Journal of Environmental Economics and Management 110 (2021) 102517

Contents lists available at ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Carbon pricing of international transport fuels: Impacts on carbon emissions and trade activity☆

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ARTICLE INFO

JEL classification:
F14
F18
F64
H23
H87
Q54
Q56

Keywords:
CO_2 emissions
Maritime trade
Carbon taxation
Feebate

ABSTRACT

We study the impacts of carbon taxation of international transport fuels on CO_2 emissions and trade activity, focusing on maritime transport, which constitutes the most important international trade transport activity. Our estimated bunker price elasticities range from −0.03 to −0.42. For the current level of international trade, a global tax of US$ 40 per ton of CO_2 will reduce CO_2 emissions by 7.65% for the heaviest traded products (at the 6-digit HS level of aggregation) transported by sea. The greatest CO_2 emission reductions are for products with relatively low value-to-weight ratios such as fossil fuels and ores. Using our estimates, we present a plan with a gradual increase in the carbon tax, including some transition to zero emissions vessels, for reaching the emissions target of the International Maritime Organization by 2050. We compare the reduction in CO_2 emissions with a carbon tax policy with CO_2 reductions with a feebate policy.

1. Introduction

To limit drastic climate change and its devastating consequences, it is necessary to implement appropriate and optimal policy instruments in core economic sectors to reduce greenhouse gas (GHG) emissions at a global scale. No international transport activity today faces any meaningful tax on the CO_2 it emits. This has at least three adverse consequences for the shipping sector, which are the main concerns of this study. The *first* is a higher than optimal activity in international shipping (types of vessels and their technologies, their travel routes and distances, travel time, and the amounts and types of goods being transported). The *second* is too high consumption of fuels per ton-nautical mile and fuels with high carbon content, causing CO_2 emissions that are too high. The *third* is the

☆ We are grateful for the comments received during the Carbon Pricing Leadership Coalition (CPLC) Research Conference in New Delhi, India, February 14–15, 2019; the January 2020 American Economic Association meetings in San Diego, CA, USA; the University of Rochester's Virtual International Trade & Macro Seminar; and March 4–5, 2021 CESifo Energy and Climate Economics Conference. We are also very thankful for suggestions and comments from Jonas Teusch and Kurt Van Dender, and to Manuel Arellano for his advice on the econometrics. This paper has been greatly improved thanks to the comments and suggestions of the editor and two referees. Ian Young thanks the Integrated Marine Observing System and the Australian Research Council (ARC grant no. DP160100738) for funding. We are the only authors responsible for the contents of this paper. Any opinions and conclusions expressed herein are those of the authors and do not necessarily represent the views of the World Bank Group. All errors are our own.

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https://doi.org/10.1016/j.jeem.2021.102517
Received 12 December 2020; Received in revised form 19 June 2021; Accepted 9 August 2021
Available online 14 August 2021
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missed opportunity of raising fiscal revenues from international shipping, a critical problem for many low-income countries with low tax revenue collection (see Keen et al. (2013) for further arguments).

Today, the shares of global CO_2 emissions due to international aviation and shipping are about 2.5% each. For the transport of international goods, sea transport dominates. According to Cristea et al. (2013), in 2004, 51% of CO_2 emissions from international trade resulted from sea freight, 27% from air freight, and 22% from land (road and rail) transport. While people-oriented transport represents 85% of the aviation sector's revenues (although a lower share of ton-km), 90% of the revenues of international sea transport come from goods transport. In the Appendix, we describe stylized facts of the maritime sector in more detail.

This study aims to contribute to improving understanding of how and by how much CO_2 emissions from maritime transport can be reduced by implementing a carbon tax. As far as we know, this is the first theoretical and econometric study to analyze the impacts of changes in bunker fuel prices, which proxy carbon taxation, on global international trade and global CO_2 emissions resulting from this trade. We use a comprehensive panel dataset for products at the 6-digit HS level of aggregation covering the years 2004–2017.[1] UNCTAD (2009) indicates that fuel costs account for 50%–60% of total ship operating costs depending on the type of ship and service (see also Gohari et al. (2018)). Since carbon taxes are not today in place, we use changes in the bunker price to simulate the effects of a possible carbon tax in the maritime sector.

This work also seeks to provide guidance to the international community regarding how to attribute responsibility per country/region and traded product type to their shares in global CO_2 emissions in the maritime sector, and how carbon taxation could affect CO_2 emissions. We estimate CO_2 emissions levels from maritime transport of products at the 6-digit HS level of aggregation.

This study considers all possible worldwide country pairs, except landlocked countries, that trade the heaviest products (at the 6-digit HS level of aggregation). These products make up more than 75% of the total weight of internationally traded goods transported by sea. This paper focuses on three main topics. *First*, we theoretically and empirically analyze the impact of changes in bunker prices on trade (intensive margin) and carbon emissions. *Second*, we make carbon emission projections for 2030 and 2050 as a result of: i) a one-time implementation of a carbon tax of US$ 40, and ii) gradual increases (step-up) in carbon tax levels every 5 years toward 2050. The latter approach represents a scheme for gradually phasing out fossil fuel vessels from 2040 toward zero-emission vessels (ZEVs)[2] in response to a continuous increase in the carbon tax up to 2050. This carbon price policy might lead to the sufficient phase-out of fossil fuels by 2050 to reach the target pledged by the IMO for 2050 by providing the necessary incentives to switch to more efficient vessels and zero-carbon fuels, as well as funding for R&D into new zero-emissions technologies.

Third, we study how a feebate policy (similar to Parry et al. (2021)) could affect international trade and carbon emissions, and how it compares to a carbon tax policy with respect to the magnitude of carbon emissions reductions.

There are three main alternatives for implementing a carbon price for goods transport: i) carbon taxation (a given tax per unit of CO_2 emissions); ii) cap-and-trade schemes for trading rights to emit carbon at a (positive) carbon price established in the carbon market; and iii) a feebate scheme, as introduced by Parry et al. (2021), which is based on carbon taxation but redistributes the potential tax revenue via "benchmark" rebates.

In the first two policies, the carbon price represents the marginal cost of carbon emissions related to bunker fuel consumption by the maritime sector. Under carbon taxation, substantial revenues can be raised, some of which can be transferred to the poorest and most remote countries with high and increased trade costs (which could lead to less product variety of imports and exports and lower traded quantities), and/or to support purposes related to global climate finance. Offset or other cap-and-trade schemes are less likely to raise similar revenues considering the experience of the European Union's cap-and-trade program, which has had overly generous allocations of emissions allowances to regulated entities.

Note also that a stable and increasing carbon tax represents a better signal for green investments in more fuel-efficient and more technologically advanced ship types than a cap-and-trade scheme, where the carbon price can be much more volatile and unpredictable. It is important to emphasize that an efficient strategy to implement a carbon tax on bunker fuel requires this tax to be universal and applied worldwide to avoid free-riding problems and carbon leakage (Elliott et al. (2010); Parry et al. (2021)).

In our study, we consider carbon taxation, but our results and conclusions hold if carbon pricing was implemented through a cap-and-trade or offset scheme (given a positive and reasonably stable global carbon price for international transport fuels), instead of through a carbon tax. Furthermore, note that our analysis elucidates how carbon emissions can gradually be reduced when imposing a carbon tax on bunker fuels. The crucial issue we consider is how to immediately contribute to reducing the current high GHG emissions rate toward long-run sustainable levels.

GHG emissions from international transport have recently become a central issue of interest for various reasons. More countries and other international stakeholders are increasingly recognizing the adverse consequences mentioned above. The International Maritime Organization (IMO), a United Nations organ, regulates the international maritime sector. In April 2018, the IMO pledged to reduce GHG emissions from international shipping to half the 2008 level (1135 million tons) by 2050 (see IMO (2018a); UNCTAD (2018), section 5B). The Fourth IMO GHG Study (IMO (2020)) projects that without carbon pricing, and depending on future economic and energy scenarios and certain vessel efficiency improvements, maritime emissions will likely be between 90% and 130% of the 2008 emissions by 2050.

In Section 2 we present the theoretical model. Section 3 describes the data, econometric model, and results of the effect of a carbon tax on international seaborne trade. Section 4 outlines the estimations of the potential reductions in CO_2 emissions that could result

[1] Smith et al. (2016) conducted a simulation analysis to determine how different levels of carbon prices under different scenarios could contribute to reducing CO_2 emissions.

[2] This implies that vessels will use zero-carbon fuels including possibly hydrogen and ammonia.

from implementing carbon taxation to international maritime transport, an analysis of a stepping-up plan for reaching the IMO emissions target by 2050, and calculations on the possible financial resources that can be obtained from carbon taxation at the international level. Section 5 presents a feebate policy and projections of the effect of this policy on CO_2 emissions. Section 6 summarizes and concludes the paper, and presents policy recommendations. This paper includes an Appendix containing: 1) a description of the maritime sector and role of the IMO, 2) a review of the literature, 3) estimation results, 4) the Sargan tests, and 5) an extensive description of the feebate policy.

2. Theoretical model to analyze the effect of a carbon tax on international seaborne trade

2.1. Background

Our key analytical framework is based on recent international trade theory and serves as the basis for our econometric analysis of the possible impact of carbon tax per ton of fuel on the intensive margin of international trade, the choice of trading partners (and implicitly the distance the products will travel), and on carbon emissions.

We will not focus on the networking between firms on both sides of a trade transaction (Bernard and Moxnes (2018); Bernard et al. (2019a); Bernard et al. (2019b)), as complete data for all firms participating in international trade in all countries are not available to us.

One of the main distinctions between our work here and the canonical gravity models is that we consider the effect of carbon taxation on the combination of the quantity of trade of products at the 6-digit HS levels *times* the distance the exported product travels, and not aggregate flows of trade at the country level. Thus, exporters choose not only export quantities but also the distance to their importing countries to minimize costs, including transportation costs. We have also one practical reason for estimating the elasticity of weight – country distance with respect to bunker fuel price. This is, since we calculate CO_2 from maritime trade, we need to take into consideration the carbon emissions intensities by ship type, which are measured in ton-kilometers. Calculation of impacts of carbon taxation on carbon emissions from maritime transport then requires us to obtain the elasticities of ton-kilometers with respect to the fuel price for each 6-digit HS product category. We nonetheless consider several of the variables that are usually used for the estimation of gravity models. Our studied heaviest products are those that have been consistently the heaviest in each of the years between 2009 and 2017.

Even though our analysis and empirical implementation uses country data instead of firm data, our theoretical model follows a bottom-up analysis from (exporting) firms' behavior to countries' determination of trade of products at the 6-digit HS level of aggregation.

We follow closely the theoretical underpinnings of activities of multi-product firms in international trade (see Bernard et al. (2010, 2011); Arkolakis and Muendler (2010); Eckel and Neary (2010); Mayer et al. (2014); and Eckel et al. (2015)). In our framework, consumers in the importing countries choose which and how much of each product variety to import.

In contrast to Armington (1969) and Shapiro (2016) who assume that each country produces only one variety and that varieties are different across countries; we consider that each country produces and exports a set of product varieties. This approach will help us to determine i) what product varieties (at the 6-digit level) that are traded between the different country pairs could be most affected by the implementation of a carbon tax; and ii) which of these products are the highest emitters of CO_2. This approach is crucial in order to attribute as correctly as possible the responsibility of CO_2 emissions by country, industry, and product type.

Bernard et al. (2010, 2011) pioneered the modeling of asymmetries between products from the demand side. In their work, firms consider their productivity levels and product–market–specific demand shocks, before deciding to enter international markets. A firm then determines the scale and scope of sales in different markets, and leads to a negative correlation between prices and output prototypes. On the other hand, Eckel and Neary (2010) consider asymmetries between products on the cost side (of producing different varieties), and find that price and output prototypes are always positively correlated. We here integrate demand and supply approaches by assuming that the marginal costs of producing a variety of products and fuel costs determine the scale and scope of international trade, including the total distances that product varieties travel, which implicitly implies choosing the trading partners.

Our main contribution to the theoretical literature is to consider a typical consumer in an importing country as maximizing a two-level utility function that depends on the consumer's consumption levels (weight) of product varieties, from different industries. We model the typical exporting multi-product firm in any given industry making decisions about i) the scale and scope of its product varieties taking into account the marginal costs of each of its multi-products; and 2) the importing countries (i.e., distance) where the products will be sold. We follow the approach of Eckel and Neary (2010) and Mayer et al. (2014) by considering that firms that produce several product varieties, face "product ladder" costs. Each firm then has a core product (its "core competence"), with lower efficiency (higher costs) for products further away from this core.

We here define the core competence in which the cost linkages are *both* across product varieties and trading partners. Thus, an exporting firm's decisions about the weights and the distances that any of its product variety travels, depend on the marginal cost of *both* producing such a product variety, and delivering it to the specific importing country.

We do not consider a general equilibrium model as in Eckel and Neary (2010), to analyze factor markets as an important channel for transmission of external shocks. Our available data does not allow us to ascertain how factor prices and employment at our product level of disaggregation will be affected by changes in fuel prices and determine the general-equilibrium adjustments. Thus, we focus on a partial-equilibrium model (and reduced-form) analysis of how bunker price changes (or carbon taxes) affect international trade and CO_2 emissions of different products at the 6-digit HS levels of disaggregation.

To sum up, our theoretical model considers the impacts of changes in the bunker costs per metric ton on the traded weight – country distance of different 6-digit products.

2.2. The theoretical model[3]

2.2.1. Demand

On the demand side, we follow closely Eckel and Neary (2010), in which consumers in the importing countries buy different product varieties i from a total of N_j varieties in each industry j. There are m importing countries and k exporting countries. The typical consumer in each of the m importing countries maximizes a *two-level utility function* by choosing a level of consumption $q_m(i;j)$ of the product variety i produced in industry j. We thus define the product variety $i \in [1, N_j]$, where N_j is the measure of product variety i in industry j; and j changes over each interval [0,1].

At the lower level, the typical consumer in a given importing country m has a quadratic utility function that depends on all the varieties this consumer chooses from industry j, defined by:

$$u\left[q_m(0;j), \dots, q_m(N_j;j)\right] = a_m \int_0^{N_j} q_m(i,j)di - \frac{1}{2}b_m\left\{(1-\xi_m)\int_0^{N_j} q_m(i,j)^2 di + \xi_m\left[\int_0^{N_j} q_m(i,j)di\right]^2\right\}, \tag{1}$$

where $\int_0^{N_j} q_m(i,j)di$ in equation (1) is the consumption of all varieties in a given industry j by this typical consumer in the importing country m. The utility parameters a_m, b_m and ξ_m are assumed to be non-negative. They denote the consumers' maximum willingness to pay, the inverse market size, and the inverse degree of product differentiation, respectively. If $\xi_m = 1$, the goods are homogeneous (perfect substitutes), so that demand only depends on aggregate industry output. $\xi = 0$ describes the case when the demand for each good is completely independent of other goods.

The upper utility levels for this typical consumer in each of our m importing countries are defined by an additive function of a continuum of quadratic sub-utility functions, where each sub-utility $u[q_m(0;j)\} \dots, q_m(N_j;j)]$ (as defined in equation (1)) corresponds to industry j:

$$U\left[(u\{q_m(0;1), \dots, q_m(N_1;1)\}), \dots, \left(u\left\{q_m(0;j), \dots, q_m\left(N_j;j\right)\right\}\right)\right] = \int_{j=0}^{1} u\left\{q_m(0;j), \dots, q_m\left(N_j;j\right)\right\}dj. \tag{2}$$

The problem for the typical consumer in each importing country is to maximize a two-tier utility function with respect to $q(i,j)$:

$$U\left[(u\{q_m(0;1), \dots, q_m(N_1;1)\}), \dots, \left(u\left\{q_m(0;j), \dots, q_m\left(N_j;j\right)\right\}\right)\right] = \int_{j=0}^{1}\left\{a_m\int_0^{N_j} q_m(i,j)di - \frac{1}{2}b_m\left[(1-\xi_m)\int_0^{N_j} q_m(i,j)^2 di + \xi_m\left\{\int_0^{N_j} q_m(i,j)di\right\}^2\right]\right\}dj; \tag{3}$$

subject to the following budget constraint:

$$\int_0^1 \int_0^{N_j} p(i,j)^* q_m(i,j)di\, dj \leq E_m; \tag{4}$$

where $p(i,j)$ is the (global) price of product variety i from industry j[4]; and E_m denotes the expenditure by the typical consumer of an importing country m on a set of differentiated products from different industries.

To solve this optimization problem (equations (3) and (4)), we use the Lagrange multiplier method with λ as the Lagrangian multiplier (i.e., marginal utility of income). We assume that the budget constraint (4) is binding and solve the following Lagrangian maximization problem:

[3] The model is presented in detail in Mundaca (2021).

[4] Good markets are fully integrated (Eckel and Neary (2010)).

$$\max_{q_m(i,j),\lambda} \int_{j=0}^{1} \left(u\{q_m(0;1),\ldots,q_m(N_1;1)\}\right),\ldots,\left(u\left\{q_m(0;j),\ldots,q_m\left(N_j;j\right)\right\}\right)dj - \lambda\left[\int_{j=0}^{1}\int_{0}^{N_j} p(i,j)^{*}q_m(i,j)di\,dj - E_m\right]. \tag{5}$$

after considering equations (3) and (4).

The typical consumer's optimal choice of variety i's amount (in any given industry j) is given by the first-order condition after maximizing (5) with respect to demand of any variety *i* at any given industry *j*:

$$a_m - b_m\left[(1-\xi_m)q_m(i) + \xi_m\int_0^N q_m(i)di\right] - \lambda p(i) = 0 \tag{6}$$

The individual (inverse) linear demand function for product variety *i* is:

$$\lambda p(i) = a_m - b_m\left[(1-\xi_m)q_m(i) + \xi_m\int_0^N q_m(i)di\right] \tag{7}$$

We can assume, without losing generality, that the budget constraint is always binding and $\lambda = 1$. We also consider that consumers are identical within any importing country and across *m* importing countries. This assumption allows us to drop the subscript *m* of the utility parameters a_m, b_m and ξ_m.

To move from individual to aggregate demands, we assume that, the price of a variety *i* is the same everywhere; and there are *L* consumers (with identical preferences) in each of *k* importing countries. Thus, the aggregate demand for variety *i* in country *m*, will be equal to $q(i,m)\times L$. Thus, the inverse of the *global demand* for product variety *i* in any given industry *j*, that each exporting firm will face, as:

$$p(i) = a - b\left[(1-\xi)\int_m\{q(i,m)\times L\}dm + \xi\int_0^N\int_m\{q(i,m)\times L\}dmdi\right]; \tag{8}$$

where $\int_m\{q(i,m)\times L\}dm$ is the global demand for product variety *i*.

2.2.2. Supply

The typical firm *z* may export the product variety *i* to only *M* countries, thus $M \leq m$ countries. In addition, the exporting firm *z* in any given industry *j* and country *k*, produces a number of product varieties equal to ρ_z, where $0 \leq \rho_z \leq N_j$. These are to be exported to a portfolio of importing countries *M* located at specific distances (δ_{Mk}) from the country of the exporting firm. For a given level of the bunker fuel prices, exporters choose where to export (i.e., the size of *M*), which implicitly allows them to minimize the total distance δ_{Mk} their products need to travel, and minimize costs.

If we normalize the number of consumers *L* to be equal to 1, we define each firm *z* as maximizing the following profit function:

$$\pi_z(k) = \int_M\int_0^{\rho_z}[\{p(i)\} - C_z(i,M;\delta_{Mk})] * q_z(i,M,z)\,di\,dM; \tag{9}$$

where *p(i)* is the market price of product variety *i* in any given industry *j*; $C_z(i,M;\delta_{Mk})$ comprises the following costs: i) the shipping costs (related to the insurance rates, tariffs, border and port prices, bunker oil price, the type of ship used to transport the product variety *i*, and the distance between the exporter's country and the importer's country (δ_{Mk})) per unit of the exported product variety *i* from firm *z* (located in exporting country *k*) to importing country *M*. For given geographical locations of the importing countries, fuel prices are expected to have substantial influence on the exporter's costs. And ii) the marginal cost that exporting firm *z* faces to produce variety *i,* and is related to its core-competitiveness of producing a specific product variety *i* (in a given industry *j*). Marginal cost increases as the exported product variety moves away from the "core competence" of the exporting firm at which its marginal cost is lowest. Indeed, this "core-competence" here plays a crucial role for the net effect that the bunker price can have on the structure of trade and finally on carbon emissions.

We solve for the amount of product variety *i* to be exported by the typical firm *z* (in a given industry *j* and country *k*) to country *M*, $q_z(i,M)$, when it faces the global demand $\int_m\{q(i,m)\}dm$ for variety *i.* We shall assume that firms (like firm *z*) play a single-Cournot game, choosing simultaneously the number of product varieties (ρ_z), the quantity of each variety to produce and export, and the set of importing countries (and implicitly δ_{Mk}), taking into account that rival firms do not change their scale or scope. Keep in mind that the global price for product variety *i* will be *p(i)*. Furthermore, $q_z(i,M) > 0$ when its marginal profit of producing variety at the equilibrium price *p(i)* is also greater than zero, and this demanded variety *i* is within the firm *z*'s varieties scope of production (ρ_z) and countries scope (M). Hence, we can substitute the limit to ρ_z for N_z and M for m; and add a constraint that $q_z(i,m) > 0$ only if it is optimal for firm z to produce that variety and export it to the specific importing country, otherwise $q_z(i,m) = 0$.

Substituting equation (8) into equation (9), and taking the first-order condition for the typical firm z in a given industry j, we obtain:

$$0 \leq \frac{\partial \pi_{z'}}{\partial q_{z'}(i',m,z')} = a - 2b(1-\xi)q_{z'}(i',m,z') - 2b\xi q_{z'}(i',m,z') - b\left[(1-\xi)\int_{z\neq z'}\int_m q_z(i',m,z)dmdz + \xi\left\{\int_m \int_{i\neq i'}^{N_z} q_{z'}(i,m,z')didm + \int_m \int_{z\neq z'} \int_{i\neq i'}^{N_z} q_z(i,m,z)didzdm\right\}\right] - C_{z'}(i',m,z';\delta_{Mk}) \perp q_{z'}(i',m,z'); \tag{10}$$

where the operator $\perp$ ensures that either $\frac{\partial \pi_{z'}}{\partial q_{z'}(i',m,z')} = 0$ (i.e. the firm z' is producing a variety i optimally) or $q_{z'}(i',m,z') = 0$ (i.e. the firm z' does not produce variety i). This complementary condition accounts for firm z' selecting the number of varieties (ρ_z) to produce. Setting equation (10) equal to zero and solving for $q_{z'}(i',m,z')$ we obtain:

$$q_{z'}(i',m,z') = \frac{a - b\left[(1-\xi)\int_{z\neq z'}\int_m q_z(i',m,z)dmdz + \xi\left\{\int_m \int_{i\neq i'}^{N_z} q_{z'}(i,m,z')didm + \int_m \int_{z\neq z'} \int_{i\neq i'}^{N_z} q_z(i,m,z)didzdm\right\}\right]}{2b} - \frac{C_{z'}(i,m,z';\delta_{Mk})}{2b}. \tag{11}$$

From equation (11) we can derive:

a. The aggregate output for the typical firm z in industry j is:

$$Q_z = \int_m \int_{i\neq i'}^{N_z} q_{z'}(i,m,z')didm + \int_m q_{z'}(i',m,z')dm$$

b. The total global demand for product variety i in industry j is:

$$D(i,j) = \int_{z\neq z'}\int_m q_z(i',m,z)dmdz + \int_m q_{z'}(i',m,z')dm$$

c. The global demand for all the product varieties in industry j is:

$$F(j) = \int_m \int_{z\neq z'} \int_{i\neq i'}^{N_z} q_z(i,m,z)didzdm + Q_z$$

Thus, equation (11) shows the unique Cournot solution (for nonnegative values of a and b) with multiple firms. It further indicates that the amount of product variety i $q_{z'}(i',m,z')$, that firm z will export depends on its different costs, its own aggregate output (exports) of all other varieties in industry j, the global demand for variety i (not satisfied by firm z), and global demand for all varieties that are part of industry j (not satisfied by firm z).

3. The econometric analysis and data

3.1. The empirical strategy

We use the System of Generalized Methods of Moments (GMM) (Arellano and Bover (1995) and Blundell and Bond (1998)) for panel data as our estimation method. Our econometric strategy is to instrument for the exchange rate, bunker price per ton of fuel, and marginal costs of producing product variety i. An ideal instrumental variable is highly correlated with these three variables but not with unobserved shocks to the traded weight of the traded products. However, it is challenging to find the most appropriate and effective instrumental variables. We selected as instruments: i) the number of terror attacks on oil fields, ii) level of trade backhaul multiplied by the distance between trading partners, and iii) average wind speed and wave heights in the travelling routes between country pairs trading products internationally using maritime transport.[5]

Note that we considered the theoretical foundations of the System GMM, which are to use lagged variables of the model (except the dependent variable) as instruments for the equation in first differences, and lagged variables in differences as instruments for the equation in levels. We tested the validity of the instruments using the Sargan test. Since our econometric relation includes the bunker price per metric ton of fuel, the exchange rate, and other relevant macro variables, no time-fixed effect is included to avoid problems pertaining to collinearity.

We also obtained two-step estimates, which yield theoretically robust results (Roodman (2009a)). In addition, by applying the two-step estimator, we could obtain a robust Sargan test (same as a robust Hansen J-test). This is important for testing the validity of the instruments (or over-identifying restrictions). The validity of the model also depends on testing the presence of first- and in particular, second-order autocorrelation in the error term, as De Hoyos and Sarafidis (2006) explained.

3.2. Data

As mentioned, our empirical analysis used country data, not firm data, considering that our theoretical model follows a bottom-up analysis from (exporting) firms' behavior to countries' determination of product trade at the 6-digit HS level of aggregation. We excluded all landlocked countries and close land-connected neighbors for which pure seaborne trade data are not applicable and thus reveal less the total seaborne trade transport costs.

We used the software World Integrated Trade Solution (WITS) developed by the World Bank to extract trade data from the United Nations Comtrade's database (see https://wits.worldbank.org). These data are copyrighted by the United Nations. The World Bank's software was created in collaboration with the United Nations Conference on Trade and Development (UNCTAD), International Trade Center (ITC), United Nations Statistical Division (UNSD), and World Trade Organization (WTO). WITS allows researchers to download data on imports and exports for products at the 6-digit HS level of aggregation (or a less detailed level) by year. Our final compiled data contains *bilateral international trade in terms of weight and value by product and year* at the 6-digit HS levels of aggregation.[6] Our original dataset consisted of approximately 3.9 million observations for the period 2002–2017, including worldwide trading country partners, and more than 6000 commodities at the 6-digit HS level of aggregation. We only considered products with the highest weight consistently each year during our period of study. These products account for more than 75% of the total weight of internationally traded goods transported by sea, and are thus highly significant in terms of their total fuel consumption and total carbon emissions from international maritime trade. Our selected 6-digit HS products belong to 21 industries (2-digit HS products). Since we only had data for bunker fuel prices from 2009, our analysis of the carbon tax covers the period between 2009 and 2017, implying that our dataset has around 1.9 million observations. Our analysis of the effects of the feebate policy on traded weight-distance instead covers the period between 2004 and 2017 with around 2.9 million observations. We did not include 2002 and 2003, as the data were less complete for those years.

In addition, we used data from the Center D'Études Prospectives et D'Informations Internationales (CEPII) called GeoDist. This dataset has an exhaustive set of gravity variables, developed by Mayer and Zignago (2005), which enables us to analyze difficulties in market access in global and regional trade flows. GeoDist can be found online (http://www.cepii.fr/anglaisgraph/bdd/distances.htm).

Here, *bunker price changes* are interpreted as proxies for changes in bunker fuel taxes. The bunker fuel price data (in US$ per metric ton) were available to us for the period between 2009 and 2017. Other relevant macro data at the country level come from the World Development Indicators of the World Bank. The data for the carbon intensities by vessel type for ships come from the International Transport Forum (ITF) at the OECD (see ITF (2018)).

The data for terrorism events come from the Global Terrorism Database (GTD (2019)) developed by the National Consortium for the Study of Terrorism and Responses to Terrorism (START) at the University of Maryland (2019). The source for backhaul trade is UNCTAD (2018) (https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=32363), and for wind speed and wave height, Ribal and Young (2019).

3.3. Econometric model and estimate of the effect of bunker price changes on the weight-distance for the heaviest products at the 6-digit HS level of aggregation

Our empirical specification is closely tied to our theoretical modeling. Each firm chooses how much of each variety to produce and to which countries to export. We studied econometrically the impacts of fuel price changes on the weight *times* shipping distance of traded goods (in ton-nautical miles). The distance is determined by the location of the importing and exporting countries.

We have no firm level data, only data for traded quantities at the 6-digit HS level of aggregation between country pairs (exporting countries versus importing countries). We interpret each data point on the traded quantity of product variety (6-digit HS level) between two countries as the aggregate demand from the importing country satisfied by the supply of the exporting country's aggregate

[5] We think these instruments are relevant and appropriate given the recent work of Baumeister and Hamilton (2019), who concluded that supply shocks such as the abovementioned geopolitical variables have been more important in accounting for historical oil price movements than found in previous studies such as by Kilian and Murphy (2012, 2014).

[6] We exclusively focused on choosing all possible importing countries and their corresponding exporting partner countries that trade the different 6-digit products.

decisions of its firms about exporting product variety *i*, and behaving as Cournot competitors when deciding on the quantity of exporting product variety *i*.

When considering the bunker price per ton of fuel, our proposed econometric model for bilateral trade between a pair of countries for a product variety at the *6-digit HS level of aggregation* is represented by the following empirical relation:

$$\ln q_{ijkmt} = \alpha_{11} + \beta_{11}\ln(Bunker\ price_t) + \lambda_{11}\ln(Exchange\ Rate_t) + \varsigma_{11}C_{kt} + a_{11}Q_{jt} + b_{11}D_{ijt} + c_{11}F_{jt} + \gamma_{11}IM_{mt} + \delta_{11}EX_{kt} + \mu_{ijkm} + \varphi_{ijkmt}. \quad (12)$$

Again, note that we did not include time-fixed effects to avoid collinearity problems with the bunker price and other macroeconomic variables. In equation (12), q_{ijkmt} is the weight-distance measure obtained by multiplying the weight of product variety of type *i* (i.e., a 6-digit product) from industry *j*, traded between importing country *m* and exporting country *k* at time *t*, *times* the distance between country *m* and country *k*. φ_{ijkmt} is a random disturbance term, and μ_{ijkm} is product/industry – importing/exporting fixed effects. Table 1 provides the definitions of the variables.

According to the theory, the marginal cost C_{kt} of a traded product decreases as the product variety (to be exported) moves closer to the "core competence" of the exporting firm at which its marginal cost is lowest. We do not have data on the marginal cost a typical exporting country *k* incurs to produce variety *i*. Therefore, in this study, the marginal cost of producing variety *i* is represented by the position of variety *i* in terms of its sales value compared to all varieties sold by country *k* in each year *t* to country partners (importers). Thus, for the triplet exporter-product variety-importer by year, the product variety with the lowest sales value is the lowest ranked (rank = n) product in the exporting country's product portfolio. The product variety with the second-lowest sales value is the second-lowest core product (rank = n-1), and so on. Chatterjee, Dix-Carneiro, and Vichyanond (2013) used a similar approach. Thus, according to our theory, the parameter β_{11} should be negative and ς_{11} positive.

Having defined the marginal costs C_{kt} of the traded products, we further grouped the sales value rankings (core-competence) into four categories: *Category 1* contains exported products closest to the core competence of the exporting country beyond the third quartile of the country's sales value. *Category 2* corresponds to products between the third quartile and median of the sales value. *Category 3* is the group with products between the median and first quartile of the sales value. C*ategory 4* comprises the products furthest away from this core competence or below the first quartile of the sales value. Thus, products in *category 1* have the lowest marginal costs, C_{kt}. We estimate equation (12) for each of these four core-competence ranking categories for our heaviest 6-digit HS level products. By comparing the four estimates for β_{11}, for example, we learn whether and how the effect of changes in bunker fuel price on the weight-distance of traded product *i* vary according to the exporting country's marginal cost of producing product *i*.

The Sargan statistical tests for our estimations are presented in the Appendix in Table A.4. The tests indicate that except for the industry *Plastics,* we cannot reject the null hypothesis that over-identifying restrictions are valid. In the Appendix, we also explain how we proceeded to optimally choose our instruments to avoid generating too many moment conditions. Because of space constraints, we do not present in the paper or Appendix the effects of other background variables such as the *exchange rate,* Q_{jt}, D_{ijt}, F_{jt}, marginal costs, relevant macroeconomic variables that are part of the matrices, IM_{nt}, EX_{kt}, or tests for the first- and second-order autocorrelation in the first-differenced residuals. However, these are available on request. Note that we needed to be careful when including countries' macro variables, since these are highly correlated with the exchange rate, which is a crucial variable in international trade.

We focus on explaining the empirical results of the impact of annual changes in the global average bunker price on the weight-distance of the heaviest products at the 6-digit HS level of aggregation traded bilaterally. These estimated elasticities, reported in Table A.3 in the Appendix, are crucial in predicting possible reductions in carbon emissions due to a carbon tax. We again interpret changes in the bunker prices as a measure of changes in a carbon tax.

The elasticities of weight *times* distance with respect to the bunker fuel price across our *four categories* (core-competence ranking categories) vary (for 6-digit HS products) from −0.03 (in the furniture industry) and −0.05 (in the automobile industry), to −0.4 (for ores) and −0.42 (for fossil fuels). Thus, the elasticities of traded weight-distance with respect to the bunker price vary greatly by industry. Fig. 1 illustrates these differences considering the average elasticities across different core competence measures of the products. Brancaccio et al. (2018) found similar elasticities for bulk ships.

The heaviest 6-digit products we considered constitute almost 75% of the total traded weight, implying the substantial impact of

Table 1
Definitions of variables.

VARIABLES	DEFINITIONS
q_{ijkmt}	Weight of product variety *i* (i.e., a product at the 6-digit HS level of aggregation) from industry *j* (i.e., 2-digit industry) traded between importing country *m* and exporting country *k* at time *t*, times the distance between country *m* and country *k*.
Exchange Rate$_t$	The value of the exporter's currency in terms of the importer's currency
EX_{kt}	Exporting country *k*'s characteristics in year *t*: level of GDP in US$ of 2010; inflation rate; population, 1st official language if a colonizer, if a colony; and/or other variables considered in gravity modeling
IM_{mt}	Importing country *m*'s characteristics in year *t*: level of GDP in US$; of 2010, inflation rate; population; 1st official language if a colonizer, if a colony; and/other variables considered in gravity modeling.
C_{kt}	The (log) of sales value of a 6-digit HS level product traded between two countries. The higher its value, the closer is the product to the core competence of the exporting country.
Q_{jt}	Total exports of all other varieties (but *i*) in industry *j* by exporting country *k* at time *t*.
D_{ijt}	Global demand for product variety *i* (not satisfied by country *k*) in industry *j* at time *t*.
F_{jt}	Global demand for all varieties in industry *j* at time *t* that is not satisfied by country *k*.

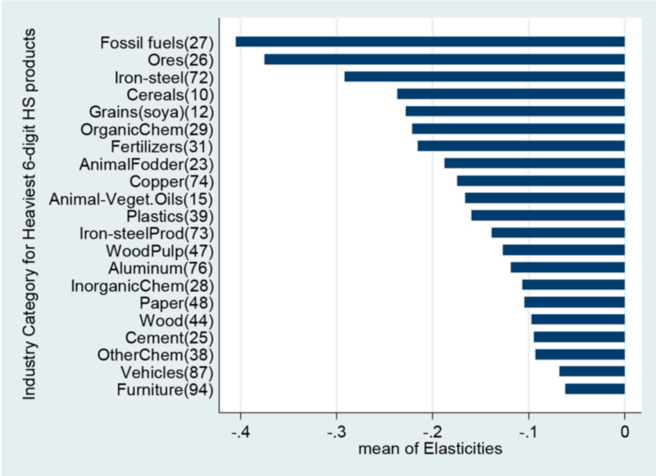

Fig. 1. Elasticities of weight-distance to changes in bunker prices for the heaviest products at the 6-digit HS level of aggregation by industry type.

fuel taxation on fuel consumption and carbon emissions for the maritime trade of these products, as the next section elaborates.

For the elasticity of weight–distance with respect to the marginal cost (i.e., parameter ς_{11} in equation (12)), we found that the further away a traded product variety moves from the core competence of its country's product portfolio, the larger the decrease in the traded weight–distance will be for that product.

Our estimates indicate that the elasticities of traded weight-distance with respect to the bunker price vary greatly, not only across the industries the 6-digit products belong to, but also according to the value of the traded product per kg. That is, the higher is the value of the traded product relative to its weight, the lower is the elasticity. Fig. 2 illustrates the elasticities and US$ (real for 2010) per kg of traded product by industry category. The vehicles and furniture industries have the highest values per kg and the lowest elasticities, while ores and fossil fuels have the lowest values per kg and highest elasticities. Thus, for products with high (low) weight to value ratios, fuel costs have a significant (minor) impact on their seaborne trade.

4. Estimation of changes in carbon emissions due to carbon taxation

CO_2 emissions and changes in such emissions as a result of increases in carbon prices depend on the type of product, and types of vessels with which the products are transported. To estimate CO_2 emissions, we used data on fuel CO_2 intensity per ton-km (i.e., grams CO_2 per ton-km) for eight types of vessels and the types of products they transport for international trade. These data come from the International Transport Forum (ITF) at the OECD (ITF (2018)). See Table 2. The ITF/OECD provides this carbon intensity index for every five years, with historical data since 2000 and projected figures up to 2050. These estimated emissions rates vary over time primarily according to the projected technological (vessel size, some fuel mix) and operational (route management, speed) efficiency for each ship category. There are also data on carbon intensities by *vessel size* for each vessel type. Here, we focus on the *average emissions* per vessel type to estimate average emission rates by vessel type as shown in Table 2, as we do not have data on which product varieties are transported by which ship sizes.

4.1. Methodology to calculate carbon emissions

Table 2 shows that the CO_2 emissions rates by vessel type, in grams per ton-km of freighted goods by 2030, vary substantially from a low value of 3.7 g for oil tankers to a high value of 33 g for vehicle carriers. Thus, assuming a single emissions rate for all ship types (as in Shapiro 2016) will lead to very large errors when calculating the carbon emissions for particular goods categories, which we avoid here. We used the data in Table 2 to estimate: i) the average annual CO_2 emissions between 2009 and 2017 (hereafter Business as Usual (BAU) CO_2 emissions) for our set of heavy 6-digit traded products, and ii) the average annual reductions in CO_2 emission that would have taken place if a carbon tax was implemented during this period (BAU emissions). It was then crucial to consider the ton-nautical miles or ton-km (and not just tons) from trading the heaviest (6-digit HS) products between all possible country pairs when estimating the elasticity of traded ton-nautical miles with respect to the bunker price per ton. These elasticities vary according to the core competence of the traded product, which we considered when estimating the total carbon emissions by product and in aggregate.

To calculate the CO_2 emissions for any given product type, we proceeded as follows:

a. Using the information in Table 2, we multiplied the carbon intensity (grams of CO_2 per ton-km) by the type of vessel transporting the specific product type, *times* the ton-km (converted from ton-nautical miles) for the traded product type.
b. Considering that 1 ton of bunker fuel consumption corresponds to emitting 3.11 tons of CO_2 (Olmer et al. (2017)), we calculated how the bunker fuel price per ton would change when introducing a carbon tax. Imposing a carbon tax of $US τ per ton of CO_2, will

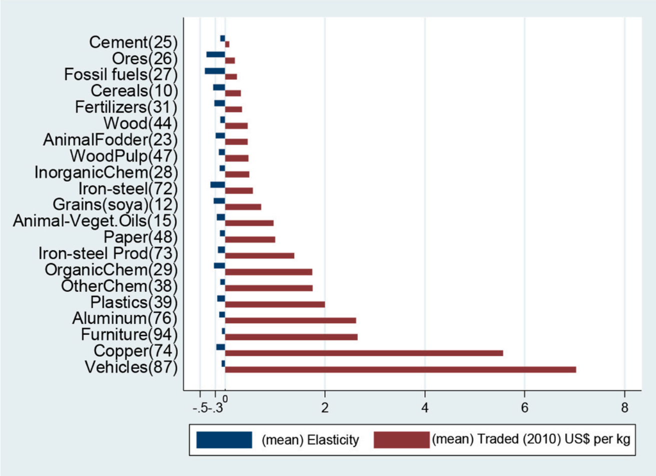

Fig. 2. Elasticities of weight-distance to changes in bunker prices for the heaviest products at the 6-digit HS level of aggregation by industry type and average trade values (in 2010 US$).

Table 2
Average carbon intensities by vessel type and transported product type.

Type of ship	Type of goods transported	Carbon Intensity (= grams CO_2/ ton-km)			
		2010	2015	2030	2050
(1)	(2)	(3)	(4)	(5)	(6)
Bulk carriers	Bulk agriculture, forestry, mining, minerals, non-ferrous metals, coal products	4.79	4.63	4.17	3.63
Container ships	Processed food, textiles, wearing apparel, leather products, wood products, paper, iron and steel, transport equipment, electronic equipment, machinery and equipment, other manufactured products	19.56	18.9	17.03	14.83
General cargo	Food products, fish, livestock	13.88	13.41	12.09	10.52
Oil tankers	Oil	4.32	4.17	3.76	3.27
LNG ships	Gas	14.37	13.88	12.51	11.27
Products tankers	Petroleum products	14.0	13.53	12.19	10.62
Chemical ships	Chemical products	10.29	9.94	8.96	7.8
Vehicle carriers	Vehicles (automobiles)	37.92	36.63	33.01	28.74

Source: International Transport Forum (ITF) (2018)

increase the bunker fuel price by US$ 3.11 $\times \tau$ per ton. A carbon tax of US$ 40 per ton of CO_2 would *increase the bunker fuel price* per ton of fuel consumption by *US$ 124.4* (= 3.11 (carbon content of 1 ton of bunker fuel) *times* US$ 40).[7] If the initial bunker price is US$ 450 per ton of fuel, the relative increase in the bunker price will be 124.4/450 = *0.27644* (or 27.64%) because of the US$ 40 of carbon tax per ton of fuel consumed.

c. We do not have data on the fuel consumption for each traded 6-digit HS product. To use procedure (b), we assumed that the bunker price elasticity with respect to the traded ton-nautical miles equals the bunker price elasticity with respect to bunker fuel consumption.
d. The *reduction* in CO_2 emissions for any product type, as a result of a US$ 40 carbon tax, was estimated by multiplying the following components: i) bunker price *elasticity* with respect to the traded ton-nautical miles for the specific product type (i.e., β_{11} in equation (12)); ii) relative increase in the bunker price, as calculated in (b) (e.g., *0.2764*); and iii) total CO_2 emissions for the given ton-km (or ton-nautical miles) of the traded product type, as indicated in (a).
e. The estimations in this section consider core competence with cost linkages across both product varieties and trading partners.

4.2. Carbon emissions in the maritime sector for heaviest products: BAU and with carbon tax

Table 4 presents our bottom-up carbon emissions calculations by industry. These estimates considered: i) the average annual

[7] Note that US$ 40 is in the lower boundary of a range for the optimal global carbon tax (US$ 40–80 per ton of CO_2) to be implemented from 2020 (Stern et al. (2017)).

Table 3
20 “trade triplets” (exporter-product-importer) with the highest CO_2 emissions from maritime transport, aggregated from 2009 to 2017.

6-digit HS Product code	Product	Importer country	Exporter country	Million tons CO_2
260111	Iron ore	China	Australia	162
260111	Iron ore	China	Brazil	40.9
120100	Soybeans	China	United States	40.0
270112	Coal	Japan	Australia	34.8
120100	Soybeans	China	Brazil	30.6
260111	Iron ore	Japan	Australia	26.3
270900	Petroleum	United States	Saudi Arabia	24.3
270900	Petroleum	Japan	Saudi Arabia	24.2
260111	Iron ore	Japan	Brazil	24.2
270112	Coal	China	Australia	19.4
270900	Petroleum	China	Saudi Arabia	19.4
270900	Petroleum	Korea, Rep.	Saudi Arabia	18.2
270900	Petroleum	Japan	United Arab Emirates	16.7
260111	Iron ore	Korea, Rep.	Australia	16.2
270112	Coal	Korea, Rep.	Australia	14.6
270900	Petroleum	United States	Iraq	13.1
270119	Coal	India	Australia	12.7
260111	Iron ore	China	India	11.7
271111	LNG	Mexico	United States	11.1
260111	Iron ore	China	South Africa	10.9

weight–distance (ton-nautical miles) of our heaviest 6-digit products, ii) average carbon intensities of the type of ship used to transport the different 6-digit products (see column 3 in Table 4) for our period of study (2009–2017),[8] iii) elasticities of the ton-nautical miles of traded 6-digit products between two countries with respect to the bunker fuel price, iv) that these elasticities vary according to the core competence of the traded 6-digit product, and v) that 1 ton of bunker fuel consumption corresponds to emitting 3.11 tons of CO_2.

Recall that the BAU activity level for each sector corresponds to the average annual activity levels between 2009 and 2017. We found that the BAU average annual carbon emissions from transporting our heaviest products at the 6-digit HS level of aggregation (belonging to 21 industries) were about 450 million tons of CO_2 (see column 4 in Table 4). This estimate is about half the total annual CO_2 emissions from the entire shipping sector over the same period (see e.g., IMO et al. (2015)).

The estimation of these emissions by 6-digit product also enabled us to estimate the emissions by an exporting or importing country. Fig. 3 shows the countries with the largest total carbon emissions resulting from their imports over the estimation period (2009–2017). As is evident, China is the greatest emitter, followed by Japan and the United States.

Table 3 presents the 20 trades of products at the 6-digit HS level of aggregation for individual importer-exporter pairs with the largest CO_2 emissions in their seaborne transport, aggregated from 2009 to 2017. These largest trade triplets are dominated by two goods categories—iron ore and fossil fuels—in addition to China’s imports of soybeans from the United States and Brazil. China and Japan dominate on the importer side, and Australia, Brazil, and Saudi Arabia on the exporter side.

Table 4 provides the estimates of total carbon emissions under BAU with no carbon tax (column 4). It also shows the potential average and percentage reductions of CO_2 emissions (BAU emissions) a year after a hypothetical implementation of a global carbon tax of US$ 40 per ton CO_2 on bunker fuel consumed in the international seaborne trade of the heaviest 6-digit HS products of the 21 industries they belong to. See columns 5 and 6, respectively.

Column 6 shows a reduction in total CO_2 emissions by 7.65% relative to BAU emissions. However, there are substantial differences by sector in these percentage reductions. The greatest reduction of about 17 million tons (or 11.5%) is for fossil fuels (by oil tankers), which also have the highest emissions of CO_2. This is followed by ores (10.4%), cereals (8.4%), iron and steel (8.3%), and fertilizers (8.1%). These goods categories are all heavy relative to their values (see Fig. 2), and will have the largest CO_2 emission reductions because as indicated above, fuel costs significantly impact their seaborne trade. In contrast, for goods with high value-to-weight ratios in our data, including motor vehicles and furniture, the percentage reductions in carbon emissions are much smaller (1.8% and 1%, respectively), because a carbon tax has much smaller impacts on their trade activity. Fig. 4 displays these emission reductions.

How would our results change when the bunker price (or oil price) varies? Our methodology, described in (b) in Section 4.1, allowed us to estimate the percentage reduction in emissions after a 1% increase in the bunker price. For a given carbon tax, a positive change in the bunker price would result in a small (large) decrease in carbon emissions if the initial bunker price level is already high (low).

4.3. *Projected CO_2 emissions: 2030 and 2050 with a one-time implementation of a carbon tax of US$ 40*

We present two estimates of possible CO_2 emissions reductions for 2030 and 2050. The *first* considers only technological progress in shipping up to 2030 and 2050. The *second* considers both technological progress and a carbon tax of US$ 40 per ton of CO_2. Tables 5

[8] We assume that the technological progress for each type of ship between 2009 and 2017, and consequently their emission intensities, has been equal to the average technological progress between 2010 and 2015.

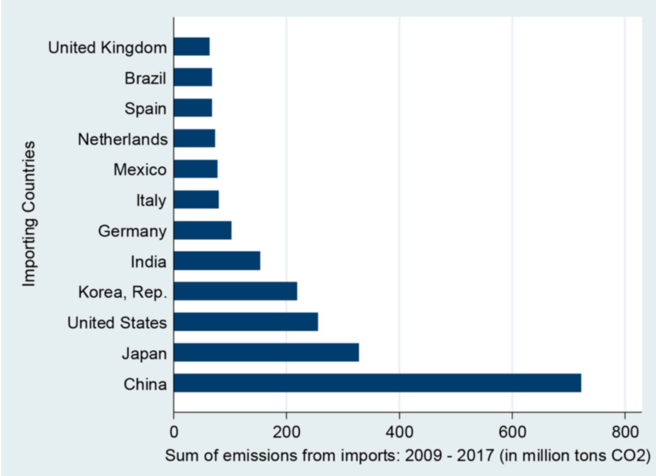

Fig. 3. Largest total carbon emissions from 2009 to 2017 by importing country.

Table 4
Estimated average annual CO_2 emissions and emission reductions in the maritime sector: BAU (2009–2017) and with hypothetical carbon tax of US$ 40/ton CO_2.

6-digit HS products per industry (1)	Industry category (2-digit HS products) (2)	Average CO_2 emissions intensities: 2010–2015 (grams per ton-km)* (3)	Average CO_2 emissions in BAU with *only* technology for 2010–2015 (1000 tons) (4)	Reductions in CO_2 emissions in BAU with US$ 40 carbon tax (1000 tons) (5)	Percent reduction in CO_2 emissions in BAU with US $ 40 carbon tax (%) (6)
Cereals	10	11.98	23196	1957	8.43
Grains, seeds (soya)	12	19.23	20627	1138	5.51
Animal-Vegetable oils	15	19.23	9323	486	5.21
Animal fodder	23	19.23	17651	1000	5.66
Salt/stone/cement	25	4.71	12894	399	3.08
Ores	26	4.71	53397	5557	10.4
Fossil fuels	27	4.245	149379	17243	11.54
Inorganic chemicals	28	10.12	7945	314	3.94
Organic chemicals	29	10.12	8005	551	6.87
Fertilizers	31	7.42	7110	575	8.08
Other chemical products	38	19.23	5040	141	2.78
Plastics	39	19.23	16719	761	4.54
Wood	44	11.98	12532	396	3.15
Wood pulp	47	11.98	7678	271	3.52
Paper	48	19.23	8792	246	2.79
Iron and steel	72	11.98	23761	1978	8.32
Iron and steel products	73	19.23	11831	458	3.86
Copper	74	19.23	2190	144	6.54
Aluminum	76	19.23	4053	159	3.9
Vehicles	87	37.28	20750	372	1.79
Furniture	94	19.23	26963	283	1.04
Total			**449846**	**34418**	**7.65**

* *Source for column 3*: International Transport Forum (ITF) (2018)

and 6, respectively, present these results.

The estimates were obtained following the methodology in Section 4.1. In addition, we assumed: i) The annual average ton-nautical miles between 2009 and 2017 remain unchanged in 2030 and 2050, ii) the average carbon intensities for the type of ship used to transport the different 6-digit products follow Table 2 for 2030 (column 3 in Table 5) and 2050 (column 3 in Table 6), iii) the estimated elasticities of ton-nautical miles of the bilateral trade of 6-digit products with respect to the bunker price (obtained from estimating equation (12) and presented in Table A.3 in the Appendix), and iv) 1 ton of bunker fuel consumption corresponds to emitting 3.11 tons

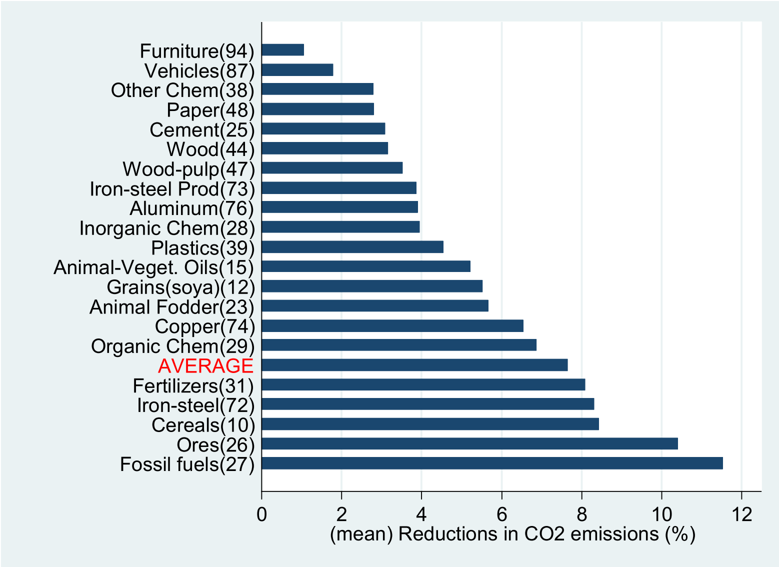

Fig. 4. Estimated possible average CO_2 emission reductions from a US$ 40/ton CO_2 tax for the heaviest products at the 6-digit HS level of aggregation by industry type for 2009–2017.

of CO_2.

In Table 5, the reductions in carbon emissions due to technological improvements from (2010–2015) to 2030 relative to BAU are presented in column 5. The reductions in emissions due to only carbon tax in 2030 are shown in column 6. Column 7 presents the percentage reduction in carbon emissions in 2030 as a result of technology improvements until 2030 and a US$ 40 carbon tax put into effect in 2030 relative to the BAU emissions.

Table 6 shows similar projections for 2050. The assessed carbon emissions intensities in column 3 are now lower because of further technological progress until 2050. As before, column 4 shows CO_2 emissions resulting from only progress in shipping technology (i.e., no carbon tax), while column 5 displays the CO_2 reductions due to this technological progress from BAU. Column 6 shows emissions reductions due to a US$ 40 per ton CO_2 carbon tax in 2050. Column 7 shows the total percentage reductions in CO_2 emissions due to both technological progress and carbon tax relative to the BAU emissions.

The total percentage reduction in emissions for our heaviest products is 18.2% in 2030 and 28.8% in 2050 relative to the BAU emissions (the annual average for 2009–2017).

Consider how our results relate to the IMO's GHG emission reduction goals for international shipping, which is 50% by 2050 relative to its 2008 level (1135 million tons of CO_2). Our estimates indicate that one could by 2050 achieve only a 28.8% reduction in CO_2 emissions from the annual average levels between 2009 and 2017 from trading only the heaviest products. Note that this 28.8% reduction requires at least a *one-time carbon tax of US$ 40 per ton CO_2*, technological and efficiency improvements in maritime transport as predicted by the ITF/OECD, and no increase in the average annual trade relative to the period 2009–2017. It is difficult to see how IMO will be able to reach its 2050 emissions target without implementing a carbon tax of at least US$ 40 per ton CO_2 or higher. See Smith et al. (2016) for similar conclusions. In the next section, we analyze how these projections for 2030 and 2050 could change under the assumption of gradually increasing carbon tax and possibility of phasing in ZEVs and fuel mixes for these vessels.

4.4. Possible emission reductions with gradual changes in carbon taxation levels and reaching the IMO target by 2050 for heavy products

How can IMO otherwise reach its emissions target of reducing the 2008 shipping emissions by 50% by 2050? Parry et al. (2021) have also designed a pathway, assuming a carbon tax increasing up to US$ 75 per ton CO_2 by 2030 and fixed from then on. They assume this tax would sufficiently incentivize improving ship technology and the phasing-in of ZEVs from 2030 with the corresponding fuels for these vehicles.

We alternatively propose a pathway based on our abovementioned econometric results combining a gradual increase in the carbon price and the ITF/OECD projections of technological and operational efficiency up to 2050 (see Table 2) for the shipping fleet. In this case, Table 7 shows how emissions from the maritime transport of heavy goods will be decreased by 2030, 2040, and 2050 given an increase in the carbon tax on shipping by US$ 20 per 5-year interval. That is, the tax starts at US$ 20 in 2025, US$ 80 by 2040 and reaches US$ 120 by 2050.[9] Our plan implies lower carbon taxes by 2025 and 2030 than Parry et al. (2021), which are US$ 37.5 and US $ 75, respectively. Our schedule will reduce carbon emissions by about 18% by 2030, 29% by 2040, and 39% by 2050 for heavy

[9] Stern et al. (2017) recommended a carbon price range between US$ 50 to US$ 100 for 2030.

Table 5
Estimated annual CO_2 emissions and emissions reductions in 2030 as a result of a one-time implementation of a US$ 40/ton CO_2 carbon tax and shipping technology improvements.

6-digit HS products per industry (1)	Industry category (2-digit HS products) (2)	CO_2 emissions intensities in 2030 (grams per ton-km)* (3)	CO_2 emissions with only technology progress up to 2030 *No carbon tax* (1000 tons) (4)	Reduction in CO_2 emissions from *only* technology progress up to 2030[a] (1000 tons) (5)	Reduction in CO_2 emissions as a result of a US$ 40 CO_2 tax in 2030 (1000 tons) (6)	CO_2 emissions reduction from both technology progress & CO_2 tax in 2030 (%) (7)
Cereals	10	10.60	20542	2654	1732	18.91
Grains, seeds (soya)	12	17.03	18268	2359	1007	16.32
Animal-Vegetable oils	15	17.03	8257	1066	430	16.05
Animal fodder	23	17.03	15632	2018	885	16.45
Salt/stone/cement	25	4.17	11418	1476	352	14.19
Ores	26	4.17	47282	6115	4920	20.67
Fossil fuels	27	3.96	132359	17019	15277	21.62
Inorganic chemicals	28	8.96	7037	907	277	14.92
Organic chemicals	29	8.96	7090	914	487	17.51
Fertilizers	31	6.57	6295	815	508	18.62
Other chemicals products	38	17.03	4463	576	124	13.91
Plastics	39	17.03	14806	1912	673	15.46
Wood	44	10.60	11098	1433	350	14.23
Wood pulp	47	10.60	6799	878	239	14.56
Paper	48	17.03	7786	1005	217	13.91
Iron and steel	72	10.60	21042	2718	1751	18.81
Iron and steel products	73	17.03	10478	1353	405	14.86
Copper	74	17.03	1940	250	127	17.24
Aluminum	76	17.03	3589	463	140	14.89
Vehicles	87	33.01	18379	2370	329	13.01
Furniture	94	17.03	23879	3084	250	12.36
Total			**398449**	**51396**	**30487**	**18.2**

[a] Technology progress from the period (2010–2015) until 2030. This column can be calculated as the difference between column 4 in Table 4 and column 4 in Table 5.
* *Source*: International Transport Forum (ITF) (2018)

products. Note that the emission reductions for 2030 are similar to those with a one-time US$ 40 carbon tax. For 2050, the one-time carbon tax is significantly smaller than with the gradual carbon tax changes.

These predictions are based on two assumptions:

1) The emission intensities of the shipping fleet follow the ITF/OECD's projections (Table 2), which are not adjusted for responses of the carbon intensities per ton-nautical miles to the stepping-up of the carbon tax over time[10]. These are central to the results of Parry et al. (2021).[11] In their work, endogenous ship carbon intensities and increases in the carbon tax up to a ceiling of US$ 75 by 2030 will be sufficient to ensure a complete phasing-in of ZEVs from then on. Note that the complete phasing-in of ZEVs as early as 2030 is uncertain, since bulk, tanker, and container fleets are all relatively new today and their lifespans average around 30 years. See Table A.1 in the Appendix for more details.
2) The projected seaborne trade (in ton-nautical miles) up to 2050 is assumed to be equal to our BAU trade activity: 2009–2017.

Our first assumption is likely to under-predict actual emission *reductions* by 2050, while the second probably over-predicts them. Therefore, we can safely argue that our estimated projections are realistic. Note also that the schedule described in Table 7 will not be far from reaching the IMO's GHG emissions target for the maritime sector by 2050: 61% of our BAU emissions will be remaining. In our plan, the carbon tax will increase to US$ 120 by 2050 to retain the incentives to take necessary measures to further reduce CO_2

[10] We then have only exogenous ship carbon intensities.
[11] The predicted emissions reductions in Parry et al. (2021) follow from five factors: 1) Improved technological efficiency in new vessels, 2) improved efficiency for used vessels, 3) improved operational efficiency for ships, 4) shifting to larger ships and higher load factors, and 5) shifting trade away from heavy goods and distant trade partners and reduced trade volume. Our estimated impacts follow from the last of these five factors, plus exogenous ship efficiency improvements in Table 2.

Table 6
Estimated annual CO_2 emissions and emissions reductions in 2050 as a result of a one-time implementation of a US$ 40/ton CO_2 carbon tax and shipping technology improvements.

6-digit HS products per industry (1)	Industry category (2-digit HS products) (2)	CO_2 emissions intensities in 2050 (grams per ton-km)* (3)	CO_2 emissions with technology progress up to 2050 *No carbon tax* (1000 tons) (4)	Reduction in CO_2 emissions from *only* technology progress up to 2050[a] (1000 tons) (5)	Reduction in CO_2 emissions as a result of a US$ 40 CO_2 tax in 2050 (1000 tons) (6)	CO_2 emissions reduction from both technology progress & US$40 CO_2 tax in 2050 (%) (7)
Cereals	10	9.229	17885	5310	1509	29.4
Grains, seeds (soya)	12	14.826	15906	4721	878	27.14
Animal-Vegetable oils	15	14.826	7189	2134	375	26.9
Animal fodder	23	14.826	13611	4040	771	27.25
Salt/stone/cement	25	3.631	9941	2953	308	25.28
Ores	26	3.631	41167	12230	4284	30.93
Fossil fuels	27	3.448	115243	34136	13302	31.76
Inorganic chemicals	28	7.799	6127	1817	242	25.92
Organic chemicals	29	7.799	6173	1834	425	28.18
Fertilizers	31	5.719	5481	1629	444	29.14
Other chemical products	38	14.826	3886	1153	109	25.04
Plastics	39	14.826	12891	3827	587	26.4
Wood	44	9.229	9663	2869	305	25.32
Wood pulp	47	9.229	5920	1757	209	25.61
Paper	48	14.826	6779	2012	190	25.05
Iron and steel	72	9.229	18321	5439	1526	29.31
Iron and steel products	73	14.826	9123	2708	353	25.87
Copper	74	14.826	1689	502	112	27.94
Aluminum	76	14.826	3125	927	122	25.9
Vehicles	87	28.743	16002	4747	287	24.26
Furniture	94	14.826	20791	6172	218	23.7
Total			**346923**	**102923**	**26546**	**28.78**

[a] Technology progress from the period (2010–2015) until 2050. This column can be calculated as the difference between column 4 in Table 4 and column 4 in Table 6.
* *Source*: International Transport Forum (ITF) (2018)

emissions, such as closing the gap between fossil fuel vessels and ZEVs. This carbon tax by 2050 is higher than Parry et al. (2021) (i.e., US$ 75), and a result of assuming both a lower initial carbon tax and a later introduction of this tax than Parry et al. (2021). To fully achieve the IMO target, one can add to our schedule phasing-in ZEVs from 2040, when our carbon tax will reach US$ 80/ton CO_2. Assuming that 20% of old (and least efficient) ships are replaced with ZEVs over the 2040–2050 period,[12] carbon emissions from the maritime fleet will be reduced by (at least) an additional 12.2% in 2050 of BAU emissions.[13] Thus, in 2050, there will be 49% of our BAU emissions, corresponding to the IMO target for 2050.

To conclude, the following remarks apply to our proposal:

i) In our view, stepping-up the carbon tax for global implementation in the maritime sector—US$ 40 per ton CO_2 by 2030 and US$ 80 by 2040—is a good alternative to plans that include a more rapid carbon tax increase, especially based on political challenges and uncertain expectations about the profitability of ZEVs. Specifically, many of the IMO's low-income member countries may resist too rapid increases in the carbon tax.
ii) There is a higher likelihood that ZEVs will become economically competitive with fossil fuel-based ships in 2040 rather than in 2030. A substantial amount of technological progress and funding are required before this target is achieved.
iii) In the Appendix, we show that a large fraction of the current shipping fleet is relatively new. Since the expected lifetime of maritime transport vessels is about 30 years, few vessels may be ready for replacement (by ZEVs) over the period 2030–2040. By 2040, many more vessels will be ready for replacement.

[12] This 20% replacement is a realistic assumption given the current age distribution of the shipping fleet. See Table A.1 in the Appendix.
[13] 12.2% = (0.20 (ZEVs) × 0.61 (BAU remaining emissions)) × 100.

Table 7
Stepping-up carbon taxation and CO_2 emissions reductions (Carbon tax increase of US$ 20 per 5-year period starting in 2025 and ending in 2050)[a].

Industry category (2-digit HS product) (1)	CO_2 emissions in 2030 with US$ 40 tax(1000 tons) (2)	Reduction by 2030 from BAU (2009–2017) (%) (3)	CO_2 emissions in 2040 with US$ 40 tax (1000 tons) (4)	Reduction by 2040 from BAU (2009–2017) (%) (5)	CO_2 emissions in 2050 with US$ 40 tax (1000 tons) (6)	Reduction by 2050 from BAU (2009–2017) (%) (7)
10	18851	18.73	16138	30.42	13816	40.43
12	17278	16.23	15246	26.08	13453	34.77
15	7834	15.97	6934	25.62	6138	34.16
23	14763	16.36	13007	26.31	11460	35.07
25	11072	14.13	10015	22.32	9059	29.74
26	42506	20.39	35645	33.24	29891	44.02
27	117490	21.34	97347	34.83	80657	46
28	6763	14.87	6064	23.66	5438	31.54
29	6612	17.39	5753	28.12	5006	37.45
31	5799	18.43	4983	29.91	4281	39.78
38	4341	13.86	3938	21.85	3573	29.09
39	14144	15.39	12605	24.6	11234	32.8
44	10753	14.18	9721	22.43	8787	29.88
47	6564	14.51	5911	23.01	5323	30.66
48	7572	13.87	6869	21.86	6232	29.11
72	19332	18.63	16569	30.26	14202	40.23
73	10079	14.8	9045	23.54	8117	31.38
74	1815	17.12	1585	27.64	1384	36.82
76	3451	14.83	3096	23.6	2777	31.46
87	18053	12.99	16546	20.25	15165	26.91
94	23635	12.34	21825	19.05	20153	25.25
SUM	**368578**	**18.06**	**318129**	**29.28**	**274586**	**38.96**

[a] Tax in 2025 = US$ 20, stepped-up by US$ 20 every 5 years, ending with US$ 120 in 2050. Calculations consider carbon taxes and technology development.

iv) Three key primary energy sources would enable zero-carbon fuels to enter the shipping fuel market, namely renewable energy, bio-energy, and fossil fuels with carbon capture and storage (CCS). The use of zero-carbon fuels, including hydrogen fuel cells[14] and batteries (for energy conversion) by ZEVs requires:

- Competitive prices together with carbon pricing to make ZEVs competitive with vessels using conventional fossil fuels.
- A sufficient increase in their energy capacity to cover the shipping energy demand.
- Because zero-carbon fuels are currently associated with some emissions due to how they are produced and transported, these fuels will need to be available and produced mainly from renewable electricity, biomass, and natural gas with CCS, and be related to the global energy system. This is important to be able to meet the 1.5 °C Paris Agreement target. For example, currently, about 96% of all hydrogen (for fuel cells) is produced via the reforming processes of fossil fuels, either natural gas, heavy oil, naphtha, or coal. These processes emit large quantities of CO_2 (see van Geem et al. (2019); Nikolaidis and Poullikkas (2017)).
- By the time new no-carbon fuels enter the market for use with ZEVs, crucial attributes need to be in place. For example, it will be necessary to have mitigation and management regulations and guidelines, and ensure the solid development of equipment and technology to maintain the safety performance of fuels such as hydrogen and methanol (see Serra and Fancello (2020), Von Hoecke et al. (2021)). Hydrogen used as fuel raises several challenges pertaining to its production, transport, storage, and related costs, as well as important safety concerns.
- The potential of hydrogen depends on the development of storage technologies and development of a new bunkering infrastructure. For a large ship travelling long distances, the revenue loss due to the storage space requirement may be very high and the reduction of storage and machinery costs would not be sufficient to compete with other options such as e-NH_3 (ammonia) and e-methanol (see Serra and Fancello (2020); Van Hoecke et al. (2021)).
- More global tanking points than today are needed, as these no-carbon fuels are less energy dense than regular bunker fuels and thus require more frequent refueling.

4.5. Calculation of global revenues from a "one-time" US$ 40 per ton carbon tax on shipping the heaviest products in 2030 and 2050

We now calculate the tax revenues from a global tax of US$ 40 per ton CO_2 on carbon emissions in 2030 and 2050 from the maritime transport of the heaviest goods categories analyzed in this study. We assume that overall trade activity will not change for these products by these timelines. This was based on our CO_2 calculations in Tables 5 and 6

The tax revenues from a US$ 40 carbon tax per ton of CO_2 in the maritime sector transporting our heaviest products will be as follows: In 2030, **US$ 14.72 billion** (= (398.4–30.5) million tons × US$ 40 per ton; see Table 5), and in 2050, **US$ 12.82 billion**

[14] A potential source to reduce GHG emissions together with ammonia, for example.

(=346.9–26.5) million tons × US$ 40 per ton; see Table 6).

Thus, the tax revenues are greater in 2030 than in 2050, as our BAU carbon emissions before carbon tax are further reduced by 2050 relative to 2030. This is because of higher projected future technological and operational efficiency in maritime transport, while assuming constant global trade measured in ton-nautical miles for heavy products.

5. Feebate policy

Parry et al. (2021) propose using a "feebate" scheme as an alternative to a standard carbon tax. Their feebate scheme is revenue neutral. Under the scheme, the carbon levy is a function of the difference between the carbon intensity (per ton-mile of sea transport) of ship *s* and a "benchmark" emission intensity (per ton-miles of sea transport) defined as the average emissions intensities across all ships of type *s*, times the number of ton-miles of the seaborne trade related to ship *s*. Individual ships whose emission intensities are above the benchmark will pay a tax, and those below it will receive a subsidy.

Taxes or subsidies are then proportional to ton-miles of transport and to the carbon tax applied. This feebate policy has two advantages over the carbon tax on maritime CO_2 emissions: 1) It is less politically contentious, and 2) it can provide direct financial support to the maritime sector. One important weakness relative to the carbon tax is that no net fiscal revenue is raised by this feebate policy.

Here, we propose a different feebate policy, which is presented in the next section. We *first* explain how our proposed feebate policy differs from the one proposed by Parry et al. (2021), and *second,* whether the possible reduction in CO_2 emissions with only a carbon tax of US$ 40 differs from emission reductions with a feebate policy with also a US$ 40 carbon tax.

5.1. Estimation of changes in carbon emissions based on a feebate policy

Our feebate policy is concisely presented here, but a more detailed description thereof is included in the Appendix. Consider that at time *t* (i.e., year), a feebate, FB_{ijkmt}, is related to the shipment of product *i* (i.e., a product at the 6-digit HS level of aggregation) from industry *j* traded between exporting country *k* and importing country *m*:

$$FB_{ijkmt} = \tau \times \left(CE_{ijkmt} - CE_t(B)\right); \tag{13}$$

where τ is the carbon tax per ton of CO_2. At *t*, this feebate is a linear function of the carbon emissions (tons CO_2) related to this shipment of product *i*, CE_{ijkmt}, minus the benchmark carbon emissions level, $CE_t(B)$, which equals the average carbon emissions (tons CO_2) across all classes of ships that transport all the traded heavy products of the industries considered in this study. Recall that the results reported in this paper only consider the heaviest products of all existing worldwide industries,[15] and that for each of our industries, we only have information about the average carbon intensity of the ships used to transport the 6-digit products in each industry.[16] Thus, at time *t*, FB_{ijkmt} would be negative for some 6-digit product trade shipments, implying that these shipments will receive a subsidy, and positive for others, indicating that these trade shipments will have to pay a tax for being above the benchmark. This policy is revenue-neutral in each year.

Our feebate policy rewards (or penalizes) trades with lower (higher) carbon footprints, which ought to result from: i) using ships with low (high) carbon intensity to transport 6-digit products relative to the average carbon intensity from all different ships used to transport all heavy products, and ii) low (high) levels of transported tons-nautical miles.

We think our benchmark might have (at least) two advantages compared to other feebate schemes we are aware of:

1) The benchmark is common for all ship types, reducing the incentive to shift trades from efficient to inefficient ships (where possible). It might also provide incentives to shift to more efficient vessels.
2) It gives greater incentives to actors in the maritime sector to shift not only to more energy- or fuel-efficient ships and less carbon intensive fuels, but to also optimize the number of ton-nautical miles to minimize CO_2 emissions.

We econometrically analyzed the effect of a feebate policy on international trade; specifically, the ton-nautical miles originated from the bilateral trade of products at the 6-digit HS level of aggregation. However, note that in contrast to our analysis of the possible effect of a carbon tax measured by changes in the bunker fuel price, our empirical analysis of the feebate should be considered a counterfactual policy. In contrast to our feebate, the bunker fuel price is a factual observable variable. We also expect that decisions made by actors in the maritime sector have been influenced by the development of the bunker price.

With a feebate policy, the cost function $C_z(i,M;\delta_{Mk})$ in our theoretical relation, equation (9) above, will now include this feebate policy to represent the carbon cost, rather than the carbon tax. Thus, exporters will make optimal decisions conditional on this counterfactual feebate policy.

[15] The heavy products we considered come from 21 industries (or products at the 2-digit HS level of aggregation).

[16] The methodology to calculate these emissions is explained in Section 4.1 and by using information in Table 2.

5.2. The (counterfactual) feebate policy versus a carbon tax policy to reduce CO_2 emissions in the maritime sector

To estimate the reductions in CO_2 emissions (and similarly in q_{ijkmt}: ton-nautical miles) by 2030 as a result of a feebate policy, we assume a counterfactual increase in the carbon tax to US$ 40 in 2030 from a counterfactual carbon tax of US$ 5 in place today.

We found that the reductions in CO_2 emissions with the feebate policy among products in the 99.88 percentile of the emissions distribution across our 6-digit products will be similar to the emission reductions from our carbon tax (using the entire emissions distribution), either from the *one-time* US$ 40 carbon tax or *step-up* carbon tax policy up to 2030. See columns (2), (4), and (6) in Table 8 compared to Table 5 (column 7) and Table 7 (column 3). Table A.5 in the Appendix presents the number of 6-digit products (column (6)) in the upper 0.12 percentile of the emissions distribution, and minimum value of the emission in that segment of the distribution.

One important conclusion from this analysis is that the benchmark for the feebate policy needs to be designed carefully. A benchmark that is too low would project unrealistic reductions in CO_2 emissions by trades with high CO_2 emissions, while a very high benchmark will lead to very large numbers of trades receiving compensation for their CO_2 emissions but not much reduction in CO_2 emissions overall. These are not unlikely scenarios given that the distributions of the CO_2 emissions across 6-digit products within the industries considered here are very skew. In any given industry, one can observe seaborne trades with relatively small emissions as well as those with very high CO_2 emissions.

Our results indicate that with a feebate policy, most 6-digit pairwise trades (at least 75%) would receive a positive payment instead of making a tax payment, while very high positive payments would be made by the largest pairwise trade relations.

6. Conclusions and policy recommendations

This paper presents a theoretical and empirical model to study the effect of carbon taxation and feebate policies on CO_2 emissions from the global international maritime trade of heavy products from 21 industries. These products comprise about 75% of the total weight in global maritime trade. To our knowledge, this is the first research to econometrically study the effect of such policies on global maritime trade activity. We used detailed data for CO_2 emission intensities by type of maritime vessels per given period, which vary substantially by vessel type and type of product transported, and bilateral trade data for products at the 6-digit HS level of aggregation that have been the heaviest (in tons) to transport by sea. Our period of study is from 2004 to 2017.

We considered factual observable changes in the bunker fuel price to represent a carbon tax, since the maritime sector has not yet faced any carbon tax.

Our analysis of the carbon tax showed that the estimated elasticities for ton-nautical miles with respect to changes in the bunker price differ substantially across industries, ranging from −0.03 to −0.42. In most cases, elasticities are lower in absolute terms for products with a higher trade value relative to their trade weight. Thus, the largest impacts of carbon taxes on ton-nautical miles are on products with the lowest trade values relative to their weight.

Imposing today a global and uniform carbon tax of US$ 40 per ton CO_2 for an annual trade activity (ton-nautical miles) similar to that between 2009 and 2017 and carbon intensities for the maritime vessels for the same period would reduce carbon emissions by about 7.65% (34.4 million tons of CO_2) for our heaviest 6-digit products. The products with the highest relative reduction in carbon emissions resulting from a US$ 40/ton CO_2 carbon tax are fossil fuels (11.5%), ores (10.5%), cereals (8.4%), iron and steel (8.3%), and fertilizers (8.1%). These products have some of the lowest value-to-weight ratios in maritime trade. Products with the lowest relative carbon emissions reductions in our data set are from the furniture (1%) and motor vehicles (1.8%) industries, and are products with the highest value-to-weight ratios. Fossil fuels were found to have the greatest reduction in CO_2 emissions, both in percentages and levels.

We also predicted the possible future reductions in carbon emissions from maritime transport of heavy products for 2030 and 2050, assuming: i) a trade activity up to 2050 equal to the 2009–2017 activity; ii) technological and operational efficiency improvements in maritime transport corresponding to the ITF/OECD predictions for 2030 and 2050; and iii) a *one-time* tax of US$ 40 per ton CO_2 on maritime transport just before 2030 and 2050, respectively. Under these assumptions, we found that annual CO_2 emissions from the seaborne transport of heavy products could be reduced by 18% in 2030 and 29% in 2050. However, the CO_2 reductions by 2050 are far smaller than the IMO target, which is a 50% reduction from the emissions of 2008 by 2050. Thus, additional measures are required to reach the IMO's target. Therefore, we proposed a plan to reach the target. This plan involves a carbon tax that increases by US$ 20 per 5-year period starting in 2025 and ending in 2050, when the carbon tax reaches US$ 120. Based on this plan, the maritime sector would face a US$ 80 carbon tax by 2040, which will continue increasing to US$ 120 by 2050, to both continue disincentivizing the use of fossil fuels and fossil fuel vessels, and to finance the replacement of 20% of all old (bunker-operated) ships with ZEVs between 2040 and 2050. We also explain in the paper that among other factors, it is equally important that zero-carbon fuels be used in these ZEVs and that prices be competitive to ensure these vessels can compete favorably with vessels operated with fossil fuels.

A carbon tax on bunker fuels at the global level would generate substantial tax revenues and give room for redistribution benefitting low-income countries, or could be spent to increase general climate action that could improve global welfare. From our calculations, a tax of US$ 40 per ton CO_2 would yield a global tax revenue close to US$ 15 billion by 2030 and close to US$ 13 billion by 2050 for the heavy transported goods categories considered here.

We also presented and discussed a feebate policy, in which a carbon tax of US$ 40 is also imposed and a rebate (tax) is provided if the 6-digit product that is bilaterally traded has carbon emissions lower (higher) than the average carbon emissions across all heavy products (benchmark). Our analysis of the feebate is an analysis of a counterfactual policy. We found that with a feebate policy, most 6-digit pairwise trades (at least 75%) would receive a positive payment instead of making a tax payment, while very high positive payments would be made by the largest pairwise trades.

Table 8
CO_2 emissions reductions in the maritime sector as a result of a feebate policy by 2030.

Industry (product at the 2-digit HS of aggregation) (1)	CO_2 emission reduction by 2030 (%) (2)	Industry (product at the 2-digit HS of aggregation) (3)	CO_2 emission reduction by 2030 (%) (4)	Industry (product at the 2-digit HS of aggregation) (5)	CO_2 emission reduction by 2030 (%) (6)
Cereals (10)	18.03	**Inorganic chemicals (28)**	14.94	**Paper (48)**	13.26
Grains, seeds (soya) (12)	16.27	**Organic chemicals (29)**	17.42	**Iron and steel (72)**	18.56
Animal-Vegetable oils (15)	15.9	**Fertilizers (31)**	18.5	**Iron and steel products (73)**	14
Animal fodder (23)	17.37	**Other chemicals products (38)**	13.45	**Copper (74)**	17.94
Stone/cement (25)	15.12	**Plastics (39)**	15.23	**Aluminum (76)**	14.55
Ores (26)	20.99	**Wood (44)**	14.77	**Vehicles (87)**	14.15
Fossil fuels (27)	22.1	**Wood pulp (47)**	14.46	**Furniture (94)**	12.75
Total	18.03				

As a policy recommendation for the maritime sector, one could argue that a carbon tax is preferable to a cap-and-trade scheme, as it is essential for the maritime sector to have a highly predictable carbon price over a long period. Predictability is not the main characteristic of the cap-and-trade scheme. This carbon tax should be implemented at the global level to avoid leakage.[17] A carbon tax will provide minimal uncertainty about future carbon market conditions, which are now critical for a sector planning to replace vessels using fossil fuels with ZEVs. The carbon tax also provides stable conditions for incentivizing more research on technological improvements for the sector, which is another crucial factor in reaching its ambitious targets.

We also propose the following recommendations regarding how to implement a regime for carbon taxation for the maritime sector.

The first recommendation is to collect the carbon tax from individual ships based on the ship's fuel consumption. As pointed out in the Appendix, the IMO is implementing a system for collecting information on (large) ships' bunker fuel consumption. When this system is fully developed, the carbon tax can be charged to individual ships based on fuel consumption by a global agency set up by the IMO for this purpose. Compliance with a carbon tax for the sector might be enforced by denying ships port access should the tax not be paid (as suggested by Parry et al. (2021)).

A second recommendation is to register all existing global tanking points and collect taxes at these tanking sites. This would be a more "upstream" and traditional, and administratively less burdensome tax collection alternative. However, it would require collecting tax on all fuels sold to tanking vessels, and no bunker fuel would be tanked at non-registered sites. This may require high levels of control related to the movements of boats and establishment of tanking sites to avoid hidden ones.

Today, the IMO can neither collect tax revenues nor oblige fuel suppliers to charge the necessary taxes. The MARPOL[18] convention could in principle be updated (with a new Annex or extending Annex VI) to give the IMO the authority to collect carbon taxes and enforce its implementation by fuel suppliers.

Numerous extensions of our work can be visualized: we intend to pursue some of these in future work. Using our approach, our analysis could be conducted, for example, at the country, continent, and regional levels, or by product type or characteristics.

Appendix A

A.1. The Maritime Sector and the International Maritime Organization (IMO): Structure, regulation, and targets

A.1.1. Some facts about the maritime sector

Global CO_2 emissions from international maritime transport was, in 2015, 932 million tons, representing 2.6% of total global CO_2 emissions (Olmer et al. (2017)). It is 2.3 times the total emissions from the United Kingdom, slightly more than the total emissions from Germany, and equivalent to emissions from 231 average-sized coal-fired power plants. CO_2 emissions from maritime transport represent 91% and 76% of total shipping CO_2-eq GHG emissions on a 100-year and 20-year time scale, respectively (Olmer et al. (2017)). Other shipping emissions include methane (CH_4), nitrous oxide (N_2O), sulfur (SO_x), carbon monoxide (CO), volatile organic compounds (VOC) and particulate matter (PM) which includes black carbon (BC) (Johansson et al. (2017); Serra and Fancello (2020)). Total shipping GHG emissions (international, domestic and fishing) increased from 977 million tons in 2012 to 1076 million tons in 2018 (a 9.6% increase). See IMO (2020)).

International shipping emissions continue to be omitted from the GHG emissions accounts of the countries involved, and from all countries' Nationally Determined Contributions (NDCs) under the Paris Agreement; only referred to as supplementary information in national inventories for communication to the UNFCCC (Nunes et al. (2017)). The European Union has however recently decided to include maritime emissions in the EU Emissions Trading Scheme from 2022 (see Knowler (2020)).

[17] In the absence of carbon tax in other transportation sectors (aviation, trucking, rail), there is a danger that trade will shift to another mode of transportation.

[18] The MARPOL Convention (International Convention for the Prevention of Pollution from Ships) is the main treaty related to environmental aspects of the maritime sector, and specifically Annex VI.

Table A.1 shows some important features of the global maritime transport fleet. Columns 2 and 3 show how numbers of vessels and their total carrying capacity (in deadweight tons) are distributed among bulk, tanker, container, and general cargo ships. Bulk ships have the greatest number of vessels, and the greatest carrying capacity. Oil tankers have the second-highest capacity, and container ships the second-highest vessel count.

Columns 4–6 in Table A.1 show age distributions by ship type. Bulk ships have the largest fractions of newly built ships, followed by container ships and oil tankers. For all three ship types, more than half of all ships are less than 10 years of age. Since average ship life is about 30 years, it will be difficult to replace all fossil-fuel based ships of these categories with new ones much before 2040, or expect to be replaced with ships using zero emissions vessels (ZEVs) in the next 20 years. General cargo vessels are generally older; the use of this ship type keeps diminishing.

Table A.1
Distributions for main maritime vessel types in the global shipping fleet by number, carrying capacity, and age, in 2018.

Ship type (1)	Number of vessels (%) (2)	Carrying capacity (%) (3)	Age distribution for each ship type		
			Less than 10 years (%) (4)	10–14 years (%) (5)	15 years or more (%) (6)
Bulk ship	36	45	71	14	15
Oil tanker	13	27	54	25	21
Container ship	16	14	56	27	17
General cargo	11	3	35	17	48
Other	24	11	41	20	39

Source: European Commission (2020).

Container ships, bulk carriers, and oil tankers represent the dominant sources of international shipping's GHG emissions. Together with chemical tankers, general cargo ships and liquefied natural gas tankers, these ship types constitute 86.5% of international shipping's total carbon emissions (see IMO (2015)). The largest share of emissions comes from container ships, followed closely by bulk carriers, and oil tankers. Container ships have far higher emissions intensities per ton-km than bulkers and tankers, as is seen also in Table 2 in the paper. This information is very important for our carbon emissions calculations.

A.1.2. Regulatory roles of the IMO

The International Maritime Organization (IMO) is a specialized UN agency in charge of developing, administering, and legally implementing international regulations for the maritime sector, with the cooperation of Governments, on matters concerning maritime safety, efficiency of navigation, and prevention and control of marine pollution from ships.[19] The IMO is thus responsible for implementing and enforcing environmental regulations for the maritime sector. This includes the setting of targets for the sector's GHG emissions, and for measures to implement these targets. Two conventions guiding much of IMO's work are UNCLOS, and MARPOL.

The 1982 UN Convention on the Law of the Sea (UNCLOS) is the legal instrument defining the rules applicable to activities occurring on the high seas.[20] UNCLOS outlines rights and obligations that must be exercised and fulfilled through instruments implemented by the IMO (see Beckman and Sun (2017)). The UNCLOS is thus an over-arching framework related to the law of the sea, and also for IMO's work and interaction with its member countries, and provides the foundation for further developments of these laws.

The 1973 International Convention on the Prevention of the Pollution from Ships (the MARPOL Convention) is the main treaty that deals with the marine environmental pollution by ships. MARPOL specifically seeks to prevent and minimize pollution by ships from operational and incidental reasons. This MARPOL convention includes 6 technical Annexes, and Annex VI of MARPOL covers mandatory efficiency measures to reduce GHG emissions from ships.[21] This Annex VI also includes regulations to limit certain types of emissions, that are ozone depleting substances, nitrogen oxides (NO_x), sulfur oxides (SO_x) and particulate matter (PM). MARPOL's Annexes have been updated several times to incorporate important environmental regulations related to noxious liquids and harmful substances carried by sea; sewage and garbage from ships; and air pollution and emissions to air from ships.

*A.1.3. IMO's **climate action pledge***

In April 2018, the IMO pledged to reduce the GHG emissions from international shipping to half of the 2008 level (1135 million tons CO_2) by 2050 (see IMO (2018a); UNCTAD (2018), section 5B), as part of the shipping sector's contribution to meet the global GHG emissions target under the Paris Agreement. The IMO has decided that these future emissions reductions must come from within the sector and not through offset schemes, contrasting the aviation sector which has a compulsory plan based on offset schemes to start in 2026 to limit the sector's contribution to global GHG emissions (see ICAO (2018)). The IMO has current plans that include candidate measures to achieve this pledge, and has been also gradually implementing certain technical and operational measures for the

[19] For this and more information on organizational aspects of the IMO, see the IMO website at https://www.imo.org/en/About/Membership/Pages/Default.aspx.

[20] See https://www.imo.org/en/OurWork/Legal/Pages/UnitedNationsConventionOnTheLawOfTheSea.aspx.

[21] For overview of the areas of environmental concern covered by MARPOL, see: https://www.imo.org/en/OurWork/Environment/Pages/Special-Areas-Marpol.aspx.

maritime sector (see below). Moreover, the IMO's Marine Environment Protection Committee (MEPC) has, in May 2021, agreed on new guidelines which require ships to reduce their carbon intensity by combining certain technical and operational measures.[22] This is an important step to account for the carbon footprint of the ships. From 2023, the IMO might be considering additional candidate strategies such as market-based measures (MBMs), and phasing-in low- or zero-carbon fuels (see ICCT (2018)). Carbon taxation is not part of the IMO's current plans.

Projections in the Fourth IMO GHG Study (IMO (2020)) indicate that, in the absence of carbon pricing, and depending on likely future economic and energy scenarios and certain vessel efficiency improvements, maritime emissions in 2050 will most likely lie between 90% and 130% of 2008 emissions. This means that the IMO's target, to reduce 2050 emissions by 50% relative to the 2008 emissions level, will be difficult to achieve unless stronger measures are taken. This clearly indicates that carbon pricing will need to be part of a plan to reach IMO's target.

MARPOL could then in principle be updated (with a new or extended Annex), to incorporate new regulations to reduce the shipping sector's current and future GHG emissions, including carbon pricing policies in the sector.

A.1.4. Specific measures taken by the IMO to address environmental issues

The IMO has been and continues taking actions to reduce the sector's GHG emissions, and other pollutants.

The IMO issued in 2011 a mandatory design standard known as Energy Efficiency Design Index (EEDI)) for new ships to reduce their emission intensities, as amendments to MARPOL Annex VI (see Hon and Wang (2011)). From January 1, 2013, a new ship design needs to meet the EEDI for its ship type. These energy efficiency standards are to be tightened every five years (see UNCTAD (2012); ICCT (2018)). The EEDI however only applies to new ships, and since a ship's operational life ranges between 20 and 35 years on average, it is unlikely that such energy efficiency standard could sufficiently reduce CO_2 emissions in the short- and medium-run, to meet the pledged IMO emissions target by 2050.[23] Some scholars have also discussed some potential problems associated with EEDI, such as reduced maneuverability, increased inventory cost, and modal shifts to land-based transport (Krüger (2011)). Psaraftis (2019) discusses some critical issues in the formulation of the index which, in the quest for EEDI compliance, could involve potential risks in terms of inefficient and less safe design.

The IMO has also initiated systematic collection of data on fuel consumption for vessels larger than 5000 gross tons, which has come into force on March 1, 2018. One purpose of this collection system is to prepare the international shipping sector for future collection of levies on vessels' fuel consumption, likely to be imposed as part of the IMO's GHG reduction plan for the maritime sector.

Table A.2
Environmental policies and regulations implemented by IMO.

Regulation or convention by IMO	Topic	Additional information	Introduced-Effective
MARPOL	Prevention of marine pollution	Regulations on pollution from the maritime sector	1973–1983
MARPOL ANNEX I	Prevention of oil spills	Covers both operational and accidental discharges	1973–1983
MARPOL Annex II	Prevention of pollution by noxious substances	Concerns 250 dangerous substances carried by bulk	1973–1983
MARPOL Annex III	Prevention of pollution by substances in packaged form	Standards on packing, stowing, labeling dangerous materials	1992
MARPOL Annex IV	Prevention of sewage pollution from ships	Prohibits discharge of sewage to the sea except when treated	2003
MARPOL Annex V	Prevention of garbage pollution from ships	Complete ban on plastics disposal; strict rules for other disposals	1973–1988
MARPOL Annex VI	Air pollution control	Sets limits on ships' SO_x and NO_x emissions	2005–2010
MARPOL Annex VI: EEDI	Energy efficiency for new vessels	Requires minimum energy efficiency for new ships, mandatory improvements per 5-year period	2011–2013
Pledge to reduce GHG emissions by 2050	GHG emissions from shipping to be reduced to half from 2008 to 2050	Within-sector emissions reductions gradual plan to 2030 No MBMs yet enacted	2018
Sulfur content in shipping fuels	Reduction of sulfur content in shipping fuels from 3-5%–0.5%	Introduced to reduce the burden of shipping on global air pollution	2020
MARPOL Annex VI: Amendment	System for data collection on fuel consumption of ships	Measure to prepare for collection of carbon taxes as part of 2050 pledge	Ongoing

Source: IMO website: https://www.imo.org/en/OurWork/Environment/Pages/Special-Areas-Marpol.aspx

The IMO has additionally, from the start of 2020, imposed a much stricter regulation than previously on the sulfur (SO_x) content in maritime fuels, with a maximum content of 0.5% instead of previous levels of 3%–5% (see UNCTAD (2017); IMO (2020)). This regulation significantly reduces the pollution from bunker oil, which has been a major global pollution problem. The IMO is also working to avoid litter from ships (see IMO (2018b)); and to reduce sea deposits of dangerous and noxious substances (see IMO (2018c)).

[22] See https://www.imo.org/en/MediaCentre/PressBriefings/pages/ISWG-GHG-8.aspx.

[23] Further information about IMO's actions to reduce GHG emissions can be found in https://www.imo.org/en/MediaCentre/HotTopics/Pages/Reducing-greenhouse-gas-emissions-from-ships.aspx.

The IMO has also in its strategic plan for the period 2018–2023 two other environmental regulations, one related to ozone-depleting substances used by ships; and another one to reduce black carbon from ships and its effects on the Arctic; see IMO (2017).

Table A.2 gives a brief but broad summary of IMO's regulations for the maritime sector to address environmental issues and climate policy engagement.

A.2. Literature review

The background literature dealing directly with the main research topics of our paper is limited. We here review the studies closest to this paper. Cristea et al. (2013) computed GHG emissions from both production and transport (air, rail and road) of internationally traded goods for one year, 2004, using data from the Global Trade Analysis Project (GTAP). They considered 28 countries and 12 (own-defined) regions; and 23 traded goods sectors and 6 non-traded service sectors. We instead consider worldwide trade between country pairs of all the possible heaviest products at the 6-digit HS level of aggregation. Their paper did not study either the impacts of fuel price changes (or carbon taxation) on international trade, which is our main objective.

Shapiro (2016), using a gravity model, estimates the effect of transport costs on trade values, for US and Australian imports over the period 1991–2010, for 13 sectors; but does not estimate CO_2 emissions. These are obtained from separate sources: from production using GTAP for 2007, and for airborne and maritime trade from the International Air Transport Association (IATA) and IMO, respectively. Shapiro considers a single emissions intensity rate of 9.53 g CO_2/ton-km for the entire maritime sector, to estimate the effect on welfare of a carbon tax. We instead take into account that carbon emission intensity rates vary by ship type, and those goods are transported in different types of ships according to the product type. His paper does not present the impacts of the counterfactual carbon tax on CO_2 emissions, as we analyze.

Parry et al. (2018) consider that a carbon tax of $75 per ton CO_2 by 2030 and to $150 per ton in 2040 on international shipping, could affect: 1) ships' technical efficiency improvements; 2) ships' operational efficiency improvements; 3) optimal ton-kilometers of trade transport activity; and 4) traded volume in ton-kilometers. Simulating a technical model for carbon emissions from shipping up to 2050, they show that these factors together will reduce CO_2 emissions from shipping by 14% by 2030 and by 23% by 2040, respectively. A reduction in trade would only contribute with 4% of these CO_2 reductions. In an update, Parry et al. (2021) consider that to reach the IMO 2050 carbon emissions target, it is necessary to phase-in zero-emissions vessels and a carbon tax no higher than $75 per ton of CO_2 by 2030. Smith et al. (2016) have studied similar impacts up to 2050 under alternative scenarios regarding technology development, ship retrofits and operation, fuel switching, and transport demand. Their simulations provide a range of results with respect to carbon emissions by 2050, depending on carbon pricing and the scope for fuel switching. Halim et al. (2019) conclude that a carbon tax up to $50 is likely to have only a small impact on trade (less than 1%). None of the referenced studies provides an econometric analysis of relationships between bunker costs and maritime fuel consumption, nor consider heavy traded goods in particular, which are our targets here.

Brancaccio et al. (2018, 2020) analyze, among other things, the effects of shipping costs and oil prices on bulk shipping using two databases, a sample of shipping contracts from Clarkson; and the Automatic Identification System (AIS) data on ship movements. They find that a 10% increase in the oil price, and in total shipping costs, reduce bulk shipping by 4.4%, and 10%, respectively. Both these papers rely on only bulk shipping, as noted. Neither of the papers studies impacts on carbon emissions, which is our objective.

Two recent papers consider impacts on global GDP levels due to carbon taxes on shipping. Lee et al. (2013) study impacts of different fuel tax levels charged to container ships, using the GTAP-E model, and find negligible impacts on the global economy for low carbon tax levels, but more significant impacts if the tax is US$90/ton CO_2, with the greatest relative impacts on China. Certain distant trade routes are discouraged by high carbon taxes. Sheng et al. (2018) consider more modest carbon tax (US$10–25/ton CO2), using a global recursive dynamic CGE model, and find that global GDP is likely to be reduced by 0.02–0.05%. Trade weights and patterns are affected, but only moderately.

Limão and Venables (2001) and Behar and Venables (2011) studied the effect of transport costs on volume of bilateral trade using gravity models. They do not analyze specifically the effects of fuel prices, but find that trade volumes decrease as transportation costs rise.

A strand of literature estimates the spatial and temporal variability of GHG emissions from shipping. Wang et al. (2007) use the waterway network ship traffic, energy, and environment model STEEM to quantify and geographically represent inter-port vessel traffic and emissions. Their model also estimates energy use, and assesses environmental impacts of shipping. The area of study is the United States, Canada and Mexico, for 2002. The Third GHG Study of IMO (IMO (2015)), also using AIS data, presents a detailed and comprehensive global inventory of shipping emissions, but in somewhat less detail for spatial and temporal variability of global emissions than Johansson et al. (2017), who use STEAM3 and AIS data to estimate global shipping emissions for 2015. Schim van der Loeff et al. (2018), using data from AIS and trade custom declarations, calculate carbon emissions per vessel and per journey for Brazilian exports in 2014. This literature does not address carbon taxation nor its possible effects on international maritime trade, as we do here.

In comparison with the related literature, we analyze econometrically how CO_2 emissions can be reduced by implementing carbon taxation on international maritime trade. We consider worldwide country pairs and all traded heaviest products to obtain the effects of carbon taxation on trade and CO_2 emissions *by product type*. We also take into consideration that emission intensities vary substantially by vessel type and the type of product vessels transport. We also analyze theoretically how international trade (intensive margin) is impacted by carbon taxation.

A.3. Estimation results on the effect of carbon tax on ton-nautical miles from seaborne trade by trade value categories and industries

Table A.3
The effect on trade weight-distance of changes in bunker prices (β_{11}): elasticities. Heaviest Products at the 6-digit HS level of aggregation. GMM estimates *(Standard errors in parentheses)*.

	Industry Category of the 6-digit HS products							
	10: Cereals	**12: Grains, seeds (soya)**	**15: Animal-Vegetable oils**	**23: Animal fodder**	**25: Stones, cement**	**26: Ores**	**27: Fossil fuels**	**28: Inorganic chemicals**
Category 1	−0.323568 (0.033915)	−0.152358 (0.02038)	−0.205159 (0.02069)	−0.20519 (0.01908)	−0.115451 (0.02101)	−0.366213 (0.031673)	−0.416961 (0.08462)	−0.161631 (0.04175)
Category 2	−0.288583 (0.036599)	−0.291335 (0.03465)	−0.139994 (0.02885)	−0.22174 (0.01801)	−0.093474 (0.02742)	−0.39628 (0.03198)	−0.430295 (0.06663)	−0.077868 (0.02429)
Category 3	−0.202138 (0.034761)	−0.272741 (0.05398)	−0.150314 (0.05189)	−0.17282 (0.02137)	−0.077462 (0.02553)	−0.38579 (0.03397)	−0.413964 (0.03092)	−0.062512 (0.03571)
Category 4	−0.154365 (0.030210)	−0.161187 (0.02289)	−0.169324 (0.03264)	−0.15099 (0.01730)	−0.091836 (0.03587)	−0.34352 (0.02897)	−0.357554 (0.02942)	−0.138097 (0.029875)
	29: Organic chemicals	**31: Fertilizers**	**38: Other chemicals products**	**39: Plastics**	**44: Wood**	**47: Wood pulp**	**48: Paper**	**72: Iron & Steel**
Category 1	−0.262999 (0.03998)	−0.32544 (0.08833)	−0.11167 (0.01941)	−0.172525 (0.00944)	−0.118817 (0.01933)	−0.132080 (0.01609)	−0.097133 (0.01025)	−0.309157 (0.00525)
Category 2	−0.187476 (0.05928)	−0.18148 (0.03251)	−0.066215 (0.03455)	−0.140684 (0.01032)	−0.094312 (0.01426)	−0.114798 (0.03902)	−0.127202 (0.02005)	−0.284867 (0.02731)
Category 3	−0.230221 (0.03935)	−0.18695 (0.04621)	−0.083835 (0.02288)	−0.167939 (0.01287)	−0.124288 (0.01929)	−0.159934 (0.01596)	−0.064431 (0.02853)	−0.265002 (0.01798)
Category 4	−0.203592 (0.02297)	−0.16718 (0.03512)	−0.108906 (0.01776)	−0.156853 (0.01561)	−0.059074 (0.02261)	−0.167454 (0.02251)	−0.128351 (0.02517)	−0.307120 (0.03574)
	73: Iron & steel products	**74: Copper**	**76: Aluminum**	**87: Vehicles**	**94: Furniture**			
Category 1	−0.146894 (0.00951)	−0.247709 (0.04141)	−0.147778 (0.01602)	−0.060011 (0.03119)	−0.086289 (0.01491)			
Category 2	−0.189526 (0.04031)	−0.241232 (0.03260)	−0.130608 (0.01922)	−0.083439 (0.02193)	−0.076606 (0.01675)			
Category 3	−0.064704 (0.02059)	−0.168705 (0.03681)	−0.081035 (0.03973)	−0.050824 (0.02377)	−0.050996 (0.02205)			
Category 4	−0.152796 (0.01901)	−0.093892 (0.03617)	−0.110637 (0.02572)	−0.078056 (0.02169)	−0.032229 (0.01910)			

A.4. Sargan tests

Table A.4
Sargan tests

Industry (2-digit HSProduct)	Category	Sargan test[a]	2-digit HS p.	Category	Sargan test[a]
10	1	Prob > chi2 = 0.2226	31	1	Prob > chi2 = 0.4035
10	2	Prob > chi2 = 0.1648	31	2	Prob > chi2 = 0.2779
10	3	Prob > chi2 = 0.1775	31	3	Prob > chi2 = 0.0783
10	4	Prob > chi2 = 0.3399	31	4	Prob > chi2 = 0.1630
12	1	Prob > chi2 = 0.1716	38	1	Prob > chi2 = 0.2625
12	2	Prob > chi2 = 0.5825	38	2	Prob > chi2 = 0.2761
12	3	Prob > chi2 = 0.3387	38	3	Prob > chi2 = 0.0832
12	4	Prob > chi2 = 0.1433	38	4	Prob > chi2 = 0.0002
15	1	Prob > chi2 = 0.1913	39	1	Prob > chi2 = 0.0020
15	2	Prob > chi2 = 0.1273	39	2	Prob > chi2 = 0.0004
15	3	Prob > chi2 = 0.999	39	3	Prob > chi2 = 0.0000
15	4	Prob > chi2 = 0.0843	39	4	Prob > chi2 = 0.0000
23	1	Prob > chi2 = 0.7305	44	1	Prob > chi2 = 0.0868
23	2	Prob > chi2 = 0.6269	44	2	Prob > chi2 = 0.1347
23	3	Prob > chi2 = 0.1934	44	3	Prob > chi2 = 0.3878
23	4	Prob > chi2 = 0.2070	44	4	Prob > chi2 = 0.6075

(*continued on next page*)

Table A.4 (*continued*)

Industry (2-digit HSProduct)	Category	Sargan test[a]	2-digit HS p.	Category	Sargan test[a]
25	1	Prob > chi2 = 0.0644	47	1	Prob > chi2 = 0.0706
25	2	Prob > chi2 = 0.2092	47	2	Prob > chi2 = 0.4345
25	3	Prob > chi2 = 0.1293	47	3	Prob > chi2 = 0.3652
25	4	Prob > chi2 = 0.3339	47	4	Prob > chi2 = 0.7794
26	1	Prob > chi2 = 0.1795	48	1	Prob > chi2 = 0.4304
26	2	Prob > chi2 = 0.5027	48	2	Prob > chi2 = 0.2362
26	3	Prob > chi2 = 0.5515	48	3	Prob > chi2 = 0.1266
26	4	Prob > chi2 = 0.1303	48	4	Prob > chi2 = 0.2438
27	1	Prob > chi2 = 0.1288	72	1	Prob > chi2 = 0.0000
27	2	Prob > chi2 = 0.2274	72	2	Prob > chi2 = 0.2829
27	3	Prob > chi2 = 0.6270	72	3	Prob > chi2 = 0.0633
27	4	Prob > chi2 = 0.0790	72	4	Prob > chi2 = 0.2491
28	1	Prob > chi2 = 0.7888	73	1	Prob > chi2 = 0.0000
28	2	Prob > chi2 = 0.9828	73	2	Prob > chi2 = 0.2086
28	3	Prob > chi2 = 0.1552	73	3	Prob > chi2 = 0.0630
28	4	Prob > chi2 = 0.1959	73	4	Prob > chi2 = 0.0000
29	1	Prob > chi2 = 0.0623	74	1	Prob > chi2 = 0.4360
29	2	Prob > chi2 = 0.9999	74	2	Prob > chi2 = 0.1074
29	3	Prob > chi2 = 0.2847	74	3	Prob > chi2 = 0.2742
29	**4**	**Prob > chi2 = 0.1937**	**74**	**4**	**Prob > chi2 = 0.1320**

Industry (2-digit HS product)	Category	Sargan test[a]
76	1	Prob > chi2 = 0.5689
76	2	Prob > chi2 = 0.2150
76	3	Prob > chi2 = 0.2866
76	4	Prob > chi2 = 0.3351
87	1	Prob > chi2 = 0.7343
87	2	Prob > chi2 = 0.3063
87	3	Prob > chi2 = 0.1887
87	4	Prob > chi2 = 0.0000
94	1	Prob > chi2 = 0.2403
94	2	Prob > chi2 = 0.1231
94	3	Prob > chi2 = 0.1492
94	4	Prob > chi2 = 0.0001

[a] With the Sargan statistics, one tests the null hypothesis of correct model specification and valid over-identifying restrictions.

A.5. *Testing **the null hypothesis that the overidentifying restrictions are valid***

Our course of action on this issue is described as follows. *First*, we were careful in using only certain lags of the instruments instead of all available lags, so the instrument count is only linear in T. With this procedure, we avoided generating moment conditions prolifically. We also needed to keep in mind that too few instruments can weaken the Sargan test. The well-known problem of too many instruments in dynamic panel data GMM is dealt with in detail in Roodman (2009b). *Second,* following this state of art, we noticed that our estimates were quite stable to our chosen number of instruments, unless we included a very large number of them. *Third*, we obtained our Sargan statistics, presented in Table A.4 above, to test the validity of our chosen instruments. One can there find a Sargan statistics test for each of our 4 categories within each of the 21 industries considered in this paper (i.e., 84 regressions and 84 Sargan statistics). As explained in the paper, each of the 4 regressions corresponds to the trade value category of the 6-digit products that are traded within that group.

The main conclusion from these Sargan tests in our econometric analysis of the effect of a carbon tax on seaborne trade measured in ton-nautical miles, is that we cannot reject any of the null hypotheses that the overidentifying restrictions are valid in each of our regressions, except those in industry 39 which is Plastics, and also in 4 alternative regressions from 4 different industries (i.e., 4 out of 80 regressions). Overall, our Sargan tests are thus extremely supportive to the validity of our overidentifying restrictions.

A.6. *Econometric **Analysis of our Feebate policy***

A.6.1. *Methodology*

Our feebate policy proposal to be applied to international shipping, complements the feebate policy proposed by Parry et al. (2021), who define the feebate F_s as:

$$F_s = carbon\ tax \times (TonMile) \times (c_s - C_S(B)). \tag{A.1}$$

c_s is the CO_2 emission rate per ton-mile by ship of type s; and $C_S(B)$ is the assigned benchmark (e.g., average) CO_2 emission rate per ton-mile for all the ships of same type (e.g., container ships). If $c_s > C_S(B)$, the ship will face a cost (i.e., payment); and if $c_s < C_S(B)$, ships will obtain a refund as a result of deviating from the benchmark. Payments or refunds are then proportional to the TonMile that result from the maritime trade and the applied carbon tax, the higher the TonMile, the higher refund or payment. This scheme might have the following advantages relative to a carbon tax level that is necessary to have meaningful reductions in maritime CO_2 emissions: 1) it could be more politically acceptable; and 2) it could generate direct financial resources to the maritime sector which may or may not be used to reduce emissions. One important disadvantage of this feebate policy relative to the carbon tax is that no net fiscal revenues could be raised, an important factor to consider especially if developing countries would be needing financial aid to transition to green infrastructure.

We are not able to implement the Parry et al. (2021) feebate relation as we do not have data on carbon intensities of the ships that have transported *each of* our 6-digit traded products, which is required for estimating (A.1). As indicated in the paper, we only have data on the carbon intensities of the average ship used in the industry to which *each of* our 6-digit products belongs.

In our analysis, we have instead defined our feebate policy as follows. Consider that at time *t* (i.e., year), there is a feebate, FB_{ijkmt}, related to the shipment of product *i* (i.e., a product at the 6-digit HS level of aggregation) from industry *j* traded between the exporting country *k* and the importing country *m*:

$$FB_{ijkmt} = \tau \times \left(CE_{ijkmt} - CE_t(B)\right); \tag{A.2}$$

where τ is the carbon tax per ton of CO_2. At any *t*, this feebate is a linear function of the carbon emissions (tons CO_2) related to this shipment of product *i*, CE_{ijkmt}, *minus* the benchmark carbon emissions level, $CE_t(B)$, which equals the average carbon emissions (tons CO_2) across all classes of ships that transport *all the heavy products of the industries* considered in this study. Recall that this paper only considers the heaviest products from all existing worldwide industries,[24] and that we only have information about the specific average carbon intensity of the ships used to transport the products for each of the industries.[25] Thus, at *t*, FB_{ijkmt} would be negative for some 6-digit product shipments, which will lead to receiving a subsidy; and positive for others which result in having the shipment making a payment for being above the benchmark. We confirm that this policy is revenue-neutral in each year.

In contrast to Parry et al. (2021), our feebate policy rewards (or penalizes) trades that have low (high) carbon footprints, which ought to result from: i) using ships with low (high) carbon intensity to transport the 6-digit products relative to the average carbon intensity from all the different ships used to transport all the heavy products; and ii) low (high) levels of transported tons per nautical mile.

We think that our benchmark has (at least) two advantages in comparison to the current feebate scheme proposals that we are aware of:

(1) The benchmark is common for all ship types, reducing the incentive to shift trades from efficient ships to inefficient ships (where possible). It could encourage the opposite effect, shifts from inefficient to efficient vessels.
(2) It will give more incentives to the actors in the maritime sector to shift not only to more energy- or fuel-efficient ships and less carbon intensive fuels, but also to minimize the number of ton-kms in order to minimize carbon emissions.

We analyze empirically the effect of a feebate policy on international seaborne trade, specifically, the ton-nautical miles originated from the bilateral trade of products at the 6-digit HS level of aggregation. Note however that in contrast to our analysis of the effect of a carbon tax, which is measured by the changes in the bunker fuel price, our empirical analysis of the feebate is instead a counterfactual policy analysis. Bunker fuel price changes are observable, factual and real, while feebates are not.

The cost function $C_z(i,M;\delta_{Mk})$ in our theoretical relation, equation (9) in the paper, will now include this feebate policy to represent the carbon cost, instead of the carbon tax. Thus, exporters will make optimal decisions conditional on this feebate policy.

To study empirically the effect of this counterfactual feebate policy on the tons-nautical miles of the traded 6-digit products, we have the following strategy:

(1) We assume that trade decisions (in ton-nautical miles) for each of the 6-digit products made at time t, depend on their expected future (counterfactual) feebates.[26] Agents are assumed to have rational expectations.
(2) The studied period is from 2004 to 2017, and we call it the business as usual (BAU) period.[27]
(3) The expected future (counterfactual) feebates in turn depend on the exporters' own expected emissions, and expected benchmark which equals the average emissions across all traded heaviest products. A counterfactual carbon price of US$ 5 applied to the maritime sector is taken into account.

[24] These heavy products come from 21 industries.
[25] The methodology to calculate these emissions is explained in Section 4.1 and using information from Table 2.
[26] Note that we cannot consider feebates on the basis of current trade. This would *first* introduce endogeneity problems as the feebates would depend on the current ton-nautical miles originated from international trade; and *second*, require that the exporters have full and concurrent information about the benchmark of the entire international trade and emissions of the heavy products we here consider.
[27] Our period of study for the feebate analysis is longer than for the carbon taxation analysis because we do not have bunker fuel prices prior to 2009 to analyze the effects of a carbon tax prior to 2009.

(4) Exporters' expected emissions depend on their expected future trades (in ton-nautical miles); and expected technological progress and carbon intensities of the different ships, used to transport their products. We use Table 2 and the methodology explained in Section 4.1 of the paper to calculate these emissions.

A.6.2. Empirical results on the effect of a feebate policy on international trade and CO_2 emissions from maritime transport

We consider the following econometric model to analyze the effect of our counterfactual feebate policy on the bilateral trade between country pairs of products at the *6-digit HS level of aggregation*:

$$\begin{aligned}\ln q_{ijkmt} = \alpha_{12} + \beta_{12} E_t\left[FB_{ijkmt+n}\right] + \lambda_{12}\ \ln(Exchange\ Rate_t) + \varsigma_{12} C_{kt} + \\ a_{12} Q_{jt} + b_{12} D_{ijt} + c_{12} F_{jt} + \gamma_{12} IM_{mt} + \delta_{12} EX_{kt} + \mu_{ijkm} + \varphi_{ijkmt}.\end{aligned} \tag{A.3}$$

q_{ijkmt} (as in equation (12) in the paper) is the weight-distance and obtained by multiplying the weight of product variety of type *i* (i.e., 6-digit product) from the *j* industry, traded between the importing country *m* and the exporting country *k* at time *t*, *times* the distance (i.e., in nautical miles) between country *m* and country *k*.

β_{12} in equation (A.3) is expected to be negative. Specifically, expectations of an additional *w* units in the feebate costs will be associated with a $[w \times \beta_{12} \times 100\%]$ decrease in q_{ijkmt}, and a proportional reduction in CO_2 emissions. Conversely, expectations of *w* fewer units in the feebate costs will be associated with a $[w \times \beta_{12} \times 100\%]$ increase in q_{ijkmt}. The estimation results of β_{12}, using the GMM method of estimation, are presented in column 2 in Table A.5 below.

A.6.3. (Counterfactual) Feebate policy versus a carbon tax policy to reduce CO_2 emissions in the maritime sector

To estimate the reductions in CO_2 emissions (and similarly in q_{ijkmt}: ton-nautical miles) by 2030 with a feebate policy, we proceeded as follows:

a) We take into account the estimates presented in column 2 in Table A.5.
b) We consider the following scenario: a counterfactual increase in the carbon tax to US\$40 per ton of CO_2 from an initial counterfactual carbon tax of US\$ 5 applied to CO_2 emissions in the BAU period.
c) We calculate the carbon emissions and feebate ($Feebate_{(US\$\ 5)}$) for each traded 6-digit product and year, as well as the benchmark, as indicated above in Section A.6.1, assuming the same trade activity that took place between 2004 and 2017 (BAU), the carbon intensities of the ships that correspond to the years 2004–2017, and the carbon tax equal to *US\$ 5*.
d) We calculate the carbon emissions and feebate ($Feebate_{(US\$\ 40)}$) for each traded 6-digit product and years, as well as the benchmark (as indicated above) assuming the trade activity between 2004 and 2017, the carbon intensities of the ships that correspond to the year 2030, and a carbon tax equal to *US\$ 40*.
e) We calculate changes in feebates by calculating the difference between (c) and (d) $\Delta Feebate = (Feebate_{(US\$\ 40)} - Feebate_{(US\ \$5)})$.
f) The percentage reduction in CO_2 emissions as a result of a change in the feebate by 2030 is equal to $\Delta Feebate^* \beta_{12}{}^*100\%$.

We find that the reductions in CO_2 emissions with the feebate policy among the products in the 99.88 percentile of the emissions distribution across our 6-digit products will be very similar to the emission reductions from our carbon tax (using the entire emissions distribution), either from a *one-time* US\$ 40 carbon tax or from a *step-up* carbon tax policy up to 2030. See columns (2), (4) and (6) in Table 8, versus in Table 5 (column 7) and Table 7 (column 3) in the paper. Table A.5 displays the number of 6-digit products (cutoff observations) in the upper 0.12 percentile of the emissions distribution (column 6), and the maximum and average values of the emission in that segment of the distribution by industry (columns 7 and 8, respectively).

One important conclusion from this analysis is that the benchmark for the feebate policy needs to be designed carefully. A too low benchmark would project unrealistic reductions in CO_2 emissions by the trades with high CO_2 emissions, while a very high benchmark will lead to very large numbers of trades receiving compensation for their CO_2 emissions, and not much reductions in CO_2 emissions as a whole. These are not unlikely scenarios given the fact that the distributions of the CO_2 emissions across 6-digit products within the industries we here consider, are very skew. In any given industry, one can observe many seaborne trades with relatively small emissions, but also some seaborne trades with very high CO_2 emissions, see column 7 in Table A.5.

Table A.5
Emissions reductions in the maritime sector from a feebate policy by 2030

Industry (product at the 2-digit HS of aggregation) (1)	*Estimated* [1] β_{12} (2)	CO_2 emission reduction by 2030 (%) (3)	Cutoff level of CO_2 emissions (1000 tons) (4)	Total obs (5)	Cutoff obs. (6)	Largest CO_2 emissions among cutoff observations (1000 tons) (7)	Average CO_2 emissions among cutoff observations (1000 tons) (8)
Cereals (10)	−0.0513 (0.0209)	18.03	650	45345	32	1794	1113
Grains, seeds (soya) (12)	−0.01897 (0.0023)	16.27	1500	36820	25	5821	3425
Animal-Veget. oils (15)	−0.1254 (0.0728)	15.9	200	63165	83	912	291

(*continued on next page*)

Table A.5 (*continued*)

Industry (product at the 2-digit HS of aggregation) (1)	*Estimated* [1] β_{12} (2)	CO_2 emission reduction by 2030 (%) (3)	Cutoff level of CO_2 emissions (1000 tons) (4)	Total obs (5)	Cutoff obs. (6)	Largest CO_2 emissions among cutoff observations (1000 tons) (7)	Average CO_2 emissions among cutoff observations (1000 tons) (8)
Animal fodder (23)	−0.0555 (0.0196)	17.37	350	54298	106	1327	526
Stone/cement (25)	−0.1268 (0.0729)	15.12	400	127843	9	1689	878
Ores (26)	−0.0076 (0.000952)	20.99	3120	33548	31	27200	8331
Fossil fuels (27)	−0.0599 (0.0346)	22.1	400	113965	566	34300	1248
Inorganic chemicals (28)	−0.1326 (0.0614)	14.94	210	163467	40	918	310
Organic chemicals (29)	−1.3943 (0.7319)	17.42	33	238176	286	419	78
Fertilizers (31)	−0.9306 (0.3264)	18.5	27	62164	625	315	60
Other chemicals (38)	−0.47204 (0.11302)	13.45	125	129571	13	302	169
Plastics (39)	−0.7475 (0.4077)	15.23	70	403162	127	272	123
Wood (44)	−0.4173 (0.0727)	14.77	70	149177	297	1358	203
Wood pulp (47)	−0.2581 (0.0558)	14.46	75	35885	209	791	180
Paper (48)	−0.6943 (0.4086)	13.26	50	249286	24	235	80
Iron and steel (72)	−0.2546 (0.0898)	18.56	240	386483	45	776	392
Iron and steel products (73)	−0.2385 (0.1466)	14	50	245206	155	1074	117
Copper (74)	−0.2189 (0.1116)	17.94	140	42156	15	332	242
Aluminum (76)	−1.580 (0.9407)	14.55	20	81293	347	293	43
Vehicles (87)	−1.0511 (0.1058)	14.15	25	191078	1436	749	68
Furniture (94)	−0.5061 (0.2728)	12.75	65	95889	60	202	110
Total		**18.03**		**2947977**	**4531**		

[1] GMM estimates. Standard error in parenthesis.

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