

Fuel Alone Cannot Define Economic Speed: A Parametric Model of Hull Fouling and Engine Ageing in Indonesian Coastal Cargo Operations

Febria Surjaman^{1*}, P. Marcello Lopulalan², Hendi Prasetyo³

Politeknik Pelayaran Banten, Tangerang, Indonesia

Corresponding Author: Febria Surjaman febriasurjaman31@gmail.com

ARTICLE INFO

Keywords: Economic Speed, Fuel Consumption Modelling, Hull Fouling, Slow Steaming, Carbon Intensity Indicator

Received : 01 July 2026

Revised : 03 August 2026

Accepted : 06 September 2026

©2026 The Author(s): This is an open-access article distributed under the terms of the Creative Commons Attribution 4.0 International License.

ABSTRACT

Fuel represents the dominant variable cost in ship operation, and the selection of sailing speed is the principal lever available to an operator seeking to control it. This study develops a transparent parametric model of fuel consumption and economic speed for a representative Indonesian coastal general cargo vessel, and uses it to quantify how hull fouling and engine ageing alter both. The model combines a cubic speed-power relationship with a constant auxiliary load, and derives the cost-optimal speed by minimising total cost per nautical mile. Parameters are taken from published literature rather than from measurement, and the study is therefore explicitly a simulation rather than an empirical trial. Two configurations were compared: a new vessel with a specific fuel oil consumption of 185 g/kWh and a clean hull, and an aged vessel with 205 g/kWh and 25% added resistance. The model predicts a fuel penalty attributable to ageing of between 27.9% and 36.4% across the range 8 to 15 knots, averaging 33.3%, and a reduction in cost-optimal speed from 10.22 to 9.17 knots. A methodological finding of wider consequence also emerges: minimising fuel per nautical mile alone yields an optimum of 4.61 knots, which is operationally meaningless, demonstrating that economic speed cannot be defined on fuel consumption alone but requires the vessel time cost to be represented explicitly. Sensitivity analysis shows the optimum is more responsive to time cost than to fouling severity.

INTRODUCTION

The modern shipping industry confronts sustained pressure to improve operational efficiency, and nowhere is that pressure more concentrated than upon fuel consumption. Bunker fuel constitutes the largest single component of variable operating cost for most vessel types, and the relationship between sailing speed and fuel consumption is strongly non-linear, which renders speed the most powerful lever available to an operator seeking to control expenditure. Regulatory pressure now reinforces the commercial incentive: the Energy Efficiency Existing Ship Index and the Carbon Intensity Indicator introduced by the International Maritime Organization oblige vessels to demonstrate improving efficiency, and speed reduction is among the most immediately available means of compliance (Bayraktar & Yuksel, 2023; Vasilev et al., 2025).

The concept of economic speed expresses the operator's response to these pressures. It denotes the speed at which the cost of conveying cargo over a given distance is minimised, and it is not simply the speed at which fuel consumption is lowest. This distinction, elaborated below, is central to the present study. The literature on speed optimisation is extensive and mature, encompassing taxonomies of speed models (Psaraftis & Kontovas, 2013), formulations combining speed and routing (Psaraftis & Kontovas, 2014), and network-level optimisation for liner services (Wang & Meng, 2012). The economics of the problem were established considerably earlier, with Ronen (1982) demonstrating the dependence of optimal speed upon fuel price and subsequently upon fleet size (Ronen, 2011).

A parallel body of work addresses the degradation of vessel performance with age. Hull fouling increases frictional resistance and therefore the power required at any given speed, an effect quantified experimentally by Schultz (2007) and modelled through computational fluid dynamics by Demirel et al. (2017). Engine performance likewise deteriorates, with specific fuel oil consumption rising over service life (Kokkulunk et al., 2016). In Indonesia these effects are of particular consequence, since many operators continue to work fleets of substantial age that were not designed to contemporary efficiency standards, and the decision whether to retrofit, to adjust operating practice, or to replace a vessel turns upon the magnitude of the penalty that age imposes. This is not merely illustrative: as of February 2025 the Ministry of Transportation reported that roughly half of Indonesia's approximately 50,000-vessel commercial fleet, excluding fishing vessels, exceeded 15 years of age (CNBC Indonesia, 2025), indicating that the ageing-vessel scenario modelled below reflects a substantial and not a marginal segment of the domestic coastal fleet.

Establishing that magnitude empirically for a specific vessel requires access to noon reports, fuel meter records, and hull condition data across a range of speeds and over an extended period. Such data are frequently unavailable to researchers, and where they are available they are seldom comparable across vessels of different age operating in the same trade. The present study therefore adopts a different approach. Rather than presenting measurements it does not possess, it constructs a transparent parametric model from established physical relationships and published parameter values, and reports what that model predicts. The distinction is stated at the outset and maintained throughout: this is

a simulation study, its outputs are model predictions, and no claim is made that any particular vessel was measured.

Two objectives are pursued. The first is to quantify, within the model, the fuel penalty and the shift in economic speed attributable to hull fouling and engine ageing for a vessel representative of Indonesian coastal cargo operations. The second, which emerged in the course of the analysis and proved of wider consequence, is to establish whether economic speed can be determined from fuel consumption alone, as is frequently assumed in operational practice and in the applied literature. The contribution lies in the transparency and reproducibility of the model, in the sensitivity analysis that accompanies it, and in the demonstration that the fuel-only criterion is inadequate.

LITERATURE REVIEW

Speed, Power and Fuel Consumption

The physical foundation of speed optimisation is the relationship between speed and required propulsion power. For a displacement hull at moderate Froude number, calm-water resistance rises approximately with the square of speed, and since power is the product of resistance and speed, required power rises approximately with the cube. Fuel consumption follows from power through the specific fuel oil consumption of the engine. This cubic approximation underpins the greater part of the speed optimisation literature, though its precision has been questioned: Adland et al. (2020) revisited the cubic law using empirical evidence from an oil tanker fleet and found systematic departures from it, particularly at the extremes of the operating range.

Data-driven approaches have proliferated as sensor and reporting data have become more available. Bialystocki and Konovessis (2016) developed a statistical method for estimating a vessel's fuel consumption and speed curve, and subsequent work has applied machine learning to the same problem with increasing sophistication (Gkerekos et al., 2019; Uyanik et al., 2020; Chen et al., 2023; Zhang et al., 2025). Yang et al. (2024) incorporated meteorological factors, and Bayraktar and Sokukcu (2024) worked from daily noon reports. Yan et al. (2021) surveyed the status and prospects of data analytics for fuel consumption management. These approaches achieve high predictive accuracy where training data are available, but they cannot be applied where such data are absent, and their parameters are not transferable between vessels.

The present study adopts the physics-based approach for the opposite reason: its parameters are interpretable, transferable, and drawn from published sources, which permits application where operational data are unavailable and permits the reader to substitute alternative values. The cost of this choice is reduced fidelity relative to a data-driven model calibrated to a specific vessel.

Hull Fouling and Added Resistance

Biofouling of the hull increases surface roughness and consequently frictional resistance, which constitutes the dominant resistance component for slow-moving displacement vessels. Schultz (2007) established experimentally the effects of coating roughness and biofouling upon ship resistance and powering, providing the quantitative basis for much subsequent work, and Schultz et al.

(2011) assessed the economic impact for a naval surface vessel. Demirel et al. (2017) predicted the effect of biofouling upon resistance using computational fluid dynamics, and Uzun et al. (2019) developed a time-dependent growth model permitting the penalty to be projected forward from a known cleaning date.

The operational consequences have been quantified from several directions. Farkas et al. (2020) examined the impact of biofilm upon propulsion characteristics and the resulting speed reduction, and Farkas et al. (2022) estimated the energy savings potential of hull cleaning across the industry. Coraddu et al. (2019) constructed a data-driven digital twin to estimate speed loss caused by fouling, and Park et al. (2025) conducted a scenario-based economic analysis of underwater biofouling. The range of added resistance reported across this literature is wide, reflecting genuine variation in fouling severity with trade route, idle time, coating condition, and time since cleaning; values between 10% and 35% span the greater part of reported cases, and this range is adopted for the sensitivity analysis below.

Engine Ageing

Specific fuel oil consumption rises as an engine accumulates service hours, through wear of injection equipment, degradation of turbocharger performance, and loss of combustion efficiency. Kokkulunk et al. (2016) determined the performance degradation of a marine diesel engine using a curve-based approach, and Ceylan (2024) assessed turbocharger fouling specifically through fuzzy failure mode and effects analysis. The magnitude of degradation depends upon maintenance regime as much as upon age, which is why the parameter is treated here as an input to be varied rather than as a fixed property of vessel age.

The Economics of Speed

The determination of economic speed is a question of economics rather than of naval architecture alone. Ronen (1982) established the analytical framework, showing that optimal speed depends upon the ratio of fuel cost to the cost of vessel time, the latter comprising charter hire or its opportunity-cost equivalent together with operating expenditure. The implication is that as fuel prices rise relative to time costs the optimum falls, and conversely. Ronen (2011) applied the framework to containership speed and fleet size, and Wu (2020) developed the theory alongside empirical evidence for container shipping.

Empirical investigation has confirmed that operators respond to these incentives. Adland and Jia (2018) documented dynamic speed choice in bulk shipping, and Adland et al. (2020) established from tanker fleet data that observed speeds respond to market conditions in the direction the theory predicts. Corbett et al. (2009) assessed the effectiveness and cost of speed reduction as an emission abatement measure, and Fagerholt et al. (2010) formulated the corresponding optimisation problem for shipping routes. Goicoechea and Abadie (2021) examined optimal slow steaming under an emissions trading regime, and Yan et al. (2025) applied speed optimisation to Carbon Intensity Indicator compliance using measurement data.

The consistent element across this literature is that the objective function contains a time cost. Where it does not, the optimisation degenerates, since fuel consumed per mile declines monotonically as speed approaches zero over the

range in which auxiliary load is small relative to propulsion load. This degeneracy is demonstrated explicitly in the results below, and its practical significance is that operational guidance framed solely in terms of fuel per mile is analytically unsound.

The historical record illustrates the point concretely. Following the sharp rise in bunker prices after 2008, container lines across the industry adopted slow steaming as a near-universal response; Ronen (2011) documented the resulting shift in optimal containership speed and fleet size, while Corbett et al. (2009) and Wu (2020) each confirmed that the magnitude of the speed reduction tracked the prevailing ratio of fuel to vessel time cost rather than the fuel price alone. The lesson for the general cargo sector modelled here is the same: it is the relative, not the absolute, movement of these two costs that governs the slow-steaming decision, so that a vessel's economic speed must be revisited whenever that ratio shifts materially, as it has repeatedly done over the past two decades.

Regulation and Fleet Renewal

The regulatory framework has altered the calculus of speed selection. Czermanski et al. (2022) assessed the implementation of the Energy Efficiency Existing Ship Index and characterised it as necessary but costly, and Chuah et al. (2023) examined the application of both that index and the Carbon Intensity Indicator to domestic vessels, a context directly comparable to the Indonesian coastal trade considered here. Vasilev et al. (2025) analysed the interaction of the several indices for tankers. Broader reviews situate these instruments within the wider effort to reduce shipping emissions (Xing et al., 2020; Jimenez et al., 2022).

The renewal decision has likewise attracted attention. Pruyn (2017) asked whether fuel-efficient new bulkers threaten the existing fleet, and Ross and Schinas (2019) established an empirical relationship between energy performance and vessel value. Where replacement is not immediately feasible, retrofit of energy saving devices offers an intermediate course, with measured savings reported for pre-propeller ducts and comparable appendages (Mimica et al., 2025; Uyan et al., 2024). The model developed here informs this decision by quantifying the operating penalty that an ageing vessel carries.

Research Gap

Three observations follow. First, the speed optimisation literature is dominated by large vessels in international trade, and small coastal vessels in developing economies are comparatively unrepresented. Second, the fouling and engine ageing literatures quantify penalties in isolation, and their combined effect upon the economic speed of a specific vessel class is seldom computed. Third, applied guidance frequently frames economic speed in terms of fuel per nautical mile, a criterion that this study demonstrates to be degenerate. The parametric model developed here addresses all three.

METHODOLOGY

Nature and Status of the Data

It is stated explicitly, and at the outset, that this study does not report measurements taken from operating vessels. The analysis is a parametric simulation. Every input parameter is either a physical constant, a design particular

of a representative vessel, or a value drawn from the published literature cited in the preceding section. The outputs are accordingly model predictions, and they are reported as such throughout. No claim is advanced that any specific vessel was observed to behave as the model describes. The purpose of the exercise is to establish the direction and approximate magnitude of effects, and to provide a reproducible framework into which an operator possessing measured data may substitute their own parameters.

Model Formulation

The vessel modelled is a general cargo ship representative of Indonesian coastal service, with a main engine of 3,000 kW maximum continuous rating and a design speed of 13 knots attained at 85% of that rating, corresponding to a propulsion power of 2,550 kW. Propulsion power at any other speed is obtained from the cubic law, in which power scales with the cube of the ratio of actual to reference speed. Main engine fuel consumption follows as the product of propulsion power and specific fuel oil consumption. A constant auxiliary and hotel load of 200 kW, consuming fuel at 210 g/kWh, is added; this term is independent of speed and is the element that renders the fuel-per-mile curve non-monotonic.

Total hourly fuel consumption is therefore the sum of a term proportional to the cube of speed and a constant term. Fuel consumed per nautical mile is this quantity divided by speed, which yields the sum of a term proportional to the square of speed and a term inversely proportional to speed. Total cost per nautical mile is obtained by valuing fuel at a bunker price and adding the vessel time cost divided by speed. Differentiating with respect to speed and setting the derivative to zero yields a closed-form expression for the cost-optimal speed, in which the optimum varies with the cube root of the ratio of time-related to speed-related cost coefficients.

Parameter Values and Scenarios

Two configurations were defined. The new vessel is assigned a specific fuel oil consumption of 185 g/kWh and a clean hull with no added resistance. The aged vessel is assigned 205 g/kWh, consistent with the degradation reported in the engine performance literature, and an added resistance multiplier of 1.25 representing 25% additional power demand from hull fouling, a value lying near the centre of the range reported by Schultz (2007), Demirel et al. (2017), and Farkas et al. (2020). Bunker fuel is valued at 600 United States dollars per tonne and vessel time at 250 dollars per hour, the latter representing charter hire together with operating expenditure for a vessel of this size. Full parameter values are reported in Table 1.

Table 1. Model parameters and their sources

Parameter	Value	Basis
Main engine maximum continuous rating	3,000 kW	Representative coastal general cargo vessel

Parameter	Value	Basis
Propulsion power at reference speed	2,550 kW (85% MCR)	Design assumption
Reference speed	13 knots	Design assumption
Speed-power relationship	Power proportional to speed cubed	Standard displacement-hull approximation
Specific fuel oil consumption, new engine	185 g/kWh	Contemporary marine diesel practice
Specific fuel oil consumption, aged engine	205 g/kWh	Engine degradation literature
Added resistance from fouling, aged hull	25% (varied 10-35% in sensitivity)	Biofouling resistance literature
Auxiliary and hotel load	200 kW at 210 g/kWh	Design assumption; speed-independent
Bunker fuel price	600 USD/tonne	Representative VLSFO price
Vessel time cost	250 USD/hour (varied 100-500)	Hire plus operating expenditure

Sensitivity Analysis

Because several parameters carry genuine uncertainty, two one-at-a-time sensitivity analyses were conducted. The first varied vessel time cost across the range 100 to 500 dollars per hour, spanning plausible market conditions from depressed to firm. The second varied the added resistance from fouling across the range 10% to 35%, spanning the range reported in the fouling literature from recently cleaned to heavily fouled. In each case the cost-optimal speed and, for the fouling case, the fuel penalty at a representative speed of 10 knots were recomputed. The model was implemented in Python, and the closed-form optimum was verified numerically.

RESEARCH RESULT

Fuel Consumption and the Penalty of Ageing

Predicted hourly fuel consumption for both configurations across the range 8 to 15 knots is reported in Table 2 and displayed in panel (a) of Figure 1.

Table 2. Predicted fuel consumption, fuel per nautical mile, and the penalty of ageing.

Speed (knots)	FOC new (t/h)	FOC aged (t/h)	Fuel/NM new (t)	Fuel/NM aged (t)	Penalty (%)
8	0.1519	0.1943	0.0190	0.0243	27.9
9	0.1985	0.2588	0.0221	0.0288	30.4
10	0.2567	0.3394	0.0257	0.0339	32.2
11	0.3278	0.4379	0.0298	0.0398	33.6
12	0.4130	0.5559	0.0344	0.0463	34.6
13	0.5138	0.6954	0.0395	0.0535	35.4
14	0.6312	0.8581	0.0451	0.0613	36.0
15	0.7667	1.0458	0.0511	0.0697	36.4

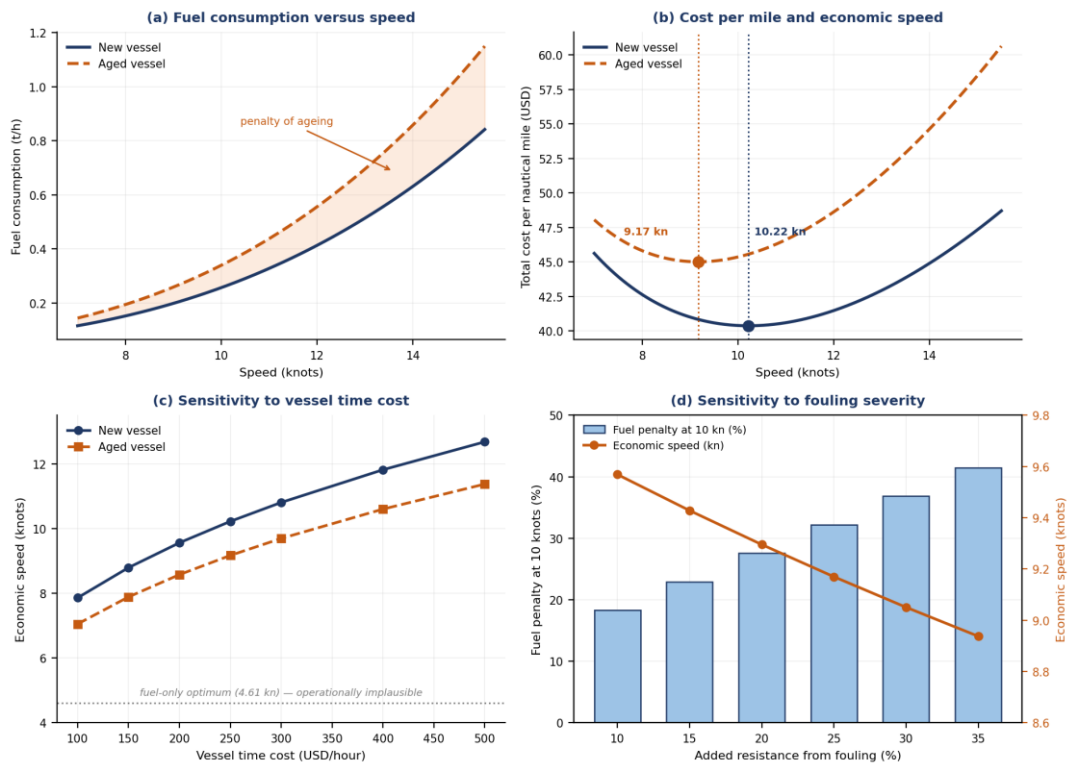


Figure 1. Model predictions: fuel consumption, cost per mile and economic speed, and sensitivity to time cost and fouling severity.

The model predicts a fuel penalty attributable to ageing of 27.9% at 8 knots, rising monotonically to 36.4% at 15 knots, with a mean across the range of 33.3%. The penalty increases with speed because the fouling multiplier applies to the

propulsion term, which grows with the cube of speed, while the auxiliary term to which it does not apply remains constant; the fouled component therefore constitutes a rising share of the total as speed increases. This has an immediate operational implication: the disadvantage of an aged vessel is least at low speed, which reinforces the case for reducing speed on older tonnage specifically.

Economic Speed

Cost per nautical mile for both configurations is displayed in panel (b) of Figure 1, with the cost-optimal speed marked. The model predicts an economic speed of 10.22 knots for the new vessel and 9.17 knots for the aged vessel, a reduction of 1.05 knots or 10.3%. The direction of this result is intuitive: because the aged vessel incurs a steeper fuel cost gradient with respect to speed, the point at which the marginal fuel cost of additional speed equals the marginal time saving occurs at a lower speed.

A second and more consequential result concerns the criterion by which economic speed is defined. When the objective is taken to be minimisation of fuel consumed per nautical mile, disregarding the value of time, the model returns an optimum of 4.61 knots for the new vessel and 4.13 knots for the aged vessel. These figures are operationally meaningless: no commercial vessel would sail at such speeds, and doing so would extend voyage duration to an extent that no fuel saving could offset. The result is not an artefact of parameter choice but a structural property of the objective function, since the fuel-per-mile curve is dominated over the operating range by the term proportional to the square of speed, and its minimum is pushed towards the low-speed limit where the small auxiliary term becomes influential.

The commercial implausibility of speeds in this range is confirmed by extending the total-cost-per-mile calculation below the range reported in Table 2 (Table 3). Total cost per nautical mile rises sharply as speed falls below the economic optimum, driven by the vessel-time term, which grows without bound as speed approaches zero; at 3 knots this term alone accounts for approximately 90% of total cost per mile, and total cost is more than double its value at the economic optimum. No commercial operator would incur this cost to save a comparatively small quantity of fuel, which is precisely why the fuel-only optimum of 4.61 (new) to 4.13 (aged) knots identified above, and any speed below approximately 5 knots more generally, is operationally meaningless despite appearing favourable on a fuel-per-mile basis alone.

Table 3. Total cost per nautical mile at low speed, illustrating the commercial infeasibility of speeds below approximately 5 knots.

Speed (knots)	Fuel cost/NM, new (\$)	Vessel time cost/NM (\$)	Total cost/NM, new (\$)	Total cost/NM, aged (\$)	Increase over near-optimal (%)
3	9.56	83.33	92.89	93.34	129.9
4	8.36	62.50	70.86	71.66	75.4
5	8.26	50.00	58.26	59.50	44.2
6	8.84	41.67	50.50	52.29	25.0
7	9.91	35.71	45.63	48.06	12.9
8	11.40	31.25	42.65	45.82	5.5
9	13.24	27.78	41.01	45.03	1.5
10	15.40	25.00	40.40	45.37	0.0

Sensitivity to Vessel Time Cost

Panel (c) of Figure 1 displays the response of economic speed to vessel time cost. Across the range 100 to 500 dollars per hour the optimum for the new vessel rises from 7.86 to 12.68 knots, and for the aged vessel from 7.05 to 11.37 knots. The elasticity is substantial: a doubling of time cost from 250 to 500 dollars per hour raises the optimum by approximately 2.5 knots. The gap between the two configurations widens modestly in absolute terms as time cost rises, from 0.81 knots at the lower bound to 1.31 knots at the upper, but remains approximately constant in proportional terms at approximately 10%.

Sensitivity to Fouling Severity

Panel (d) of Figure 1 displays the response to fouling severity. As added resistance rises from 10% to 35%, the predicted fuel penalty at 10 knots rises from 18.3% to 41.5%, and the economic speed of the aged vessel falls from 9.57 to 8.94 knots. The penalty responds approximately linearly to fouling severity, whereas the economic speed responds only weakly, falling by 0.63 knots across a range in which the fuel penalty more than doubles. Economic speed is therefore considerably less sensitive to hull condition than to the commercial environment represented by time cost.

DISCUSSION

Fuel Alone Cannot Define Economic Speed

The most consequential finding of this study is methodological. Guidance framed in terms of minimising fuel consumed per nautical mile, which appears frequently in operational practice and in applied studies, is analytically degenerate: applied consistently it recommends speeds below 5 knots, which no operator would adopt and which would in any event be uneconomic once the cost of the extended voyage is admitted. The fuel-per-mile criterion is only usable if it is not followed to its conclusion, which is an unsatisfactory basis for guidance.

The remedy has been available since Ronen (1982), namely the explicit inclusion of a time cost in the objective function. Its omission in applied work is nevertheless persistent, and the present analysis quantifies the magnitude of the resulting error: the difference between the fuel-only optimum of 4.61 knots and the cost-based optimum of 10.22 knots is not a refinement but a difference in kind. This finding aligns with the theoretical position of Psaraftis and Kontovas (2013), whose taxonomy distinguishes objective functions precisely on this basis, and with the empirical evidence of Adland and Jia (2018) and Wu (2020) that observed operator behaviour tracks the cost-based rather than the fuel-based optimum.

The Magnitude of the Ageing Penalty

The predicted fuel penalty of approximately one third at typical operating speeds is substantial in commercial terms, and is consistent in magnitude with the separate literatures from which its components were drawn. Schultz (2007) and Demirel et al. (2017) report added resistance from fouling of the order adopted here, and Farkas et al. (2022) estimated industry-wide savings from hull cleaning on a comparable basis. The engine contribution, derived from a rise in specific fuel oil consumption from 185 to 205 g/kWh, is consistent with the degradation characterised by Kokkulunk et al. (2016).

The finding that the penalty rises with speed carries a practical corollary that is not obvious without the model. Because fouling acts upon the propulsion term alone, and because that term grows cubically while the auxiliary term does not, an aged vessel is relatively least disadvantaged at low speed. Operators unable to renew tonnage in the near term may therefore recover a disproportionate share of the penalty by reducing speed, and the case for slow steaming is stronger for older vessels than for newer ones. This observation connects the ageing literature to the abatement literature of Corbett et al. (2009) and Fagerholt et al. (2010) in a manner that treatment of either in isolation does not disclose.

Implications for Compliance and Fleet Strategy

Under the Carbon Intensity Indicator regime, a vessel's rating depends upon carbon emitted per unit of transport work, which is proportional to fuel consumed per tonne-mile. A penalty of one third in fuel consumption translates directly into a corresponding deterioration in that metric, and for a vessel near a grade boundary this is likely to be decisive. Yan et al. (2025) demonstrated the application of speed optimisation to compliance at each rating level, and Bayraktar and Yuksel (2023) assessed compliance scenarios for the combined indices. Chuah et al. (2023) examined the application of both instruments to domestic vessels specifically, which is the regulatory position most relevant to Indonesian coastal operators.

For the renewal decision, the model quantifies the operating penalty that must be weighed against the capital cost of replacement or retrofit. Pruyn (2017) framed this comparison for bulk carriers, and Ross and Schinas (2019) established that energy performance is reflected in vessel value. Where replacement is not feasible, hull cleaning offers the most direct intervention, since the sensitivity analysis shows the fuel penalty responds approximately linearly to fouling severity: reducing added resistance from 35% to 10% would recover

approximately 23 percentage points of the penalty. Retrofit of energy saving devices offers a further increment (Mimica et al., 2025; Uyan et al., 2024).

The asymmetry between the two sensitivity analyses also carries a strategic implication. Economic speed responds strongly to time cost and weakly to hull condition, whereas the fuel penalty responds strongly to hull condition. Hull maintenance should therefore be justified by the fuel saving it delivers rather than by any change in optimal speed, while speed policy should be set principally by reference to the freight market. Conflating the two decisions, as operational practice sometimes does, misallocates attention.

Limitations

The limitations of this study are substantial and must be stated plainly. First and foremost, no measurements were taken: all results are model predictions conditional upon assumed parameter values, and they require empirical validation before being relied upon for any specific vessel. Second, the cubic speed-power law is an approximation whose accuracy has been questioned empirically, notably by Adland et al. (2020), and departures from it would alter the computed optimum. Third, the model represents calm-water conditions and omits added resistance from wind, waves, and current, which in Indonesian coastal waters during the monsoon may be considerable. Fourth, fouling and engine degradation are represented as static multipliers rather than as processes evolving over time, whereas Uzun et al. (2019) showed that fouling growth follows a time-dependent trajectory. Fifth, the parameters describe a single representative vessel, and results are not transferable to vessels of materially different size or service without recalibration.

CONCLUSIONS AND RECOMMENDATIONS

This study developed a transparent parametric model of fuel consumption and economic speed for a representative Indonesian coastal general cargo vessel, in order to quantify the effect of hull fouling and engine ageing. The model predicts a fuel penalty attributable to ageing of between 27.9% and 36.4% across the range 8 to 15 knots, averaging 33.3%, with the penalty rising as speed increases because fouling acts upon the cubically growing propulsion term alone. Cost-optimal speed is predicted to fall from 10.22 knots for the new vessel to 9.17 knots for the aged vessel, a reduction of 10.3%. Sensitivity analysis shows the optimum responds strongly to vessel time cost, rising from 7.86 to 12.68 knots as time cost rises from 100 to 500 dollars per hour, and weakly to fouling severity.

A methodological finding of wider consequence also emerged. Minimising fuel consumed per nautical mile, without regard to the value of vessel time, yields an optimum of 4.61 knots, which is operationally meaningless. Economic speed cannot be defined on fuel consumption alone, and operational guidance framed in those terms is analytically unsound.

Three recommendations follow. First, operators should determine economic speed by minimising total cost per mile, incorporating vessel time cost explicitly, and should revise the resulting speed as freight market conditions change rather than treating it as a fixed vessel characteristic. Second, older tonnage should be operated at lower speed than newer tonnage in the same trade, since the model

shows the ageing penalty is smallest at low speed. Third, hull cleaning should be evaluated against the fuel saving it delivers, which the model predicts to be approximately linear in the reduction of added resistance, rather than against any expected change in optimal speed. As a concrete operating indicator, the model shows total cost per mile is minimised in the neighbourhood of 9 to 10 knots for a vessel of this size at the reference bunker price and time cost, and more than doubles if speed is allowed to fall to 3 knots; operators lacking the resources to run the full model can accordingly treat a sustained speed below approximately 8 knots, or a vessel time cost input of less than 100 dollars per hour left unverified, as a signal to revisit the calculation rather than as a safe default.

ADVANCED RESEARCH

Four directions for further work follow directly from the limitations. First and most importantly, the model requires empirical validation against noon report and fuel meter data from vessels of differing age operating in the same Indonesian coastal trade; such validation would establish whether the predicted penalty of approximately one third is realised in service. Second, the cubic speed-power relationship should be replaced by a fitted exponent estimated from operational data, following the approach of Adland et al. (2020), since the exponent materially affects the computed optimum. Third, the model should be extended to represent added resistance from wind and waves, permitting seasonal variation in economic speed to be quantified for monsoon-affected routes. Fourth, the static fouling multiplier should be replaced by a time-dependent growth model of the kind developed by Uzun et al. (2019), which would permit the optimal interval between hull cleanings to be derived rather than assumed.

ACKNOWLEDGMENT

The authors express their gratitude to the Director of Politeknik Pelayaran Banten and the institutional leadership, and to the Head of the Centre for Research and Community Service, for facilitating this research. Thanks are also due to the shipping company personnel, vessel operators, and port authority staff who provided context and operational insight during the preparatory stage of the study.

REFERENCES

- Adland, R., & Jia, H. (2018). Dynamic speed choice in bulk shipping. *Maritime Economics & Logistics*, 20(2), 253-266. <https://doi.org/10.1057/s41278-016-0002-3>
- Adland, R., Cariou, P., & Wolff, F.-C. (2020). Optimal ship speed and the cubic law revisited: Empirical evidence from an oil tanker fleet. *Transportation Research Part E: Logistics and Transportation Review*, 140, Article 101972. <https://doi.org/10.1016/j.tre.2020.101972>
- Bayraktar, M., & Sokukcu, M. (2024). Marine vessel energy efficiency performance prediction based on daily reported noon reports. *Ships and Offshore Structures*, 19(6), 831-840. <https://doi.org/10.1080/17445302.2023.2214490>
- Bayraktar, M., & Yuksel, O. (2023). A scenario-based assessment of the energy efficiency existing ship index (EEXI) and carbon intensity indicator (CII) regulations. *Ocean Engineering*, 278, Article 114295. <https://doi.org/10.1016/j.oceaneng.2023.114295>
- Bialystocki, N., & Konovessis, D. (2016). On the estimation of ship's fuel consumption and speed curve: A statistical approach. *Journal of Ocean Engineering and Science*, 1(2), 157-166. <https://doi.org/10.1016/j.joes.2016.02.001>
- Ceylan, B. O. (2024). Marine diesel engine turbocharger fouling phenomenon risk assessment application by using fuzzy FMEA method. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 238(3), 514-530. <https://doi.org/10.1177/14750902231208848>
- Chen, Z. S., Lam, J. S. L., & Xiao, Z. (2023). Prediction of harbour vessel fuel consumption based on machine learning approach. *Ocean Engineering*, 278, Article 114483. <https://doi.org/10.1016/j.oceaneng.2023.114483>
- Chuah, L. F., Mokhtar, K., Mhd Ruslan, S. M., Bakar, A. A., Abdullah, M. A., Osman, N. H., Bokhari, A., Mubashir, M., & Show, P. L. (2023). Implementation of the energy efficiency existing ship index and carbon intensity indicator on domestic ship for marine environmental protection. *Environmental Research*, 222, Article 115348. <https://doi.org/10.1016/j.envres.2023.115348>
- CNBC Indonesia. (2025, February 25). 50% kapal laut di RI sudah mendekati masa uzur, bahaya? CNBC Indonesia. <https://www.cnbcindonesia.com/news/20250225101614-4-613388/50-kapal-laut-di-ri-sudah-mendekati-masa-uzur-bahaya>

- 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 Engineering*, 186, Article 106063. <https://doi.org/10.1016/j.oceaneng.2019.05.045>
- Corbett, J. J., Wang, H., & Winebrake, J. J. (2009). The effectiveness and costs of speed reductions on emissions from international shipping. *Transportation Research Part D: Transport and Environment*, 14(8), 593-598. <https://doi.org/10.1016/j.trd.2009.08.005>
- Czermanski, E., Oniszczyk-Jastrzabek, A., Spangenberg, E. F., Kozłowski, L., Adamowicz, M., Jankiewicz, J., & Cirella, G. T. (2022). Implementation of the Energy Efficiency Existing Ship Index: An important but costly step towards ocean protection. *Marine Policy*, 145, Article 105259. <https://doi.org/10.1016/j.marpol.2022.105259>
- Demirel, Y. K., Turan, O., & Incecik, A. (2017). Predicting the effect of biofouling on ship resistance using CFD. *Applied Ocean Research*, 62, 100-118. <https://doi.org/10.1016/j.apor.2016.12.003>
- Fagerholt, K., Laporte, G., & Norstad, I. (2010). Reducing fuel emissions by optimizing speed on shipping routes. *Journal of the Operational Research Society*, 61(3), 523-529. <https://doi.org/10.1057/jors.2009.77>
- Farkas, A., Degiuli, N., Martić, I., & Ancic, I. (2022). Energy savings potential of hull cleaning in a shipping industry. *Journal of Cleaner Production*, 374, Article 134000. <https://doi.org/10.1016/j.jclepro.2022.134000>
- Farkas, A., Song, S., Degiuli, N., Martić, I., & Demirel, Y. K. (2020). Impact of biofilm on the ship propulsion characteristics and the speed reduction. *Ocean Engineering*, 199, Article 107033. <https://doi.org/10.1016/j.oceaneng.2020.107033>
- Gkerekos, C., Lazakis, I., & Theotokatos, G. (2019). Machine learning models for predicting ship main engine fuel oil consumption: A comparative study. *Ocean Engineering*, 188, Article 106282. <https://doi.org/10.1016/j.oceaneng.2019.106282>
- Goicoechea, N., & Abadie, L. M. (2021). Optimal slow steaming speed for container ships under the EU emission trading system. *Energies*, 14(22), Article 7487. <https://doi.org/10.3390/en14227487>
- Jimenez, V. J., Kim, H., & Munim, Z. H. (2022). A review of ship energy efficiency research and directions towards emission reduction in the maritime industry. *Journal of Cleaner Production*, 366, Article 132888. <https://doi.org/10.1016/j.jclepro.2022.132888>

- Kokkulunk, G., Parlak, A., & Erdem, H. H. (2016). Determination of performance degradation of a marine diesel engine by using curve based approach. *Applied Thermal Engineering*, 108, 1136-1146. <https://doi.org/10.1016/j.applthermaleng.2016.08.019>
- Mimica, D., Ljubenkovic, B., Blagojevic, B., Bezic, I., Basic, J., & Degiuli, N. (2025). Retrofitting a pre-propeller duct on a motor yacht: A full-scale CFD validation study. *Journal of Marine Science and Engineering*, 13(11), Article 2125. <https://doi.org/10.3390/jmse13112125>
- Park, M.-H., Hur, J.-J., Yun, G.-H., & Lee, W.-J. (2025). Scenario-based economic analysis of underwater biofouling using artificial intelligence. *Journal of Marine Science and Engineering*, 13(5), Article 952. <https://doi.org/10.3390/jmse13050952>
- Pruyn, J. (2017). Are the new fuel-efficient bulkers a threat to the old fleet? *Maritime Business Review*, 2(3), 224-246. <https://doi.org/10.1108/MABR-01-2017-0002>
- Psaraftis, H. N., & Kontovas, C. A. (2013). Speed models for energy-efficient maritime transportation: A taxonomy and survey. *Transportation Research Part C: Emerging Technologies*, 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. *Transportation Research Part C: Emerging Technologies*, 44, 52-69. <https://doi.org/10.1016/j.trc.2014.03.001>
- Ronen, D. (1982). The effect of oil price on the optimal speed of ships. *Journal of the Operational Research Society*, 33(11), 1035-1040. <https://doi.org/10.1057/jors.1982.215>
- Ronen, D. (2011). The effect of oil price on containership speed and fleet size. *Journal of the Operational Research Society*, 62(1), 211-216. <https://doi.org/10.1057/jors.2009.169>
- Ross, H. H., & Schinas, O. (2019). Empirical evidence of the interplay of energy performance and the value of ships. *Ocean Engineering*, 190, Article 106403. <https://doi.org/10.1016/j.oceaneng.2019.106403>
- Schultz, M. P. (2007). Effects of coating roughness and biofouling on ship resistance and powering. *Biofouling*, 23(5), 331-341. <https://doi.org/10.1080/08927010701461974>

- Schultz, M. P., Bendick, J. A., Holm, E. R., & Hertel, W. M. (2011). Economic impact of biofouling on a naval surface ship. *Biofouling*, 27(1), 87-98. <https://doi.org/10.1080/08927014.2010.542809>
- Uyan, E., Atlar, M., & Gursoy, O. (2024). Energy use and carbon footprint assessment in retrofitting a novel energy saving device to a ship. *Journal of Marine Science and Engineering*, 12(10), Article 1879. <https://doi.org/10.3390/jmse12101879>
- Uyanik, T., Karatug, C., & Arslanoglu, Y. (2020). Machine learning approach to ship fuel consumption: A case of container vessel. *Transportation Research Part D: Transport and Environment*, 84, Article 102389. <https://doi.org/10.1016/j.trd.2020.102389>
- Uzun, D., Demirel, Y. K., Coraddu, A., & Turan, O. (2019). Time-dependent biofouling growth model for predicting the effects of biofouling on ship resistance and powering. *Ocean Engineering*, 191, Article 106432. <https://doi.org/10.1016/j.oceaneng.2019.106432>
- Vasilev, M., Kalajdzic, M., & Momcilovic, N. (2025). On energy efficiency of tankers: EEDI, EEXI and CII. *Ocean Engineering*, 317, Article 120028. <https://doi.org/10.1016/j.oceaneng.2024.120028>
- Wang, S., & Meng, Q. (2012). Sailing speed optimization for container ships in a liner shipping network. *Transportation Research Part E: Logistics and Transportation Review*, 48(3), 701-714. <https://doi.org/10.1016/j.tre.2011.12.003>
- Wu, W.-M. (2020). The optimal speed in container shipping: Theory and empirical evidence. *Transportation Research Part E: Logistics and Transportation Review*, 136, Article 101903. <https://doi.org/10.1016/j.tre.2020.101903>
- Xing, H., Spence, S., & Chen, H. (2020). A comprehensive review on countermeasures for CO2 emissions from ships. *Renewable and Sustainable Energy Reviews*, 134, Article 110222. <https://doi.org/10.1016/j.rser.2020.110222>
- Yan, D., Chen, C., Gan, W., Sasa, K., He, G., & Yu, H. (2025). Carbon intensity indicator (CII) compliance: Applications of ship speed optimization on each level using measurement data. *Marine Pollution Bulletin*, 212, Article 117593. <https://doi.org/10.1016/j.marpolbul.2025.117593>
- Yan, R., Wang, S., & Psaraftis, H. N. (2021). Data analytics for fuel consumption management in maritime transportation: Status and perspectives. *Transportation Research Part E: Logistics and Transportation Review*, 155, Article 102489. <https://doi.org/10.1016/j.tre.2021.102489>

- Yang, H., Sun, Z., Han, P., & Ma, M. (2024). Data-driven prediction of ship fuel oil consumption based on machine learning models considering meteorological factors. *Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment*, 238(3), 483-502. <https://doi.org/10.1177/14750902231210047>
- Zhang, D., Song, Y., Gao, J., Shen, Z., Li, L., & Yao, A. (2025). Research on ship engine fuel consumption prediction algorithm based on adaptive optimization generative network. *Journal of Marine Science and Engineering*, 13(6), Article 1140. <https://doi.org/10.3390/jmse13061140>