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Abstract

We study impacts of carbon taxation to international transport fuels on CO_2 emissions and trade activity, focusing on maritime transport which constitutes the most important international trade transport activity for the years 2009-2017. The bunker-price elasticities range from -0.003 to -0.42. For the current level of international trade, a global tax of $40 per ton CO_2 tax, will reduce carbon emissions by about 7% for the heaviest traded products (at the 6-digit HS levels of aggregation) transported by sea. The greatest CO_2 emission reductions are for products with particularly low value-to-weight ratios such as fossil fuels and ores.

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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 for the CO_2 it emits. This has at least three adverse consequences for the shipping sector, of main concern of this paper. The *first* is a higher than optimal activity in international shipping (types of vessels and their technologies, their travel routes, and the amounts and types of goods being transported), as the sector does not face the true global costs of international trade. The *second* is too high fuel consumption (and too polluting fuels), and consequently too high CO_2 emissions. The *third* is low fiscal revenue raised from international shipping transport, a common and critical problem for many low-income countries with low tax revenues collection (see Keen, Parry, and Strand (2013) for further arguments). Today, the shares of global CO_2 emissions due to international aviation and shipping are each about 2.5%. According to Cristea et al. (2013), 51% of CO_2 emissions from international trade in 2004 resulted from sea freight; 27% from air freight; and 22% from land (road and rail) transport.

This paper aims to contribute to better 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 are aware, this is the first theoretical and empirical study to analyze the impacts of changes in bunker fuel prices, which proxy carbon taxation, on *global international trade* and on *global CO_2 emissions* resulting from this trade, using a comprehensive panel dataset for products at the 6-digit HS level of aggregation covering the years from 2009 to 2017. UNCTAD (2009) indicates that fuel costs account for 50% to 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 seeks to provide a guidance to the international community about how to attribute responsibility per country/region and traded product type to their shares in the 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 that trade the *heaviest* products (6-digit HS level of aggregation). It focuses on two main topics. *First*, we analyze theoretically and empirically the impact of changes in bunker prices on trade (intensive margin). *Second,* we estimate the possible impact on carbon emissions as a result of changes in the structure of the international goods' trade that follow from carbon taxation (i.e. inferred from changes in bunker prices), for 2030 and 2050.

In principle, carbon pricing (which includes carbon taxation) could impact on carbon emissions from international goods freight in three main ways: 1) via changes between and within the three main modes of transport, sea, air and land transport; 2) changes in the structure of trade including the weight of shipped products and the choice of trading partners and product types; and 3) changes in energy use per ton-km by transport mode. For international goods transport, sea transport dominates, but all three modes are important. Apart from land-based transport, international person transport is dominated by aviation. While people-oriented transport represents 85% of the aviation sector's revenues (although a lower share of ton-km), 90% of international sea transport's revenues are derived from goods transport.

There are two main alternatives for implementing a carbon price for goods transport: i) *carbon taxation* (a given tax per unit of carbon emissions); and ii) *cap-and-trade* schemes for trading rights to emit carbon at a (positive) carbon price established in the carbon market. In both cases, a 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 fewer product varieties, and lower traded quantities); and/or to support global climate finance purposes. Offset or other cap-and-trade schemes are less likely to raise similar revenues. It is important to emphasize that an efficient strategy to implement a carbon tax to bunker fuel requires this tax to be universal, worldwide cooperation, and avoidance of free riding problems in order to prevent the carbon leakage phenomenon (Elliott et al. 2010).

In our study we consider carbon taxation, but our results and conclusions will hold if carbon pricing is 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. Note also that our analysis sheds light on how carbon emissions can gradually be reduced when imposing a carbon tax on bunker fuels. The crucial issue we here consider is: how to immediately contribute to reducing the current, highly excessive, GHG emissions rate toward long-run sustainable levels.

GHG emissions from international transport have recently become a central issue of interest, for various reasons. The adverse consequences mentioned above are increasingly recognized by more countries and other international stakeholders. In 2017, the IMO implemented a new set of technical carbon intensity vessel standards, and in April 2018, the International Maritime Organization (IMO) decided on a plan to reduce the GHG emissions from international shipping to half the 2008 level (1,135 million tons) by 2050 (see IMO (2018)). However, without implementing any type of carbon pricing, the Third IMO GHG Study (IMO (2015)) projects that conditional on future economic and energy developments, and planned vessel efficiency improvements, maritime emissions could increase by between 50% and 250% by 2050 under a business-as-usual scenario. All these projections under different scenarios are greater than emissions for 2012. International shipping emissions continue to be omitted from the GHG emissions accounts of the countries involved, as they are only referred as supplementary information in national inventories for communication to the UNFCCC (Nunes et al. (2017)).

Due to lack of data, we do not study here how carbon taxation could: i) reallocate trade of products between transport modes (air and sea transport); ii) induce more technologically efficient and less carbon intensive shipping modes; and iii) incentivize development of more environmentally friendly fuels.

In the continuation we present a literature review in Section 2, while the theoretical model is presented in section 3; the data description and the empirical analysis and results of the effect of a carbon tax on international trade can be found in section 4. Section 5 presents the estimations of the potential reductions in CO_2 emissions that could result from implementing carbon taxation to shipping international trade. Section 6 includes the possible financial resources that can be obtained from carbon taxation at the international level. Section 7 sums up and concludes.

2. Review of related literature

The background literature dealing directly with the main research topics of our paper is limited. We here revise the studies closest to this paper. Cristea et al. (2013) computed GHG emissions from both production and transport (air, rail and trucks) 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 here 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 grams 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 that 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. These factors together will contribute to a reduction in CO_2 by 14% by 2030 and 23% by 2040, respectively. A reduction in trade would only contribute with 4% of such CO_2 reductions.

Brancaccio et al. (2018, 2020) analyze, among other things, the effects of shipping costs and oil prices on only bulk shipping using two databases, a small sample of shipping contracts from Clarkson; and the Automatic Identification System (AIS) data on ship movements. Brancacchio et al. (2020) find that a 10% increase in the oil price, and in total shipping costs, reduces bulk shipping by 4.4%, and 10%, respectively. Their trade elasticity with respect to the oil price varies between -0.1 (when the oil price is low) and -1.2 (with high oil price). These effects are larger than those found in our study. Both these papers rely on only bulk shipping, and a limited sample of shipping contracts. We use global maritime trade data, and a wider range of products at the 6-digit HS level of aggregation. Neither of these two 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 of 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/t 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 rises.

A strand of literature also estimates the spatial and temporal variability of GHG emissions from shipping traffic. 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 North America: 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 the AIS data to estimate global shipping emissions for 2015. Schim et al. (2018), using data from AIS and trade custom declarations, calculate carbon emissions per vessel and per journey for Brazilian export shipments in 2014. This literature does not address carbon taxation nor its possible effects on international maritime trade, as we do here.

Thus, in comparison with the related existing 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.

3. The theoretical model

3.1 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. (2018), Bernard et al. (2017)), 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 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 is because to calculate CO_2 from maritime trade. We need to take into consideration that carbon emissions intensities by type of ship and products it transports, 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. We again remark that we only consider the heaviest products, i.e. products 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, Redding, and Schott (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 industry, and product type.

Bernard, Redding, and Schott (2010, 2011) pioneered the modelling 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 ton-km per type of product and vessel on: i) the traded weight – country distance of different 6-digit products; and ii) CO_2 emissions after taken into consideration that ships specialize in transporting different products and have different carbon emission intensities.

3.2 The model

3.2.1 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:

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

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 ξ_m =1, the goods are homogeneous (perfect substitutes), so that demand only depends on aggregate industry output. ξ=0 describes the case when the demand for each good is completely independent of other goods. Thus, the last two terms in equation (1) indicate that consumers give increasing weight to the distribution of consumption levels across varieties.

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 $u[q_m(0;j)\}$ ..., $q_m(N_j;j)]$ (as defined in equation (1)) corresponds to industry j:

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

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

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

subject to the following budget constraint:

$$\int_0^1\int_0^{N_j} p(i,j)*q_m(i,j)di\,dj \le E; \qquad (4)$$

where *p(i,j)* is the (global) price of product variety *i* from industry *j*[1]; and *E* denotes the expenditure by the typical consumer of an importing country on a set of differentiated products from different industries in different exporting countries.

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:

$$\max_{q_m(i,j),\lambda}\int_{j=0}^{1}(u\{q_m(0;1),...,q_m(N_1;1)\}),...,(u\{q_m(0;j),...,q_m(N_j;j)\})dj - \lambda\left[\int_{j=0}^{1}\int_0^{N_j} p(i,j)*q_m(i,j)di\,dj - E_m\right] \qquad (5)$$

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*:

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

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

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

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

We can assume, without losing generality, that the budget constraint is always binding and λ=1. We also consider that consumers are identical within any importing country and across *m* importing countries. Thus, the utility parameters a_m, b_m and ξ_m are assumed to be identical for all consumers of variety *i* from any given industry *j*, which allows us to drop the subscript *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:

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

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

3.2.2 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 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_{Mz}) from the exporting firm location. For any 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_{Mz} 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 as maximizing the following profit function:

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

where *p(i)* is the price of product variate *i* in any given industry *j*; $C_z(i,M;\delta_{mk})$ comprises the following costs: i) shipping costs (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 cost;

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 any give 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 per traded ton-km 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 any 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_{Mz}), 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, add a constraint that $q_z(i,M) > 0$ only if it is optimal for firm z to produce that variety and export 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 any given industry, we obtain:

$$0 \le \frac{\partial \pi_{z'}}{\partial q_{z'}(i',m)} = \frac{a - 2b(1-\xi)q_{z'}(i',m) - 2b\xi q_{z'}(i',m)}{\lambda} - \frac{b\left[(1-\xi)\int\limits_{z\neq z'}\int\limits_{m} q_z(i,m)dmdz + \xi\left\{\int\limits_{m}\int\limits_{i\neq i'}^{N_z} q_z(i,m)didm + \int\limits_{m}\int\limits_{z\neq z'}\int\limits_{i\neq i'}^{N_z} q_z(i,m)dmdzdi\right\}\right]}{\lambda} - C_z(i,M;\delta_{Mk}) \perp q_{z'}(i',m); \qquad (10)$$

where the operator $\perp$ ensures that either $\frac{\partial \pi_{z'}}{\partial q_{z'}(i',m)} = 0$ (i.e. the firm z' is producing a variety i optimally) or $q_{z'}(i',m) = 0$ (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 $q_{z'}(i',m)$ we obtain:

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

In equation (11):

a. The aggregate output for the typical firm *z* is:

$$Q_z = \int\limits_{m}\int\limits_{i\neq i'}^{N_{j,z}} q_z(i,j)didm + \int\limits_{m} q(i',j,z',m)dm$$

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

$$D(i,j) = \int\limits_{z\neq z'}\int\limits_{m} q_{z'}(i,j)dmdz + \int\limits_{m} q(i',j,z',m)dm$$

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

$$F(j) = \int\limits_{m}\int\limits_{z\neq z'}\int\limits_{i\neq i'}^{N_j} q_{z'}(i,j)didzdm + \int\limits_{m} q(i',j,z',m)dm$$

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* $q_{z'}(i,m)$, that firm *z* will export depends on the different costs its total aggregate output, the total world production of variety *i*, and global production of all varieties that are part of industry *j*.

4. The econometric analysis and the data

4.1 The empirical strategy

We use the System of Generalized Methods of Moments (GMM) [Arellano–Bover (1995)/Blundell–Bond (1998)] for panel data as our estimation method. Our econometric strategy is to instrument for the exchange rate, the bunker price per ton of fuel and the marginal costs of producing product variety *i*. An ideal instrumental variable is one that is highly correlated with these three variables but not with unobserved shocks to traded weight (quantity equation) of the traded products. However, it is challenging to find the most appropriate and effective instrumental variables. We have chosen as instruments: i) number of terror attacks to oil field; 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. [2]

Note that we take into account 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 test the validity of the instruments with the Sargan test. When our econometric relation includes the bunker price per metric ton of fuel, no time-fixed effect will be included to avoid collinearity problems.

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

4.2 Data

As mentioned, our empirical analysis uses country data instead of firm data taking into consideration that 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.

Our data source is World Integrated Trade Solution (WITS) from the World Bank which contains *bilateral international trade in terms of weight and value by product and year*, at the 6-digit HS levels of aggregation. Our original dataset consists of approximately 3.9 million observations for the period 2009–2017, including worldwide trading country partners, and more than 6,000 commodities at the 6-digit HS level of aggregation. We only consider the products that have had the highest weight consistently each year during our period of study. These products make up 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 chosen 6-digit HS products belong to 21 (2-digit) industries.

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

After we excluded all the landlocked countries and close land connected neighbors, we ended up with around 2.2 million observations.

We also use the data from the Centre D'Études Prospectives et D'Informations Internationales (CEPII) called GeoDist. This dataset has an exhaustive set of gravity variables developed in Mayer and Zignago (2005) that allows us to analyze market access difficulties in global and regional trade flows. GeoDist can be found online (http://www.cepii.fr/anglaisgraph/bdd/distances.htm) for empirical economic research including geographical elements and variables. A common use of these files is the estimation by trade economists of gravity equations describing bilateral patterns of trade flows as functions of geographical distance.

Bunker price changes are here interpreted as proxies for changes in bunker fuel taxes. The bunker fuel price data (in $ per metric ton) are available for the period between 2009 and 2017. Relevant macro data at the country level from the World Development Indicators from the World Bank have been used. The data for fuel (bunker) consumption by vessel type for ships come from the ITF/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 is Ribal and Young (2019).

4.3 The econometric model for estimating 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 tied closely to our theoretical modeling. Since each firm chooses not only how much of each variety to produce but also to which countries to export, we study econometrically the impacts of fuel price changes on the weight *times* shipping distance of traded goods (in ton-kilometers). The distance is determined by the location of the importing and exporting country.

Again, we do not have firm level data, only data for the traded quantity of products at the 6-digit HS levels of disaggregation between country pairs (exporting countries versus importing countries). We shall then 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 decisions of its firms about exporting product variety *i*, and behaving as Cournot competitors when deciding on exporting product variety *i* in.

When we consider the bunker price per ton of fuel, our proposed econometric model for the 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:

$$\begin{aligned} \ln q_{ijkmt} = \alpha_{11} + \beta_{11}\ln(Bunker\ price_t) + \lambda_{11}\ln(Exchange\ Rate_t) + \varsigma_{11}C_{kt} + \\ a_{11}Q_{it} + b_{11}D_{ijt} + c_{11}F_{jt} + \gamma_{11}M_{mt} + \delta_{11}X_{kt} + \mu_{ijkm} + \varphi_{ijkmt}. \end{aligned} \tag{12}$$

Note again that we do not include time-fixed effects to avoid collinearity problems with the bunker price. In equation (12), at time t, q_{ijkmt} is the weight-distance measure and is obtained by multiplying the weight of product variety of type *i* (i.e. a 6-digit product) from the *j* industry, traded between the importing country *m* and the exporting country *k* at time *t*, *times* the distance between country *m* and country *k*. φ_{jkmt} is a random disturbance term; while μ_{ijkm} is product/industry – importing/exporting effects. The variable definitions are given in Table 1.

Table 1. Definition of variables

EXPLANATORY VARIABLES	**DEFINITIONS**
q_{ijkmt}	**Weight** of product of variety *i* (i.e. a product at the 6-digit HS level of aggregation) from industry *j* (i.e. 2-digit industry) traded between the importing country *m* and the exporting country *k* in time period *t*, **times** the **distance** between country *m* and country *k*.
X_{kt}	The exporting country *k*'s characteristics in year *t*: GDP growth rate, level of GDP in US$, Inflation rate, population, 1st official language, if a colonizer, if a colony, Current Account/GDP, and other variables considered in gravity modelling
M_{mt}	The importing country *m*'s characteristics in year *t*: GDP growth rate, level of GDP in US$, Inflation rate, population, 1st official language, if a colonizer, if a colony, Current Account/GDP, and other variables considered in gravity modelling.
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.
Price (p_{ijkmt})	(log) Total value of the 6-digit HS level products divided by total weight of the 6-digit HS level products (within each 2- and 4-digit category, respectively).
Q_{it}	Total output of variety *i* in exporting country *j*
D_{ijt}	Total world output of product variety *i*
F_{jt}	Global output of all the varieties in industry *j*

The marginal cost C_{kt} of a traded product, according to the theory, 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 that a typical exporting country *k*'s incurs to produce variety *i*. Therefore, in this study, the marginal cost of producing variety *i* is represented by the position of this variety *i* in terms of its sales value, when compared to all varieties sold by country *k* in each year *t* to its 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 second lowest sales value is the second lowest core product (rank=n-1); and so on. A similar approach has been used by Chatterjee, Dix-Carneiro, and Vichyanond (2013). The parameters β_{11} and ξ_{11} should both be negative, according to our theory.

Once we determined the marginal cost C_{kt} of the traded products, we have further defined the sales value ranking (core-competence) into 4 categories:: *category 1* contains the 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 the median of the sales value; *category 3* is the group with products between the median and the first quartile of the sales value; and *category 4* comprises the products furthest away from this core competence or below the first quartile of the sales value. Thus, products in *category 1* are the ones with the lowest marginal costs, C_{kt}. We estimated equation (12) for each of these 4 core-competence ranking categories for our heaviest 6-digit HS level products. From comparing the 4 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* varies according to the exporting country's marginal cost of producing and exporting this product *i*.

We here 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 2, are crucial to predict the 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 the weight – distance with respect to the bunker fuel price across our *4 categories* (core-competence ranking categories) can vary (for 6-digit HS products) from –0.003 (in the furniture industry) and -0.022 (in the automobile industry), to -0.4 (for ores) and -0.42 (for fossil fuels). The elasticities of traded weight-distance with respect to the bunker price thus vary greatly by industry. Figure 1 illustrates these differences when considering the average elasticities across different core competence measures of the products.

Table 2. The effect on trade weight-distance of changes in bunker prices. Heaviest Products at the 6-digit HS level of aggregation. GMM estimates. Core linkages across products and trading partners *(Standard errors in parentheses)*

	Industry Category of the 6-digit HS products							
	10: Cereals	**12: Misc.grains (soya, etc.)**	**15: Animal-Vegetable oils**	**23: Animal fodder**	**25: Salt, stones, cement**	**26: Ores**	**27: Fossil fuels**	**28: Inorganic chemicals**
	(1)	**(2)**	**(3)**	**(4)**	**(5)**	**(6)**	**(7)**	**(8)**
Elasticity lnBunkerPrice								
Category 1	-.3167253	-.267283	-.1194384	-.226084	-.168464	-.399043	-.268136	-.185988
	(.0384785)	(.038564)	(.0360417)	(.025037)	(.036067)	(.040514)	(.099553)	(.014499)
Category 2	-.2708739	-.204212	-.1335528	-.180023	-.075225	-.364205	-.419043	-.119009
	(.050876)	(.05023)	(.0303404)	(.023125)	(.028269)	(.036674)	(.048573)	(.029796)
Category 3	-.1342549	-.182484	-.1195597	-.171604	-.046518	-.381997	-.399921	-.055966
	(.0613848)	(.05887)	(.0273407)	(.023708)	(.045944)	(.054714)	(.034374)	(.031242)
Category 4	-.1766457	-.240899	-.1629229	-.203508	-.078417	-.309274	-.419406	-.088050
	(.0341268)	(.032778)	(.031513)	(.027254)	(.028332)	(.041377)	(.029511)	(.029196)
	29: Organic chemicals	**31: Fertilizers**	**38: Other chemicals**	**39: Plastics**	**44: Wood**	**47: Wood pulp**	**48: Paper**	**72: Iron & Steel**
Elasticity lnBunkerPrice								
Category 1	-.2503799	-.3136591	-.133128	-.171858	-.126398	-.120166	-.081344	-.314474
	(.011859)	(.023212)	(.02378)	(.012968)	(.015270)	(.042681)	(.015465)	(.015874)
Category 2	-.1747001	-.184081	-.077378	-.143714	-.150651	-.166612	-.108389	-.185106
	(.019566)	(.054366)	(.034452)	(.025138)	(.018592)	(.017303)	(.021645)	(.021639)
Category 3	-.1446763	-.1415578	-.049072	-.132576	-.118661	-.128015	-.086957	-.189936
	(.040146)	(.048201)	(.030936)	(.020052)	(.014973)	(.023359)	(.023483)	(.027626)
Category 4	-.308295	-.1286671	-.1002387	-.181394	-.119221	-.099471	-.134247	-.318016
	(.012813)	(.040055)	(.035148)	(.022008)	(.018626)	(.022824)	(.018002)	(.043459)

	Industry Category of the 6-digit HS products				
	73: Iron & steel products	**74: Cooper**	**76: Aluminum**	**87: Vehicles**	**94: Furniture**
	(17)	**(18)**	**(19)**	**(20)**	**(21)**
Elasticity lnBunkerPrice					
Category 1	-.185685	-.181851	-.125604	-.086893	-.086946
	(.028941)	(.039596)	(.027870)	(.027381)	(.021733)
Category 2	-.090727	-.063762	-.104594	-.071957	-.071329
	(.022915)	(.070681)	(.028389)	(.042104)	(.025531)
Category 3	-.011024	-.211283	-.103306	-.021779	-.044445
	(.042178)	(.031674)	(.041742)	(.022268)	(.036509)
Category 4	-.003480	-.137916	-.077377	-.045349	-.003279
	(.028299)	(.026170)	(.028155)	(.021938)	(.024746)

Figures 1 and 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

Figure 1

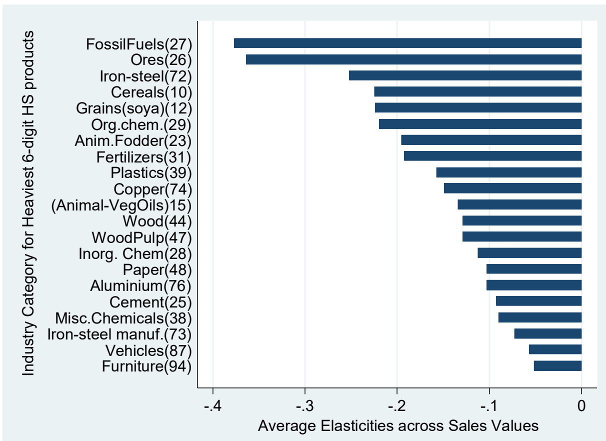
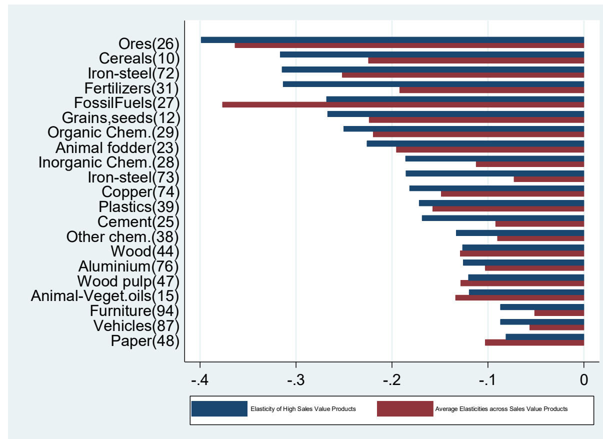


Figure 2

Average elasticities and the elasticities to core products (i.e. highest sales values)

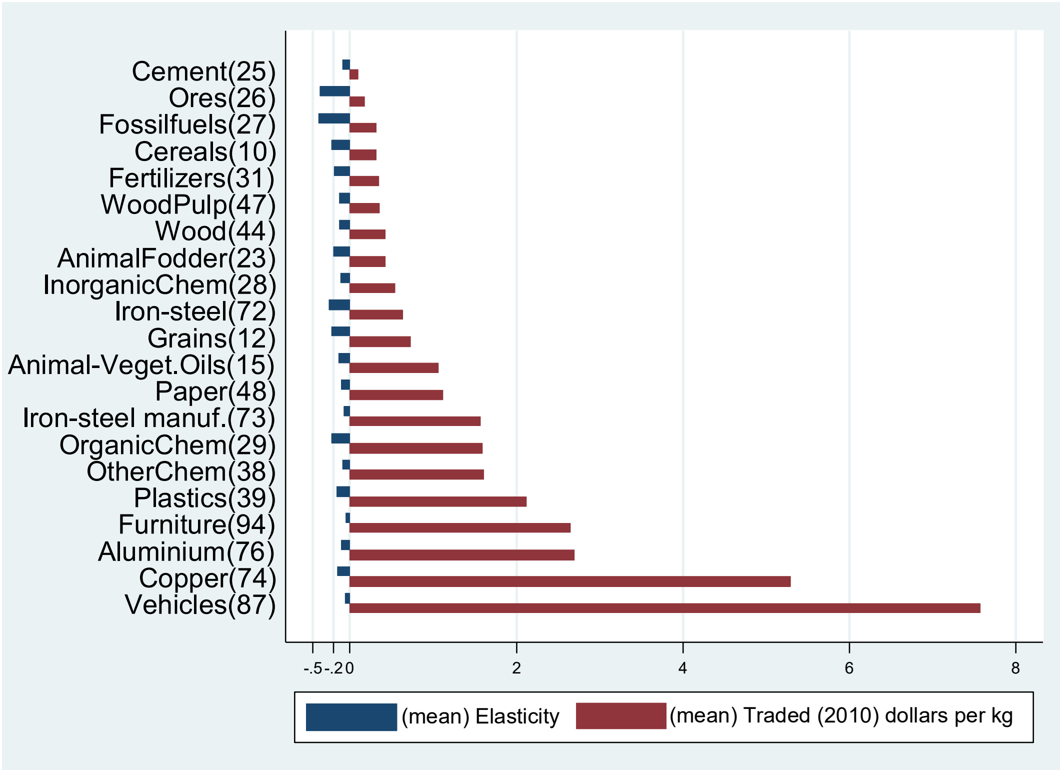


Since the heaviest goods categories by 6-digit sectors considered by us constitute almost 75% of total traded weight, this implies a very substantial impact of fuel taxation on fuel consumption and carbon emissions for maritime trade of these heaviest products, as shown in the next section.

Note also that the elasticities of traded weight-distance with respect to the bunker price vary greatly not only with the industry the 6-digit products belong to, but also with 1) the core competence of the traded good, the closer is the product to the core competence of the country's product portfolio, the lower the net elasticity is; and ii) the higher value of the traded product relative to its weight is, the lower the elasticity is. Figure 2 illustrates the average elasticities of our heaviest products at the 6-digit HS level by industry category, and the corresponding elasticities for the high-core products (highest sales values). Figure 3 shows the elasticities and the US dollars (real of 2010) per kg of traded product by industry category.

Regarding the elasticity of weight – distance with respect to the marginal cost, we have 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.

Figure 3. 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$)



Due to space constraints, we do not present in the paper the effects of other background variables such as the *exchange rate*, M_{nt}, X_{kt}, Q_{it}, D_{ijt}, F_{jt}, the marginal costs, and the main statistical tests (Sargan and autocorrelation), but they are available upon request. We however confirm that for example a depreciation of the importing country's currency reduces the weight-distance of traded goods; while higher population in the importing country increases the weight-distance of trade products.

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

The CO_2 emissions, and changes in such emissions as a result of increases in carbon prices, depend on the type of product and the types of vessels with which the different products are transported. To estimate CO_2 emissions, we use data on fuel CO_2 intensity per ton-kilometer (i.e. grams CO_2 per ton-km) for 8 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 3. The ITF/OECD provides this carbon intensity index for every 5 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 progress in the shipping industry, but also vessel size and speed among other characteristics for each ship category. There are also data on carbon intensities by *vessel size* for each vessel type. We here focus on the *average size* per vessel type, to estimate average emission rates by vessel type as shown in Table 3, as we do not have data on which product varieties are transported by which ship sizes.

5.1 Methodology to calculate carbon emissions

Table 3 shows that 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 grams for oil tankers, to a high value of 33 grams for vehicle carriers. Assuming a single emissions rate for all ship types (as in Shapiro 2016) will then lead to very large errors when calculating the carbon emissions for particular goods categories, which we here avoid. We use Table 3 to estimate: i) the average annual CO_2 emissions between 2009 and 2017 (Business as Usual (BAU) CO_2 emissions) for our set of heavy 6-digit traded products; and ii) the average change in CO_2 emission that would have taken place if a carbon tax would have been implemented during this period (BAU emissions). It was then crucial that we consider the ton-km (and not just tons) from trading the heaviest (6-digit HS) products between all possible country pairs, to estimate the elasticity of this traded ton-km with respect to the bunker price per ton.[3] These elasticities vary according to the core competence of this traded product, and we take this into account when estimating the total carbon emissions by product and in aggregate.

Table 3: Average freight emissions by vessel type and transported product type

Type of ship	**Types of goods transported**	**Carbon Intensity (= grams CO2/ton-km**			
		2010	**2015**	**2030**	**2050**
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 manufactures	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	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, OECD) (2018)

[3] The weight of the exported commodity is measured in tons and the distance in kilometers.

To calculate the CO2 emissions for any given product type, we proceed as follows:

a. Using the information in Table 3, we multiply the amount of the CO_2 or carbon intensity (in grams of CO_2) per ton-km emitted by the vessel type transporting the specific product type, *times* the ton-km for the traded product type.
b. One ton of bunker fuel consumption corresponds to emitting 3.11 tons of CO_2 (Olmer et al. (2017)), which is used to calculate how the bunker fuel price per ton will change when introducing a carbon tax. For every US$ of carbon tax per ton of CO_2, the bunker fuel price will increase by US$3.11. A carbon tax of US$ 40 per ton of CO_2 would *increase the bunker fuel price* per ton of fuel by *US$124.4* (= 3.11 (carbon content of 1 ton of bunker fuel) *times* $40).[4] If the bunker price is $450 per ton of fuel, the increase in the bunker price will be 124.4/450 = *0.27644* (or 27.64%) due to the US$ 40 of carbon tax per ton of fuel consumed.
c. We do not have data on the fuel consumption for each our traded 6-digit HS products. To be able to use procedure (b), we assume that our bunker price elasticity with respect to the traded ton-km equals the bunker price elasticity with respect to bunker fuel consumption.
d. The *reduction* in CO_2 emissions for any product type, due to a US$ 40 carbon tax, is estimated by multiplying the following components: i) the bunker price *elasticity* with respect to the traded ton-km for the specific product type ((i.e. β_{11} in equation (12)); ii) the relative increase in the bunker price, as calculated in (b) (e.g. *0.2764*); iii) the total CO_2 emissions for the given ton-km of the traded product type as indicated in (a).
e. The estimations in this section considers the core competence with cost linkages across both product varieties and trading partners. The Appendix presents an alternative set of estimations, based on the core competence model with cost linkages only across product varieties.

5.2 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 take into account: i) the average annual weight–distance (ton-km) of our heaviest 6-digit products; ii) the average carbon intensities for the type of ship used to transport the different product categories (see column 3 in Table 4), for our period of study (2009 – 2017)[5]; iii) the elasticities of the ton-km

[4] Note that US$40 is a lower bound of a range for the optimal global carbon tax (US$ 40 – US$ 80 per ton of CO_2) to be implemented from 2020 (Stern, Stiglitz and others (2017)).

[5] We assume that the technological progress that took place in each of the ship type between 2009 and 2017, and consequently their emission intensities, has been the same as the technological progress that occurred between 2010 and 2015.

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 one 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 find 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). This estimate is about half of total CO_2 emissions from the entire shipping sector over the same period (see e.g. IMO (2015)).

We also estimate what would have been the annual average reductions in CO_2 emissions (BAU emissions), and percentage reductions, if a global carbon tax of \$40 per ton CO_2 on bunker fuel for transporting heavy products, would have been implemented each year from 2009 to 2017. See respectively columns 5 and 6 in Table 4. Column 6 shows a reduction in total CO_2 emissions by about 6.6% relative to the BAU emissions. There are however substantial differences in reductions by sector. By far the greatest reduction in tons is estimated to take place for the freight of fossil fuels (by oil tankers), which also have the highest emissions of CO_2. Emissions from transport of fossil fuels can be reduced by around 12 million tons (or about 8%) due to this carbon tax. The largest percentage reduction is however for ores (10.9%) followed by cereals (8.4%), fossil fuels (8%), and iron and steel (7.8%). These are all very reasonable results as these goods categories are all heavy relative to their values, and fuel costs should have significant impact on the amounts of these goods transported. See Figure 4.

Figure 4. Estimated average carbon emissions reduction from a US$ 40/ton CO_2 tax for the heaviest products at the 6-digit HS level of aggregation by industry type during 2009 - 2017

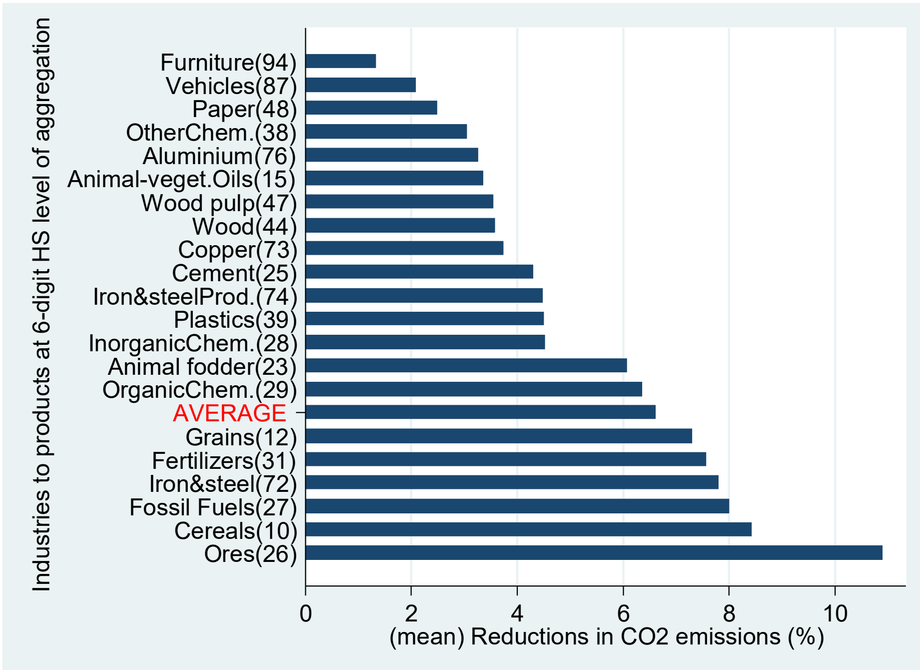


Table 4 thus gives estimates of total carbon emissions both under BAU with no carbon tax (column 4), as well the potential changes in carbon emissions due to a \$40 per ton CO_2 carbon tax, for the heaviest 6-digit HS products in each of the 21 industries they belong to (column 5).

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

6-digit HS products per industry (1)	Industry category (2)	Average Carbon emissions intensities: 2010 - 2015 (grams per ton-km) (3)	BAU CO_2 emissions with *only* technology of 2010-2015 (1000 tons) (4)	Reductions in CO_2 in BAU with \$40 carbon tax (1000 tons) (5)	Percent reduction in CO_2 in BAU with \$40 carbon tax (%) (6)
Cereals	10	11.98	23216	-1954	8.41
Grains, seeds (soya)	12	19.23	20634	-1505	7.29
Animal-Vegetable oils	15	19.23	9338	-313	3.35
Animal fodder	23	19.23	17657	-1073	6.07
Salt/stone/cement	25	4.71	12897	-556	4.30
Ores	26	4.71	53426	-5819	10.89
Fossil fuels	27	4.245	149695	-11967	7.99
Inorganic chemicals	28	10.12	7954	-360	4.52
Organic chemicals	29	10.12	8001	-509	6.36
Fertilizers	31	7.42	7109	-538	7.57
Other chemical prod.	38	19.23	5039	-154	3.05
Plastics	39	19.23	16703	-752	4.50
Wood	44	11.98	12526	-449	3.58
Wood pulp	47	11.98	7682	-273	3.56
Paper	48	19.23	8807	-219	2.49
Iron and steel	72	11.98	23768	-1855	7.80
Iron and steel products	73	19.23	11824	-442	3.73
Copper	74	19.23	2191	-98	4.48
Aluminum	76	19.23	4055	-132	3.25
Vehicles	87	37.28	20779	-434	2.09
Furniture	94	19.23	26951	-360	1.33
Total			**450254**	**-29763**	**6.61**

* Source: International Transport Forum (ITF) (2018).

5.3 Projections of carbon emissions: 2030 and 2050

To estimate CO_2 emissions reductions for 2030 and 2050, we consider i) only technological progress in shipping up to 2030 and 2050; and ii) both technological progress and a carbon tax of US\$ 40 per ton of CO_2. The results are presented respectively in Tables 5 and 6.

These estimates are obtained following the methodology used in Section 5.2. We thus consider: i) the annual average ton-km 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 product categories in 2030 (column 3 in Table 3) and 2050 (column 4 in Table 3); iii) the elasticities of the ton-km of traded 6-digit products between two countries with respect to the bunker fuel price, and that they vary according to their core competence; and iv) that one ton of bunker fuel consumption corresponds to emitting 3.11 tons of CO_2.

Table 5: Estimated annual carbon emissions and emissions reductions in 2030, due to a $40/t CO_2 carbon tax and shipping technology improvements

6-digit HS products per industry (1)	CO_2 emissions intensities in 2030 (grams per ton-km)* (2)	CO_2 emissions with technology of 2030. ***No carbon tax*** (3)	Reduction in CO_2 from *only* technology progress between 2010 and 2030[a] (1000 tons) (4)	Reduction in CO_2 emissions due to CO_2 tax in 2030 (1000 tons) (5)	CO_2 reduction from both CO_2 tax & technology progress in 2030 (%) (6)
Cereals	10.60	20560	-2656	-1730	18.9
Grains, seeds (soya)	17.03	18273	-2360	-1333	17.9
Vegetable oils	17.03	8269	-1068	-278	14.4
Animal feed	17.03	15637	-2019	-950	16.8
Salt/stone/cement	4.17	11419	-1477	-492	15.3
Ores	4.17	47307	-6119	-5153	21.1
Fossil fuels	3.96	132639	-17056	-10604	18.5
Inorganic chemicals	8.96	7045	-908	-319	15.4
Organic chemicals	8.96	7086	-914	-451	17.1
Fertilizers	6.57	6294	-815	-477	18.2
Chemical products	17.03	4463	-576	-136	14.1
Plastics	17.03	14792	-1910	-666	15.4
Wood	10.60	11093	-1433	-398	14.6
Pulp	10.60	6803	-879	-242	14.6
Paper	17.03	7799	-1007	-194	13.6
Iron and steel	10.60	21048	-2719	-1643	18.4
Iron and steel products	17.03	10471	-1352	-391	14.7
Copper	17.03	1941	-250	-87	15.4
Aluminum	17.03	3591	-464	-117	14.3
Vehicles	33.01	18405	-2374	-384	13.3
Furniture	17.03	23868	-3083	-319	12.6
Total		**398810**	**-51443**	**-26362**	**17.3**

* Source: International Transport Forum (ITF) (2018)

[a] Technology progress from the period (2010-2015) up to 2030. This column can be calculated as the difference between from column 4 in Table 4, and column 4 in Table 5.

The reduction in carbon emissions due to technological improvements from (2010 – 2015) and up to 2030 are presented in column 4, Table 5. The reductions in emissions due to only carbon tax in 2030 are shown in column 5, Table 5. Column 6 presents the percentage reduction in carbon emissions in 2030, due to technology improvements up to 2030 and a $40 carbon tax put into effect in 2030, relative to the BAU emissions with *only* technology progress. Similar carbon emissions projections for 2050 are given in Table 6.

Table 6: Estimated carbon emissions and emissions reductions in 2050, due to a \$40/t CO_2 carbon tax and shipping technology improvements

6-digit HS products per industry (1)	Carbon emissions intensities in 2050 (grams per ton-km)* (2)	CO_2 emissions with technology of 2050. ***No carbon tax*** (3)	Reduction in CO_2 from *only* technology progress between 2010 and 2050[a] (1000 tons) (4)	Reduction in CO_2 emissions due to CO_2 tax in 2050 (1000 tons) (5)	CO_2 reduction from both CO_2 tax & technology progress in 2050 (%) (6)
Cereals	9.229	17901	-5315	-1507	29.4
Grains, seeds (soya)	14.826	15911	-4723	-1161	28.5
Vegetable oils	14.826	7200	-2137	-242	25.5
Animal feed	14.826	13615	-4042	-827	27.6
Salt/stone/cement	3.631	9943	-2954	-428	26.2
Ores	3.631	41189	-12237	-4486	31.3
Fossil fuels	3.448	115487	-34208	-9232	29.0
Inorganic chemicals	7.799	6134	-1820	-278	26.4
Organic chemicals	7.799	6170	-1831	-393	27.8
Fertilizers	5.719	5480	-1629	-415	28.7
Chemical products	14.826	3886	-1153	-119	25.2
Plastics	14.826	12879	-3823	-580	26.4
Wood	9.229	9658	-2868	-346	25.7
Pulp	9.229	5923	-1759	-211	25.6
Paper	14.826	6791	-2016	-169	24.8
Iron and steel	9.229	18327	-5441	-1430	28.9
Iron and steel products	14.826	9117	-2706	-340	25.8
Copper	14.826	1690	-502	-76	26.3
Aluminum	14.826	3127	-928	-102	25.4
Vehicles	28.743	16025	-4754	-335	24.5
Furniture	14.826	2072	-6169	-278	23.9
Total		**347238**	**-103015**	**-22953**	**28.0**

* Source: International Transport Forum (ITF) (2018)

[a] Technology progress from the period (2010-2015) to 2050. This column can be calculated as the difference between column 4 in Table 4, and column 4 in Table 6.

Note that the new different assessed carbon emissions intensities for 2050, in column 2, have been reduced due to further technological progress up to 2050. Column 3 as before shows CO_2 emissions resulting from only shipping technological progress (i.e. no carbon tax), while column 4 displays the CO_2 reductions as a result of only technological progress from the period

(2010 – 2015) and up to 2050. Column 5 shows the impacts on CO_2 emissions from shipping, due to a \$40 per ton CO_2 carbon tax in 2050. Column 6 shows the total percentage reductions in CO_2 emissions due to both technical progress and to carbon tax. The total reduction in emissions relative to the annual average CO_2 emitted between 2009 and 2017 for our heaviest products, would be in this case 28.0% which is larger than for 2030 (17.3%).

Our CO_2 estimates strongly indicate that predicted advances in ship technology, combined with a moderate carbon tax (US\$ 40), will be far from sufficient to fulfill the IMO target emissions rate reduction by 2050 which is 50% relative to the 2008 level. Additional instruments and tools are needed. Even a higher carbon tax, for example \$80 per ton CO_2 in 2050 (close to the high end of the globally optimal range by 2030 in Stern, Stiglitz and others (2017)) would lead to a total reduction in carbon emissions from international shipping by at most 34% by 2050. And even this reduction is probably over-stated as it is based on our assumption that international maritime trade activity will not increase from now up to 2050.

We can also compare our results with the IMF simulation study by Parry et al. (2018). That study predicts the impacts of a carbon tax on international bunker fuels on all traded goods, imposed gradually and increasing by \$7.50 per year from 2021 onwards, reaching \$75 by 2030, and \$150 by 2040. They predict a reduction in carbon emissions from international shipping by 14% (due to the \$75 per ton CO_2 tax) in 2030, and by 23% (due to the \$150 tax) in 2040. These carbon emission reductions in Parry et al (2018) are a result of a combination of four factors: 1) improvements in ships' technical efficiency; 2) improvements in ships' operational efficiency; 3) shifting to larger ships and higher load factors; and 4) shifting trade away from heavy goods and distant trade partners, and reduced trade volume. All our estimated impacts follow from the last of these factors, reduced trade volumes and country distances, measured in ton-kilometers. In Parry et al. (2018), only a small share (4%) of their total estimated carbon emission reductions (of 14%), when imposing a US\$ 75 carbon tax, are a result of reduced volume – distance of international trade. A crucial difference between our study and Parry et al. (2018) is that only our study provides estimations on real historical data. All the results in Parry et al. (2018) are based on simulations of a theoretical model.

Our results show that the emission reduction from international maritime trade of the heaviest products (at the 6-digit HS level of aggregation) as a result of imposing a carbon tax are much greater than those predicted by Parry et al (2018) when considering total worldwide maritime trade.

Trade in our heaviest products represent about half of the total carbon emissions from global shipping today.

We here remark that the only possible way to obtain an overall small effect of a carbon tax on trade and consequently on CO_2 emissions, as in Parry et al. (2018), would be that the impacts of carbon taxation on the rest of (less heavy) maritime trade are significantly smaller than our estimated impacts on the heaviest categories, or close to zero.

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, which was 1,135 million tons of CO_2 (Parry et al. (2018)). Our estimates indicate that one could achieve in 2050, only a 28% reduction in CO_2 emissions from the annual average levels between 2009 and 2017 from trading only the heaviest products. Also note that the 28% reduction requires a carbon tax of $40 per ton CO_2, technological and efficiency improvements in maritime transport, and no increase in the average annual trade relative to the period 2009 – 2017. Recall also that IMO has not committed yet to any carbon price scheme. Therefore, it is difficult to see how IMO will be able to reach its goals without implementing a carbon tax of at least US$ 40 per ton CO_2, and preferably higher. Technology and efficiency progress will not be sufficient. See Smith et al. (2015, 2016) for similar conclusions.

6. Calculation of global revenues from a $40 per ton carbon tax on shipping heaviest products in 2030 and 2050

We can now calculate the tax revenues from a global tax of UD$ 40 per ton CO_2, on carbon emissions from maritime transport of the heaviest goods categories analyzed on this paper, in 2030 and 2050, assuming that overall trade activity does not change for these products by these timelines. This is done using our CO_2 calculations from Tables 5 and 6.

The tax revenues with a $40 carbon tax per ton of CO_2 in the maritime sector transporting our heaviest products will be: in 2030, **US$ 14.90 billion** (= (398.8 – 26.4) million tons × US$40 per ton; see Table 5); and in 2050, **US$ 12.98 billion** (=347.4 – 23.0) million tons × US$40 per ton; see Table 6).

Tax revenues are thus greater in 2030 than in 2050 from our calculations, as "baseline" carbon emissions before tax are assumed to be reduced by 2050 relative to 2030 due to more technically efficient transport at the later date, assuming constant global trade volume in ton-kilometers for heavy products. Since the relative reduction in emissions is assumed independent of this baseline level, the absolute emissions reduction from a given carbon tax will be lower in 2050 than in 2030.

7. Conclusions

We present a theoretical and empirical model of international trade of products at the 6-digit HS level of aggregation between country pairs, to study among other things the effect of carbon taxation on CO_2 emissions from global international maritime trade. The firms of the exporting countries face differing marginal costs with each product variety.

To our knowledge, our paper is the first to estimate impacts of carbon taxation on global maritime trade activity, using detailed data for CO_2 emissions intensities by type of maritime vessel used for such trade transport, which vary substantially by vessel type and transported product.

We estimate our empirical model using the WITS data set with products at the 6-digit HS level of aggregation which have been the heaviest (in tons) to transport by sea, consistently in each year from 2009 to 2017. Since the maritime sector does not face any carbon tax, or any other type of tax, we simulate the effect of a carbon tax on international trade by analyzing the effect that changes in the bunker fuel prices will have on this trade. These 6-digit HS products are part of 21 industries.

In our econometric analysis, we model the weight-traveled distance (ton-km) for our heaviest traded products which correspond to our theoretical model specification, to obtain the elasticities for ton-km (assumed proportional to bunker fuel consumption for a given goods category) with respect to changes in the bunker price. These elasticities are in most cases found to have lower (absolute) values for exported product varieties that have lower marginal costs. This means that a country that exports a product variety with lower marginal costs or that is closer to its core competence, will have a relatively lower response, in terms of changes in ton-km of transport activity, to changes in the bunker prices. It is then very important for this exporting country to sell its least costly product, regardless of the size of a carbon tax. Elasticities differ substantially, from low (absolute) values of about -0.003, to a high value of about -0.42. We also find that the largest impacts of carbon taxes on maritime trade are on the products with the lowest sales values relative to their weight.

We thus find that increases in the bunker fuel price, which is used as a proxy for carbon taxation of bunker fuel, lead to substantial reductions in the ton-km for internationally traded 6-digit HS products, but that the reduction varies greatly with the product variety type and industry.

Consequently, such reductions will proportionally reduce the bunker fuel consumption and carbon emissions from international shipping.

Imposing today a global and uniform carbon tax of $40 per ton CO_2 for an annual trade activity (ton-km) similar to the period between 2009 and 2017, would reduce carbon emissions, by about 6.6% (30 mill tons of CO_2) in total for the heaviest 6-digit HS level products. These products comprise about 75% of total weight in global maritime trade. The products with the highest relative reduction in carbon emissions resulting from a $40/ton CO_2 carbon tax are ores (10.89%), cereals (8.41%), fossil fuels (7.99%), iron and steel (7.80%), and fertilizers (7.57%). The products with the lowest relative carbon emissions reductions are furniture (1.33%), motor vehicles (2.09%), and paper (2.49%). Fossil fuels are found to have the greatest reduction in CO_2 emissions.

We also predict the possible future reductions in carbon emissions from maritime transport of heavy products for 2030 and 2050, assuming the 2009 – 2017 trade activity, and considering two factors together: i) technical and efficiency improvements in maritime transport corresponding to 2030 and 2050; and ii) a tax of US$40 per ton CO_2 on maritime transport. We find that these two factors could reduce the annual CO_2 emissions from the transport of these heavy products, by 78 million tons CO_2 in 2030: from an annual average of 450 million tons (found in our based period, 2009 – 2017) to 372 million tons in 2030. And by 126 million tons in 2050: from 450 million tons to 324 million tons in 2050. These estimates are again obtained assuming no growth in international maritime trade from 2017 and up to 2050. Still, our estimated reduction by 2050 is far less than the reduction target set by the IMO, which is to reduce CO_2 emissions from the entire maritime sector to 560 million tons CO_2. It is thus clear that other and more forceful measures are required to reach the goal of the IMO. Among those measures, a higher carbon tax than US$40 is clearly necessary.

A $40 per ton CO_2 tax on bunker fuels at the global level would generate substantial tax revenues, and give room for redistribution benefitting low-income countries, or be spent to increase general climate action that could also lead to higher global welfare. From our calculations, such a tax will 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.

As far as we are aware, this is the first combined theoretical and econometric analysis of impacts of carbon taxes on the shipping sector, and on bunker fuel prices, and maritime trade activity and carbon emissions from trade in heavy goods, based on historical global trade and bunker price data, and detailed data on CO_2 emissions intensities for the ship types transporting the goods categories we study.

An innovation of our work, relative to other studies, is that it yields a much richer set of implications of carbon taxation on international trade activity and CO_2 emissions. Numerous extensions of our work can be visualized; we intend to pursue some of these in future work.

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