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Capesize time charter equivalent optimization based on speed and environmental regulations

Tamara Apostolou, Ioannis N. Lagoudis and Ioannis N. Theotokas
Department of Maritime Studies, University of Piraeus, Piraeus, Greece

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Abstract

Purpose – This paper aims to identify the interplay of standard Capesize optimal speeds for time charter equivalent (TCE) maximization in the Australia–China iron ore route and the optimal speeds as an operational tool for compliance with the International Maritime Organization (IMO) carbon intensity indicator (CII).

Design/methodology/approach – The TCE at different speeds have been calculated for four standard Capesize specifications: (1) standard Capesize with ecoelectronic engine; (2) standard Capesize with non-eco engine (3) standard Capesize vessel with an eco-electronic engine fitted with scrubber and (4) standard Capesize with non-eco engine and no scrubber fitted.

Findings – Calculations imply that in a highly inflationary bunker price context, the dollar per ton freight rates equilibrates at levels that may push optimal speeds below the speeds required for minimum CII compliance (C Rating) in the Australia–China trade. The highest deviation of optimal speeds from those required for minimum CII compliance is observed for non-eco standard Capesize vessels without scrubbers. Increased non-eco Capesize deployment would see optimal speeds structurally lower at levels that could offer CII ratings improvements.

Originality/value – While most of the studies have covered the use of speed as a tool to improve efficiency and emissions in the maritime sector, few have been identified in the literature to have examined the interplay between the commercial and operational performance in the dry bulk sector stemming from the freight market equilibrium. The originality of this paper lies in examining the above relation and the resulting optimal speed selection in the Capesize sector against mandatory environmental targets.

Keywords Bunker prices, Iron ore freight, Time charter equivalent optimization, Optimal speed, Carbon intensity indicator

Paper type Research paper

Introduction

Speed optimization and speed reduction are being examined amongst shipping stakeholders such as shipowners and operators (Star Bulk, 2021), as well as consultancies and the academia (Lindstad *et al.*, 2011; Lindstad and Eskeland, 2015; CE Delft, 2023), as a operational measure for reducing greenhouse gas (GHG) emissions from international shipping. However, the speed reduction for emission mitigation might come in stark contrast with speed optimization for commercial objectives. Speed optimization may have different objectives in the context of different management levels, while meeting various constraints related to the operation of the vessel (Psaraftis, 2019).

Speed optimization objectives are related to the gross profit maximization (ship owner's perspective in the spot market) or voyage cost minimization (charterer's perspective in the period market). In either view, the chartering strategy involves voyage planning defined by the charter parties, where the choice of speed has an impact on fuel consumption (Poulsen *et al.*, 2022).

While most of the studies have covered the use of speed as a tool to improve efficiency and emissions in the maritime sector, few have been identified in the literature to have examined the interplay between the commercial and operational performance resulting from the optimal speed selection. Such exercise cannot be done uniformly across the fleet, since the

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shipping industry is characterized by different dynamics; thus, it should be examined for each trading route, vessel type, size and technology. This paper aims at exploring the interplay between the commercial and operational performance under specific bunker price assumptions for the Capesize sector by determining the optimal speed against the CII 2026 targets. This is important, as depending on market conditions, commercial considerations for TCE maximization via optimal speed sailing might be or not be sufficient for environmental compliance and therefore might come in conflict with operational efficiency considerations.

In order to relate the commercial decision of optimal speed to bunker prices and freight rates, the pair of bunker prices and freight rates dictated by the elasticity of bunker prices on iron ore freight rates is established first, assuming that steel mill fundamentals in China, which is one of the fundamental iron ore trade demand drivers, remain unchanged to 2021 levels. After determining the iron ore freight rates corresponding to the assumed bunker price level, speed optimization is approached from the microeconomic perspective of maximizing daily gross profit, equivalent to the time charter equivalent (TCE) per day, achieved by minimizing the largest variable cost component of the vessel, which is the voyage cost (i.e. fuel consumption, congestion and ports costs). Stopford (2009) defines the TCE as "The spot freight rate converted into a daily hire rate for the voyage by deducting voyage costs from the gross freight and dividing by the days on the voyage, including necessary ballast time" [1]. This approach differs from the definition of optimal speed in the context of the ship energy efficiency management plan (SEEMP), where optimal speed is defined as the speed that minimizes fuel consumption per tonmile, without the commercial factor of freight rates and bunker prices being accounted for.

After solving for the first objective, which is the speed that maximizes the TCE the second objective is estimated, which is the speed that minimizes the fuel consumption intensity using the annual energy efficiency ratio (i.e. the speed that minimizes CO_2 emissions per deadweight mile), so that the minimum CII required is achieved for compliance. The Baltic exchange has estimated the carbon intensity per transport work for the dry bulk routes it assesses, based on its standard vessel designs (i.e. using fuel consumption at design speeds both eco and full speeds on the ballast and laden legs). However, here the mandated annual efficiency ratio (AER) metric is used, while optimal speeds stem from the commercial decision to maximize the TCE and the actual daily fuel consumption figures at the determined speed levels.

The energy efficiency operational indicator (EEOI) measured in gCO2/tonmile is a nonmandatory additional reporting method, but might be more realistic for the carbon intensity measurement (Siglar Carbon, 2021), as the actual transport work is taken into consideration, i.e. demand-based efficiency metric, while the AER measured in gCO2/dwt nautical mile might be overestimating the efficiency and thus underestimating the carbon intensity, as it does not take into consideration the vessel's utilization, i.e. it is a supply based efficiency metric (Panagakos *et al.*, 2019). In this respect, AER measures the carbon intensity of the fleet by dividing the amount of CO_2 a ship emits by its maximum cargo carrying capacity expressed in deadweight tonnage and by the nautical miles the ship traveled in a year. Market stakeholders have voiced concerns over the efficiency of this metric, as it does not account for the actual cargo carried and thus does not correlate with the actual transport work, potentially creating market distortions.

When determining the optimal speed of a vessel, several variables are taken into consideration, amongst others being the vessel design, cargo intake and the voyage parameters, i.e. days at sea, days at port and fuel consumption at different speeds. The gross profit maximization approach takes actual freight levels into consideration when the vessel is fixed (laden condition) and freight market expectations when the vessel is ballast and looking for employment. To calculate the speed, which maximizes the TCE, bunker prices along with the vessel's fuel consumption under different weather and operating conditions (Ballast/Laden) are factored in as well. The general assumption is that fuel consumption in relation to speed is a cubic function, i.e. fuel consumption is proportional to sailing speed to a power of three – usually down from the design speed – while the cubic function might not hold when speed reductions are implemented from already lower speeds, as per a recent study (Adland *et al.*, 2020).

On the relation of bunker prices, freight rates and speed, Adland and Jia (2018) examine the dynamic speed choice in dry bulk using multiple regression models with explanatory macroeconomic variables, as well as operational and technical constraint variables, amongst others. They conclude that higher bunker prices do not contribute to a reduction in speed and emissions, while vessel specific variables related to the age and design speed have a higher explanatory power on speed adjustment.

In this paper, the level of iron ore freight rates corresponding to the bunker price level assumed is correlated after performing regression on a double log model. The local optimal speed for each bunker price and freight rate pair is estimated, as well as the speed that satisfies the minimum carbon intensity requirements in order to determine the trade-off between the two. The speed optimization exercise is approached under the assumption of structurally higher bunker prices. Higher bunker prices are relevant as a scenario in the coming years, as the global fossil energy supply complex is expected to tighten following uncertain prospects on investments in the oil sector, while oil consumption for transport fuels is projected to decline only post 2026 (IEA, 2023), implying a high oil price trajectory until then. The International Energy Agency (IEA) Stated Policies Scenario (STEPS) projects oil price levels rising towards \$90/bbl in \$2021 terms between 2021 and 2025 (IEA, 2022). In addition, the forthcoming preparation of the bunker supply chain towards the transition to low and zero carbon fuels, is likely to exercise inflationary pressures on conventional fuel prices, as they will continue to prevail in the fuel consumption mix, until alternative fuel propulsion systems gain traction and start to dominate in vessel order books and deliveries.

The rest of the paper is organized as follows. The literature review section focuses on the current regulatory framework for the sector's GHG emission mitigation, vessels' speed as a commercial and operational tool and their effect on CO_2 emissions. The problem description and methodology follows on (1) relating bunker prices to iron ore freight rate via the econometric estimation of the long-term elasticity of bunker prices on the dollar per ton freight and (2) solving a speed optimization exercise on one representative Capesize iron ore route, namely the Australia–China round voyage, which represented approximately 83% of Australia's iron ore exports in 2021 (Commonwealth of Australia, 2022). The results on optimal speeds for four standard Capesize technologies and the resulting CO_2 emissions per tonmile are presented next: (1) standard Capesize with eco-engine, (2) standard Capesize with noneco engine, (3) scrubber fitted standard Capesize with eco-engine and (4) scrubber fitted standard Capesize with non-eco-engine. Finally, key insights and suggestions for future research are presented in the conclusion section.

Literature review

Shipping's decarbonization targets imply that the industry will have to go through a technological and fuel transition shift over the next two decades in order to comply with IMO's revised GHG strategy and alignment with the Paris agreement targets. Such technological shifts are expected to bring about a profound fleet supply restructuring with elevated investment and operational costs, as well as fuel costs (Tsiropoulos *et al.*, 2022). Fleet supply restructuring along with freight markets are expected to react differently to these shifts depending on the current technological fleet profile of each shipping sector (i.e. dry bulk, tankers, containers) and the impact elevated fuel costs have on freight rates and thus the scrappage and renewal function of the fleet.

However, in the short to medium term, the deployment of technical and operational measures that aim at improving the fleet's efficiency is serving as a transitory decarbonization step, before a massive fleet renewal takes place, as future technology uncertainty entails the risk of having invested too early in capital intensive assets that might be rendered stranded. The contribution of technical and operational measures to the decarbonization targets has limitations and thus zero carbon fuels will need to meaningfully penetrate the market for the sector's deep decarbonization (Cullinane and Yang, 2022).

IMO follows a two-tier approach to GHG emissions mitigation from the maritime sector with mandatory short and medium-term measures targeting GHG emission intensity in support of the long-term GHG emissions reduction measures. The initial IMO GHG strategy called for a 50% GHG reduction in emissions from shipping by 2050 compared to 2008, in parallel with a 40% CO_2 emission reduction per transport work as an average by 2030 and 70% by 2050 (IMO, 2018). A revision of this strategy was adopted in the Marine Environment Protection Committe (MEPC) 80, leveling up the ambition to reach net-zero well-to-wake GHG emissions close to 2050, along with indicative check-points for GHG emissions reduction by at least 20% (striving for 30%) by 2030 and at least 70% (striving for 80%) by 2040 compared to 2008 levels (IMO, 2023).

Previously, at MEPC 76, which took place in 2021, additional short term technical and operational mandatory measures were adopted covering all existing cargo and cruise ships, with entry into effect in January 1st 2023. One of these measures is the mandatory carbon intensity indicator (CII), an intermediate operational efficiency measure in support of the IMO's 40% carbon intensity (CO2 emissions per transport work) reduction target by 2030 compared to 2008. The CII foresees a rating scheme where all cargo and cruise ships above 5,000 GT are given a rating from A (major superior performance) to E (inferior performance) every year, with the C rating denoting the minimum-required performance for compliance (moderate performance). The key decision at MEPC 76 was to establish reduction factors for the CII. The ratings will derive from the attained CII, which will be calculated on an annual basis, compared with the required CII, which is set against a 2019 reference line. With 2019 as the base year, the reduction rates were set at 1% per year for the period between 2020 and 2022, followed by 2% per year for the period between 2023 and 2026, or 11% cumulatively by 2026 compared to 2019 (IMO, 2021).

The above developments put more weight on the successful deployment of efficiency measures during this period by maritime stakeholders, including the use of speed as an operational tool that will contribute to environmental compliance. However, commercial decisions may be more important for energy efficiency than operational decisions (Poulsen *et al.*, 2022). Drawing from Psaraftis and Kontovas (2013), as cited in (Poulsen *et al.*, 2022, p. 3), there is a debate regarding the approach to optimal speeds, including potential misalignments between the commercial approach for profit maximization and the operational approach for energy efficiency gains, with the decision on the former depending on dynamic market conditions.

Corbett *et al.* (2009) examined profit maximizing principles on the impact of speed reduction and CO_2 emissions from a cap on CO_2 emissions and a fuel tax for certain containership routes, in the context of stable market conditions. The profit maximizing function they develop assumes that freight rates remain constant for the period they study, assuming that the latter are not impacted by the voyage cost changes quantified in their scenarios. They conclude that the speed reduction remains an option for CO_2 emission reduction.

Açık and Başer (2018) examined the bunker price and speed relation econometrically and found that there is asymmetric causality between rising bunker prices and declining average dry bulk speeds, implying that ship owners adjust speed downwards instantly when fuel prices are rising to mitigate voyage costs, but do not respond the same way when bunker prices are declining, i.e. they do not immediately adjust speeds upwards as this choice is directly influenced by freight market levels.

Speed is not only an operational measure to reduce emissions, but a factor that impacts the productivity of the fleet also. Stopford (2009) notes that "The productivity of a fleet of ships measured in ton miles per deadweight depends upon four main factors: speed, port time, deadweight utilization and loaded days at sea." Ships generally operate below the speed design capacity, while optimal speed is influenced by fuel prices, ship efficiency and the duration of the voyage.

Another important article of motivation to this study is the work by Psaraftis and Kontovas (2013). They provide an overview of speed models in transportation research. They assert that "In periods of depressed market conditions, as is the typical situation these days, ships tend to slow steam. The same is the case if bunker prices are high. Conversely, in boom periods or in case fuel prices are low, ships tend to sail faster." This is consistent with the conjectures presented in the introduction to this paper. They also provide a useful taxonomy of studies of maritime vessel speeds with various optimization criteria.

Vessels' speeds have declined following the slowdown in global trade in 2008, as speed reduction became an operational practice for fuel cost savings. As a result, many studies as identified in Leaper (2019) analyzed the impact of fuel savings and the potential for GHG emission reductions from slow steaming. Lindstad has been the lead author of at least three studies examining the relationship amongst GHG emissions, shipping costs and speed. Lindstad *et al.* (2011) found that CO_2 emissions could be reduced between 19 and 28% by lower speeds at negative and zero abatement cost respectively. Lindstad *et al.* (2013) note that fuel costs as a percent of total operating costs have been increasing, accounting for 50% of the total cost. They also note that emissions could be reduced at negative abatement costs with high fuel prices and a moderate CO_2 levy as a market-based measure via an improved payoff from building energy efficient vessels. Lindstad and Eskeland (2015) focus on crude oil carriers and the interactions amongst the speed, size and slenderness of vessels for reducing emissions and energy consumption. They indicated that among the different approaches on emission reduction, reduced speed is a short-term approach. They suggest that if emission abatement costs lead to an increase in bunker costs, then speeds and emissions may decrease more compared to when higher oil prices prevail.

In a more recent work, Lindstad *et al.* (2017) identified that scrubber-fitted vessels would be incentivized to raise speeds by one knot compared to those with no scrubbers installed, due to lower bunker prices, despite their higher specific fuel oil consumption, leading to increased fuel consumption and CO_2 emissions as a result.

In the same year, Faber *et al.* (2017) examined speed as a short-term measure for reducing emissions, by deploying speed reduction scenarios of 10%, 20% and 30% across the global fleet compared to a baseline scenario. The speed reduction percentages were estimated to lead to 13%, 24 and 33% emission reduction by 2030, after accounting for the increase in deadweight required to serve the same transport work at lower speeds.

Comer *et al.* (2018) analyzed a combination of measures including improvements in the technical efficiency of newbuilding, speed reduction and the penetration of low carbon fuels in support of achieving the IMO's GHG emissions reduction targets by 2050 and used Monte-Carlo simulation to estimate the probability of achieving them. They used speed reduction assumptions of 10%, 20 and 30% compared to business-as-usual scenarios and found that the combination of accelerating the newbuild technical efficiency standards by 5 years and reducing speeds by 30% can lead to the highest probabilities of meeting the IMO's targets for 2050.

Zhao *et al.* (2019) examined optimization decisions for speed and route selection in the context of maximizing profits and minimizing carbon emissions for coastal shipping. They found a trade-off between the emissions optimal speed and profit optimal speeds. They explore this dilemma under four different scenarios for different vessel types, including small bulker vessels. Their four scenarios are defined by fuel price and vessel load. The vessel load is the ratio of distance outside an emission control area (ECA) to the total voyage distance.

One of their conclusions is that larger vessels like a Panamax bulker should aim for profits during low fuel price and high load environments without slowing down and having to sail further outside an ECA to consume cheaper heavy fuel oil, as opposed to smaller vessels, where the increase in the price differential between marine gasoil consumed in the ECA and heavy fuel oil consumed outside of the ECA may force a slow-down in speeds in the ECA and more steaming outside of it.

Most recent literature has examined the covariance between freight rates and TCE rates, by using speed-fuel consumption curves to quantify the financial impact of the IMO 2020 regulation to shipowners (Sigalas, 2022). The author modeled the TCE for Capesize iron ore trades before and after the IMO 2020 regulation, assuming that for different fuel oil prices there is a specific speed that maximizes the TCE rate. Finally, Tan *et al.* (2022) have factored in alternative propulsion in speed optimization and speed reduction assessment focusing on a dual liquefied natural gas (LNG) fueled neo-Panamax container. They analyze the impact of imposing a maximum average speed limit on optimal speeds, carbon intensity and emissions in relation to the fleet deployment. They suggest that although speed reduction and subsequent emission reduction is possible, dual fueled vessels may be efficiently operated at higher speeds and not correlated with optimal speeds, which comes in contrast to the speed reduction and emissions reduction relationship.

Problem description and methodology

This paper aims to identify the interplay of standard Capesize optimal speeds for TCE maximization in the Australia–China iron ore route and the optimal speeds as an operational tool for CII compliance. For this purpose, we calculate the speed that maximizes the TCE under certain market conditions and the CII of standard Capesize with different technology specifications using the AER.

A total of 279 speed-TCE combinations have been quantified for the different Capesize technology specifications for the Australia–China round voyage, out of which 54 are presented for the purpose of this paper. These combinations relating bunker prices to the dollar per ton iron ore freight rates and TCE results (for speeds ranging from 10 knots to 14 knots) were selected on the basis of a high oil price trajectory between 2021 and 2026 and the freight dollar per ton implied by their long-term elasticity with respect to bunker prices. Calculations are made for four different standard Capesize specifications: (1) standard Capesize with ecoelectronic engine; (2) standard Capesize with non-eco engine (3) standard Capesize vessel with an eco-electronic engine fitted with scrubber and (4) standard Capesize with non-eco engine with scrubber fitted. The calculations are made under the assumption that the shipowner controls the speed decision in this trade.

The average 2020 dry bulk steaming speed declined by around −18% compared to 2008, but in 2021 a +1.8% increase is observed, bringing the speed decline compared to 2008 down by −16.5%, according to data processed from the Clarksons Shipping Intelligence Network (Clarksons, 2022). The sharp increase in ton-miles from both dry bulk and containers has contributed to the increase in steaming speeds during the year. As a result, dry bulk speeds increased in 2021, along with CO_2 emissions due to booming freight market conditions but were still short of 2008 levels.

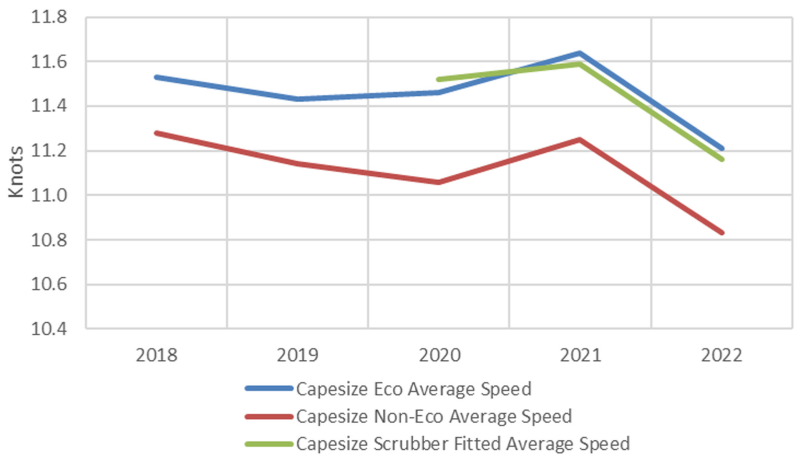
Focusing on the Capesize sector, steaming speeds have exhibited higher volatility compared with other sizes. In addition, the IMO sulfur cap [2] introduced in 2020 led to the penetration of exhaust gas cleaning systems (scrubbers with highest uptake seen in the largest size of the dry bulk fleet). Capesize vessels fitted with scrubbers represent approximately 48% of the total Capesize fleet (combined very large ore carriers -VLOC/Newcastlemax/standard Capesize), while standard Capesize vessels (170,000–180,000 dwt) fitted with scrubbers represent 32% of the total standard Capesize fleet (Clarksons, 2022).

Steaming speeds of scrubber fitted Capesize vessels have diverged upwards compared to nonscrubber vessels due to lower heavy sulfur fuel oil (HSFO) prices, following closely steaming speeds of more efficient Capesize vessels with an eco-electronic engine (Figure 1). The high scrubber uptake makes the commercial speed optimization decision more complicated for the sector as a whole.

Since fuel consumption and CO_2 emissions are highly correlated with steaming speeds, here it is attempted to relate the commercial choice of speed, as a gross profit maximizing tool via the control in fuel consumption and costs, to the CO_2 emissions. For this purpose, a set of four scenarios with two variants has been developed, where structurally higher bunker prices relate to certain levels of $/ton freight rate as defined by the Australia–China Baltic route (C5). The scenarios were formulated after estimating the long-term elasticity of bunker price to C5 to determine the $/ton freight level that is relevant to the specific bunker price level for very low sulfur fuel oil (VLSFO) and HSFO.

Monthly timeseries of the Baltic Exchange C5 dollar per ton, Singapore bunker prices, iron ore spot prices CFR (cost and freight) N. China, as well as China's steel prices from March 2009 to December 2022 were used (Clarksons, 2022). A proxy for China's gross steel mill profitability was estimated by subtracting iron ore prices from China steel prices (1,6 tons of iron ore for 1 ton of steel produced), after converting the latter from yuan to dollars [6]. China's steel mill profitability is treated as an iron ore demand driver and the resulting derived Capesize demand in the examined trade. Bunker prices are treated as a proxy for vessels' supply, as higher bunker prices all else being equal, decrease effective vessels' supply (or increase deadweight requirements to fulfill the same transport demand) via speed reduction (Taskar and Andersen, 2020). In addition, high steel mill profitability and high bunker prices imply an inflationary environment, which has the potential to push shipping costs higher.

In the first stage, a linear regression on a double log function is performed (Equation 1). The fully modified ordinary least squares (FMOLS) regression showed that the independent variables explain the variations in the dependent variable with R^2 of 0.5. Despite a relatively moderate R^2, the estimation was pursued on the grounds of (1) statistically significant coefficients and (2) the existence of cointegration. The trace statistic of the Johansen cointegration test indicates that there is a long-term relationship amongst the time series, with three cointegrating variables.



Source(s): Data adopted from Clarksons Research Services Limited, Shipping Intelligence Network (accessed December 2022)

Figure 1. Graphical display of Capesize steaming speeds

In the second stage, an error correction model was deployed (ECM), in order to identify the short-term elasticity and the speed of adjustment to the long run equilibrium on the monthly time series. The variables are stationary at first differences with the residuals also being stationary, therefore, we use first differences in the variables, in order to estimate the error correction term i.e. the residuals of the long-run regression lagged by one period (Equation 2 and Equation 3), which we then merge (Equation 4).

The long-term elasticity of \$/ton C5 to China's steel mill profitability has been estimated at 0.84 and the elasticity to Singapore bunker prices at 0.29 deriving from Equation 1 [3]. Both elasticities are found to be positive but inelastic with respect to the dollar per ton freight. The short-term elasticity of \$/ton C5 to China's steel mill profitability has been estimated at 0.47 and the elasticity to Singapore bunker prices at 0.46, deriving from Equation (3). The short run relationship revealed that the system corrects its previous period disequilibrium at a speed of 16% monthly.

Equation 1 (long run model)

$$\mathrm{Log}\ (\mathrm{F_{i,t}}) = \mathrm{a_0} + \sum_{\mathrm{i=1}}^{n} \mathrm{a_i} \log(X_{\mathrm{i,t}}) + \mathrm{u_{i,t}} \tag{1}$$

where: $\mathrm{F_{i,t}}$ = Australia–China Iron Ore Freight \$/ton

$X_{i,t}$ = *Independent Variables* (China Gross Steel Profitability in \$/ton, *Bunker Price in \$ per ton*)

$u_{i,t}$ = *error term*

Equation 2

$$\mathrm{u_{t-1}} = \ln(F_{t-1}) - \mathrm{a_0} - \beta_1 \cdot \ln(P_{t-1}) - \beta_2 \cdot \ln(B_{t-1}) \tag{2}$$

Equation 3 (short run model)

$$\Delta\ln\ (\mathrm{F}_t) = \mathrm{a}_{0s} + \beta_{1s} \cdot \Delta\ln(P_t) + \beta_{2s} \cdot \Delta\ln(B_t) + \beta_3 \cdot \mathrm{u_{t-1}} + \mathrm{v_t} \tag{3}$$

Equation (2) into Equation (3):

Equation 4 (ECM)

$$\begin{aligned}\Delta\ln(\mathrm{F}_t) = {} & a_{0s} + \beta_{1s} \cdot \Delta\ln(P_t) + \beta_{2s} \cdot \Delta\ln(B_t) \\ & + \beta_3 \cdot [\ln(F_{t-1}) - a_0 - \beta_1 \cdot \ln(P_{t-1}) - \beta_2 \cdot \ln(B_{t-1})] + v_t\end{aligned} \tag{4}$$

where:

F_t = Australia–China Iron Ore Freight \$/ton at time t

F_{t-1} = Australia–China Iron Ore Freight \$/ton at time t-1

P_t = *China steel profitability at time t*

P_{t-1} = *China steel profitability at time t−1*

B_t = *Bunker Price in per ton at time t*

B_{t-1} = *Bunker Price in per ton at time t*−1

a_0 = *the constant* – *long run* (a_{0s} = *the constant* – *short run*)

β_1 = *long run elasticity of \$ per ton with respect to China gross steel profitability – Positive* ($\beta_1 s$ = *short run elasticity*)

β_2 = *long run elasticity of \$ per ton with respect to Bunker prices- Positive* ($\beta_2 s$ = *short run elasticity*)

β_3 = *the error correction term, where* β_3 *is the error correction term coefficient (speed of adjustment), where* $-1<\beta_3<0$

U_{t-1} = *the error correction term, where* β_3 *is the error correction term coefficient (speed of adjustment), where* $-1<\beta_3<0$

v_t = *white noise error term*

Assuming changes in bunker prices only, with steel mill profitability returning to 2021 levels between 2023–2026, the level of the \$/ton iron ore freight relevant to the bunker prices assumed is predicted from Equation (4) (Table 1).

Using a reference bunker price of \$680 per ton for HSFO, a price level close to the maximum range observed in 2008, 2011 and 2022, which were inflationary years and assuming a differential to VLSFO of \$220/ton (a differential observed in 2022 at these HSFO price levels), then the VLSFO price level is assumed at \$900/ton [4]. If the dollar per ton is determined in the market by the nonscrubber vessel consuming VLSFO, then – all else being equal – the level of bunker prices selected leads to C5 at \$13.3/ton, while if it is determined by the scrubber vessel, the dollar per ton equilibrates lower at \$12.3/ton. Testing the model backwards we compare the predicted C5 values with VLSFO and HSFO as the independent variables, against actual C5 values since September 2019, when VLSFO price assessments became available at the data source (Figure 2). We find that average C5 predicted values with HSFO as the independent variable for the period September 2019 to August 2023 closely track actual C5 values, deviating upwards by just +\$0.02/ton. The corresponding C5 predicted values with VLSFO as the independent variable for the same period outperform the actual C5 values by approximately +\$0.5/ton on average over the period. The fleet deployment mix in a certain basin (i.e. share of scrubber and nonscrubber vessels competing) might dictate which type of vessel sets the rates. A high concentration of scrubber vessels in the Australia–China iron ore trade route, would imply a lower \$/ton in a high scrubber premium context, where cheaper HSFO prices impact freight pricing.

Based on the above relation, the TCE is estimated (Figure 3), expressed in dollars per day deriving from multiplying the dollar per ton freight to the cargo intake of the vessel and subtracting voyage costs, ports costs and chartering commission fees [5]. The net revenues for the voyage are then divided by the round voyage days for the C5 Australia (Port Headland as Loading Port) China (Qingdao as Discharge Port) iron ore route, taking into consideration waiting days at both the discharging and loading ports (Equation 5). As congestion conditions

Singapore Bunker Price-C5 pairs (\$/ton)	VLSFO	HSFO	VLSFO-HSFO spread	C5-\$/ton
Actual Annual Average (2021)	535.1	416.5	118.6	12.0
If \$/ton defined by the nonscrubber vessel	900.0	680.0	220.0	13.3
If \$/ton defined by the scrubber vessel	900.0	680.0	220.0	12.3

Source(s): Authors

Table 1. Bunker price-iron ore freight assumptions based on long-term elasticity of bunker price on freight

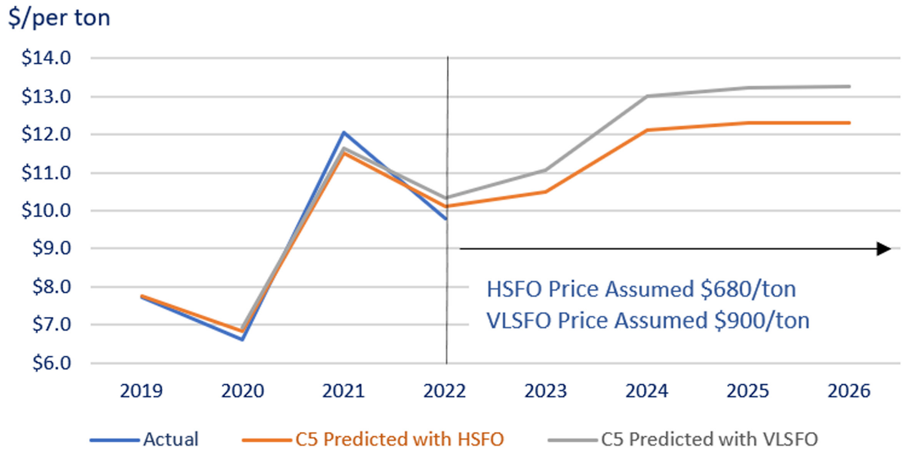


Figure 2. Actual C5 vs predicted C5*

Source(s): Authors * Predicted C5 at certain bunker price levels assumed for the projection period

Figure 3. Schemetic TCE calculation

Source(s): Authors

increase during the upward phase of the dry bulk shipping cycle, 10 days are used here, which are above than average days at ports. The calculation is made for both a non-scrubber fitted Capesize and a scrubber fitted Capesize, differentiated between an eco-electronic engine and non-eco electronic engine using VLSFO and HSFO based on bunker prices in Singapore.

Equation 5

$$TCE_{i,j,i} = \frac{((F_{j,i} * Cint) - Vc_{i,j,i} - Cc_{i,j} - Pc_{i,j} - Com_{i,j,i}))}{Rv_{i,j,i}} \tag{5}$$

where:

$TCE_{i,j,i}$ = Australia (j) – China (i) Round Voyage $/Day Earnings (Time Charter Equivalent)

$F_{j,i} = Iron\ Ore\ Dollar\ per\ ton\ (C5)$ West Australia–China

$Cint - Standard\ Capesize\ Cargo\ Intake$

$Vc_{i,j,i} = Voyage\ Cost\ (Round\ Voyage\ Fuel\ Consumption\ x\ Bunker\ Price)$

$Cc_{i,j} = Congestion\ Cost\ (Fuel\ Consumption\ during\ days\ at\ port)$

$Pc_{i,j} = Port\ Costs$

$Com_{i,j,i} = Commission\ Fees$

$$Rv_{i,j,i} = Round\ Voyage\ Days\ (Days\ at\ Sea + Days\ at\ port)$$

The calculation of fuel consumption for the Australia–China round voyage within a year derives from Equation (6).

Equation 6

$$\mathrm{FC}_{\mathrm{i,j,i,v,t}} = \sum_{\mathrm{i,j,v}} \left[(\mathrm{Fcb}_{\mathrm{i,j,v}} \cdot \mathrm{Db}_{\mathrm{i,j,v,t}}) + (\mathrm{Fcl}_{\mathrm{j,i,v}} \cdot \mathrm{Dl}_{j,\mathrm{i,v,t}}) + (\mathrm{Fcp}_{\mathrm{i,j}} \cdot \mathrm{Dp}_{\mathrm{i,j,t}}) \right] \tag{6}$$

where:

$\mathrm{FC}_{\mathrm{i,j,i,v,t}}$ = Total annual fuel consumption for the round voyage at steaming speed v at time t

$\mathrm{Fcb}_{\mathrm{i,j,v}}$ = Daily ballast fuel consumption from i to j at steaming speed v

$\mathrm{Fcl}_{\mathrm{j,i,v}}$ = Daily Laden Fuel Consumption from *j* to *i* at steaming speed v

$\mathrm{Db}_{\mathrm{i,j,v,t}}$ = Days Ballast from *i* to *j* at steaming speed *v* for year t

$\mathrm{Dl}_{\mathrm{j,i,v,t}}$ = Days Laden from *j* to *i* at steaming speed *v* for year t

$\mathrm{Fcp}_{\mathrm{i,j}}$ = Daily Fuel Consumption at ports *i* and *j*

$\mathrm{Dp}_{\mathrm{i,j,t}}$ = Days at Ports *i* and *j* for year t

The optimal speed is the speed at which the voyage cost per nautical mile sailed is the lowest, so that TCE is maximized. As speed increases, the cost of time per nautical mile decreases, while the fuel cost per nautical mile increases. The speed at which both the fuel costs and the cost of time are minimized is the optimal speed (the TCE is maximized). Local optimal speed is the speed that corresponds to the minimum of the cost curve (voyage and congestion costs per nautical mile) for a given freight level and bunker price (Equation 7). This is compared with the speed at which fuel consumption per dwt nautical mile is minimized to the point that it satisfies the CII required (Equation 8).

Equation 7 - optimal speed

$$V_{i,j,i,t} = argmax\ (TCE)\ \forall\ [F_{i,j}, B] \tag{7}$$

Equation 8 - CII required speed

$$V_{i,j,i,t,aer} = argmin\left(\frac{FC_{i,j,i,v,t}}{Dwt * NM_{i,j,i,v,t}}\right) \forall\ [AER = CII\ \ Required] \tag{8}$$

where:

$V_{i,j,i,t}$ = Optimal Speed for round voyage at time t (TCE maximizing speed)

$V_{i,j,i,t,\ aer}$ = Speed that satisfies CII required for round voyage at time t

$F_{i,j}$ = *Iron Ore Dollar per ton* (*C*5) West Australia–China

B = Bunker Price

Dwt = Standard Capesize Deadweight Capacity

$NM_{i,j,i,v,t}$ = *Annual Distance Travelled between i and j in round voyage at* steaming speed v *in year t*

Daily fuel consumption at different steaming speeds for different Capesize specifications has been built from data provided by dry bulk companies.

CII emission measurement method

Total CO_2 emissions are calculated by multiplying a fixed carbon dioxide emission factor per ton of fuel by the total fuel consumption for the round voyage (Equation 9). Deadweight miles are calculated by multiplying the standard Capesize 180kdwt capacity by the round voyage distance, which are then used as input to calculate the annual carbon intensity in tons of CO_2 per dwt mile or else the CII attained (Equation 10), compared against the required CII (Equation 11).

Equation 9 - CO2 emissions

$$CO2_{i,j,i,t} = Ef_f \cdot \mathrm{FC}_{\mathrm{i,j,i,v,t}} \tag{9}$$

where:

$CO2_{i,j,i,t}$ = *CO2 emissions for the Australia – China* round voyage *in year t*

Ef_f = *Tank to Wake Emission Factor per fuel type* (*VLSFO*= 3.151, *HSFO*= 3.114)

$\mathrm{FC}_{\mathrm{i,j,i,v,t}}$ = *Annual Fuel Consumption for* round voyage *in year t* including consumption at ports

Equation10 - AER (CII Attained)

$$AER_{i,j,i,t} = \frac{CO2_{i,j,i,t}}{Dwt * NM_{i,j,i,v,t}} \tag{10}$$

where,

$AER_{i,j,i,t}$ = *Carbon Intensity per deadweight nautical miles travelled in round voyage between i and j in year t*

Dwt = Standard capesize deadweight capacity

$NM_{i,j,i,v,t}$ = *Annual Distance Travelled between i and j in round voyage at* steaming speed v *in year t*

Equation 11 - required CII

$$CII_{i,j,i,t} = \frac{100 - Z}{100} * CIIref \tag{11}$$

where:

$CIIref$ = 4,745 × 180,000^−0.622 = 2.56 (for a standard Capesize)

Z = Reduction factor (Z%) for the CII relative to the 2019 reference line

Scenario results

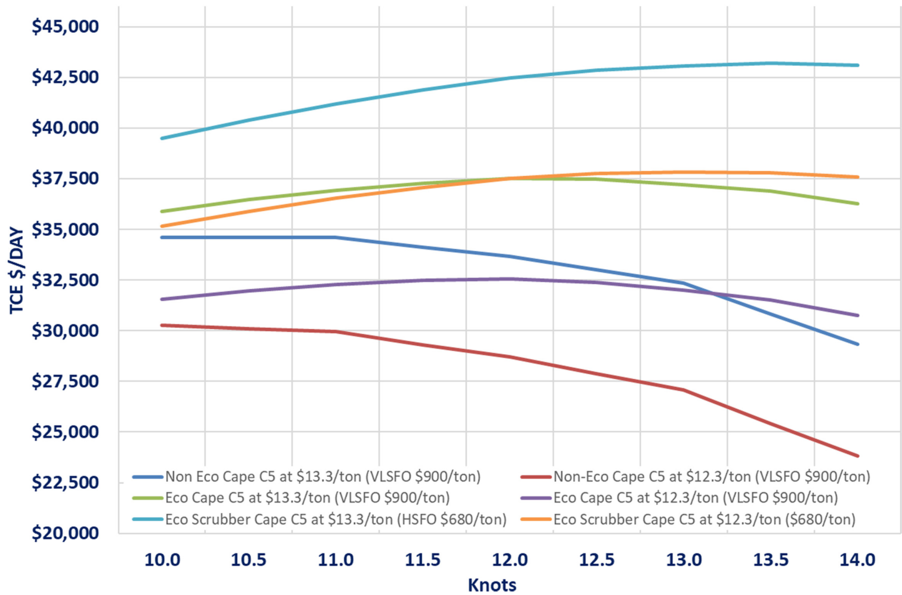
Figure 4 illustrates the different TCE results for different market conditions pairs at different speeds. The speed that maximizes the TCE differs per Capesize technology on fuel consumption and fuel price differentiation. Eco Capesize vessels with and without scrubbers have a higher optimal speed (for a higher TCE) result compared to non – eco Capesize vessels with and without scrubbers.

Scenario 1: standard Capesize with eco-electronic engine (VLSFO Price at $900/ton – C5 at $13.3/ton)

In this scenario, where VLSFO bunker prices are assumed at $900 per ton corresponding to C5 of $13.3 per ton, the optimal speed level is calculated at 12.0 Knots (Figure 5), which is 5.0% above the 2019 average eco-Capesize speed (Clarksons, 2022). However, the steaming speed required to satisfy the minimum CII required in these market conditions is calculated at 13.5 knots. There is no incentive to sail at this speed, as albeit small, this speed level entails a TCE loss of -$641 per day, while the optimal speed that maximizes the TCE and at the same time offers a higher CII rating (B) is at 12.0 knots (Table 2).

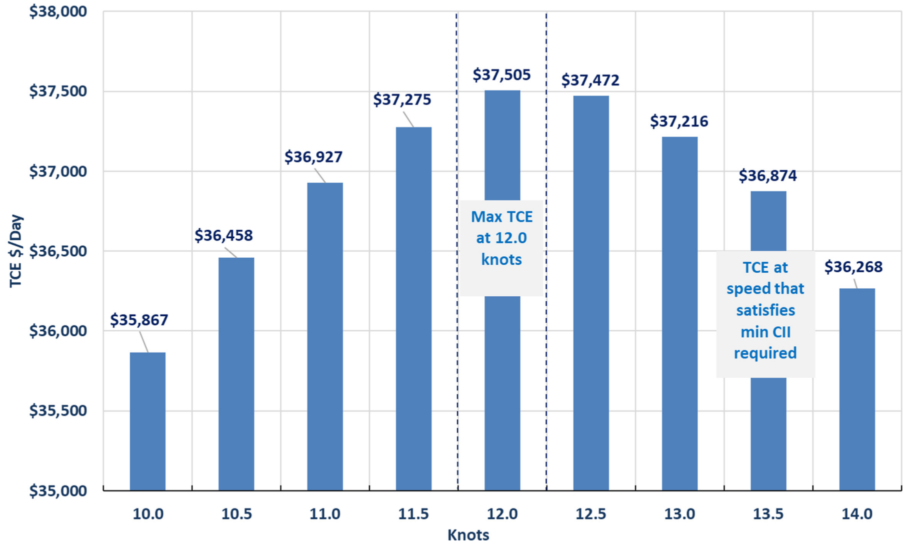
Scenario 2a – standard Capesize with eco-electronic engine fitted with scrubber (HSFO Price at $680/ton – C5 at $13.3/ton)

In this scenario, where HSFO bunker prices are assumed at $680 per ton, and C5 determined by the nonscrubber vessel at $13.3 per ton, the optimal speed level is calculated at 13.5 knots (Figure 6), which is 18.1% above the 2019 average eco-Capesize speed (Clarksons, 2022). This is also calculated to be the steaming speed that satisfies the minimum CII required in these market conditions. However, the speed that entails a TCE loss ($333 per day) but leads to a higher CII rating (B) is calculated at 12.5 knots (Table 3). The implicit market penalty for not



Source(s): Authors Calculations

Figure 4.
TCE at speed range 10 to 14 knots for different C5-Bunker price pairs



Source(s): Authors

Figure 5.
Optimal speed for a standard Capesize with eco electronic engine (VLSFO $900/ton-C5 at $13.3)

Table 2.
TCE vs CII at different speeds (Eco Capesize)

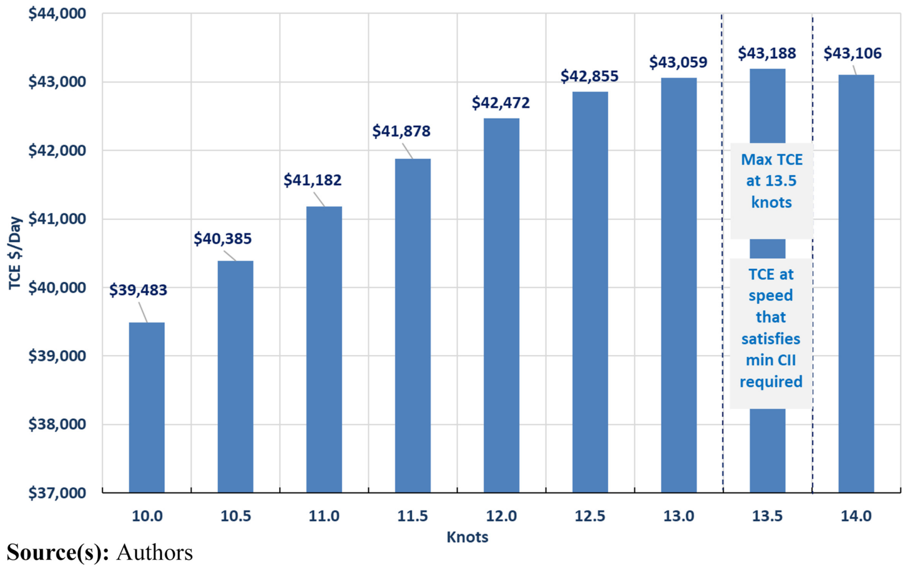
AER eco Capesize (VLSFO @$900/ton - C5@$13.3/ton)	Baltic speed (eco)	Baltic speed (max)	Optimal speed	Min CII required (C rating)
Speed (knots)	12.5	14.0	12.0	13.5
TCE (Eco – Nonscrubber)	$37,472	$36,268	*37,505*	*36,874*
Annual distance travelled	64,677	69,252	63,103	67,680
Annual fuel consumption (tons)	7,566	9,456	7,019	8,777
Attained CII gCO2/dwtmile	2.05	2.39	1.95	2.27
Attained CII/Required CII	0.90	1.05	0.86	1.0
Implied rating	B	C	B	C

Source(s): Authors

achieving this rating must be higher than $333 per day to sail at this speed level, in this market context.

Scenario 2b: standard Capesize with eco-electronic engine fitted with scrubber (HSFO Price at $680/ton – C5 at $12.3/ton)

In the scenario variant (2b), where HSFO bunker prices are assumed at $680/ton and C5 determined by the scrubber vessel at $12.3/ton, the optimal speed level is calculated at 13.0 knots (Figure 7), which is 13.7% above the 2019 average eco-Capesize speed (Clarksons, 2022). The optimal speed is 0.5 knots below the speed that satisfies the minimum CII required, with an almost identical TCE; therefore, the incentive to sail at the lower speed that both maximizes the TCE and offers lower carbon intensity is high. Sailing below this speed to improve the CII rating to B (i.e. speed equal to 12.5 knots), entails a small TCE loss of $59 per day. The implicit market penalty for not achieving this rating must be higher than $59 per day to sail at this speed level, in this market context, implying an insignificant trade-off between the TCE loss compared to the CII rating improvement from sailing at a lower than the TCE optimal speed (Table 4).



Source(s): Authors

Figure 6. Optimal speed for a standard Capesize with eco-engine fitted with scrubber (HSFO $680/ton-C5 at $13.3)

AER eco scrubber Capesize (HSFO @$680/ton - C5@$13.3/ton)	Baltic speed (eco)	Baltic speed (max)	Optimal TCE speed	Min CII required (C rating)
Speed (knots)	12.5	14.0	13.5	13.5
TCE (Eco-Scrubber)	$42,855	$43,106	*43,188*	*$43,188*
Annual distance travelled	64,677	69,112	67,680	67,680
Annual fuel consumption (tons)	7,637	9,546	9,048	9,048
Attained CII gCO2/dwtmile	2.04	2.39	2.31	2.31
Attained CII/Required CII	0.90	1.05	1.02	1.02
Implied rating	B	C	C	C

Source(s): Authors

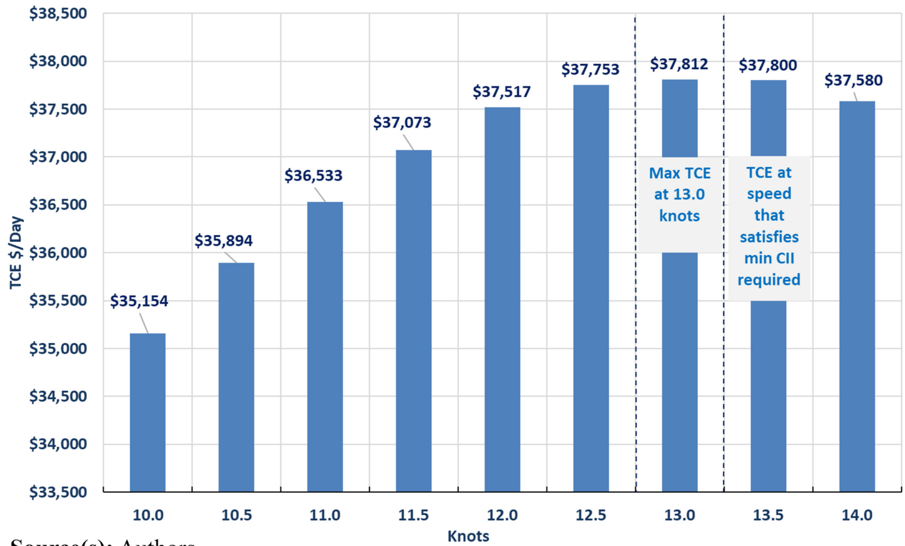
Table 3. TCE vs CII at different speeds (Eco Capesize fitted with scrubber)

Scenario 3: standard Capesize noneco/nonscrubber fitted (VLSFO Price at $900/ton – C5 at $13.3/ton)

In this scenario, VLSFO bunker prices are assumed to be $900/ton, corresponding to C5 of $13.3/ton, leading to a TCE optimal speed level of 10.0 knots (Figure 8), which is −10.2% below the 2019 average noneco Capesize speed (Clarksons, 2022). However, the steaming speed required to satisfy the minimum CII required in these market conditions is calculated at 12.2 knots. There is no incentive to sail at this speed, as it entails both a TCE loss of $1,285 per day and a lower CII rating (C); therefore, in this market context, a speed of 10.0 knots is optimal both commercially and operationally as it maximizes both the TCE and improves the CII rating towards the A boundary (Table 5).

Scenario 4a: standard Capesize non-eco scrubber fitted (HSFO Price at $680/ton – C5 at $13.3/ton)

In this scenario, where HSFO bunker prices are assumed at $680/ton and C5 determined by the non-scrubber vessel at $13.3/ton, the optimal speed level for a scrubber fitted non – eco



Source(s): Authors

Figure 7. Optimal speed for a standard Capesize with eco-engine fitted with scrubber (VLSFO $680/ton-C5 at $12.3)

AER eco scrubber Capesize (HSFO @$680/ton - C5@$12.3/ton)	Baltic speed (eco)	Baltic speed (max)	Optimal TCE speed	Min CII required (C rating)
Speed (knots)	12.5	14.0	13.0	13.5
TCE (Eco-Scrubber)	$37,753	$37,580	*37,812*	*$37,800*
Annual distance travelled	64,677	69,112	66,202	67,680
Annual fuel consumption (tons)	7,637	9,546	8,606	9,048
Attained CII gCO2/dwtmile	2.04	2.39	2.25	2.31
Attained CII/Required CII	0.90	1.05	0.99	1.02
Implied rating	B	C	C	C

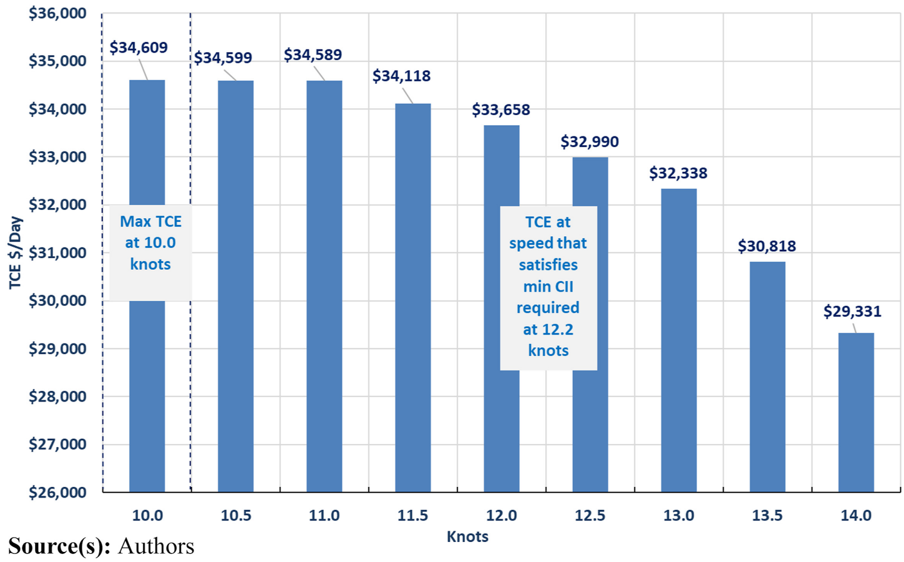
Source(s): Authors

Table 4. TCE vs CII at different speeds (Eco Capesize fitted with scrubber) – C5 adjusted

Capesize is calculated at 12.0 knots (Figure 9), i.e. 7.7% above the 2019 average Capesize non-eco speed (Clarksons, 2022). The optimal speed is 0.2 knots below the speed that satisfies the minimum CII required for a C Rating (Table 6). Sailing below this speed to improve the CII rating to B (i.e. at the speed of 11 knots), entails a small TCE loss of $122/day in this market context.

Scenario 4b: standard Capesize noneco scrubber fitted (HSFO Price at $680/ton – C5 at $12.3/ton)

Here, HSFO bunker prices are assumed at $680 per ton, with C5 determined by the scrubber vessel at $12.3 per ton, leading to a optimal speed for a scrubber fitted non – eco Capesize at 11.0 Knots (Figure 10), which is −1.3% below the 2019 average Capesize noneco speed (Clarksons, 2022). The optimal TCE speed is 1.2 knots below the speed that satisfies the minimum CII required and achieves a higher CII rating at the B boundary in this market context (Table 7).



Source(s): Authors

Figure 8. Optimal speed for a noneco standard Capesize

AER non eco Capesize (VLSFO @$900/ton - C5@$13.3/ton)	Baltic speed (eco)	Baltic speed (max)	Optimal TCE speed	Min CII required (C rating)
Speed (knots)	12.5	14.0	10.0	12.2
TCE (Non eco-nonscrubber)	$32,990	$29,331	*34,609*	*$33,324*
Annual distance travelled	64,800	69,252	56,255	62,782
Annual fuel consumption (tons)	9,085.7	11,743.7	5713.3	8,500.1
Attained CII gCO2/dwtmile	2.45	2.97	1.78	2.37
Attained CII/Required CII	1.08	1.31	0.78	1.04
Implied rating	D	E	A	C

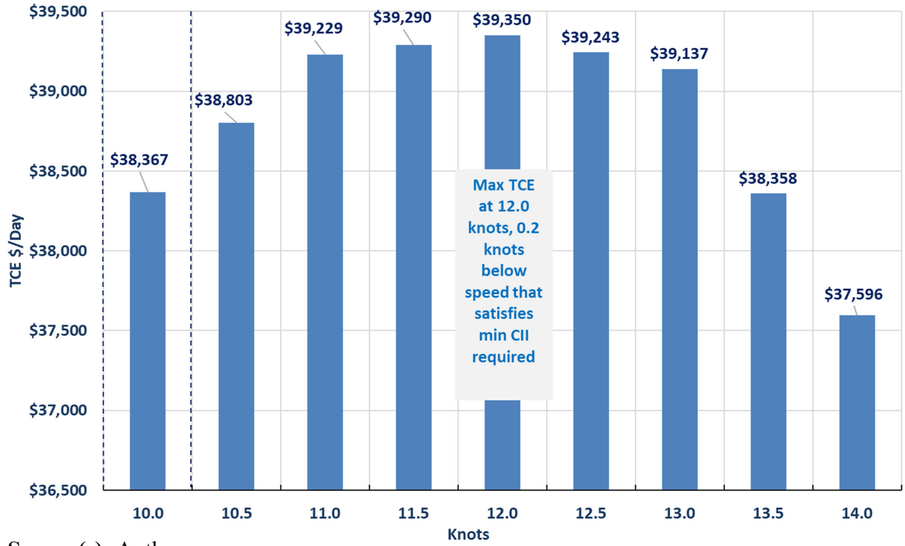
Source(s): Authors

Table 5. TCE vs CII at different speeds – non eco Capesize

Discussion and conclusions

Findings from the optimization exercise indicate that for the determined freight rates-bunker price pairs, standard eco Capesize fitted with scrubbers are less sensitive to high bunker prices and have a higher optimal speed (13.5 knots) compared to noneco standard Capesize with and without scrubbers. The optimal speed for ecostandard Capesize fitted with scrubbers in an inflationary bunker price context identifies with the speed required to comply with the minimum CII at a C5 of $13.3/ton with VLSFO as the predictor, while at a C5 of $12.3/ton with HSFO as the predictor, the optimal speed deviates 0.5 knots below the speed required for minimum CII compliance. At this speed level, there is insignificant TCE gain, but an improvement in AER albeit within the C boundary rating. Improvements in AER resulting in CII rating at B for a small TCE loss take place at speeds close 12.5 knots, implying a high incentive for deviating below the speed that maximizes the TCE in this market context.

The results show a higher effort needed in terms of speed reduction by the noneco standard Capesize fleet with and without scrubbers with a theoretical D-E rating calculated at Baltic eco and full speeds, respectively, in order to be CII compliant. For the determined freight rates-bunker price pairs, the speed required to achieve a C rating deviates 1.3 knots



Source(s): Authors

Figure 9. Optimal speed for a noneco standard Capesize fitted with scrubber

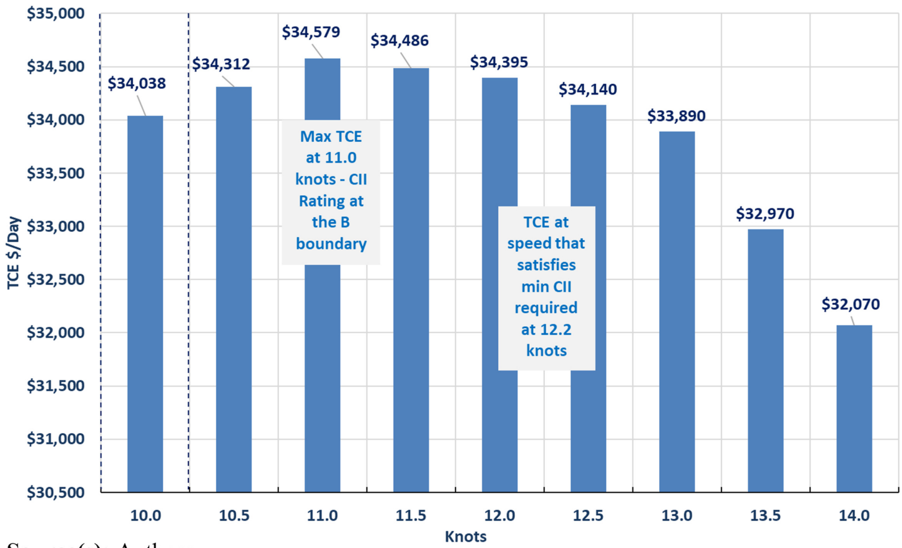
Table 6. TCE vs CII at different speeds – noneco scrubber fitted Capesize

AER non eco scrubber Capesize (HSFO @$680/ton - C5@$13.3/ton)	Baltic speed (eco)	Baltic speed (max)	Optimal TCE speed	Min CII required (C rating)
Speed (knots)	12.5	14.0	12.0	12.2
TCE (Non Eco – Scrubber)	$39,243	$37,596	*39,350*	*$39,296*
Annual distance travelled	64,677	69,112	63,103	63,739
Annual fuel consumption (tons)	9,172	11,856	8,418	8,711
Attained CII gCO2/dwtmile	2.45	2.97	2.31	2.36
Attained CII/Required CII	1.08	1.30	1.01	1.04
Implied rating	D	E	C	C

Source(s): Authors

below that of ecostandard Capesize with and without scrubbers and is estimated at close to 12 knots. These results imply that structurally higher bunker prices can endogenously push optimal speeds lower supporting CII compliance. Increased deployment of non-eco Capesize fitted with scrubbers in the Pacific would theoretically increase the CII attained for the average Capesize fleet in the area. On the other hand, increased non-eco Capesize deployment in such a market context would push optimal speeds structurally lower close to 10 knots to offer larger CII ratings improvements.

If non-eco standard Capesize vessels fitted with scrubbers opt to sail with the optimal speed under the predetermined market conditions, then the fleet weighted average CII attained for the segment, will marginally achieve a C rating. This may particularly be the case if the dollar per ton iron ore freight is set by the non-scrubber vessel, while if the scrubber vessel dictates the level of freight in the area -implying a lower dollar per ton at the given bunker price according to the long-term elasticity – then the optimal steaming speed for the non-eco scrubber-fitted Capesize equilibrates lower from 12 knots down to 11 knots. The latter tracks the speed required to satisfy the CII target for a B rating. This implies that in a



Source(s): Authors

Figure 10. Optimal speed for a noneco standard Capesize fitted with scrubber

Table 7. TCE vs CII at different speeds – non-eco scrubber fitted Capesize

AER non eco scrubber Capesize (HSFO @$680/ton - C5@$12.3/ton)	Baltic speed (eco)	Baltic speed (max)	Optimal TCE speed	Min CII required (C rating)
Speed (knots)	12.5	14.0	11.0	12.2
TCE (Non-Eco – Scrubber)	$34,140	$32,070	*34,579*	*$34,267*
Annual distance travelled	64,677	69,112	59,794	63,739
Annual fuel consumption (tons)	9,172	11,856	6,983	8,711
Attained CII gCO2/dwtmile	2.45	2.97	2.02	2.36
Attained CII/Required CII	1.08	1.30	0.89	1.04
Implied rating	D	E	B	C

Source(s): Authors

dynamic equilibrium, iron ore freight would have to be pushed lower in a high bunker prices context for CII improvements to be achieved.

Last but not least, if the whole Capesize segment is taken into consideration (i.e. very large ore carriers, Newcastlemax and Standard Capes) with all the iron ore trade routes served, the outcome on the elasticity of bunker prices to freight rates and the optimal speeds might differ, as iron ore miners and charterers may be the representative agents that shape the commercial decision-making rather than shipowners assumed in this paper. This is justified by (1) the oligopolistic structure of the iron ore market in combination with the miners' integrated fleet under time charter and (2) the competition in the standard Capesize market, making shipowners price takers.

Future research

Current research covers to a great extent the speed reduction as a measure to reduce CO_2 emissions and models to a lesser extent the dynamic optimal speed choice with different conclusions on the effect of bunker prices on speed; however, there is limited to no coverage in literature regarding the discrete choice problem between shipowners and charterers amongst a finite set of choices that minimize costs for each stakeholder factoring in the freight market level. The cost minimization exercise differs between charterers and shipowners depending on the chartering strategy (voyage fixture, time charter, contract of affreightment), the type of commodity trades these agents are engaged in and the point in the shipping market cycle that impacts the negotiating power between the two players. Each player has their own strategy and payoff function and acts individually to maximize the payoff. However, the payoff of a player is contingent on not only their own strategy, but also the strategies of the other players in the commercial chartering game and thus the speed optimization exercise in a commercial context should be approached for different combinations of decisions.

Strategies defined separately for the shipowner and the charterer but with a joint constraint for all players being the environmental compliance is pending research. The equilibria found from this exercise may be instructive for the legislator, on how to formulate the penalties (or optimal charges) under which market players comply with the environmental targets (Krawczyk, 2005), including the level of a potential GHG fuel levy.

Notes

1. The equivalency of TCE with gross profit draws from microeconomics and differentiates with net profit, where other expenses including operational are subtracted.
2. "The upper limit of the sulfur content of ships' fuel oil was reduced to 0.5% (from 3.5% previously) – under the so-called "IMO 2020" regulation prescribed in the MARPOL (International Convention for the Prevention of Pollution from Ships) Convention. This significantly reduces the amount of sulfur oxide emanating from ships." https://www.imo.org/en/MediaCentre/PressBriefings/Pages/02-IMO-2020.aspx
3. An United Nations Conference on Trade and Development (UNCTAD) empirical study in 2010 found the elasticity of iron ore freight rates to oil prices to be at parity, with eight commercial iron ore routes taken into consideration using Drewry's monthly (1993–2008) spot iron ore freight rates (UNITED NATIONS CONFERENCE ON TRADE AND DEVELOPMENT Oil Prices and Maritime Freight Rates: An Empirical Investigation, 2010).
4. Singapore Bunker Prices were selected as more observations were provided by the data source, while the representative bunkering port for Australia–China is Shanghai, where bunker prices were estimated to be discounted to Singapore (10-year average 2012-2022 discount of Shanghai HSFO prices to Singapore of approx. $23/ton and VLSFO prices discount since January 2020 of approx. $15.0/ton), therefore a slightly higher VLSFO-HSFO price differential is implied but that does not impact the elasticities outcome.
5. Port costs and chartering commission fees were assumed as per S&P Global Commodity Insights Specifications Guide- Global Freight (May 2022).
6. Assumption of 1.6 tons of iron ore to produce 1 ton of steel (https://www.bhp.com/-/media/documents/business/2019/191119_whatisironore.pdf).

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Corresponding author
Tamara Apostolou can be contacted at: tapostolou@unipi.gr

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