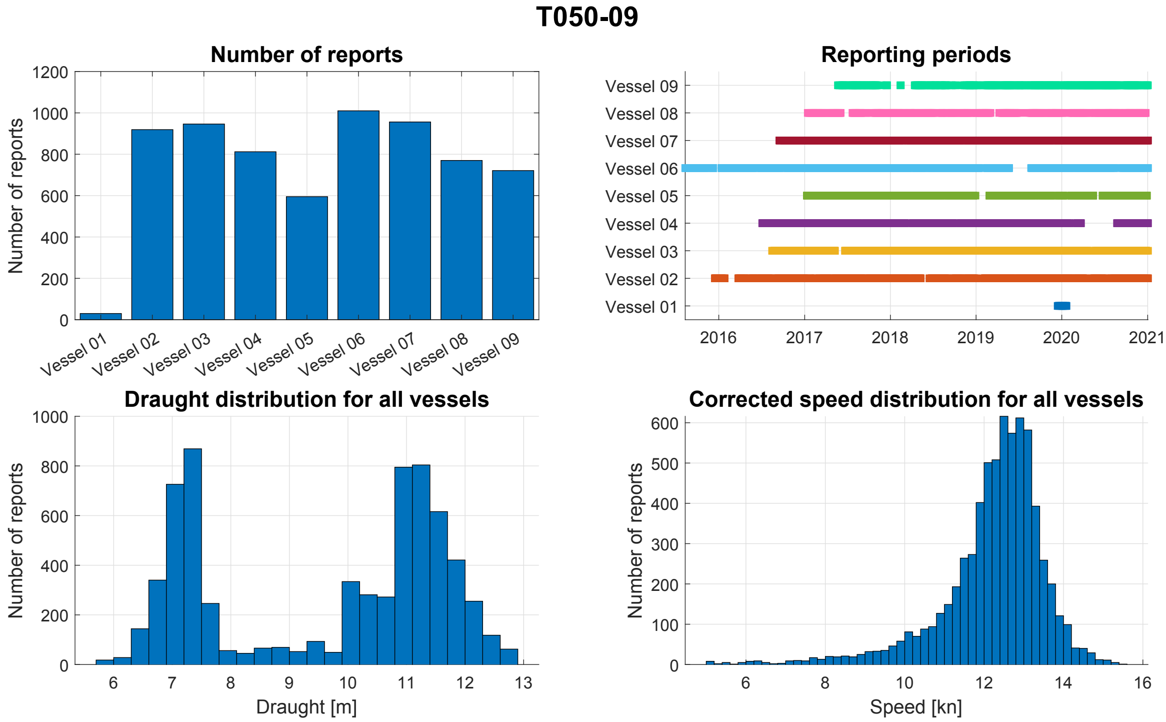

Fig. 3. Descriptive statistics for the vessel group T050-09.

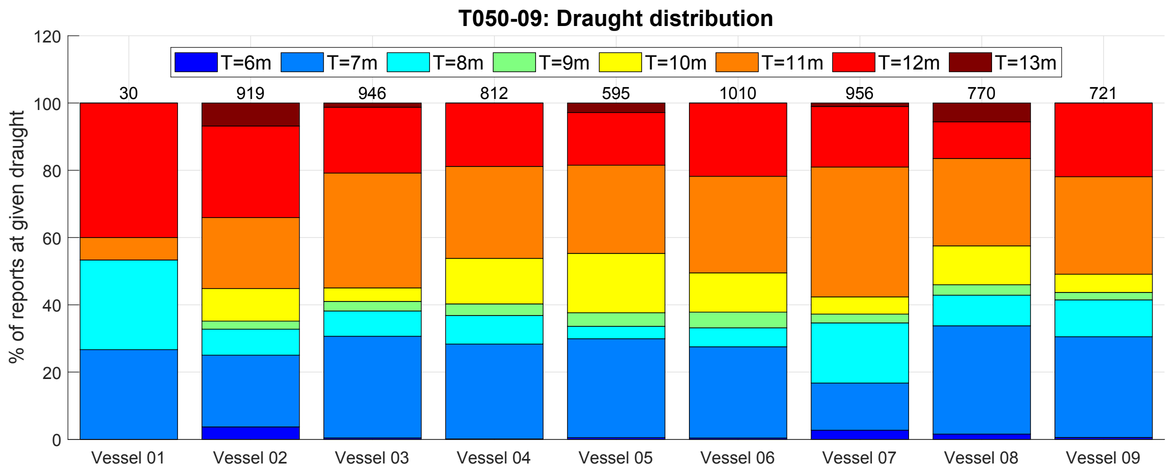

Fig. 4. Draught distribution for all the T050-09 vessels where similar distributions are seen for each vessel.

4.1.1. Vessel group T050-09

Vessel group T050-09 has many vessels with many noon reports for each vessel. This can be seen in Fig. 3 where the number of reports and reporting periods are shown. It is seen that the vessels have not been reporting every day. This can be seen for Vessel 06 which has been reporting to COACH Solutions for more than five years and only has 1010 noon reports, with reports "missing" because the vessel does not sail every single day due to port stays, idle periods, drydocking, etc. The draught and corrected speed distributions can also be seen for all 9 vessels. It is seen that the vessels sail mostly at 2 draughts where the first is a ballast draught at around 7 [m] and the second is a laden draught at around 11 [m] which agree with the design draught seen in Table 2. The draught distribution can be seen for every single vessel in Fig. 4 which shows that the vessels have individual draught distributions that agree well with the draught distribution for the group as a whole. A similar observation is seen from the speed distribution in Fig. 5 which shows that the vessels primarily sail at 12–13 [kn]. It is seen that Vessel 1 deviates, relative to the other vessels, in both figures as the vessel only has 30 noon reports compared to the other vessels that have 600–1000 noon reports. Overall it can be concluded that the vessels operate relatively similar with regard to draught and speed which means that similar power levels are expected for the vessels as they are

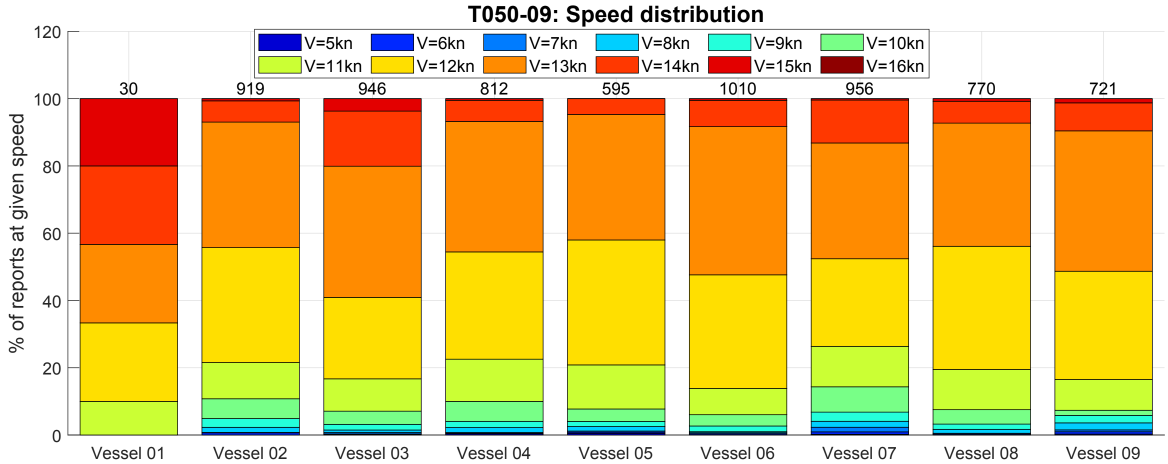

Fig. 5. Speed distribution for all T050-09 vessels where similar distributions are seen for each vessel.

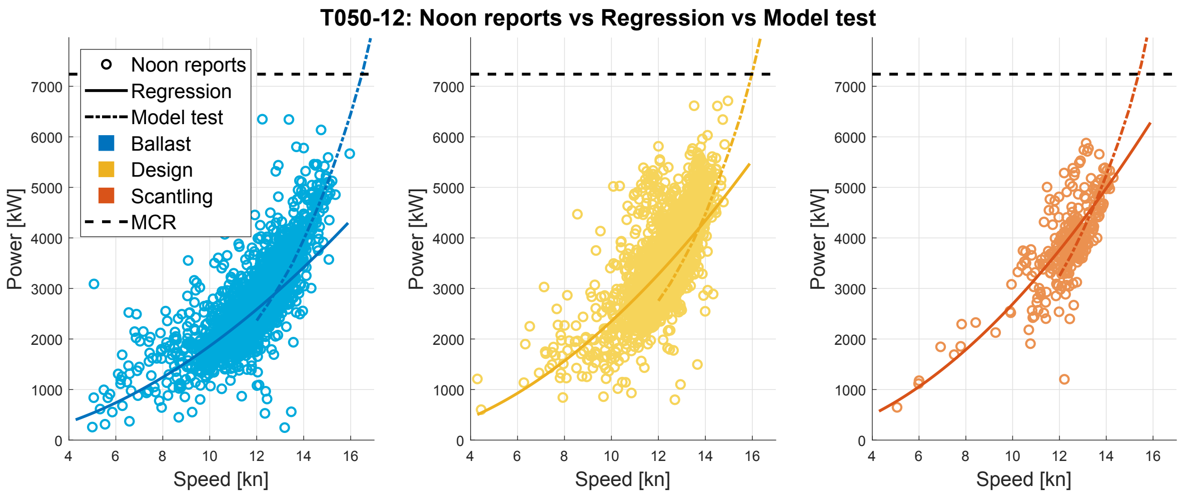

Fig. 6. Speed-power models from simple regression plotted together with the draught-grouped noon reports and the model test curves for T050-12 at the three draught conditions: ballast, design and scantling.

identical.

As indicated above, the descriptive statistics for the vessel group T050-12 are almost identical to what has been shown for vessel group T050-09. The plots corresponding to T050-12 are included in the appendix, see Figs. A.14–A.16. It is noteworthy that similar plots have been prepared also for all the other sister groups; although not shown they were used for initial investigations.

4.1.2. Summarised statistics for all vessels and vessel groups

Tables B.11–B.15 present descriptive statistics of average speed, power and draught in ballast and laden conditions for all vessels and all vessel groups. Ballast and laden conditions are here defined as $(T_d - 1\,[\mathrm{m}])$ for the MR1 vessels, $(T_d - 2\,[\mathrm{m}])$ for the MR2 and LR1 vessels and $(T_d - 3\,[\mathrm{m}])$ for the LR2 vessels. This is done based on the specific draught distributions, cf. Fig. 4. For T050-09 the 'separation draught' would be at $T = 9\,[\mathrm{m}]$ which is the green part in Fig. 4 and at a "valley" in the draught distribution for all vessels in Fig. 3.

The descriptive statistics reveal that the mean speed and draught are relatively similar for vessels within the same deadweight segments. This especially apply to the MR2 vessels (see Tables B.11 and B.12) and LR1 vessels (see Table B.15) since the vessels in those vessel groups almost have the same dimensions and deadweight. But it is clear that the power differ within the deadweight segments. T050-09 and T053-13 in the MR2 segment both use much more power at the same average speed and draught than the 3 other vessel groups in the segment which all are around 3150 [kW] (mean across all vessels and all draughts). T050-09 has a mean power of 3961 [kW] for all draughts and T053-13 has 4301 [kW] for all draughts. A similar "consistency" is not observed between T050-09 and T050-12. In Table B.13 it is seen that the average speed for T050-09 and T050-12 are 12.2 [kn] and the average draught is 9.7 [m] for both vessel groups. But there are 734 [kW] difference in average power which is about 20%. The statistics are based on 6759 and 5359 noon

Table 6
Speed-power exponent for all single vessels as well as vessel groups at ballast, design and scantling draughts, denoted by T_b, T_d, and T_s, respectively.

Vessel	T_b	T_d	T_s
T035-03			
V01	1.79	1.83	1.85
V02	1.19	1.66	1.95
V03	2.54	2.05	1.74
Group	2.24	1.95	1.77
T039-06			
V01	2.02	1.54	1.22
V02	2.35	1.95	1.68
V03	1.85	1.66	1.53
V04	2.23	1.80	1.51
V05	2.13	1.85	1.66
V06	2.37	1.45	0.84
Group	2.17	1.72	1.42
T050-04			
V01	1.76	2.39	2.71
V02	1.52	2.12	2.42
V03	1.85	2.25	2.44
V04	1.52	1.40	1.33
Group	1.70	1.77	1.80
T050-09			
V01	3.46	2.37	1.88
V02	1.91	1.38	1.14
V03	2.04	1.42	1.14
V04	2.23	1.35	0.96
V05	1.21	1.38	1.46
V06	1.92	1.56	1.40
V07	2.32	1.47	1.09
V08	1.74	1.19	0.95
V09	1.78	1.73	1.70
Group	1.98	1.43	1.19
T050-10			
V01	1.94	1.91	1.89
V02	2.51	1.83	1.42
V03	2.19	1.72	1.44
V04	1.70	1.87	1.98
V05	1.68	1.99	2.17
V06	1.94	2.41	2.69
V07	1.57	1.86	2.05
V08	1.54	2.17	2.55
V09	2.19	2.25	2.28
V10	1.49	1.93	2.20
Group	1.89	1.97	2.02

Vessel	T_b	T_d	T_s
T050-12			
V01	1.73	1.27	1.01
V02	2.11	1.93	1.82
V03	2.30	2.45	2.54
V04	2.59	2.89	3.06
V05	1.79	1.80	1.81
V06	1.58	2.31	2.72
V07	1.72	2.27	2.58
V08	2.44	1.88	1.56
V09	1.74	2.28	2.59
V10	1.62	1.34	1.18
V11	0.94	1.38	1.63
V12	1.59	1.73	1.81
Group	1.81	1.82	1.83
T053-13			
V01	1.04	1.34	1.46
V02	1.84	1.92	1.95
V03	1.55	2.85	3.40
V04	1.52	1.00	0.79
V05	1.25	0.95	0.83
V06	1.41	1.15	1.04
V07	2.23	1.53	1.24
V08	1.18	1.42	1.51
V09	0.88	0.95	0.98
V10	1.41	1.17	1.07
V11	1.33	0.80	0.57
V12	2.73	2.33	2.16
V13	1.44	1.02	0.84
Group	1.33	1.11	1.02
T074-02			
V01	2.30	0.66	0.35
V02	2.30	1.65	1.52
Group	2.22	0.97	0.73
T074-04			
V01	2.31	1.64	1.36
V02	2.25	1.61	1.34
V03	2.06	2.00	1.98
V04	2.62	2.35	2.23
Group	2.31	1.79	1.56

Vessel	T_b	T_d	T_s
T075-02			
V01	2.25	1.09	0.56
V02	2.12	1.79	1.64
Group	2.10	1.59	1.35
T075-04			
V01	2.53	1.61	1.43
V02	2.48	1.39	1.19
Group	2.50	1.50	1.32
T075-05			
V01	1.84	1.64	1.55
V02	2.81	2.06	1.71
V03	1.58	1.72	1.78
V04	2.26	1.88	1.70
V05	2.20	1.69	1.45
Group	1.97	1.82	1.75
T075-08			
V01	1.49	1.06	0.86
V02	1.59	1.64	1.66
V03	2.35	2.03	1.88
V04	1.62	1.25	1.09
V05	2.02	1.48	1.23
V06	2.11	1.34	0.98
V07	2.38	2.09	1.96
V08	2.79	1.77	1.31
Group	1.99	1.38	1.10
T105-02			
V01	-2.21	2.07	2.40
V02	1.82	1.16	1.11
Group	1.83	1.19	1.13
T110-06			
V01	2.21	2.17	2.15
V02	1.91	1.83	1.81
V03	2.01	1.45	1.31
V04	1.97	1.48	1.36
V05	2.38	1.46	1.23
V06	2.49	1.86	1.70
Group	2.13	1.74	1.64

reports respectively.

A significant variation in the LR1 segment is seen in Table B.15. Thus, the power varies between 3870 [kW] and 5026 [kW] for all draughts for the 6 vessel groups. It can be concluded that T074-02 and T075-08 are similar, T074-04, T075-02 and T075-05 are similar and T075-05 is by itself in the middle with 4430 [kW] (all draughts).

There is in general larger speed and power in laden than in ballast which apply to almost all vessels - only 12 out of 88 vessels have larger speed in ballast than in laden. Only Vessel 1 in T050-09 has larger power in ballast than in laden but it is based on only 30 noon reports as described in Section 4.1.1. The larger speed in laden condition agrees with the fact that time constraints and contracts have to be complied with when sailing with cargo (Adland et al., 2020). The larger power in the laden condition agrees with the larger speed for the laden condition but also the general fact that increased draught increases power.

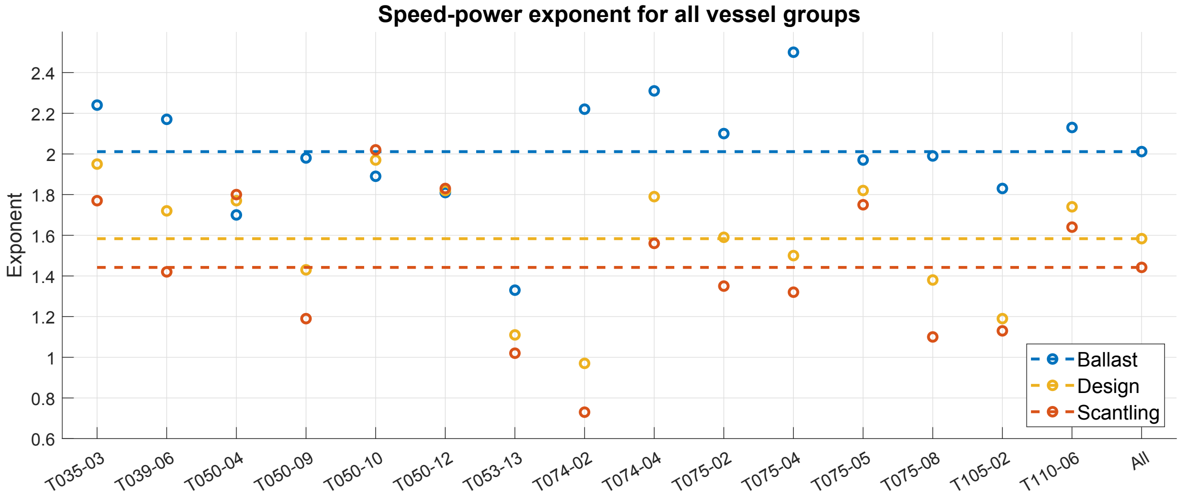

Fig. 7. Speed-power exponent from the simple regression model for all vessel groups at three draught conditions and the average over all vessel groups for three draught conditions.

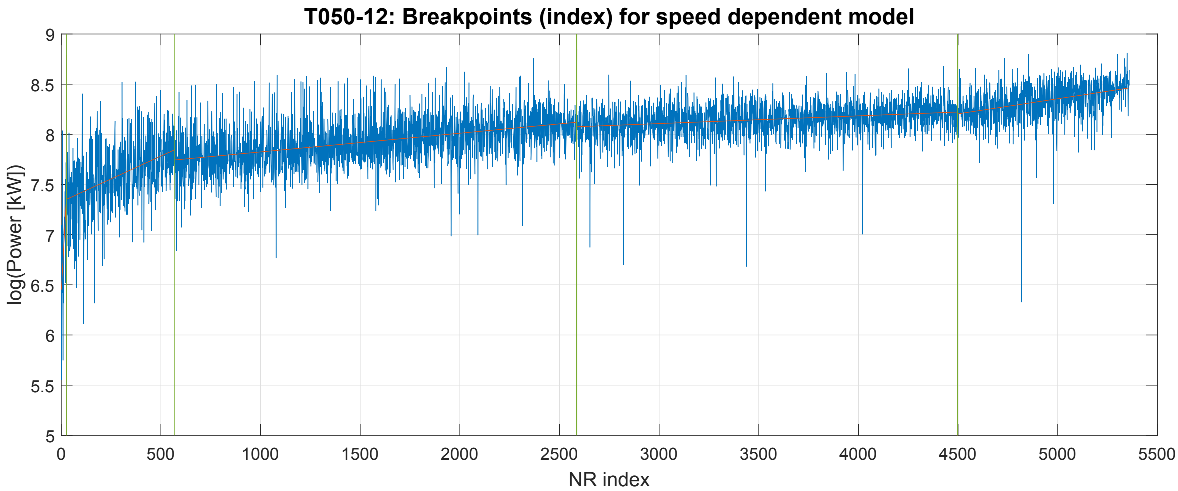

Fig. 8. Plot generated by `findchangepts` in MATLAB where the power (log) from the speed-sorted noon reports are plotted as function of noon report index for T050-12. The function then finds the breakpoints (changepoints) based on changes in slope and mean shown by the red lines. The breakpoints are based on a threshold manually set.

4.2. Simple model for each vessel and vessel group

Initially, the simple model extended with the draught as additive and interaction effects, see Eq. (6), is used for all the vessels on an individual basis to determine the speed-power exponent when it is *not* considered as speed-dependent. At the same time, the analysis is done to study the draught dependency. As such, the outcome is three regression-based speed-power curves, cf. Fig. 6.

In Table 6, the exponents can be seen for all vessels at ballast (T_b), design (T_d) and scantling (T_s) draughts, where the draughts are from Tables 1–4. The exponents are determined with the simple speed-power model with draught as both additive and interaction effects (Eq. 6). The speed-power exponent for each vessel group is also determined when the model considers noon reports for all vessels collectively in a given vessel group (denoted by “Group”). This means that the exponent for the individual vessel *groups* is not an average of the vessel specific exponents of ships in a given group but independently modelled on all ship-specific data from the given group. Thereby the regression is based on much more data which makes its outcome more reliable. This group-wise regression is justified by the descriptive statistics presented earlier, where it was observed that the vessels within given groups are sailing with relatively similar draught, speed and power. The speed-power exponents of the individual groups has been included in Table 6 and they are presented graphically in Fig. 7. In all of the remaining, including Section 4.3, only outcome from a group-wise regression analysis is considered.

It is clearly seen that the exponent is significantly smaller than 3. It is also seen that the speed-power exponent is in general

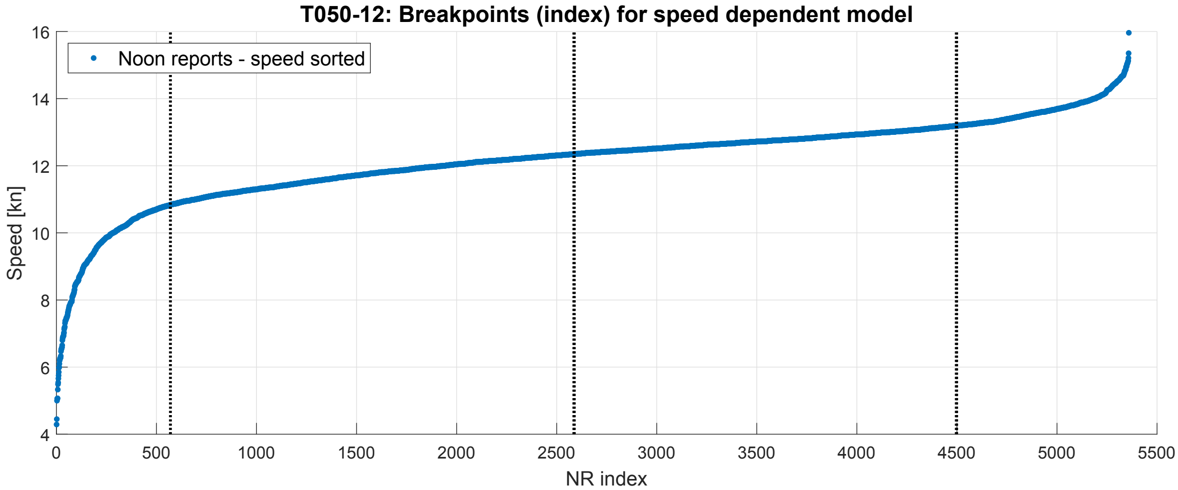

Fig. 9. Speed from the speed-sorted noon reports plotted as a function of noon report index for T050-12. The breakpoints from `findchangepts` are then marked in order to find the associated speeds.

Table 7
Coefficients used in Eq. (10).

x_1	x_2	x_3	x_4	x_5	x_6	x_7
4.1170	1.2940	0.0662	−0.0026	0.8273	0.0103	1.3334

decreasing with increasing draught for a given vessel group. Thus, the exponent is dependent on draught but for some of the vessel groups there are less dependency, e.g. T050-12. From Table 6 it also appears evident that some vessels are outliers due to the exponent being based on too few noon reports, e.g. Vessel 01 in T050-09 which has only 30 noon reports, and Vessel 01 in T105-02 that has just two ballast noon reports. Fig. 7 also shows that there is no size dependency, as the plot reveals no trend in the data, noticing that deadweight increases going from left to right on the x-axis. Similarly, when comparing with year of construction, no age dependency is observed for the speed-power exponent.

In general, the simple model shows that the speed-power exponent cannot be assumed to be 3 when considering all speed intervals. Taking the vessel group T050-12 as an example, the simple regression model is plotted together with the noon reports and speed-power curves from model test in Fig. 6, where the noon reports have been grouped based on draught for clarity. It is clear that the regression model does not capture the relationship for the higher speeds, but it does for the bulk of the noon reports; noticing that about 75–90% of the reported speeds generally are in the range 11–13 [kn]. It is appreciated that the model test curves follow the steeper path exhibited by the noon reports at the higher speeds.

4.3. Speed dependent speed-power models for all vessel groups

As presented by Eq. (9), speed can be included as a variable in the extended speed-power model. In practice, a number of speeds (breakpoints) is added to the model depending on the vessel group, and for each interval, the data is modelled. As introduced, the MATLAB function `findchangepts` is used to determine the breakpoints, based on the speed-sorted noon reports.

In the following, the vessel group T050-12 is used as an example. As observed from Fig. 8, four breakpoints are detected using `findchangepts`. However, for practical reasons it is decided that a speed interval must contain at least 150 noon reports, similar to Adland et al. (2020), and the first breakpoint occurring at the NR index of about 50 (i.e. less than 150) is therefore removed. It is interesting to note the variation, or scatter, in power which makes it a quite noisy signal. The scatter exists in spite of the fact that a smooth curve could be expected; keeping in mind that an increase on the horizontal axis represents a gradual increase in speed in terms of a speed-sorted NR index. Basically, the scatter could be a sign that more aggressive filters in preproccesing of the data might be necessary to reduce uncertainty in the output from the model. However, this is outside the scope of the present investigation.

In Fig. 9, the noon report speed-sorted indices are translated to speed which means that the associated speeds to the breakpoints can be seen. The breakpoints are at 10.8 [kn], 12.4 [kn] and 13.2 [kn]. From this plot it is clear that most of the noon reports are in the interval 11–13 [kn]. Even though the breakpoints look very spread out in the two figures, they will not be in a speed-power plot because the data is so centred around the average speed which is 12.2 [kn] for T050-12, as found in the descriptive statistics.

The speed dependent speed-power regression model is using the determined breakpoints. The breakpoints apply to all draughts as all data for the specific vessel group is used when determining the breakpoints. In the following, the resulting speed-power curves at just the ballast, the design and the scantling draughts are generated, thus enabling a comparison with the model test curves, but it is

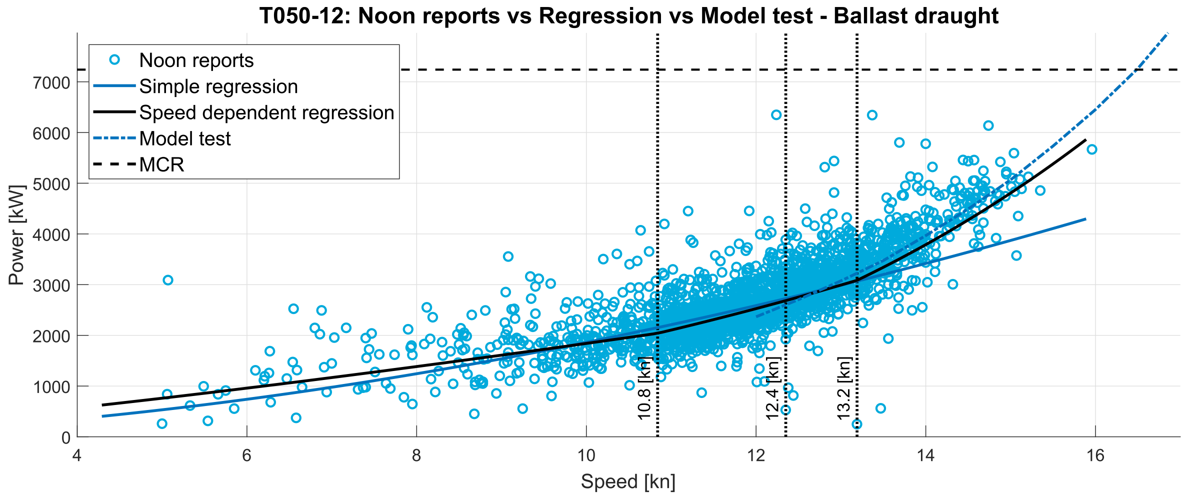

Fig. 10. The speed dependent speed-power model plotted together with noon reports, model test curve and the simple regression model for ballast for T050-12.

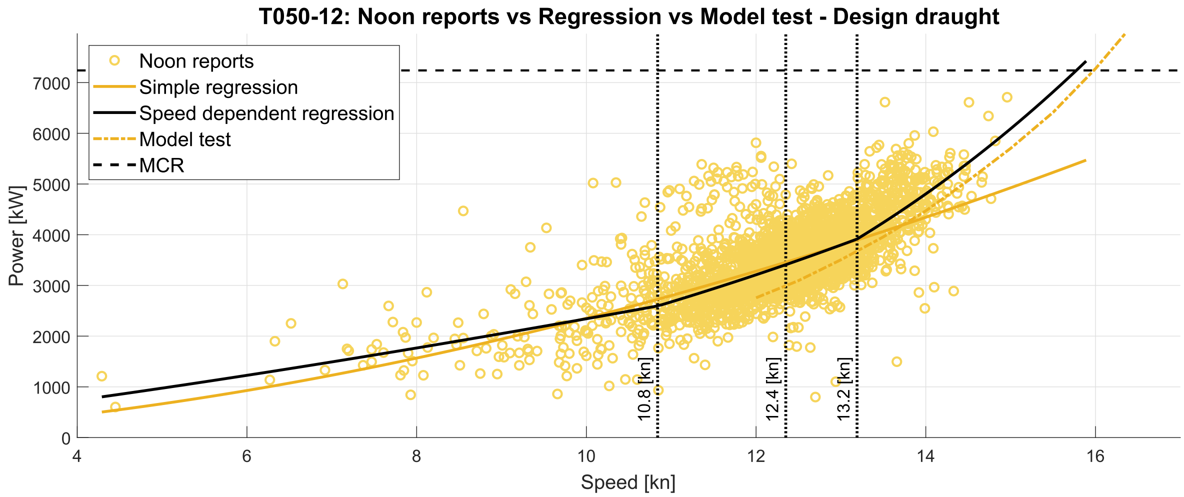

Fig. 11. The speed dependent speed-power model plotted together with noon reports, model test curve and the simple regression model for design for T050-12.

possible to generate speed-power curves at any given draught with the regression model. Specifically, the speed-power curve as a function of draught T and speed V for T050-12 is modelled as:

$$\begin{aligned}\ln(P) = \quad & \ln(x_1) + x_2\ln(V) + x_3T + x_4\ln(V)T + x_5(\ln(V) - 10.8)V_{d1} \\ & + x_6(\ln(V) - 12.4)V_{d2} + x_7(\ln(V) - 13.2)V_{d3}\end{aligned} \tag{10}$$

and with the coefficients listed in Table 7. And the dummy variables are defined as:

$$V_{d1} = \begin{cases} 0, & \text{if} \quad V \leqslant 10.8 \\ 1, & \text{if} \quad V > 10.8 \end{cases} \tag{11}$$

$$V_{d2} = \begin{cases} 0, & \text{if} \quad V \leqslant 12.4 \\ 1, & \text{if} \quad V > 12.4 \end{cases} \tag{12}$$

$$V_{d3} = \begin{cases} 0, & \text{if} \quad V \leqslant 13.2 \\ 1, & \text{if} \quad V > 13.2 \end{cases} \tag{13}$$

From Eq. (10) the speed-power exponent for the ballast draught $T_b = 7$ [m] at $V = 14$ is, cf. Eq. (9):

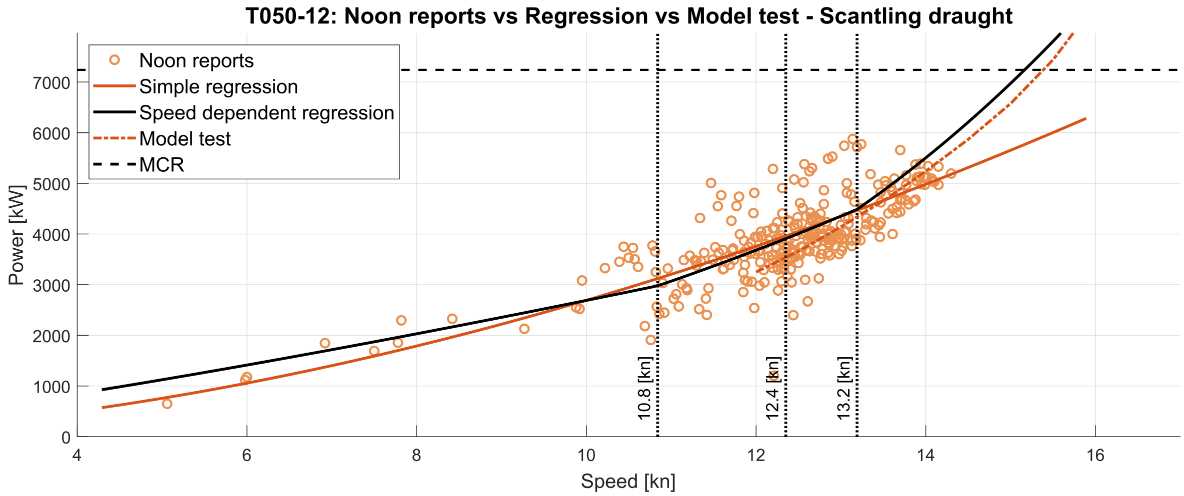

Fig. 12. The speed dependent speed-power model plotted together with noon reports, model test curve and the simple regression model for scantling for T050-12.

$$Exponent = x_2 + 7x_4 + x_5 + x_6 + x_7 = 3.45 \tag{14}$$

In Figs. 10–12, the speed dependent regression model is plotted at ballast, design and scantling draughts together with the draught-grouped noon reports; noticing that the vessel group T050-12 is considered. The single plots also include the outcome of the simple regression model and, in addition, the model test curves. It is seen that the speed dependent model estimate the power better at the higher speed intervals compared to the simple model which was underestimating the power, cf. Fig. 6. This means that the speed dependent regression model looks more similar to the speed-power curves from model test; emphasising that the model test curves are given only in the (high-speed) interval 12–16+ [kn]. Albeit the speed-power curves from the speed dependent regression do not exactly coincide with the model test curves, the set of curves are nearly parallel which means that the exponents are relatively close to each other in their numerical values. At lower speed intervals the speed dependent regression model deviates only slightly from the simple model, capturing the speed-power relationship well.

The numerical values of the speed-dependent exponent, as determined for the single vessel groups, are presented in Tables 8 and 9. The main observations from the tables, including Figs. 10–12, are the following: (a) Only a very few cases reveal a speed-power exponent equal to or larger than 3; in the majority of cases, the exponent is smaller. (b) Three out of fifteen speed-power exponents at the scantling draught are above 3 at the highest speed interval. These three vessel groups are T050-04, T050-10 and T050-12 which have been shown to be very similar. In the ballast condition, for the highest speed interval, seven out of fifteen speed-power exponents are above 3. (c) For the particular case of T050-12, it is seen that the exponent is 3.45, 3.44 and 3.43 for the ballast, design and scantling conditions, respectively, when the speed is above 13.2 [kn]. The exponents for the model test curves for the same draughts are 3.57, 3.44 and 3.31, cf. Table C.16. (d) Generally, it is seen that the speed-dependent regression with two or more speed intervals increase the exponent at the high speed intervals compared to the simple regression model only taking draught into account, cf. Table 6. At the same time, it is seen that the exponent is significantly higher for the ballast draught than for the scantling draught for many of the vessel groups.

4.4. Coefficient of determination (r^2) for the simple and extended model

In Table 10, the r^2 (R-squared) for the simple model and extended model for each vessel group can be seen. Most of the vessel groups have an r^2 of 0.60–0.80 for both models. This agrees well with the findings in Adland et al. (2020). It is noted, though, that T053-13 is an outlier, with $r^2 = 0.376$ and $r^2 = 0.381$ for the two models, although a lot of noon reports are available for this group. The explanation for this odd behaviour was introduced previously and is a result of the fact that the group consists of older vessels installed with relative large engine power, thus designed to go at a higher speed than what they have been actually sailing during the considered reporting period. In turn, this means that the performance varies significantly depending on encountered conditions; altogether making the outcome of this group much more scattered than for the other vessel groups.

Overall, the r^2 values increase for all vessel groups when the speed-dependent, extended regression model is considered. This was observed also by visual inspection of the plots in Figs. 10–12. Indeed, the piecewise model did capture the trend of the NR data, and, at the same time, the modelled output matched the model test curves at the higher speed intervals. Although not shown in the paper, similar visual observations can be made for the other vessel groups considered in the study.

Table 8
Speed-power exponent and speed intervals from the speed dependent regression model for all vessel groups at three draughts: ballast (T_b), design (T_d) and scantling (T_s). (Continues in Table 9).

Vessel Group	Speed [kn]	Exponent			No. of NR- [–]
		T_b	T_d	T_s	
T035-03	*(Threshold = 2)*				
Interval 1	$V \leqslant 9.1$	1.38	1.13	0.98	208
Interval 2	$9.1 < V \leq 11.0$	3.48	3.23	3.08	223
Interval 3	$11.0 < V \leq 13.1$	1.83	1.58	1.42	1207
Interval 4	$13.1 < V$	2.77	2.52	2.37	175
T039-06	*(Threshold = 3.5)*				
Interval 1	$V \leqslant 11.3$	1.90	1.34	0.95	1881
Interval 2	$11.3 < V \leqslant 12.2$	3.26	2.69	2.31	1682
Interval 3	$12.2 < V \leqslant 13.2$	1.93	1.36	0.98	2310
Interval 4	$13.2 < V$	3.38	2.81	2.43	880
T050-04	*(Threshold = 2)*				
Interval 1	$V \leqslant 11.9$	1.08	1.10	1.11	277
Interval 2	$11.9 < V$	3.01	3.04	3.05	799
T050-09	*(Threshold = 2.5)*				
Interval 1	$V \leqslant 10.0$	1.46	0.85	0.58	425
Interval 2	$10.0 < V \leqslant 11.4$	2.50	1.89	1.62	807
Interval 3	$11.4 < V \leqslant 13.0$	2.23	1.62	1.35	3762
Interval 4	$13.0 < V$	1.98	1.37	1.10	1765
T050-10	*(Threshold = 1.5)*				
Interval 1	$V \leqslant 9.8$	1.11	1.12	1.12	222
Interval 2	$9.8 < V \leqslant 11.8$	2.10	2.11	2.11	1239
Interval 3	$11.8 < V \leqslant 13.1$	2.38	2.39	2.39	2148
Interval 4	$13.1 < V$	3.17	3.18	3.19	517
T050-12	*(Threshold = 2)*				
Interval 1	$V \leqslant 10.8$	1.28	1.27	1.26	570
Interval 2	$10.8 < V \leqslant 12.4$	2.10	2.09	2.09	2016
Interval 3	$12.4 < V \leqslant 13.2$	2.11	2.10	2.10	1911
Interval 4	$13.2 < V$	3.45	3.44	3.43	862
T053-13	*(Threshold = 6)*				
Interval 1	$V \leqslant 10.6$	1.05	0.81	0.70	922
Interval 2	$10.6 < V \leqslant 12.0$	1.63	1.39	1.28	2518
Interval 3	$12.0 < V \leqslant 13.2$	1.36	1.11	1.00	5192
Interval 4	$13.2 < V$	2.11	1.87	1.76	1601

4.5. Model validation

In order to validate the speed-dependent regression model, the regression can be setup using the NR data for a given vessel group but *leaving out* one vessel. Subsequently, the established model can be tested on the vessel left out. Such a validation has been made with the vessel group T050-12; noticing that Vessel 03 has arbitrarily been selected as the vessel *not* included. The result of this analysis can be seen in Fig. 13, where it is seen that the regression model agrees nicely with the NR data from Vessel 03. It can further be noted that speed breakpoints are the same as when Vessel 03 is included, and the regression model is very close to the previous one seen in Figs. 10–12.

5. Discussion

5.1. Data

Noon reports are fundamentally based on averages over 24 h which means that the data will be describing how the vessels – on average – sail during a given 24-h period. Even though the dataset in this study is based on weighted averages of data by use of AIS-data, which improves the data, the data is still being defined by the speed that the vessel sails at most of the time. This implies that the higher speed intervals, which the vessel rarely sails within, will be more difficult to capture, if the vessel does not sail at high speeds in the majority of the given 24-h period. Thereby, a noon report, where a vessel sails relatively fast in a good amount of time, will still be a

Table 9
(Table 8 continued) Speed-power exponent and speed intervals from the speed dependent regression model for all vessel groups at three draughts: ballast, design and scantling.

Vessel Group		Speed [kn]	Exponent			No. of NR [–]
			T_b	T_d	T_s	
T074-02	*(Threshold = 2)*					
Interval 1		$V \leqslant 11.6$	1.91	0.57	0.31	490
Interval 2		$11.6 < V$	2.76	1.42	1.17	1080
T074-04	*(Threshold = 4)*					
Interval 1		$V \leqslant 11.5$	1.85	1.23	0.96	404
Interval 2		$11.5 < V$	2.98	2.35	2.08	1528
T075-02	*(Threshold = 3)*					
Interval 1		$V \leqslant 10.7$	1.09	0.50	0.23	170
Interval 2		$10.7 < V$	2.64	2.05	1.78	979
T075-04	*(Threshold = 7)*					
Interval 1		$V \leqslant 11.7$	2.32	1.18	0.96	626
Interval 2		$11.7 < V$	2.93	1.79	1.58	1547
T075-05	*(Threshold = 2)*					
Interval 1		$V \leqslant 11.5$	1.33	0.81	0.57	460
Interval 2		$11.5 < V$	3.28	2.76	2.51	1207
T075-08	*(Threshold = 3)*					
Interval 1		$V \leqslant 10.9$	1.60	0.93	0.63	711
Interval 2		$10.9 < V \leq 14.0$	2.28	1.61	1.30	3498
Interval 3		$14.0 < V$	3.76	3.09	2.79	362
T105-02	*(Threshold = -)*					
Not enough data. Only 327 NR in total.						
T110-06	*(Threshold = 1.5)*					
Interval 1		$V \leqslant 11.5$	1.70	1.20	1.08	504
Interval 2		$11.5 < V \leq 13.5$	2.89	2.40	2.27	1570
Interval 3		$13.5 < V$	3.25	2.75	2.63	244

Table 10
R-squared (r^2) for the simple and extended model for each vessel group.

Vessel Groups	r^2 - Simple model	r^2 - Extended model	No. of NR
T035-03	0.694	0.704	1813
T039-06	0.681	0.687	6753
T050-04	0.662	0.722	1076
T050-09	0.609	0.616	6759
T050-10	0.668	0.693	4126
T050-12	0.652	0.675	5359
T053-13	0.376	0.381	10233
T074-02	0.751	0.760	1570
T074-04	0.776	0.791	1932
T075-02	0.699	0.716	1149
T075-04	0.725	0.727	2173
T075-05	0.719	0.757	1667
T075-08	0.665	0.678	4571
T105-02	0.824	–	327
T110-06	0.790	0.812	2318

lower speed data point if the vessel also sails at a lower speed in a fair amount of time. If the study instead had been based on continuous monitoring data, the shorter periods where the vessel sails fast will be better captured, as also discussed by Themelis et al. (2018). Similarly, it is expected that the uncertainty associated with the modelled results could be minimised by using continuous monitoring data (Aldous et al., 2015).

5.2. *Existing literature*

To the knowledge of the authors, there is just one similar study available in the literature. In the study by Adland et al. (2020),

Fig. 13. The speed dependent regression model for group T050-12 without Vessel 03. The model is plotted together with noon reports from Vessel 03 at three draughts. The plots also include the corresponding model test curves and the curves based on the simple regression model.

7,600 noon reports for a group of aframax tankers and 4,325 noon reports for a group of suezmax tankers are considered; that is, 11,925 noon reports in total. As such, the 51,826 noon reports in the present study seems like a large extension, but when it is divided between 15 vessel groups and half of the vessel groups only consists of 2,000 or less noon reports, the vessel groups with more data are comparable with the vessel groups in Adland et al. (2020). If it was possible to combine similar vessel groups and consider it as one collective group, there would be a lot more data available for the regression. In fact, it was an initial thought to combine similar vessel groups but as has been shown in the descriptive statistics there can actually be a lot of variation between vessel groups that, on paper, look quite similar. Nonetheless, the combination of three vessel groups has been investigated. In the particular case, albeit not shown, three MR2 vessel groups were combined in order to have 10,562 noon reports in total, but the speed dependent model did not change/ improve much from the three vessel group specific models.

This study also differs from Adland et al. (2020) in regards to tanker sizes since the vessels are significantly smaller in this study. This difference, however, is not considered to have a large affect on the outcome of the respective regression models. On the other hand, Adland et al. (2020) is only considering ballast and laden conditions by defining models for each loading condition resulting in different speed breakpoints for each loading condition. In the present study, the data is divided into ballast, design and scantling draughts when plotting, but the actual model is using *all* data where draught is defined as both an additive and interactive term in the model definition. Thereby, the regression is based on more data and, at the same time, is taking the speed-power exponent as function of draught into account. In this sense, it is expected that uncertainty in the modelled results is reduced.

Based on the comparison of the R-squared values, which to some extent can be considered a measure of the uncertainty of the modelled results, the present study is in line with Adland et al. (2020). In the strict sense, it is thus not part of the (direct) findings that uncertainties are reduced by combining principles from naval architecture with an economic framework, repeating that Adland et al. (2020), in contrast, rely completely on the latter. On the other hand, it is difficult to compare on a 1-to-1 basis since the underlying datasets are not the same. Moreover, from a perspective of ship motion dynamics in relation to wave-ship interactions and the related physics, it is anticipated that the (many) manual choices and decisions, necessary in the pure econometric framework, for describing and defining wind and waves could/should have a large influence on the modelled results. Unfortunately, however, this was not investigated by Adland et al. (2020) and it would therefore be interesting to set up a direct comparative study based on the same dataset, but this is left as a future exercise.

5.3. Slow steaming debate

Based on the results from this study, it is clear that the speed-power exponent is (significantly) below 3 at lower speeds, while it has been more difficult to show/ prove that the exponent is above 3 at the higher speeds. In consequence, it will definitely lead to overestimation of the effect of slow steaming if an exponent of 3–4 is assumed at lower speed intervals, which in turn means underestimation of the needed power and thereby fuel. This means that slow steaming at even lower speeds is necessary to achieve the desired minimisation of fuel. All of this is relevant for the slow steaming debate which can be described as speed optimisation versus speed reduction (Psaraftis, 2019b). In the present study, the regression-based speed-power exponent is also draught dependent which means that the exponent for scantling draught is lower than for the ballast draught. Together with the speed dependent speed-power exponent this makes it more feasible to slow steam on a ballast voyage than a laden voyage. There is therefore better potential for slow steaming at ballast draughts than for laden draught conditions where speed optimisation would be a better alternative.

This study has been made with data from tankers and the results will therefore not apply to all vessel types but, since bulk carriers are relatively similar to tankers, similar conclusions could possibly be drawn for bulk carriers. Container ships, on the other hand, differ a lot in hull shape, vessel parameters and operational speed, and the current results cannot be transferred to this ship segment. The literature often states that the speed-power exponent is higher for container vessels than for tankers and bulk carries, reaching values in the region 4–5 or maybe higher (Psaraftis and Kontovas, 2013; Kristensen, 2010; Kristensen, 2018). However, in the light of this study, it is possible that the speed-power exponent for container vessels are just as dependent on speed as has been seen for tankers. This could be relevant to study further with operational data, and, in fact, planing of such a study has been initiated.

As a final comment, it is important to note that fuel consumption and emissions always will be reduced when reducing the speed and thus power. So, even if the speed-power exponent is lower than expected at lower speeds, the fuel consumption will be lower if the transport work is kept constant. But it will just not be as rewarding when the increased sailing time is taken into account compared to an exponent above 3 (Kristensen, 2018). Therefore speed optimisation could be a better solution than just blindly implementing speed reduction in order to decrease emissions.

6. Concluding remarks and future work

This paper has studied the relationship between attained speed and used power by ships sailing at sea. Notably the paper presented results focused on the speed-power exponent, or elasticity, of this relationship. A data-driven analysis was made on the basis of a model established from principles of naval architecture and an economic framework.

Based on noon report data from 88 tankers in the 35,000–110,000 DWT segment, and the development of a draught- and speed-dependent regression model, it can be concluded that the speed-power exponent for this vessel type is significantly lower than 3 at speed intervals below the design speed. The study showed that the amount and quality of data can be influential. In order to have enough data, vessel groups consisting of sister vessels have been studied instead of individual vessels. This choice was based on descriptive statistics where the operational profile in terms of draught, speed and power was used as metric(s). It has been shown that the regression model yields results in good agreement with the reported operational data. As part of the investigation, it was observed that it is more difficult to show an exponent of 3 or above at high speed intervals than it is to show that the exponent is (much) smaller than 3 at low speed intervals. As such, in a context of practical vessel performance monitoring, the study showed that resistance model test curves, often used as benchmark, cannot blindly be extrapolated to the full operational speed range by assuming a constant speed-power exponent.

A speed-power relationship with a constant speed-power exponent will clearly underestimate the needed power when slow steaming. This means that the effect of slow steaming with respect to fuel consumption is overestimated. It is therefore not as good an option to slow steam as sometimes stated in the literature. Furthermore, the exponent is almost always stated in literature to be at least 3, and the International Maritime Organization reports (IMO, 2014) "to ensure simplicity of analysis, the speed-resistance relationship is held as a cubic and no uncertainty is applied". This gives – erroneously – a good reason for slow steaming when the fuel consumption is to be decreased. However, since the assumption about a constant speed-power exponent is not valid, speed *optimisation* is a better alternative to speed *reduction* in order to sail more sustainable.

6.1. Future work

The established regression model is kept fairly simple for clarity. At the same time, it is easier to combine it with physics and first principles; in this case from naval architecture. As has been mentioned, additional terms, both additive and interactive, could be included in the regression model. Thus, it could be interesting to study the effect of, say, trim, water salinity, water temperature and water depth. In particular, trim is known to be important in general resistance modelling; especially during sailing in relatively calm water (small waves).

Added resistance in waves is a complex topic (Ström-Tejsen et al., 1973; Salvesen, 1978; Faltinsen et al., 1980), and a lot of work is ongoing to improve existing empirical formulas and computational methods for its prediction; noticing that in relative terms the added resistance in waves become more important for ships sailing at reduced speeds. Although the ISO standards (ISO, 2016a,b,c) include a method to correct for the added resistance, it could be interesting to apply more advanced methods (e.g., Lang and Mao, 2020; Liu and Papanikolaou, 2016, 2020; Mittendorf et al., 2021), possibly including one relying on machine learning. At this point, it is noteworthy that the overall framework itself could be replaced by a machine learning method. In fact, this was attempted by Adland et al. (2020), finding that the performances of two machine learning techniques (boosting and neural network) were comparable to the ordinary regression model. However, the details in the purely data-driven approaches are not reported and further investigations, pursuing machine learning, should be interesting.

Next to what is listed above, the paper has already mentioned a number of other points deserving future considerations, and the following list summarises these potential future works:

- Conduct a study based on continuous monitoring data, and compare with findings based on noon report data.
- What findings apply to container vessels, where the speed reduction, in absolute numbers, is larger compared to tankers.
- A study should look into how to determine a general relationship between speed and the speed-power exponent as obtained from towing tank tests conducted around the design speed.

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Appendix A. Operational profile of Vessel Group T050-12

Figs. A.14–A.16

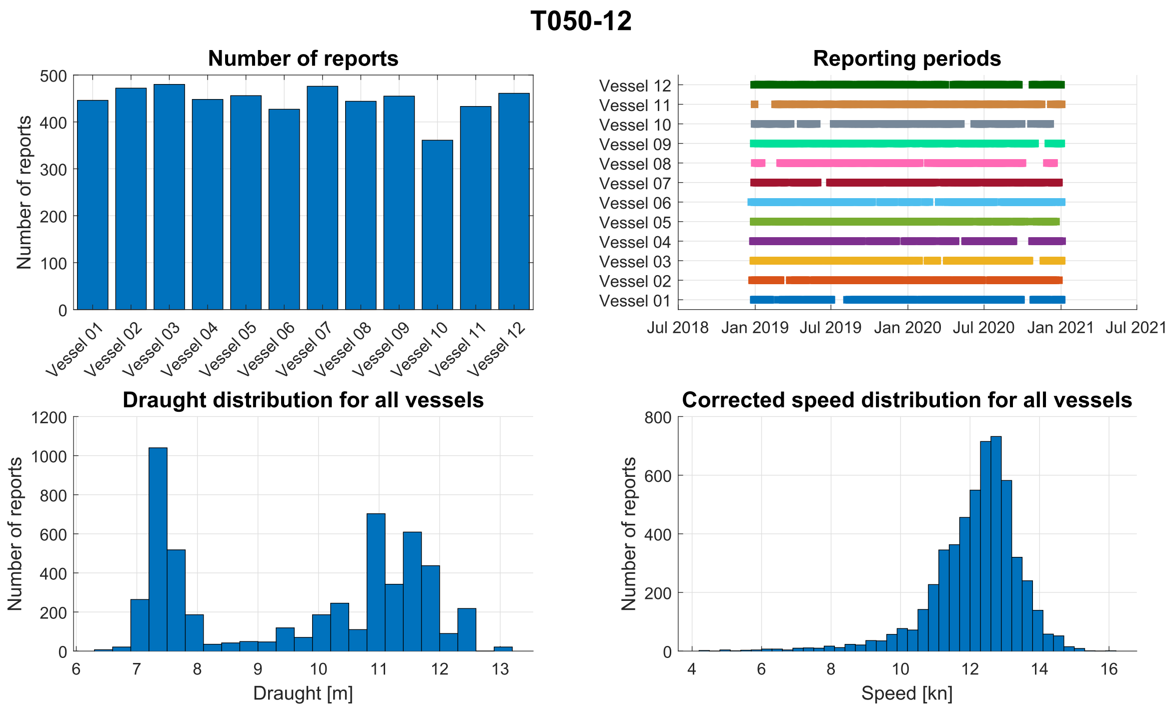


Fig. A.14. Descriptive statistics for the vessel group T050-12.

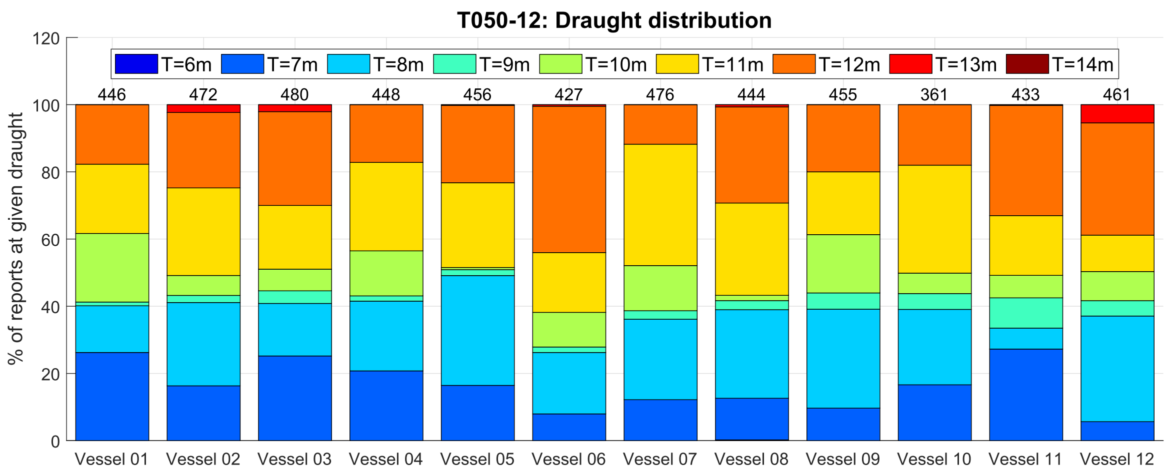


Fig. A.15. Draught distribution for all the T050-12 vessels where similar distributions are seen for each vessel.

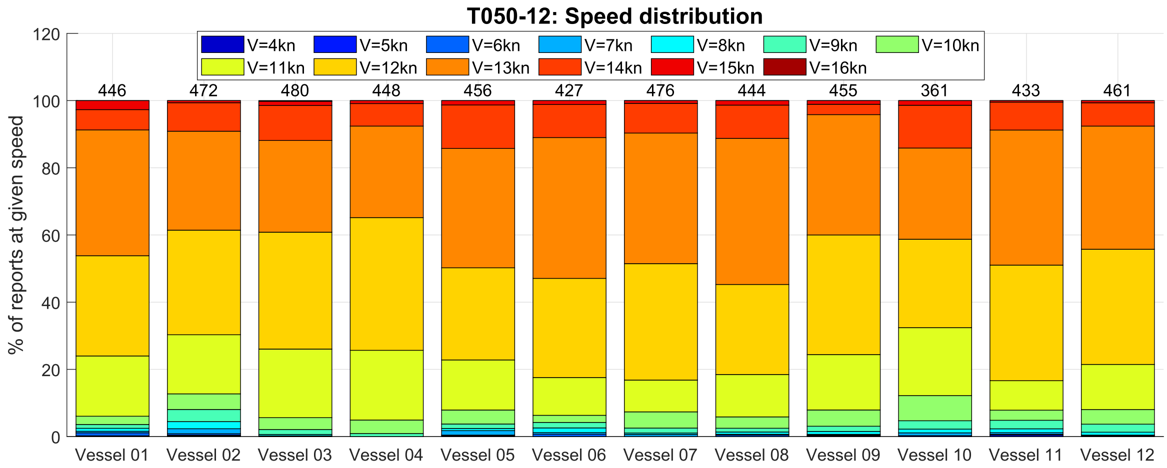


Fig. A.16. Speed distribution for all T050-12 vessels where similar distributions are seen for each vessel.

Appendix B. Descriptive statistics of all vessels and groups

Tables B.11–B.15

Table B.11
Descriptive statistics for the MR2 vessels and vessel groups.

Vessel	Speed [kn]			Power [kW]			Draught [m]			No. of NR [–]		
	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.
T050-04												
V01	12.3	12.0	12.5	3020	2544	3460	9.3	7.2	11.3	231	111	120
V02	12.6	12.4	12.7	3212	2869	3496	9.3	7.2	11.0	395	179	216
V03	12.3	12.2	12.4	3124	2723	3482	9.3	7.1	11.3	286	135	151
V04	12.2	12.4	12.1	3271	2922	3383	10.2	6.8	11.3	164	40	124
All	12.4	12.2	12.5	3156	2754	3463	9.4	7.1	11.2	1076	465	611
T050-09												
V01	13.2	13.6	12.8	3749	3909	3567	9.4	7.5	11.6	30	16	14
V02	12.1	12.0	12.2	4069	3323	4452	9.9	7.1	11.4	919	312	607
V03	12.5	12.7	12.4	4158	3829	4375	9.6	7.3	11.2	946	375	571
V04	12.1	11.9	12.3	3752	3192	4114	9.5	7.3	11.0	812	319	493
V05	12.1	12.1	12.1	3790	3294	4049	9.7	7.3	11.0	595	204	391
V06	12.4	12.2	12.5	4055	3378	4424	9.7	7.2	11.1	1010	356	654
V07	12.1	12.2	11.9	3851	3430	4087	9.8	7.4	11.2	956	344	612
V08	12.2	12.0	12.3	3922	3267	4426	9.4	7.2	11.1	770	335	435
V09	12.3	12.0	12.5	4002	3300	4532	9.5	7.3	11.2	721	310	411
All	12.2	12.2	12.3	3961	3394	4308	9.7	7.3	11.1	6759	2571	4188
T050-10												
V01	11.9	11.6	12.1	2997	2387	3417	9.8	7.5	11.4	454	185	269
V02	11.9	11.5	12.2	3142	2755	3493	9.4	7.4	11.1	377	179	198
V03	12.0	11.8	12.1	3226	2855	3517	9.7	7.7	11.3	453	199	254
V04	11.9	12.1	11.8	3238	3113	3359	9.5	7.7	11.4	404	199	205
V05	12.1	11.9	12.2	3380	2884	3708	9.8	7.6	11.3	434	173	261
V06	12.2	11.8	12.5	3152	2520	3603	9.6	7.6	11.1	408	170	238
V07	11.8	11.6	12.1	2911	2588	3211	9.3	7.3	11.2	389	187	202
V08	11.7	11.2	12.0	2980	2336	3413	9.7	7.6	11.1	316	127	189
V09	12.1	11.7	12.4	3305	2745	3727	9.8	7.7	11.3	428	184	244
V10	12.2	12.2	12.2	3150	2853	3401	9.6	7.6	11.2	463	212	251
All	12.0	11.8	12.2	3154	2722	3494	9.6	7.6	11.2	4126	1815	2311
T050-12												
V01	12.2	11.7	12.5	3186	2656	3548	9.5	7.4	10.9	446	181	265
V02	11.9	11.5	12.2	3212	2623	3660	9.7	7.7	11.3	472	204	268
V03	12.2	11.9	12.4	3075	2545	3470	9.7	7.4	11.4	480	205	275
V04	12.1	11.8	12.3	3241	2718	3619	9.6	7.5	11.0	448	188	260

(continued on next page)

Table B.11 (*continued*)

Vessel	Speed [kn]			Power [kW]			Draught [m]			No. of NR [–]		
	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.
V05	12.3	11.9	12.6	3279	2774	3767	9.4	7.5	11.3	456	224	232
V06	12.3	11.2	12.7	3281	2385	3623	10.3	7.5	11.3	427	118	309
V07	12.3	12.3	12.3	3079	2769	3275	9.7	7.6	11.0	476	184	292
V08	12.4	12.2	12.4	3162	2764	3421	9.9	7.6	11.4	444	175	269
V09	12.1	11.8	12.2	3209	2802	3528	9.5	7.7	11.0	455	200	255
V10	12.0	11.8	12.1	3303	2804	3657	9.6	7.5	11.0	361	150	211
V11	12.2	11.8	12.5	3371	2757	3717	9.9	7.5	11.2	433	156	277
V12	12.2	12.2	12.1	3363	2970	3608	9.9	7.6	11.4	461	177	284
All	12.2	11.9	12.4	3227	2720	3570	9.7	7.6	11.2	5359	2162	3197

Table B.12
Descriptive statistics for the MR2 vessels and vessel groups (Table B.11 continued).

Vessel	Speed [kn]			Power [kW]			Draught [m]			No. of NR [–]		
	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.
T053-13												
V01	12.4	12.4	12.4	4529	4069	4737	9.7	7.4	10.8	835	261	574
V02	12.0	11.0	12.3	3744	2972	3961	10.4	7.4	11.2	32	7	25
V03	12.7	13.1	12.5	4153	3913	4300	9.7	7.8	10.8	58	22	36
V04	12.2	12.0	12.4	4326	3903	4592	9.3	7.1	10.7	1367	527	840
V05	12.2	12.2	12.1	4045	3750	4293	9.2	7.3	10.8	858	392	466
V06	12.3	12.3	12.3	4488	4240	4630	9.5	7.2	10.8	1318	482	836
V07	12.5	12.6	12.4	4334	3999	4559	9.5	7.2	11.0	1066	427	639
V08	12.1	12.1	12.1	4175	3813	4394	9.4	7.0	10.8	1107	416	691
V09	11.8	11.8	11.8	4446	4103	4715	9.2	7.0	11.0	958	421	537
V10	12.1	12.2	12.1	4066	3727	4301	9.3	7.0	10.9	998	409	589
V11	12.1	12.0	12.2	4247	3693	4577	9.5	7.1	10.9	1060	396	664
V12	12.2	11.3	12.5	4666	3612	4980	10.4	7.6	11.2	48	11	37
V13	12.1	11.7	12.4	4329	3748	4810	9.2	7.0	10.9	528	239	289
All	12.2	12.1	12.2	4301	3911	4552	9.4	7.1	10.9	10233	4010	6223

Table B.13
Descriptive statistics for the MR1 vessels and vessel groups.

Vessel	Speed [kn]			Power [kW]			Draught [m]			No. of NR [–]		
	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.
T035-03												
V01	11.7	11.4	12.0	3561	3130	4046	8.7	7.0	10.6	499	264	235
V02	11.0	10.8	11.3	3028	2612	3455	9.1	7.2	11.1	241	122	119
V03	11.5	11.0	11.9	3178	2716	3584	8.9	6.8	10.6	1073	502	571
All	11.5	11.1	11.8	3264	2825	3685	8.9	6.9	10.7	1813	888	925
T039-06												
V01	11.8	11.3	12.2	2969	2455	3394	9.1	7.0	10.8	1176	533	643
V02	12.0	11.6	12.3	2964	2584	3292	8.9	7.0	10.5	1145	530	615
V03	11.6	11.1	12.0	2793	2365	3215	8.9	7.1	10.6	1200	595	605
V04	11.6	11.2	11.9	2652	2306	2937	9.0	7.0	10.7	1074	485	589
V05	11.6	11.0	12.2	2821	2271	3253	9.0	7.1	10.6	1168	514	654
V06	11.6	11.1	12.1	2792	2265	3278	8.8	6.8	10.7	990	475	515
All	11.7	11.2	12.1	2835	2378	3230	9.0	7.0	10.6	6753	3132	3621

Table B.14
Descriptive statistics for the LR2 vessels and vessel groups.

Vessel	Speed [kn]			Power [kW]			Draught [m]			No. of NR [–]		
	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.
T105-02												
V01	11.9	11.9	11.9	6368	5874	6387	12.8	7.5	13.0	53	2	51
V02	11.6	11.1	11.9	5435	4072	6436	10.4	7.2	12.8	274	116	158
All	11.6	11.2	11.9	5586	4103	6424	10.8	7.2	12.8	327	118	209
T110-06												
V01	12.0	11.8	12.1	4882	4312	5256	11.1	7.7	13.2	490	194	296
V02	12.1	11.8	12.3	4804	4105	5359	10.7	7.4	13.3	479	212	267
V03	12.6	12.6	12.6	5366	4910	5698	10.7	7.5	13.1	425	179	246
V04	11.9	11.6	12.0	4756	3904	5139	11.7	7.7	13.5	348	108	240
V05	12.1	11.8	12.2	4935	4126	5270	11.6	7.5	13.3	287	84	203
V06	12.1	11.5	12.3	4824	3723	5231	11.8	7.5	13.3	289	78	211
All	12.1	11.9	12.3	4935	4262	5328	11.2	7.5	13.3	2318	855	1463

Table B.15
Descriptive statistics for the LR1 vessels and vessel groups.

Vessel	Speed [kn]			Power [kW]			Draught [m]			No. of NR [–]		
	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.	All	Ba.	La.
T074-02												
V01	11.6	11.4	11.8	5107	4307	5678	10.3	7.4	12.3	742	309	433
V02	12.3	11.9	12.7	4870	4007	5732	10.2	7.7	12.6	828	414	414
All	12.0	11.7	12.2	4982	4136	5704	10.2	7.5	12.5	1570	723	847
T074-04												
V01	12.2	12.1	12.2	4103	3600	4524	10.3	7.4	12.7	500	228	272
V02	12.1	11.8	12.3	3851	3075	4338	10.8	7.4	12.9	529	204	325
V03	11.9	11.4	12.2	3812	2783	4302	11.0	7.4	12.7	440	142	298
V04	12.6	12.5	12.6	4148	3535	4525	10.7	7.3	12.8	463	176	287
All	12.2	12.0	12.3	3978	3287	4417	10.7	7.4	12.8	1932	750	1182
T075-02												
V01	12.3	12.1	12.4	4036	3249	4513	10.6	7.8	12.3	363	137	226
V02	12.2	11.5	12.6	4180	3028	4894	10.7	7.8	12.5	786	301	485
All	12.2	11.7	12.5	4134	3097	4773	10.7	7.8	12.5	1149	438	711
T075-04												
V01	11.9	11.2	12.6	4349	3296	5331	10.2	7.6	12.6	1133	547	586
V02	12.3	11.9	12.6	4518	3858	5120	10.4	8.2	12.5	1040	496	544
All	12.1	11.6	12.6	4430	3564	5229	10.3	7.9	12.6	2173	1043	1130
T075-05												
V01	11.8	11.3	12.3	3730	3289	4283	9.0	7.1	11.3	320	178	142
V02	11.9	11.4	12.3	3590	2863	4179	9.8	7.1	11.9	369	165	204
V03	12.1	11.5	12.4	4105	3394	4603	9.6	6.8	11.6	432	178	254
V04	12.2	11.5	12.6	3996	3045	4517	10.1	6.9	11.9	464	164	300
V05	12.4	12.9	12.0	3730	3483	3953	9.2	6.7	11.5	82	39	43
All	12.0	11.5	12.4	3870	3173	4406	9.7	7.0	11.7	1667	724	943
T075-08												
V01	12.2	11.7	12.4	5325	4189	5905	10.2	6.8	11.9	385	130	255
V02	12.5	12.1	12.8	4988	4027	5675	10.2	7.3	12.3	525	219	306
V03	12.6	12.6	12.6	4996	4278	5485	10.4	7.1	12.6	397	161	236
V04	11.5	11.7	11.4	5343	4883	5557	10.7	6.9	12.5	723	229	494
V05	12.4	12.0	12.6	4759	3804	5451	10.1	6.9	12.5	723	304	419
V06	12.1	11.9	12.2	4940	3970	5442	10.8	7.1	12.7	639	218	421
V07	12.3	11.9	12.6	4940	4030	5638	10.5	7.5	12.7	636	276	360
V08	12.8	12.4	13.1	5012	4051	5703	10.3	7.2	12.6	543	227	316
All	12.3	12.0	12.4	5026	4131	5589	10.4	7.1	12.5	4571	1764	2807

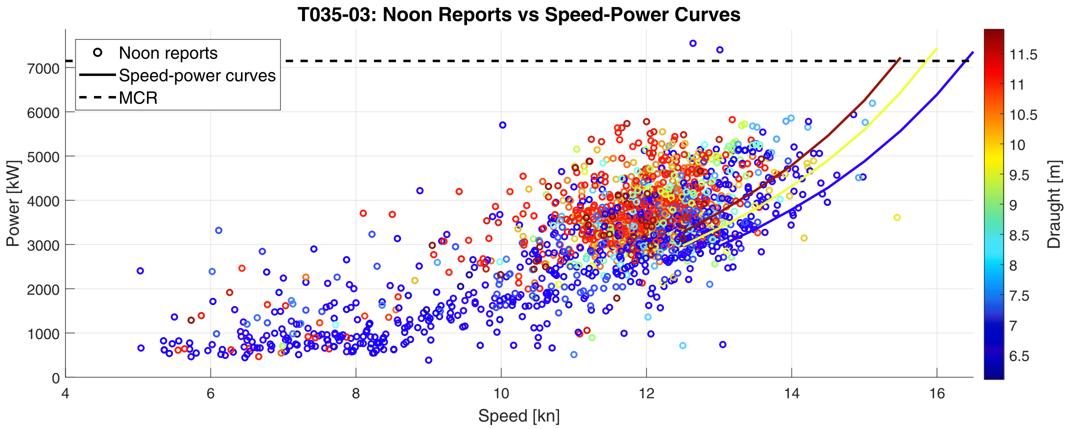
Appendix C. Speed-power exponents for model test curves

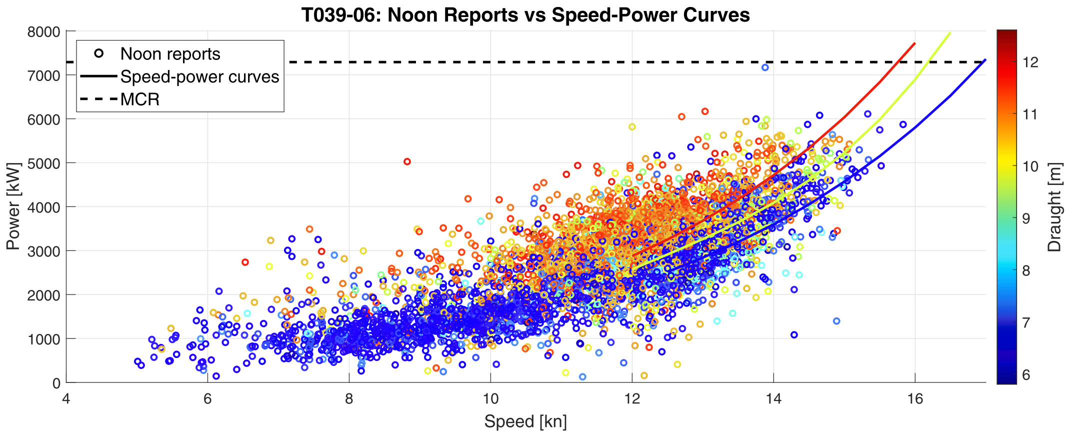
Table C.16

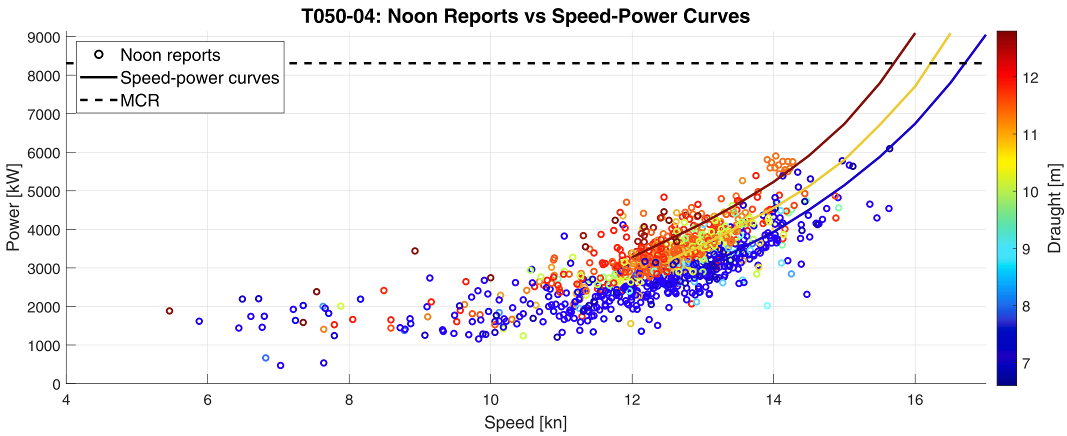
Table C.16
Speed-power exponent for the model test curves for each vessel group at the associated draughts. Some vessel groups have up to six speed-power curves from the model test but most of them have three curves.

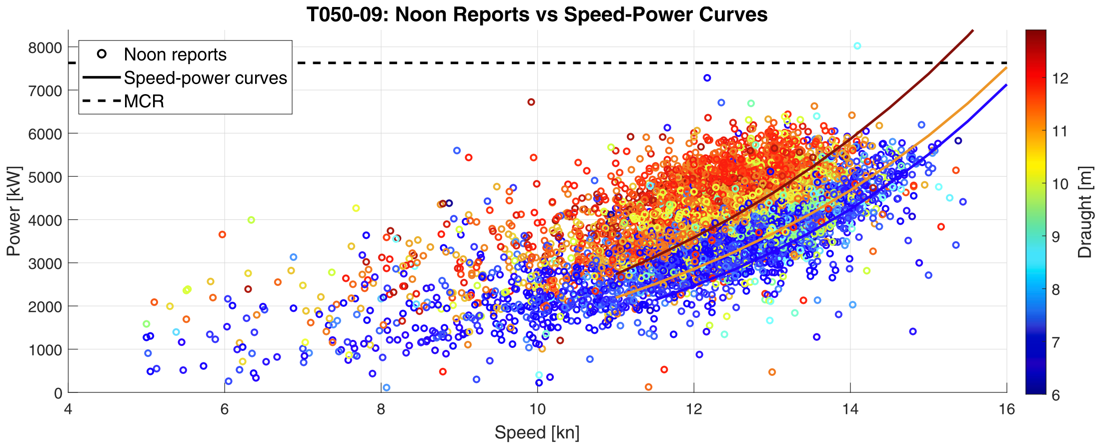
Vessel Groups	Ballast			Design	Scantling	
T035-03		$T = 6.5$ m		$T = 9.8$	$T = 11.8$ m	
		3.80		3.69	3.65	
T039-06		$T = 6.7$ m		$T = 9.8$ m	$T = 11.9$ m	
		3.49		3.49	3.44	
T050-04		$T = 6.8$ m		$T = 11.0$ m	$T = 13.1$ m	
		4.06		3.71	3.47	
T050-09		$T = 6.7$ m		$T = 11.0$ m	$T = 12.9$ m	
		3.65		3.29	3.24	
T050-10		$T = 7.2$ m		$T = 11.0$ m	$T = 13.3$ m	
		3.54		3.40	3.24	
T050-12		$T = 7.0$ m		$T = 11.0$ m	$T = 13.3$ m	
		3.57		3.44	3.31	
T053-13	$T = 7.2$m	$T = 8.0$ m	$T = 9.9$ m	$T = 11.0$ m	$T = 12.1$ m	$T = 13.2$ m
	3.45	3.38	3.25	3.12	3.06	3.04
T074-02	$T = 7.0$ m	$T = 10.7$ m	$T = 12.2$ m	$T = 13.0$ m	$T = 13.8$ m	$T = 14.4$ m
	3.86	3.65	3.56	3.43	3.44	3.48
T074-04		$T = 7.2$ m		$T = 12.2$ m	$T = 14.4$ m	
		3.86		3.27	3.22	
T075-02		$T = 7.2$ m		$T = 12.2$ m	$T = 14.5$ m	
		3.74		3.31	3.06	
T075-04	$T = 7.0$ m	$T = 11.9$ m		$T = 13.2$ m	$T = 14.4$ m	
	3.94	3.70		3.64	3.48	
T075-05		$T = 7.0$ m		$T = 11.0$ m	$T = 12.9$ m	
		3.81		3.56	3.22	
T075-08		$T = 6.4$ m		$T = 12.0$ m	$T = 14.6$ m	
		3.9		3.73	3.65	
T105-02	$T = 6.8$ m	$T = 10.2$ m		$T = 14.0$ m	$T = 15.6$ m	
	3.80	3.46		3.24	3.13	
T110-06		$T = 7.3$ m		$T = 13.6$ m	$T = 15.2$ m	
		3.42		3.02	2.98	

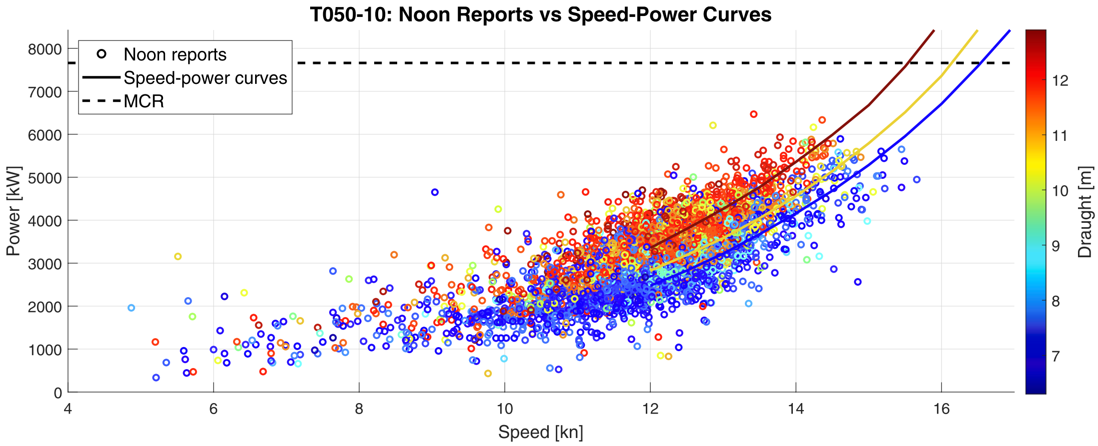
Appendix D. Noon reports vs speed-power curves

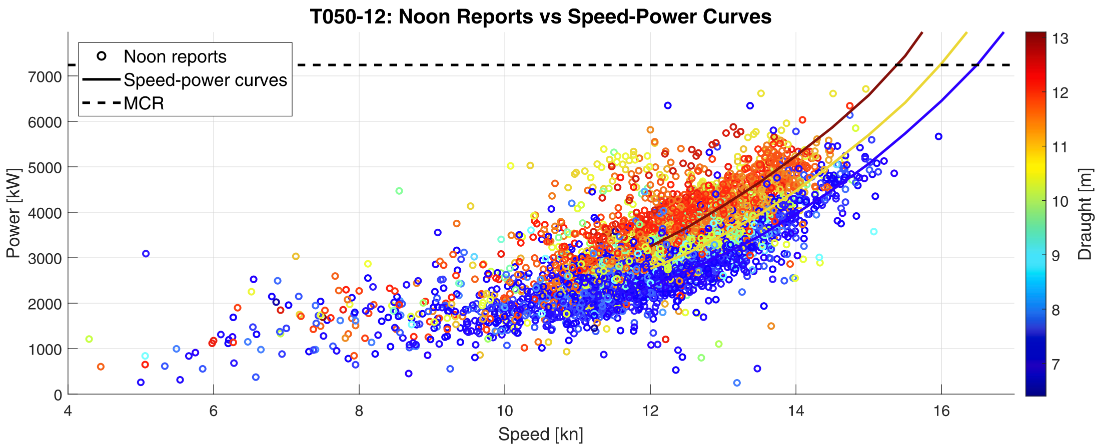


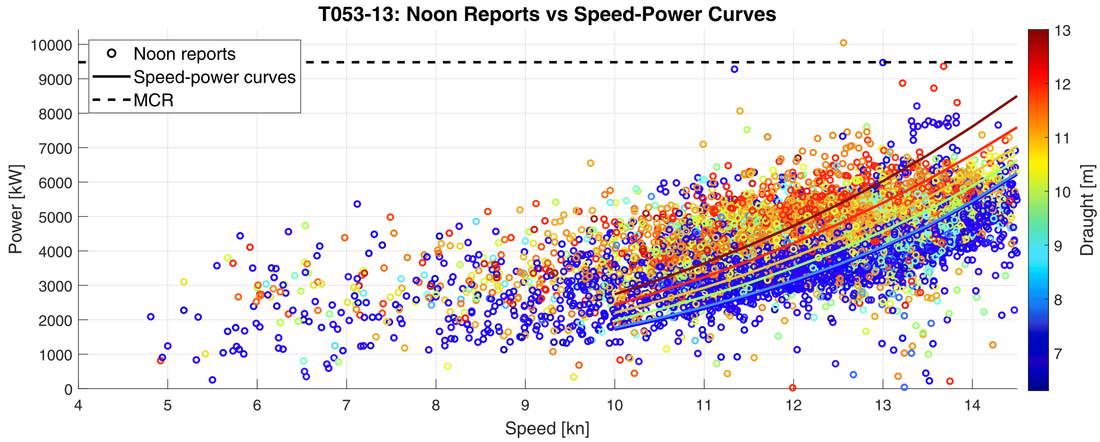


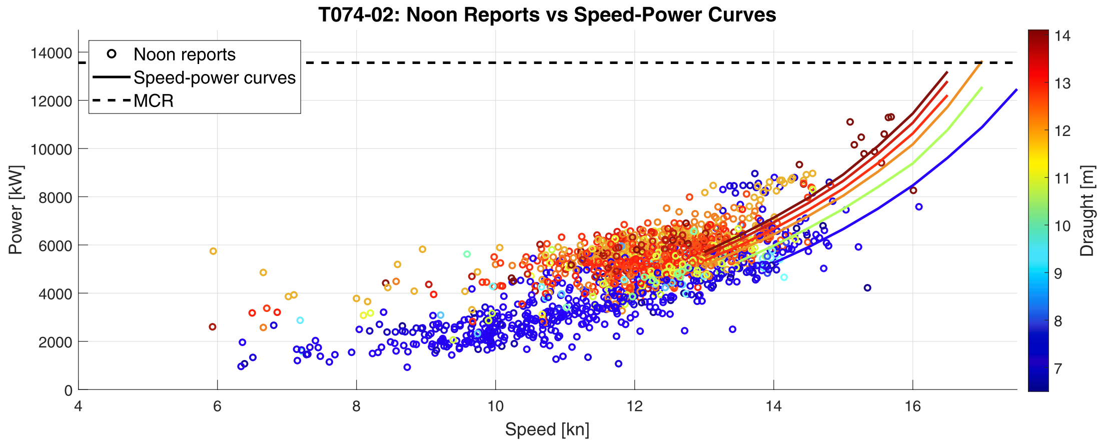


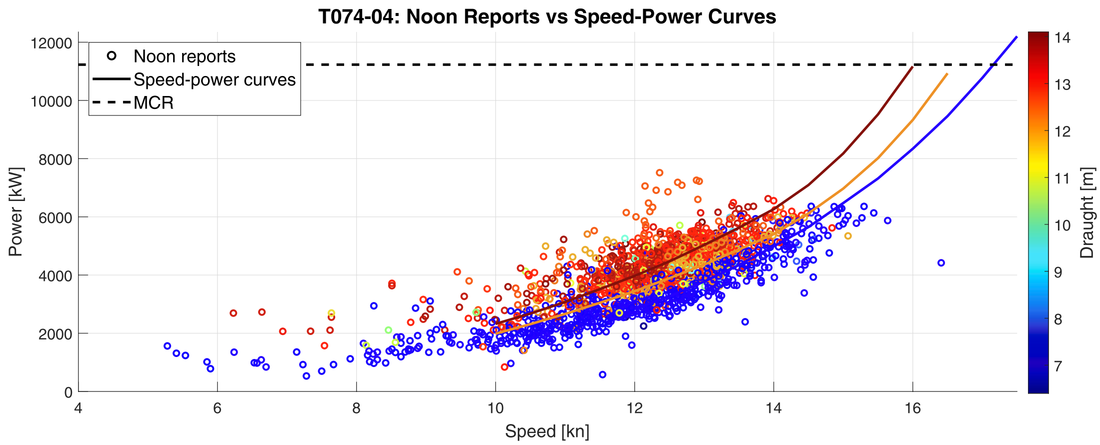

T050-09: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]

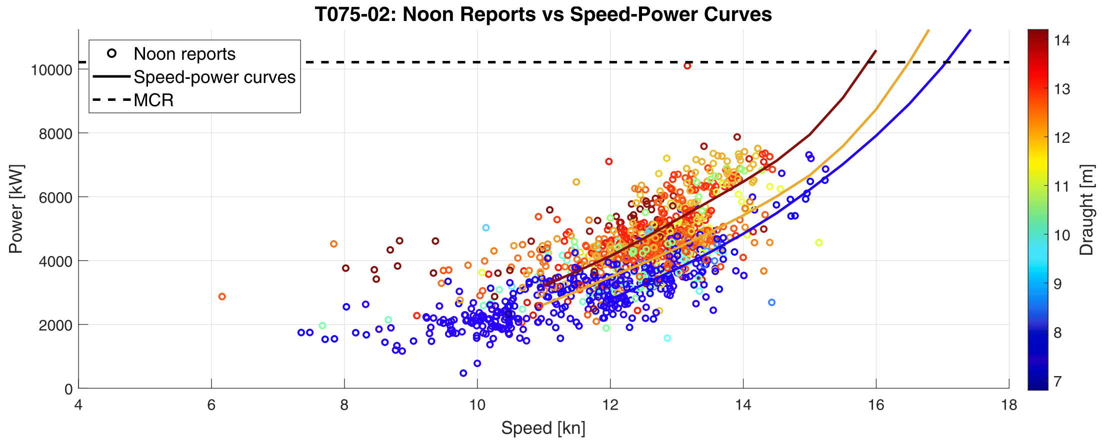

T050-10: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]

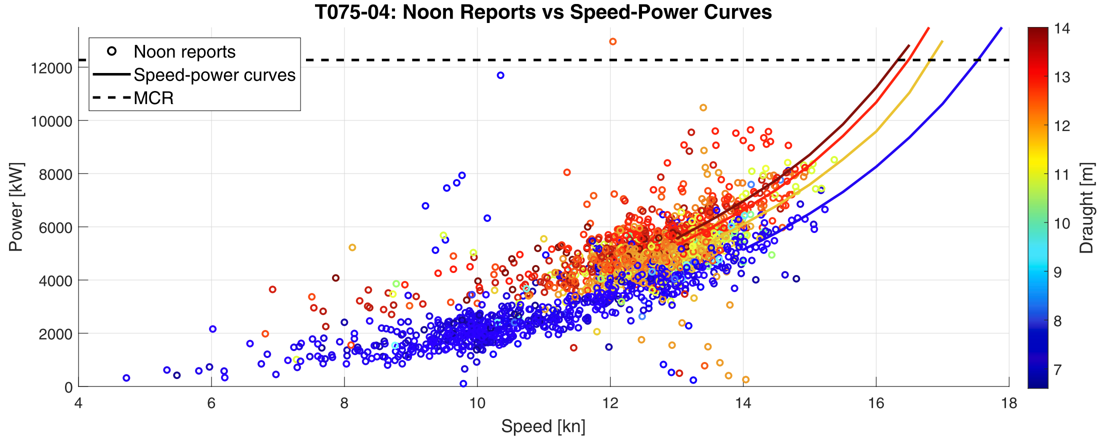

T050-12: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]

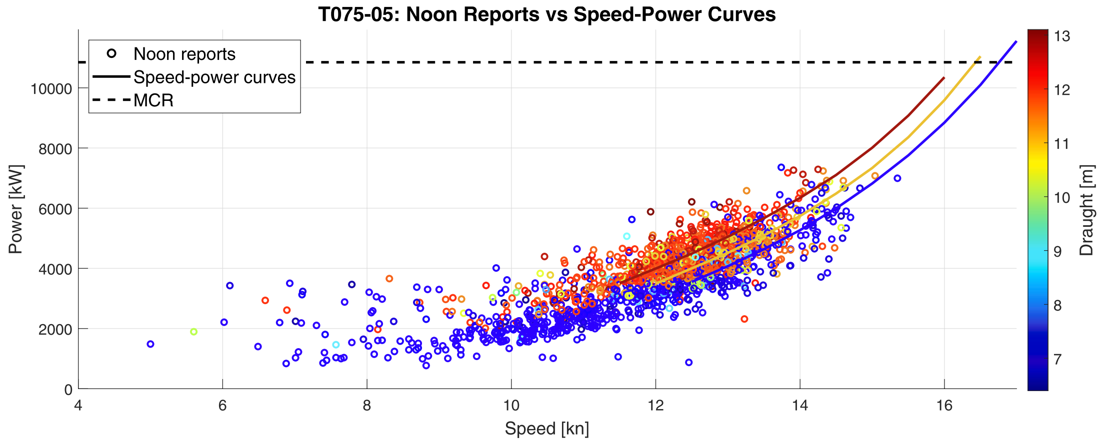

T053-13: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]

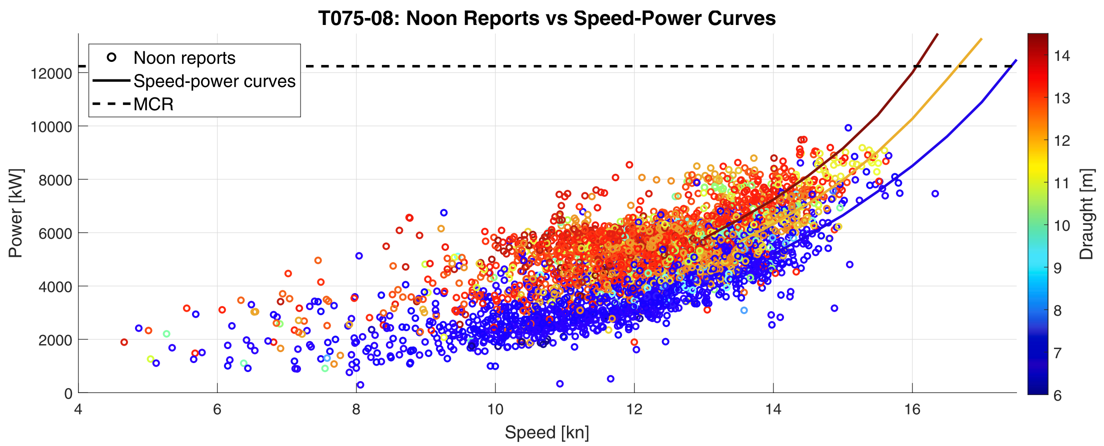

T074-02: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]

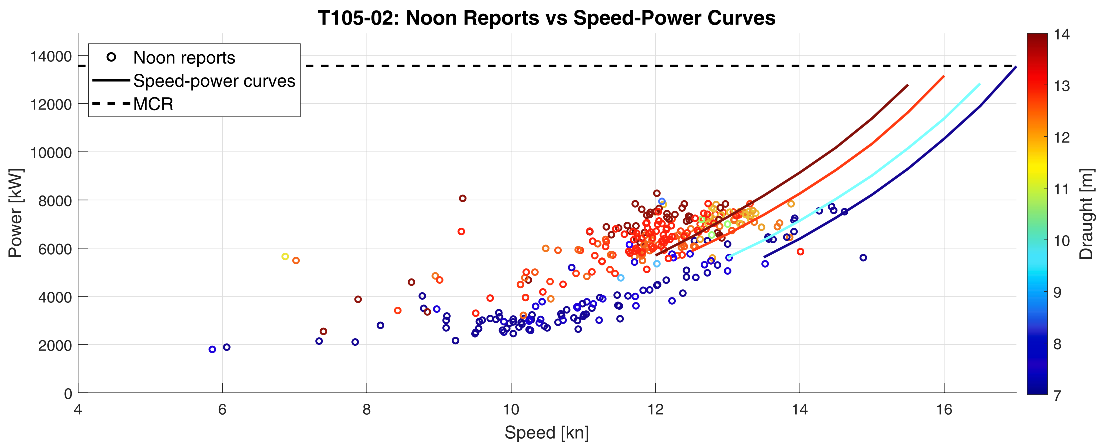

T074-04: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]


T075-02: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]


T075-04: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]


T075-05: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]


T075-08: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]
0
2000
4000
6000
8000
10000
12000
4
6
8
10
12
14
16
6
7
8
9
10
11
12
13
14


T105-02: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]
0
2000
4000
6000
8000
10000
12000
14000
4
6
8
10
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14
16
7
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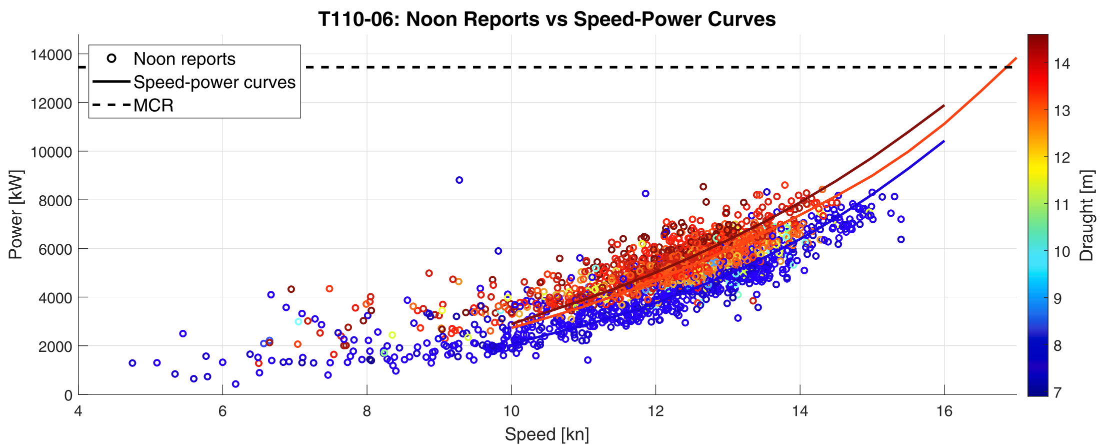
9
10
11
12
13
14


T110-06: Noon Reports vs Speed-Power Curves
Noon reports
Speed-power curves
MCR
Power [kW]
Speed [kn]
Draught [m]
0
2000
4000
6000
8000
10000
12000
14000
4
6
8
10
12
14
16
7
8
9
10
11
12
13
14

References

Adland, R., Cariou, P., Jia, H., Wolff, F.C., 2018. The energy efficiency effects of periodic ship hull cleaning. J. Cleaner Prod. 178, 1–13.

Adland, R., Cariou, P., Wolff, F.C., 2020. Optimal ship speed and the cubic law revisited: Empirical evidence from an oil tanker fleet. Transp. Res. Part E 140. https://doi.org/10.1016/j.tre.2020.101972.

Aldous, L., Smith, T., Bucknall, R., Thompson, P., 2015. Uncertainty analysis in ship performance monitoring. Ocean Eng. 110, 29–38.

Bazari, Z., 2007. Ship energy performance benchmarking/rating: Methodology and application. Proc. Inst. Mar. Eng. Sci. Technol. Part A: J. Mar. Eng. Technol. 4177, 11–18.

Cariou, P., 2011. Is slow steaming a sustainable means of reducing CO2 emissions from container shipping? Transp. Res. Part D 16, 260–264.

Copernicus Climate Change Service (C3S), 2018. Ship performance along standard shipping routes derived from reanalysis and seasonal forecasts. https://cds.climate.copernicus.eu/cdsapp#!/dataset/sis-shipping-consumption-on-routes?tab=doc.

Coraddu, A., Oneto, L., Baldi, F., Cipollini, F., Atlar, M., Savio, S., 2019. Data-driven ship digital twin for estimating the speed loss caused by the marine fouling. Ocean Eng. 186, 106063.

Corbett, J.J., Wang, H., Winebrake, J.J., 2009. The effectiveness and costs of speed reductions on emissions from international shipping. Transp. Res. Part D 14, 593–598.

Dalheim, O., Steen, S., 2020. Preparation of in-service measurement data for ship operation and performance analysis. Ocean Eng. 212, 107730.

Degiuli, N., Martic, I., Farkasa, A., Gospic, I., 2021. The impact of slow steaming on reducing CO2 emissions in the Mediterranean Sea. Energy Rep. https://doi.org/10.1016/j.egyr.2021.02.046.

Eide, M., Endresen, Ø., Skjong, R., Longva, T., Alvik, S., 2009. Cost-effectiveness assessment of co2 reducing measures in shipping. Marit. Policy Manage. 36, 367–384. https://doi.org/10.1080/03088830903057031.

Faber, J., Nelissen, D., Hon, G., Wang, H., Tsimplis, M., 2012. Regulated Slow Steaming in Maritime Transport: An Assessment of Options, Costs and Benefits. Technical Report. CE Delft, Delft, Holland.

Fagerholt, K., Laporte, G., Norstad, I., 2010. Reducing fuel emissions by optimizing speed on shipping routes. J. Oper. Res. Soc. 61, 523–529. https://doi.org/10.1057/jors.2009.77.

Faltinsen, O., Minsaas, K., Liapis, N., Skjørdal, S., 1980. Prediction of resistance and propulsion of a ship in a seaway. In: Proc. 13th Symposium on Naval Hydrodynamics, Tokyo, Japan.

Ferrari, C., Parola, F., Tei, A., 2015. Determinants of slow steaming and implications on service patterns. Marit. Policy Manage. 42, 636–652.

Gobillon, L., Wolff, F.C., 2017. The local effects of an innovation: Evidence from the French fish market. CERP Discussion paper, No. 11757.

Gobillon, L., Wolff, F.C., 2020. The local effects of an innovation: Evidence from the French fish market. Ecol. Econ. 171, 106594.

Hersbach, et al., 2020. The ERA5 Global Reanalysis. Quart. J. Roy. Meteorol. Soc. https://doi.org/10.1002/qj.3803.

Hersbach, et al., 2021. ERA5 hourly data on single levels from 1979 to present. https://doi.org/10.24381/cds.adbb2d47. https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=overview.

Hüffmeier, J., Johanson, M., 2021. State-of-the-art methods to improve energy efficiency of ships. J. Mar. Sci. Eng. 9 https://doi.org/10.3390/jmse9040447.

IMO, 2014. Third IMO Greenhouse Gas Study 2014. International Maritime Organization.

IMO, 2020. Fourth IMO Greenhouse Gas Study 2020. International Maritime Organization.

ISO, 2016a. ISO 19030-1 - Ships and marine technology - Measurement of changes in hull and propeller performance - Part 1: General principles. International Organization for Standardization.

ISO, 2016b. ISO 19030-2 - Ships and marine technology - Measurement of changes in hull and propeller performance - Part 2: Default method. International Organization for Standardization.

ISO, 2016c. ISO 19030-2 - Ships and marine technology - Measurement of changes in hull and propeller performance - Part 3: Alternative methods. International Organization for Standardization.

ITTC, 2017a. 1978 ITTC Performance Prediction Method. ITTC - Recommended Procedures and Guidelines 7.5-02-03-01.4.

ITTC, 2017b. Preparation, Conduct and Analysis of Speed/Power Trials. ITTC - Recommended Procedures and Guidelines 7.5-04-01-01.1.

Karagiannidis, P., Themelis, N., 2021. Data-driven modelling of ship propulsion and the effect of data pre-processing on the prediction of ship fuel consumption and speed loss. Ocean Eng. 222, 108616.

Kauffeldt, A., Hansen, H., 2018. Enhanced performance analysis and benchmarking with CFD baselines. In: Proc. of 3rd Hull Performance and Insight Conference, Redworth, United Kingdom.

Kristensen, H.O.H., 2010. Model for environmental assessment of container ship transport. Trans. Soc. Nav. Architec. Mar. Eng. 118, 122–139. SNAME Annual Meeting 2010.

Kristensen, H.O.H., 2018. Speed and emission reduction from ships. The Naval Architect, September, 2–5.

Lang, X., Mao, W., 2020. A semi-empirical model for ship speed loss prediction at head sea and its validation by full-scale measurements. Ocean Eng. 209, 107494.

Lindstad, H., Asbjørnsletta, B.E., Strømman, A., 2011. Reductions in greenhouse gas emissions and cost by shipping at lower speeds. Energy Policy 39, 3456–3464. https://doi.org/10.1016/j.enpol.2011.03.044.

Lindstad, H., Asbjörnsletta, B.E., Strömman, A., 2013. Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market. Transp. Res. Part D 19, 5–12. https://doi.org/10.1016/j.trd.2012.11.001.

Liu, S., Loh, M., Leow, W., Chen, H., Shang, B., Papanikolaou, A., 2020. Rational processing of monitored ship voyage data for improved operation. Appl. Ocean Res. 104, 102363.

Liu, S., Papanikolaou, A., 2016. Fast approach to the estimation of the added resistance of ships in head waves. Ocean Eng. 112, 211–225.

Liu, S., Papanikolaou, A., 2020. Regression analysis of experimental data for added resistance in waves of arbitrary heading and development of a semi-empirical formula. Ocean Eng. 206, 107357.

Lu, R., Turan, O., Boulougouris, E., Banks, C., Incecik, A., 2015. A semi-empirical ship operational performance prediction model for voyage optimization towards energy efficient shipping. Ocean Eng. 110, 18–28.

Maloni, M., Paul, J.A., Gligor, D.M., 2013. Slow steaming impacts on ocean carriers and shippers. Marit. Econ. Logist. 15, 151–171.

MAN Energy Solutions, 2012. Slow steaming - benefiting retrofit solutions from MAN PrimeServ. (Published as MAN Diesel & Turbo).

MAN Energy Solutions, 2018. Basic principles of ship propulsion. MAN Energy Solutions.

MathWorks, 2016. findchangepts. https://se.mathworks.com/help/signal/ref/findchangepts.html.

Meyer, J., Stahlbock, R., Voss, S., 2012. Slow Steaming in Container Shipping, in: Proc. 45th Hawaii International Conference on System Sciences, Maui, HI, USA.

Neter, J., Wasserman, W., Kutner, M.H., 2003. Applied linear regression models, fourth ed. McGraw-Hill Higher Education.

Nielsen, U.D., 2021. Spatio-temporal variation in sea state parameters along virtual ship route paths. J. Operat. Oceanogr. https://doi.org/10.1080/1755876X.2021.1872894.

Nielsen, U.D., Johannesen, J., Bingham, H., Blanke, M., Joncquez, S., 2021. Indirect Measurements of Added-wave Resistance On an In-service Container Ship. In: Okada, T., Suzuki, K., Kawamura, Y. (Eds.), PRADS 2019. Springer Nature, Yokohama, Japan, pp. 115–132.

Norlund, E., Gribkovskaia, I., 2013. Reducing emissions through speed optimization in supply vessel operations. Transp. Res. Part D 23, 105–113. https://doi.org/10.1016/j.trd.2013.04.007.

Mittendorf, M., Nielsen, U.D., Bingham, H.B., 2021. Data-Driven Prediction of Added-Wave Resistance on Ships in Oblique Waves - A Comparison Between Tree-Based Ensemble Methods and Artificial Neural Networks. Appl. Ocean Res. (under review).

Oikonomakis, A., Galeazzi, R., Dietz, J., Nielsen, U., Holst, K., 2019. Application of Sensor Fusion to Drive Vessel Performance, in: Proc. of 4th Hull Performance and Insight Conference, Gubbio, Italy.

Oikonomakis, A., Nielsen, U., Holst, K., Dietz, J., Galeazzi, R., 2021. How good is the STW sensor? An account from a larger shipping company. J. Mar. Sci. Eng. 9 https://doi.org/10.3390/jmse9050465.

Pardoe, I., Simon, L., Young, D., 2021. Stat 501: Regression methods (online course material. https://online.stat.psu.edu/stat501/lesson/welcome-stat-501. (About the course: https://online.stat.psu.edu/statprogram/stat501) (accessed: 2021-01-18).

Pedersen, B., 2014. Data-driven Vessel Performance Monitoring. Ph.D. thesis. DTU Mechanical Engineering, Technical University of Denmark. DCAMM Special Report No. S180.

Psaraftis, H.N., 2019a. Speed optimization versus speed reduction: Are speed limits better than a bunker levy? Marit. Econ. Logist. 21, 524–542.

Psaraftis, H.N., 2019b. Speed Optimization vs Speed Reduction: the Speed Limit Debate, in: Proc. of IAME, Athens, Greece.

Psaraftis, H.N., Kontovas, C.A., 2013. Speed models for energy-efficient maritime transportation: A taxonomy and survey. Transp. Res. Part C 26, 331–351. https://doi.org/10.1016/j.trc.2012.09.012.

Psaraftis, H.N., Kontovas, C.A., 2014. Ship speed optimization: Concepts, models and combined speed-routing scenarios. Transp. Res. Part C 44, 52–69. https://doi.org/10.1016/j.trc.2014.03.001.

Psaraftis, H.N., Kontovas, C.A., 2015. Slow Steaming in Maritime Transportation: Fundamentals, Trade-offs, and Decision Models. In: Lee, C.Y., Meng, Q. (Eds.), Handbook of Ocean Container Transport Logistics: Making Global Supply Chains Effective.

Salvesen, N., 1978. Added resistance in waves. J. Hydronaut. 12, 24–34.

Spandonidis, P.T.C., Themelis, N., Giordamlis, C., Fassois, S., 2021. Evaluation of different deep-learning models for the prediction of a ships propulsion power. J. Mar. Sci. Eng. 9 https://doi.org/10.3390/jmse9020116.

Ström-Tejsen, J., Yeh, H., Moran, D., 1973. Added resistance in waves. Trans. SNAME 81, 109–143.

Taskar, B., Andersen, P., 2020. Benefit of speed reduction for ships in different weather conditions. Transp. Res. Part D 85. https://doi.org/10.1016/j.trd.2020.102337.

Themelis, N., Spandonidis, C., Christopoulos, G., Giordamlis, C., 2018. A comparative study on ship performance assessment based on noon report and continuous monitoring system datasets. In: 2018 Annual Meeting of Marine Technology, organised by the Hellenic Institute of Marine Technology.

Tillig, F., Ringsberg, J.W., Mao, W., Ramne, B., 2018. Analysis of uncertainties in the prediction of ships fuel consumption from early design to operation conditions. Ships Offshore Struct. 13, 13–24. https://doi.org/10.1080/17445302.2018.1425519.

Tillig, F., Ringsberg, J.W., Psaraftis, H.N., Zis, T., 2020. Reduced environmental impact of marine transport through speed reduction and wind assisted propulsion. Transp. Res. Part D 83. https://doi.org/10.1016/j.trd.2020.102380.

Trodden, D., Murphy, A., Pazouki, K., Sargeant, J., 2015. Fuel usage data analysis for efficient shipping operations. Ocean Eng. 110, 75–84.

Tsujimoto, M., Orihara, H., 2018. Performance prediction of full-scale ship and analysis by means of onboard monitoring (Part 1 ship performance prediction in actual seas). J. Mar. Sci. Technol. 1–18. Accessed online.

Woo, J., Moon, D.S., 2014. The effects of slow steaming on the environmental performance in liner shipping. Marit. Policy Manage. 41, 176–191.