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Tax regimes, investment subsidies and the green transformation of the maritime industry

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Abstract

Maritime nations aim at establishing an environmentally sustainable shipping industry by 2050. We use insight from real options theory to target tax reforms that may facilitate the industry's transformation to sustainability. We demonstrate that a zero-cost tax package, which includes subsidies on green investments and a return to a regular income tax regime, can reduce investment thresholds. "Flags of convenience" and tonnage tax systems do not contribute to the sharing of risk between shipowners and governments. From a shipowner's perspective a higher degree of risk sharing reduces the value of waiting to invest, which may shift an individual investment decision towards a sustainable optimum level.

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Keywords

Sustainable maritime transport; Maritime tax reforms

1. Introduction

The International Maritime Organisation (IMO) targets a 50% cut in greenhouse gas (GHG) emissions by 2050 and aims at phasing out GHG emissions from shipping as soon as possible this century. IMO expects a reduction in carbon intensity by at least 40% by 2030 and aims at a 70% reduction by 2050 given projected growth in seaborne trade (IMO, 2018).

To reach the IMO targets large scale investments in low- and zero carbon technologies are called for. For long-haul shipping, proven zero carbon technologies are not available at reasonable cost levels. That is, an early introduction of low- and zero carbon technologies is associated with high technological and economic uncertainty. These unchartered waters add to the risks already faced by shipowners due to high income and asset value volatility in long-haul shipping. All risks united, the volatility of a cashflow generated by an investment in a ship, that meets the high environmental standards of the future, is probably substantial.

In this paper we discuss investment subsidies and tax reductions as climate policy instruments for inducing investments in and facilitating the transformation of the maritime industry. The paper focuses on tonnage tax versus regular profit tax regimes and these tax regimes' effect on the willingness to invest. To our knowledge the paper is a novel extension and application of real option theory to show that a zero-cost tax package, which includes subsidies on green investments and a return to a regular income tax regime, can reduce the thresholds for environmentally sustainable investments in the maritime industry. We discuss the implication of mean reversion in cashflows and tonnage taxes in light of the literature on investment subsidies.

Most international maritime shipping companies pay tonnage taxes, in contrast to land-based companies that operate under regular income tax regimes. International shipping is heavily subsidised under current tonnage tax regimes (Merk, 2020). Tonnage taxes are calculated based on the transport capacity of a company's vessels, which makes the tax independent of the operation of the vessels, i.e., the calculation of taxes is independent of resources used or profits generated.

The paper is organised as follows. In section two we discuss the literature on taxes, subsidies and investment under uncertainty, and the literature on maritime applications of real options theory (ROT). Section three develops a model of optimal investment under uncertainty and different tax regimes. Section four presents model simulations. Section five discusses a zero-cost tax reform for the maritime industry. Section six discusses a reformed tax system under altered market dynamics due to the process towards a sustainably transformed shipping industry. Section seven discusses the model and recent EU, IMO, OECD tax and green shift initiatives.

2. Tax regimes and the willingness to invest under uncertainty

Maritime subsides in OECD countries, like tonnage tax regimes, are defensive, rather than strategic and have partly emerged in reaction to the success of flags of convenience (OECD 2019). In 1957 Greece was the first country to introduce a national tonnage tax regime. Today tonnage taxes dominate in European shipping and are also introduced in key Asian shipping nations like South Korea – in 2005 – and Japan – in 2009.

Tax reduces the return on a risky asset, and this may limit an investor's appetite for investing in the asset. However, regular income taxes imply that the government shares in the risk-taking, which may affect a risk averse investor's investment behaviour (Domar and Musgrave, 1944). To what degree the government shares in the downside, depends on the investor's ability to offset losses against other income. Tax not only reduces the expected value, but it may also reduce the variance and higher order moments of future profits. The substitution effect of reduced riskiness is likely negative, which implies that the overall effect of higher taxes is ambiguous (Sandmo 1970).

Income taxes may have distorting effects on optimal investment behaviour under uncertainty if depreciation rates do not match actual economic decay. The challenge of determining the correct depreciation rate can be avoided by introducing cashflow based taxation (Brown, 1948). For irreversible investments Niemann (1999) shows, in a geometric Brownian motion setting, that a tax system that corresponds to cashflow taxation, is neutral. Sureth (2002) confirms the neutrality of cashflow and Johansson-Samuelson type taxes, (Samuelson, 1964), i.e., for a tax system with uniform marginal taxes and a match of tax-deductible and real economic depreciation, for partially irreversible investments under uncertainty.

Changes to the stochastic nature of an investor's private risk – due to taxation and subsidies – may affect the value of investment flexibility and the investor's optimal exercising of optionality – even in the risk neutral case. Pennings (2000) shows that a combination of a lump-sum investment subsidy and taxation of future profits, which as a package is neutral in terms of net present cost, can lower investment thresholds and reduce the expected time to investment – relative to a regular corporate income tax regime. The rationale is that a proportional income tax implies future profit sharing with the government, while excise taxes, including a lump sum subsidy, do not affect the risk characteristics of investments.

Yu et al. (2007) show that for a given investment threshold the expected net present value of a tax reduction is higher than the cost of an upfront investment subsidy. Danielova and Sarkar (2011) derive an optimal combination of corporate tax reductions and up-front investment subsidies for an exogenously given government's threshold target in the case of debt leverage and risk of bankruptcy. They find that investment subsidies may not dominate tax reductions in the case of leveraged firms. Sarkar (2012) shows that a combination of tax reductions and subsidies may be optimal if investors and the government do not share a common discount rate. Azevedo et al. (2021) study the effect on investment thresholds of zero cost packages of subsidies, depreciation rates and taxes. Results are ambiguous. A tax increase, which finances a higher depreciation rate or a higher subsidy, may hasten or deter an investment – dependent on the initial level of the tax rate. They find that a variable subsidy, in contrast to a lump sum, is favourable for promoting larger scale investments.

The freedom of the seas implies that a ship is not restricted to a specific geographical region regardless of the flag the vessel is carrying.[1] This implies that shipowners often hold the option to switch flags without major restrictions on international operation. Change of flags often implies changes to the tax regime and regulatory conditions. Tax competition due to flags of convenience and the traditional shipping nations' response, in the form of favourable tonnage tax regimes, have led to a taxation of the maritime industry, which is significantly lower than the taxation of traditional land-based industries (Merk 2020).

Kavussanos and Tsekrekos (2011) develop a ROT model for the optimal switching between a national flag and a flag of convenience under freight rate uncertainty, partly correlated cashflows and costs of switching. They assume regular proportional corporate profit tax under the national flag and a flat fixed tax under the flag of convenience, i.e., a simple tonnage tax system. Chondrokouki and Tsekrekos (2022) empirically test the predictions of the ROT flag switching model of Kavussanos and Tsekrekos and find that increased freight rate volatility is associated with a higher probability of a switch of flags.

In Niemann, Sureth, Pennings, Yu et al., Danilova and Sarkar, Sarkar, Azevedo et al. and Kavussanos and Tsekrekos the economic systems' underlying uncertainty is given by random walk processes. This assumption is convenient to keep the complexity of ROT models low. However, the arithmetic or geometric Brownian motions are hardly reasonable descriptions of the long-run stochastics of maritime industries' income streams. Conventional shipping is typically characterized by short periods of high and volatile returns followed by long periods of low and stable returns. Traditional theoretical maritime economics suggest that freight rates are stationary. Contrary to theoretical models, early empirical studies indicated that a unit root in freight rates cannot be ruled out. However, in a recent empirical study and literature overview, Kou et al. (2018) find support for the classical theoretical mean reversion assumption during restricted sample windows defined by structural breaks and for the post 2008 financial crisis period.

In the theoretical asset pricing model of Bjerksund and Ekern (1995) the freight rate is assumed to follow an Ornstein-Uhlenbeck process, i.e., an arithmetic mean reversion process. Consequently, the freight rate may take negative values. Tvedt (1997) suggests to model freight rates by a geometric mean reversion process. The geometric nature of the process implies that freight rates cannot take negative values, which is reasonable if lay-up and other types of operations flexibility restrict the downside risk in freight rates.

Mean reversion typically reduces a process' long-run variance. Lower long-run variance reduces the value of real options. See Tsekrekos, 2010, Tvedt, 2022 for discussions of the effect of mean reversion on optimal entry and exit under uncertainty and Wong and Yi (2013) for a discussion of investment thresholds under mean reversion and degrees of investment irreversibility. The geometric stochastic process in Tsekrekos and in Wong and Yi is slightly different from that in Tvedt (1997) and (2022). Both processes appear to be relevant for modelling maritime freight rates.

Sødal et al. (2008) apply an Ornstein-Uhlenbeck process to model the cash flow spread between dry bulk and tanker markets and derive the optimal threshold for switching combination carriers between these markets. Adland et al., 2017, Adland et al., 2017 follows Sødal et al. and model the spread between dry bulk freight rates in the Atlantic vs the Pacific basin by an Ornstein-Uhlenbeck process to study the spatial efficiency of the markets. Adland et al., 2017, Adland et al., 2017 carry out a related analysis on the potential for switching between the clean and dirty oil transportation markets. Kou and Luo (2018) argue that dry bulk freight rates may be modelled as Ornstein-Uhlenbeck processes and test empirically investment thresholds derived by a ROT model for the Capsize, Panamax and Handysize dry bulk markets.

3. A model of investments under uncertainty and income vs tonnage taxes

In this section we develop a ROT model for investment under uncertainty with tonnage and income taxes. The structure is as follows.

A shipping company holds the option to invest in an expansion of its operation, e.g., to invest in a new vessel or to install an environmentally friendly new technology. The pre-tax cashflow of one unit of transportation capacity at any time *t* is given by P_t. Let the dynamics of the cashflow be given by an Ornstein-Uhlenbeck process

$$dP_t = \kappa(\alpha - P_t)dt - \sigma\ dB_t \tag{1}$$

where dB_t is the increment of a standard Brownian motion, σ is the standard deviation of the change in P_t, α is the mean level of the instantaneous cashflow, and κ is the speed of mean reversion. In the case that the freight rate P_t is below the mean level α, the probability of an instantaneous increase is higher than the probability of an instantaneous decline in freight rates, and vice versa.

Let the company's pre-tax cashflow be given by $X_t = \varepsilon P_t$ where the constant ε represents the capacity of the company before an investment is made. The company may choose to invest in new capacity. The cashflow at any time *t* after the investment is made is given by $Y_t = \mu P_t$ where μ represents the post-investment capacity. The investment, which enables the shift in capacity from ε to μ, is given by K.

After-tax profitability is potentially affected by three types of taxes: tonnage taxes, excise duties[2] and income taxes.

The tonnage tax is determined by physical characteristics of a ship and may change in the case of a capacity expansion. Let tonnage taxes be given by l_t, which is a lump sum, l^a, if there is no change in capacity and jumps to a different lump sum level, l^b, if an investment is made.

Let a non-stochastic cost component, e.g., an excise duty at any time *t*, be given by c_t.. The model allows for different costs ex-ante and ex-post the capacity expansion, i.e., $c_t \in \left\{c^a, c^b\right\}$. Excise duties, e.g., carbon charges levied on fuel, may affect short-term operations decisions. However, to focus solely on investment decisions any such effects on operations from taxes are ignored.

Income taxes are proportional and given by the fixed tax rate ϑ_t – taking values between zero and one. The model allows for different tax rates ex-ante and ex-post, i.e., $\vartheta_t \in \left\{\vartheta^a, \vartheta^b\right\}$. Let investment costs be deductible against taxable income according to a geometric depreciation rate, $\delta \geq 0$.

The after tax cashflow ex-ante is then $\pi_t^a = (X_t - c^a)(1-\vartheta^a) - l^a$ and the after tax cashflow ex-post is $\pi_t^b = \left(Y_t - c^b\right)\left(1-\vartheta^b\right) - l^b + \vartheta^b \delta e^{-\delta(t-\theta)} K$, where θ is the point of time the investment is carried out. In the discussions below it is assumed that the company either pays tonnage taxes or income taxes – not both types of taxes at the same time. However, from a model technical point-of-view a combination is possible. Excise duties is typically levied independently of whether the shipowner pays tonnage taxes or income taxes. In this model, in the income tax regime excise duties are assumed deductible.

The ex-ante value of the company is $\Phi_t^a(p_t)$, and the ex-post value of the company is $\Phi_t^b(p_t)$. The ex-ante value is given by the expected value of the certainty equivalent discounted future cash flows in the case of no future expansion and the value of the real option to optimally expand capacity at time θ, i.e.,

$$\Phi_t^a = \sup_{\theta^*} E^Q\left[\int_0^\infty e^{-\rho s}\left(\pi_t^a I_{s<\theta^*} + \pi_t^b(1 - I_{s<\theta^*})\right)ds - e^{-\rho\theta^*}K + e^{-\rho\theta^*}\int_{\theta^*}^\infty \vartheta^a \delta e^{-(\rho+\delta)(s-\theta^*)} K(1 - I_{s<\theta^*})ds \middle| \mathscr{F}_t\right] \quad (2)$$

where ρ is a constant discount factor that represents the real interest rate and the economic depreciation of the production unit and where $\mathscr{F}_t$ is a filtration of information up to time t. The control θ^* is the optimal point of time for exercising the option to invest. $I_{s<\theta}$ is an indicator function that takes the value one ex-ante and takes the value zero ex-post an investment and Q is a certainty equivalent probability measure.

In a capital asset pricing setting (Bjerksund and Ekern, 1995) let

$$dB_t = d\widehat{B}_t - \lambda dt \quad (3)$$

where $\widehat{B}_t$ is a standard Brownian motion under the certainty equivalent Q probability measure, i.e., the increment $d\widehat{B}_t$ has a mean of zero and a variance of dt under the Q measure. The constant λ is the market price of risk. The Ornstein-Uhlenbeck process under the Q measure is then given by

$$dP_t = \kappa(\widehat{\alpha} - P_t)dt - \sigma\ d\widehat{B}_t \quad (4)$$

where the risk adjusted mean level of the cash flow process is given by $\widehat{\alpha} = \alpha - \frac{\sigma\lambda}{\kappa}$. From Ito's lemma, the profit in the ex-ante state, which dependents on X_t, is then given by

$$d\pi_t^a = \kappa(\widetilde{\alpha} - \pi_t^a)dt - \varepsilon\sigma(1-\vartheta^a)d\widehat{B}_t \quad (5)$$

where $\widetilde{\alpha} = (\varepsilon\widehat{\alpha} - c^a)(1-\vartheta^a) - l_t^a$, which is the mean reversion level, in risk adjusted terms, of profits in the ex-ante state.

The value of the company after the investment is made is given by the expected value of discounted future cashflows under the certainty equivalent probability measure. That is,

$$\Phi_t^b = E^Q\left[\int_t^\infty e^{-\rho s}\pi_t^b ds \middle| \mathscr{F}_t\right] = e^{-\rho t}\left(\mu\left(1-\vartheta^b\right)\left(\frac{p_t - \widehat{\alpha}}{\rho+\kappa} + \frac{\widehat{\alpha} - c^b}{\rho}\right) - \frac{l^b}{\rho} + K\frac{\vartheta^b\delta}{\rho+\delta}\right) \quad (6)$$

The parts inside the brackets of equation (6), to the right, are: 1) the expected net present value, in certainty equivalent terms, of future income after regular income tax, 2) the net present value of tonnage taxes (which is deterministic) and 3) the net present value of future income tax deductions due to depreciation.

Due to the time homogenous property of value function (2) it follows that $\Phi_t^a = e^{-\rho t}V^a(p_t)$. For the timing of the investment to be optimal the following partial differential equation must hold

$$-\rho V_a + \kappa(\widehat{\alpha} - p)V_a' + \frac{1}{2}\sigma^2 V_a'' + \pi^a = 0 \quad (7)$$

Equation (7) implies that the instantaneous return on the value of operating using the original capacity, and optimally utilising the option to invest in a new capacity in the future, is given by the change in the value due to the change in the instantaneous profit, plus the after tax instantaneous profit, π_t^a.

A solution to equation (7), i.e., the value function V_a, under reasonable border conditions[3] is given by

$$V_a(x) = A\begin{pmatrix} M\left(\frac{\rho}{2\kappa}, \frac{1}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - p)^2\right) \\ -\frac{\sqrt{\kappa}}{\sigma}(\widehat{\alpha} - p)\frac{\Gamma\left(\frac{1}{2}\right)\Gamma\left(\frac{\rho+\kappa}{2\kappa}\right)}{\Gamma\left(\frac{3}{2}\right)\Gamma\left(\frac{\rho}{2\kappa}\right)}M\left(\frac{\kappa+\rho}{2\kappa}, \frac{3}{2}, \frac{\kappa}{\sigma^2}(\widehat{\alpha} - p)^2\right)\end{pmatrix} + \frac{\pi^a - \widetilde{\alpha}}{\rho+\kappa} + \frac{\widetilde{\alpha}}{\rho} \quad (8)$$

where $M(\bullet)$ is Kummer's (confluent hypergeometric) function, $\Gamma(\bullet)$ is the gamma function and A is a constant. The particular solution to the inhomogeneous part of equation (7), given by $\frac{\pi^a - \widetilde{\alpha}}{\rho+\kappa} + \frac{\widetilde{\alpha}}{\rho}$, represents the net present value of future operations using existing capacity only.

The general solution to the homogeneous part of equation (7), i.e., the constant *A* times the expression in brackets, represents the value of optimally exercising the real option to change capacity.[4]

The first time the underlying freight rate reaches the optimal threshold is given by

$$\theta^* = inf\{s \geq 0 : p_s = p^* > 0, s > t\} \quad (9)$$

The expected first-passage time until the optimal investment threshold is reached, $\overline{\theta}^*$, in the case that the current freight rate level is equal to the long-run mean, i.e., $p_t = \alpha$, is given by

$$\overline{\theta}^* = E[\theta^* | \mathscr{F}_t] = \frac{1}{2\kappa} \sum_{n=1}^{\infty} \frac{\sqrt{2^n}\left(\frac{p^*-\alpha}{\sqrt{\sigma^2/\kappa}}\right)^n}{n!} \Gamma\left(\frac{n}{2}\right) \quad (10)$$

For details see the appendix.

4. Taxation and the optimal time to invest – model properties

Table 1 shows the parameter values that are applies to illustrate the property of the model, except for tax related parameter values, which are discussed in more detail below.[5]

Table 1. Base case parameter values.

Parameter	Description	Base case value
κ	Speed of mean reversion	0.05
α	Mean level of cash flow	100
σ	Standard deviation	50
ε	Capacity factor ex-ante	1.00
μ	Capacity factor ex-post	1.25
K	Investment cost	500
ρ	Discount rate	0.05
λ	Price of a unit of risk	0

Fig. 1 shows the optimal thresholds for investment under different tax regimes. The horizontal scale is expected net present value of tax income to the government measured at the time of investment. The lower-right dotted horizontal line is the Marshallian trigger level, i.e., the lowest level at which the project has positive net worth. At this level the value of real options is ignored, and the net present value of future after tax profits is equal the investment cost. The Marshallian level in the base case is 100.

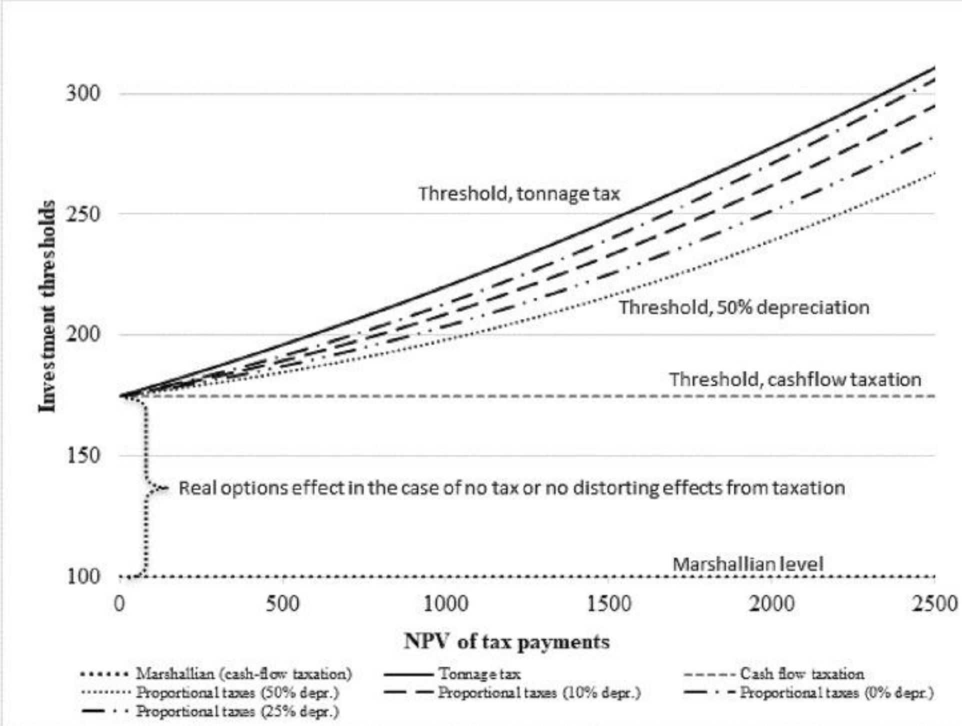

Fig. 1. Investment thresholds for different tax regimes and levels of tax costs.

The grey dashed horizontal line, directly above the Marshallian line, is the thresholds in the case of a proportional income tax and an infinitely high rate of depreciation, i.e., the investment expenditure, K, is instantly deductible against other income. This income tax system corresponds to a cashflow tax system. In line with the general literature, in this case there is no distorting effect on investment triggers from taxation. The real option threshold, regardless of the government's income, is 174.4. The high real options threshold, relative to the Marshallian level, follows mainly from the high base case standard deviation.

The standard results of the literature[6] regarding the effects on optimal switching due to changes in: a) volatility, b) mean reversion, c) the price of a unit of risk and d) switching costs, also apply to the spread between the real option threshold under cashflow taxation and the Marshallian threshold:

a) The spread increases for higher values of the standard deviation.

b) The effect of increased mean reversion is mixed. Higher mean reversion reduces the long-run variance, which reduces the value of waiting and pushes the investment threshold downwards. For income levels above the long run mean, higher mean reversion reduces the expected value of future cashflows, which pushes the investment threshold upwards. The overall result is ambiguous. For income levels below the long run mean, higher mean reversion increases the expected value of future cashflows, which pushes the investment threshold downwards, i.e. in the same direction as the variance effect, and the overall effect is clear.

c) The spread increases for a higher price of a unit of risk, i.e., for higher risk aversion.

d) The spread increases for a higher value of the investment cost, i.e., for a higher cost of switching from one state to another.

For low and moderate proportional income tax levels with depreciation of invested capital, the thresholds increase in the net present value of future tax payments. The figure shows the thresholds for an expected net present value of tax costs of up to 2500. The dashed and dashed-dotted lines, above and to the left, are for proportional income taxes and different levels of the depreciation rate – from right to left respectively 50%, 25%, 10% and zero. In these cases, there is a mismatch between the economic depreciation, which in the model is represented by the discount rate, and the depreciation tax allowances based on the initial investment cost. That is, the tax system does not in these cases comply with Johansson-Samuelson neutrality.

In the base case, the tonnage tax payed by the company is assumed to be linked to the capacity factor, which due to the investment jumps 25%. That is, the tonnage tax depends on the investment decision, which implies that ex-post the tonnage tax is 25% higher. The tonnage tax is a lump-sum tax if there is no investment. The black solid line in Fig. 1 is the investment thresholds in the case of the described tonnage tax. A lump sum tonnage tax has no effect on the risk profile of the company's income, i.e., there is no sharing of risk with the government – it only affects the expected value of future tax costs.

The investment thresholds are lower for proportional taxes than for a tonnage tax – for identical expected net present value of tax costs. A high depreciation rate implies that the investment cost, i.e., the switching cost, is to some extent compensated for – with a delay – and the compensation increases in the level of the proportional tax rate. This dampens the effect on the threshold level from an increase in tax payments. For cashflow taxation, the sharing of risk and investment costs between the shipowner and the government is perfect, and the threshold level is independent of the expected net present value of future tax payments. There is no such dampening effect in the case of a tonnage tax. It follows that the thresholds for a proportional tax system with no depreciation is closest to the tonnage tax thresholds – for equal expected net present value of future tax payments.

Given a deterministic tonnage tax and a deterministic discount rate, for equal expected values, the effect of a tonnage tax on investment thresholds is equivalent to an increase in the investment cost, i.e., the switching cost. A tonnage tax under these conditions are equivalent to an excise duty on the investment cost.

Yu et al.'s proposition 2, says that for equal expected present values, the threshold under an entry cost subsidy is lower than that under a tax rate reduction. Given that a fixed tonnage tax under deterministic discount rates is equivalent to an excise duty,[7] the reverse of Yu et al.'s propositions holds. That is, for equal expected present values, the threshold under an entry cost excise duty (or deterministic tonnage tax under a deterministic discount rate) is higher than the threshold under a proportional tax. This also holds if there is a mismatch between the depreciation tax allowances and the real economic decay of the production unit.

5. A zero-cost package for a reduced investment threshold

As illustrated above, given an equal expected net present value of future tax payments, the structure of the tax system affects investment thresholds. Proportional income taxes, combined with a high depreciation rate, imply a lower investment trigger than the tonnage tax system. From a risk sharing perspective the extremes are the tonnage tax system (no sharing) and the cashflow taxation system (perfect sharing). In this section this insight is applied to the dry bulk market. We construct a zero-cost tax package that lowers the optimal investment threshold and bring ship-owning companies back to a regular income tax regime. That is, we outline a reform to facilitate reflagging of ships from flags of convenience and tonnage tax systems to domestic flags under regular income tax systems. This increases the risk sharing between shipowners and governments.

5.1. Illustrative base case: A zero-cost packages for investing in a Capesize carrier

Our illustrative starting point, based on the investment in a Capesize dry bulk carrier, is as follows. Ex-ante there is no capacity, and at the time of investment one Capesize dry bulk vessel is acquired. That is, the capacity factor ex-ante $\varepsilon = 0$ and ex-post $\mu = 1$. Parameter values are on a monthly basis.

We assume a lump sum tonnage tax of USD21,000 per year, which is in the upper end of current European tonnage tax regimes, i.e., $l^b = 1,750$ per month. We assume for simplicity that the project is financed by equity only, which implies a tonnage tax in percent of average profits that on average is below the 6% that Merk (2020) reports as an effective tax rate – derived from tonnage taxes – of corporate income in dry bulk shipping.

In the following we disregards risk aversion and let the price of risk $\lambda = 0$. This secures that all numbers are in real USD and no number is in risk adjusted value term, which is convenient for the discussion of the valuation of cash-transfers between shipowners and governments in the form of taxes, duties and subsidies. The effect of a positive price on a unit of risk, i.e., the effect of a risk averse shipowner, is discussed at the end of section six.

Based on observations of one year time charter rates from 1983:10 to 2014:07 Kou and Luo (2018) report the following mean estimates of the parameters for an Ornstein-Uhlenbeck process on an monthly basis: $\sigma = 71,130$, $\kappa = 0.0171$ and $\alpha = 606,060$. For the year 2014 they report an investment cost of USD59million for one Capesize vessel, i.e., $K = 59,000,000$.

Under a time-charter contract a ship owner does not pay voyage related costs. For simplicity assume that all uncertainty is related to the volatility in the time-charter freight rates, and let there be a fixed cost of USD 200,000 per month – representing non-voyage related operation costs and fixed overhead, i.e., $c^b = 200,000$.

In the following we assume that a regular tax system, which applies to domestic flag vessels, implies a proportional income tax of 24% and a depreciation rate of 10% annually (i.e., a monthly depreciation rate of approximately 0.00833). All cashflows are on a continuous time basis – in line with the above model.

Given these base case parameters the optimal threshold is USD1,014,035 if the ship is registered under a domestic flag paying full 24% tax. This corresponds to a time-charter rate of USD33,801 per day.

Alternatively, assume that the vessel is registered under a flag of convenience and pays a tonnage tax of USD1,750 per month. The tonnage tax implies an investment threshold of USD915,056 – which corresponds to a time-charter rate of USD30,502 per day. The expected net present value of future taxes is in this case about USD250,000, if calculated at the time of investment – which corresponds to a proportional income tax rate of about 0.35%. The low percentage follows from the high income at the time of investment. Only the pure tonnage tax is included. Other duties like harbour fees, that are be based on the ship's tonnage, may add to the tax percentage of a tonnage-based system.

The insight from the previous section can be used to create a zero-cost tax reform that reduces the investment trigger and makes a domestic flag equally attractive as a flag of convenience. That is, the shipowner pays the proportional income tax of 24%, given a 10% depreciation rate, and the difference between the net present values of expected future tax payments, under the regular income tax regime and the tonnage tax regime, is used to subsidise the investment cost. That is, on the one hand, the shipowner switches away from a low tonnage tax regime to a regular income tax regime (increased risk sharing). On the other hand, the investment cost K is reduced by the government's subsidy (reduced switching cost). Assuming a zero-cost package, the investment threshold drops to USD881,126 – which corresponds to a time-charter rate of USD29,371per day. That is, the zero-cost package implies an investment threshold that is 3.8% lower than the investment threshold in the case of a tonnage tax. The government's tax incomes have equal present value.

5.2. Zero-cost packages for Capesize, Panamax and Handysize investments

In addition to the parameters above, Kou and Luo report median values of the Ornstein-Uhlenbeck process's parameters for the Capesize market and mean and median values for the Panamax and Handysize markets. If the markets are characterised by the median instead of the mean estimated parameter values of the price process, this contribute to reducing the value of the real options to invest. This follows since the median puts less weight on extreme values than the mean. In the following we apply the mean values as reported by Kou and Luo.

Table 2 shows the estimated mean parameters for the Capesize, Panamax and Handysize markets, the discount rate[8] and investment cost. The non-voyage operation costs are estimates close to levels reported by market observers. The investment trigger levels in the case of a tonnage tax, $p^*_{Ton.}$, and the investment trigger in the case of a zero-cost package, p^*_{ZC}, are derived as described above. The annual Panamax tonnage tax is set to USD10,800 and the annual Handysize tonnage tax is set to USD7,200. The numbers in the table below are on a monthly basis.[9] The column "$\Delta\%$" shows the percentage reduction from the tonnage tax to the zero-cost package thresholds.

Table 2. Parameter values and investment thresholds under a tonnage tax and a zero-cost tax package for dry bulk markets investments.

	O-U-parameters			**Disc.**	**Inv.**	**Op.**	**Ton.**	**Base case thresholds**		
Market	κ	α	σ	ρ	K	c^b	l^b	$p^*_{Ton.BC}$	$p^*_{ZC,BC}$	$\Delta\%$
Capesize	0.0171	606.06′	71.13′	0.007	59′′	200′	1750	30,502	29,371	−3.7%
Panamax	0.0154	378.47′	36.05′	0.007	33′′	165′	900	18,529	18,004	−2.8%
Handysize	0.0105	267.26′	16.81′	0.007	20.5′′	150′	600	12,404	12,203	−1.6%

For all markets the thresholds of the structured zero-cost packages are below the tonnage tax regime's investment threshold. For the Panamax and Handysize the reduction is smaller than for the Capesize. For these markets the real option values are lower due to lower standard deviation and despite a somewhat weaker mean reversion. The Marshallian levels for the Suezmax, Panamax and Handysize tonnage tax cases are respectively USD21,199 per day, USD14,582 per day and USD11,145 per day. That is, for the Handysize tonnage tax case the threshold is closer to the Marshallian level, which leaves less room for a significant reduction in the investment threshold from a zero-cost tax package.

The zero-cost package turns part of the uncertain future tax cashflow into a certain investment subsidy. Cashflow taxation, in our case represented by an instant depreciation of the investment cost, implies a threshold, $p^*_{Cashflow}$, equal to the no-tax case, $p^*_{neutral}$. That is, cashflow taxation is a non-distorting taxation system in this model setup. This is in line with the findings of Niemann for the geometric Brownian motion specification. Instant depreciation in the Capesize case, regardless of the rate of taxation under ordinary taxation, implies a threshold of USD30,411. Note that the non-distorted level is lower than the tonnage tax threshold. The zero-cost package threshold may be higher or lower than the neutral tax threshold. However, the Marshallian level is a lower bound to the zero-cost package. That is, in the case of volatility and a positive tonnage tax;

$$p^*_{Marshallian} < p^*_{No-tax} = p^*_{Neutral} = p^*_{Cashflow} < p^*_{Tonnage} \quad (11)$$

$$p^*_{Marshallian} < p^*_{ZeroCost} < p^*_{Tonnage} \quad (12)$$

The zero-cost package threshold may be lower than the no-tax threshold, and still the expected future tax income in the zero-cost-package case can be positive equal to the net present value of the tonnage tax. That is, the zero-cost package may represent a distortion to the optimal investment strategy under neutral taxation. This will typically be the case if the tonnage tax is low and volatility is high. The zero-cost tax package combines the security of an up-front subsidy and the volatility reducing effect of a proportional income tax regime. Investment cost is reduced (due to the subsidy), and the cash flow volatility is subdued (due to the introduction of a proportional tax), which both contribute to a reduction in investment thresholds.

6. A zero-cost package for a green transformation

Flags of convenience, and the widespread use of favorable tonnage tax systems among leading shipping nations, means that international sea transport is heavily subsidized compared to conventional industries that pay regular income taxes. (Merk 2020). International shipping probably attracts too much capital over time relative to peers, due to low taxes. That is, low taxes are likely to entail overinvestments in environmentally harmful conventional fossil fuel technologies in the maritime sector over time. If this hypothesis is correct, sea transport becomes too inexpensive, which boost international trade and adversely affects the economic geography of global manufacturing. Over-allocation of capital to the maritime industry, and excess international trade, probably have a negative environmental footprint.

If capital, due to tax subsidies, is excessively inexpensive, a structured zero-cost tax package that increases the willingness to invest in new tonnage is, from a macroeconomic perspective, undesirable. However, a temporary structured zero-cost tax package may be a useful instrument considering the need for speeding up the green transformation. For long-haul shipping the risks related to investing in novel and partly untested low- and zero carbon technologies, are high. The gains from introducing new technology and solutions may be substantial from an environmental point of view. However, the gains from a shipowner's point of view – if any – are often low.

Sustainable investments can be facilitated by switching existing tax subsidies towards sustainability and by introducing tax regimes that dampen private uncertainty and thereby reduce the value of waiting to invest.

6.1. A zero-cost package under higher uncertainty

A green transformation of the maritime industry may change the dynamics and the predictability of future cashflows. Table 3 shows, for the three shipping segments, the effects on the investment thresholds of an increase in the standard deviation parameter σ. We let the standard deviation in the high volatility case, σ_{High}, be two times the standard deviation in the base case, σ_{BC}. The base case thresholds in Table 3 are the same as in Table 2 – the numbers are repeated to facilitate comparison. The tax neutral thresholds, $p^*_{Neu.BC}$, are also included.

Table 3. Investment thresholds under a tonnage tax regime and a zero-cost tax package for base case (BC) parameters and high volatility.

	Standard dev.		Base case thresholds			High volatility thresholds			
Market	σ_{BC}	σ_{High}	$p^*_{Ton.BC}$	$p^*_{Neu.BC}$	$p^*_{ZC,BC}$	$p^*_{Ton.h.\sigma}$	$p^*_{Neu.h.\sigma}$	$p^*_{ZC,h.\sigma}$	Δ%
Capesize	*71.13′*	142,26′	30,502	30,411	29,371	40,353	40,263	38,053	−5.7%
Panamax	*36.05′*	72,10′	18,529	18,481	18,004	23,485	23,440	22,357	−4,8%
Handysize	*16.81′*	33.62′	12,404	12,373	12,203	14,614	14,587	14,119	−3.4%

The high volatility thresholds, for the tonnage tax cases, $p^*_{Ton.h.\sigma}$, for the tax neutral cases, $p^*_{Neu.h.\sigma}$, and the zero-cost packages, $p^*_{ZC,h.\sigma}$, are all higher than in the base case. The thresholds for the zero-cost packages remain lower than in the tonnage tax cases and the tax neutral cases. The difference in thresholds between the tonnage tax cases and the zero-cost package cases has increased due to higher volatility.

6.2. A zero-cost package under reduced mean reversion

The green transformation of the industry may reduce predictability and reduced mean reversion of freight rates. This may typically be the case if technological and economic uncertainty imply that it is tougher to make qualified individual investment decisions, which on an aggregate level makes it harder for the market to return to a long-run equilibrium. As discussed above, changes in mean reversion affects both the variance and the expected mean of the time-charter freight rate process.

Table 4 shows the effects on the investment thresholds from a reduction in the mean reversion parameter κ, given the high standard deviation. We let the mean reversion in the reduced reversion case, κ_{MR}, be half the reversion in the base case, κ_{BC}. The reduced mean reversion thresholds, for the tonnage tax cases, $p^*_{Ton.MR.}$, the neutral cases, $p^*_{Neu.MR}$, and the zero-cost packages, $p^*_{ZC.MR}$, are all lower than in the high volatility case. The thresholds for the zero-cost packages remain lower than in the tonnage tax cases and the tax neutral cases.

Table 4. Investment thresholds under a tonnage tax regime and a zero-cost tax package in the high volatility cases ($h.\sigma$) and reduced mean reversion (MR).

	Mean reversion		High volatility thresholds			+ Low mean reversion thresholds			
Market	κ_{BC}	κ_{MR}	$p^*_{Ton.h.\sigma}$	$p^*_{Neu.h.\sigma}$	$p^*_{ZC,h.\sigma}$	$p^*_{Ton.MR.}$	$p^*_{Neu.MR}$	$p^*_{ZC.MR}$	$\Delta\%$
Capesize	0.0171	0.0086	40,353	40,263	38,053	39,615	39,551	37,150	−6.2%
Panamax	0.0154	0.0077	23,485	23,440	22,357	22,882	22,850	21,665	−5.3%
Handysize	0.0105	0.0053	14,614	14,587	14,119	14,122	14,103	13,590	−3.7%

Note that a change in the mean reversion parameter changes the Marshallian level,[10] e.g., in the Handysize investment case the lower mean reversion reduces the Marshallian level from USD11,145 per day to USD10,474 per day. That is, the Handysize zero-cost threshold in Table 4 is 29.7% higher than the Marshallian level, whereas in the high volatility case the zero-cost threshold is 26.7% higher than the Marshallian level.

6.3. The rate of depreciation and the design of a zero-cost package

The rate of depreciation may play a part in the construction of a zero-cost tax package, even though changes to the depreciation rate do not affect the zero-cost threshold. As discussed above, if a Capesize investment was made under normal corporation tax rules, at a proportional income tax of 24% and a depreciation rate of 10%, the threshold level, as discussed above, would be USD33,801. An instant depreciation ($\delta \to \infty$), i.e., a cashflow tax regime, pushes the threshold level down to USD30,411 – a reduction of 10.0%. A zero-cost package, combined with instant depreciation, push the threshold level down to USD29,371 – an additional reduction of 3.4%. This threshold level is identical to the threshold in the case of a regular income tax of 24%, with a 10% rate of depreciation, combined with a zero-cost tax package. However, the direct subsidies that bring the thresholds down to the same low level is lower in the cashflow case than in the regular income tax case, respectively USD2,962,263 and USD15,295,494, i.e., the direct subsidies represent respectively 5.0% and 25.9% of the investment cost. That is, a high depreciation rate means that investment subsidies to a limited degree are accounted for in public budgets. This may be a useful property for increasing the probability of a tax reform.

6.4. Threshold levels and the expected first passage time

Due to the mean reversion nature of cashflows, only marginal changes to the threshold levels, especially if the threshold levels are far from the long-run mean, may imply a significant change in the expected first passage time, i.e., the expected time until the optimal investment threshold is reached. Table 5 shows the expected first passage time, $\bar{\theta}^*$, under the condition that the current freight rate is equal to the long-run mean.

Table 5. The expected first passage time until the optimal investment threshold is reached.

	Base case			High volatility			+ Low mean reversion		
Market	$\bar{\theta}^*_{Ton.BC}$	$\bar{\theta}^*_{ZC,BC}$	Δyrs	$\bar{\theta}^*_{Ton.h.\sigma}$	$\bar{\theta}^*_{ZC,h.\sigma}$	Δyrs	$\bar{\theta}^*_{Ton.MR.}$	$\bar{\theta}^*_{ZC.MR}$	Δyrs
Capesize	4.5	3.9	−0.6	4.4	3.7	−0.7	5.5	4.7	−0.8
Panamax	5.5	4.9	−0.6	5.1	4.3	−0.8	6.0	5.2	−0.8
Handysize	8.6	7.9	−0.7	6.6	5.9	−0.7	7.8	6.9	−0.9

Higher volatility implies higher thresholds, but the likelihood that a given threshold is reached increases as well. Lower mean reversion reduces the expected first passage time.

In the simulations, an introduction of a zero-cost tax package reduces the expected time to investment. For all markets, and for all cases, the decline in the expected time is between 7 and 11 months, i.e., 8% to 16%. This partly illustrate the potential for stimulating green investments in shipping via tax reforms. However, the effects of a zero-cost tax package are sensitive to the assumed dynamics for the time-charter freight rate, the structure of the model and estimated parameter values.

6.5. The effects of risk aversion

For clarity, risk aversion has so far been left out of the discussion. However, risk aversion is a key factor that affect investment behaviour and the effect of investment subsidies.

Shipowners and governments hardly have the same attitude towards freight rate risk. In the following assume that the government offers a subsidy based on a risk neutral evaluation of a zero-cost tax package. Assume that the shipowner is risk averse. Let risk aversion be represented by a positive price on a unit of risk, equal in all markets, given by $\lambda = 0.05$.[11]

The Capesize investment threshold under risk aversion in the tonnage tax case is USD38,968 per day and under an investment subsidy USD35,298 per day. The expected first passage times are respectively 10.8 years and 7.6 years. That is, the reduction in terms of expected passage time due to the zero-cost tax package is 3.2 years or 29.3%.

Table 6 below shows the investment thresholds, and the expected first passage times until the optimal investment threshold is reached, for base case parameter values and risk aversion. A higher price on a unit of risk, i.e., higher risk aversion, increases the difference between the tonnage tax and the zero-cost package thresholds. It also increases the expected first passage times and spreads in the expected first passage times between the tonnage tax and the zero-cost package.

Table 6. Investment threshold and expected first passage time under a positive price on a unit of risk.

Base case parameter values and λ=*0.05*						
Market	$\overline{P}^*_{Ton.BC}$	$\overline{P}^*_{ZC,BC}$	$\Delta\%$	$\overline{\theta}^*_{Ton.h.\sigma}$	$\overline{\theta}^*_{ZC,h.\sigma}$	Δyrs
Capesize	38,968	35,298	−9.4%	10.8	7.6	−3.2
Panamax	23,425	21,499	−8.2%	13.7	9.9	−3.8
Handysize	15,192	14,253	−6.2%	21.2	16.0	−5.2

7. Conclusions

According to the literature on investment incentives for inducing early investments, direct upfront subsidies are more efficient than tax reductions – due to the effect on the time value of flexibility. Contrary to this result, coastal states try to attract shipping investments by offering zero income tax combined with a marginal tonnage tax. In theory, tonnage taxes have a distorting effect on investment thresholds, since there is no sharing of risk between shipowners and the government. That is, the tonnage tax system is not neutral with respect to investment behaviour. The actual distortion is, however, limited due to the low level of most tonnage taxes.

Today's tonnage tax regimes represent significant subsidies to international sea transportation – compared to any business that pays full regular income tax. In order to promote sustainable investments, we argue that this subsidy can better be applied as an up-front subsidy on sustainable investments combined with the return of shipping to a regular income tax regime. This reduces the investment cost and depresses the volatility of future after-tax profits. Both reduce investment thresholds and the expected time to investment.

A zero-cost tax package may complement ongoing international environmental and tax related initiatives. In December 2021 OECD released the Global anti-Base Erosion (GloBE) rules under Pillar Two, which will secure a global minimum corporate tax rate of 15% for multinational companies with revenues above EUR750 million. The rules ensure that these companies pay at least 15% tax on income from each of the jurisdictions in which they operate. International maritime shipping is excluded from the GloBE-rules. According to a published commentary to the GloBE-rules' article 3.3, issued 14. March 2022, international shipping is excluded because the industry often operates under tax regimes outside the scope of corporate income tax, e.g., tonnage tax regimes, and to include it in the GloBE-rules would "…raise policy questions in light of the policy choices of these jurisdictions.".

The commentary argues that the advantages of tonnage taxes are less volatile tax outcomes for shipping and a more stable basis for long term investment. Our model shows the contrary – the tonnage tax system creates the least stable system for long term investment among the systems studied. The key to the success of the tonnage tax system from a shipowner's point of view is the low level of tax costs – not the creation of stability. The tonnage tax does not contribute to sharing of risk between shipowners and governments. The lack of convincing arguments for the special tax treatment of the maritime industry may suggest that international shipping will be included in the GloBE-rules in future revisions.

EU is not happy about the current speed of new GHG emission cut initiatives from IMO. Late 2021 the European Commission suggested to include maritime emissions in the EU Emissions Trading System (ETS). This unilateral initiative was triggered by IMO's failure to introduce a global system for GHG emission pricing. 50% of the emissions from voyages starting or ending outside of the EU (extra-EU-voyages), all emissions that occur when ships are at berth in EU ports and 100% of GHG emissions from intra-EU trades will according to the suggestion be subject to the EU ETS. 29 June 2022 the EU Council supported the move to include maritime shipping in the EU ETS. 18. December 2022 the Council and the EU Parliament, in a provisional deal, agreed to include maritime shipping emissions within the scope of the EU ETS – with full effect in 2026. To include the extra-EU-voyages in the EU ETS may be a breach of the freedom-of-the-seas principle, given that EU de facto will tax GHG emissions in international waters from non-EU flagged vessels.

The OECD's GloBE-rules and the EU-ETS initiatives may be prewarnings that sustainable pricing of GHG emissions and the reestablishment of regular tax regimes are parts of a future maritime industry. A zero-cost tax package as outlined above may help smooth the transitions from fossil fuels to low- and zero GHG emission technologies, and from low tonnage tax to regular income tax regimes.

International shipping is dominated by tonnage under flags of convenience or under equivalent international registers of conventional flag states. A transfer from one register to another is generally straightforward, as discussed in Chondrokouki and Tsekrekos, 2022, Kavussanos and Tsekrekos, 2011 – including a transfer from a flag of convenience to a traditional flag. Some changes to safety standards or ownership may apply for switching flags. However, conventional flag requirements are probably no major obstacles for introducing zero-cost tax packages.

From a sustainable investment point of view, a zero-cost tax package is especially relevant for new tonnage that incorporates low- or zero carbon technologies from the time of construction. To enjoy the investment subsidies, vessels may be required to be subject to conventional taxes and national flag from the time of delivery from the yard.

The results above are sensitive to model assumptions and parameter values. For example, only a moderate increase in the assumed discount rate or operation costs implies that the time until investment increases significantly.

This paper presents a conceptual model. It focuses on the effects of tax regimes and subsidies under volatility and mean reversion. The model should not be regarded as a fine-tuned model for investment decisions in the dry bulk market. However, potential extensions may add more realism to the model:

The arithmetic Ornstein-Uhlenbeck process represents a simplification of the complex dynamics of freight rates. The process probably overstates the downside risks and understates the potential for short-term peaks in freight rates. Alternative specifications are available, but they add to the analytical complexity.

The model only contains one real option – the option to invest. Ex-post the shipowner will often hold multiple real options, like expansion and modification, choice of flag, maintenance strategy, lay-up, market switch, and finally the option to scrap the vessel under volatile steel prices. On the one hand, to exclude these real options understates the value of the option to invest. On the other hand, the model's infinite horizon is a simplification that, though partly compensated for by the level of the depreciation rate, may overstate the value of the option to invest.

The dynamics of freight rates may be affected by changes to tax regimes, e.g., the shipowners' investment responses affect aggregate supply. This suggests that market equilibrium models may be helpful for understanding the full effect of tax reforms and investment incentives. An equilibrium setting may be useful for studying the effect of risk aversion and differences in risk tolerance between shipowners and governments. An equilibrium setting may also be useful for evaluating the environmental impact of tax reforms.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix.

Deriving the first passage time of an Ornstein-Uhlenbeck process

Define the process $Z_t = P_t - \alpha$, where P_t is the Ornstein-Uhlenbeck process (1) above. This implies that Z_t follows the Ornstein-Uhlenbeck process

$$dZ_t = -\kappa Z_t dt + \sigma \ dB_t \tag{A-1}$$

Assume $P_0 \sim N\left(\alpha, \sigma^2/2\kappa\right)$, which gives unconditional moments $E[P_t] = \alpha$ and $Var[P_t] = \sigma^2/2\kappa$. Define an alternative time unite $\tau = t/\kappa$. Let for this time unit the mean reversion be unity and the standard deviation, $\breve{\sigma}$, is given by equality in unconditional variance for equal time horizon, i.e.,

$$Var[P_t] = \sigma^2 \Big/ 2\kappa = Var[P_{\kappa\tau}] = \breve{\sigma}^2 \Big/ 2 \tag{A-2}$$

It follows that $\breve{\sigma} = \sqrt{\sigma^2/\kappa}$. Equation (A-1) for the alternative time unit is then

$$dZ_t = -Z_t dt + \breve{\sigma} dB_t \tag{A-3}$$

The first-passage time in terms of the alternative time unit is

$$\tau_{p^*} = inf\{t \geq 0 : z_t = p^* - \alpha > 0\} \quad \text{(A-4)}$$

A precise representation of the expected first passage time is given by

$$E[\tau_{p^*}|\mathscr{F}_t] = \frac{1}{2}\sum_{n=1}^{\infty} \frac{\sqrt{2^n}\left(\frac{p^*-\alpha}{\breve{\sigma}}\right)^n}{n!}\Gamma\left(\frac{n}{2}\right) \quad \text{(A-5)}$$

for $z_0 = 0$. See Ricciardi and Sato (1988) equation (9) and theorem 2 (p 48). In terms of the original time unit the expected first passage time is given by

$$E[\theta^*|\mathscr{F}_t] = \frac{1}{\kappa}E[\tau_{p^*}|\mathscr{F}_t] = \frac{1}{2\kappa}\sum_{n=1}^{\infty} \frac{\sqrt{2^n}\left(\frac{p^*-\alpha}{\sqrt{\sigma^2/2\kappa}}\right)^n}{n!}\Gamma\left(\frac{n}{2}\right) \quad \text{(A-6)}$$

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1 UN's convention on the law of the sea, article 87 (freedom of the seas) and 92 (status of ships). Notable exceptions are the US Jones Act and limitations by coastal states to the access to domestic short-sea trades and national safety and environmental standards.

2 Whereas payable excise duties typically are affected by operations decision, e.g. greenhouse gas taxes are affected by the choice of fuel and speed, the tonnage tax is unaffected by operations decisions. In the case that an excise duty is independent of operations decisions, an excise duty and a tonnage tax may be equivalent.

3 The general solution contains two constants (Abramowitz and Stegun, 1972). One constant can be determined by the boarder condition that the value of the real options to invest should be zero in the case that the freight rate approaches zero. See Sodal et al. (2008) for the solution to a similar mathematical problem.

4 The value of the constant, *A*, and the optimal trigger level for investing in the new technology, p^{a*}, can be determined by value matching and smooth pasting conditions. See Dixit (1993). That is, at the optimal time for exercising the option to invest, θ^*, the value before investing, minus the investment cost, should equal the value after the

investment: $V_a(p^{a*}) = V_p(p^*) - K$, where $V_p(p^*) = e^{\rho t}\Phi_t^p(p^*)$, and the marginal change in the value functions from a change in the model's underlying process, p_t, immediately before and after the investment, should be equal: $V_a{}'(p^*) = V_p{}'(p^*)$.

5 In this section we rely on numerical examples for illustrating the effects of changes to parameter values on thresholds and first passage times. Note that closed form analytical solutions are not available for the effects of changes to parameter values, given that the constant *A* in equation (8) only is constant for a given set of parameter values. A new set of parameter values requires a renewed estimation of the constant *A* – based on value matching and high contact conditions.

6 See Tsekrekos (2010) and Tvedt (2022) for a more detailed discussions for slightly different mean reversion processes.

7 Note that the equivalence only holds for an excise duty or subsidy on entry that do not affect operations. This is the case for the standard investment incentive real option model (Penning 2000), but in a maritime shipping context this may not be the case, e.g. environmental excise duties that typically are targeted at changing operations behavior.

8 Kou and Luo apply different discount rates for between markets. Here we apply the same annual discount rate of 8.5% for all markets. The discount rate is lower than in Kou and Luo. A high discount rate would in this model, and for the given parameter values, implied a low probability of reaching the investment thresholds.

9 The tonnage tax numbers are in the upper range of a typical European tonnage tax. To avoid model complexity, due to leverage, the equity ratio in the simulations is assumed to be 100%. In real cases tonnage tax is payable for equity, whereas the holders of the debt pay regular taxes on income from interests received. That is, the debt ratio will affect the percentage of the tonnage tax relative to profits payable to the holders of the equity.

10 The dependence of the parameter κ follows from the property of the conditional expected value of the mean reversion process, i.e., $E[P_\tau|\mathscr{F}_t] = \left(\alpha - \frac{\sigma^2}{2\kappa}\right)\left(1 - e^{-\kappa(\tau - t)}\right) + e^{-\kappa(\tau - t)}P_t$.

11 For this level of λ Capesize and Panamax investment thresholds are somewhat lower and the Handysize investment threshold is slightly higher than the ROT thresholds reported by Kou and Luo. That is, the chosen price on a unit of risk appears to be a reasonable calibration of the model.