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

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Abstract

We study impacts of carbon pricing to international transport fuels on fuel consumption and carbon emissions, trade activity, focusing on sea freight which constitutes the most important international trade transport activity. We use the WITS global dataset for international trade for the years 2009-2017 to estimate the impacts of changes in the global average bunker fuel price on the weight *times* distance for goods transported and carbon emission from international shipping. We find quite strong but variable negative effects of fuel cost increases on weight times distance for traded goods, and on carbon emissions from sea freight, for the heaviest goods categories at the 6-digit HS levels of aggregation in global trade, with bunker-price elasticities ranging from -0.03 up to -0.52. Considering an increase in the bunker fuel price as a proxy for a fuel tax, our results then indicate substantial impacts of bunker fuel taxes on the volume of sea transport, on bunker fuel consumption, and on carbon emissions from the international shipping sector. Our results indicate that, for the current level of international trade, a global tax of $40 per ton CO_2 tax will reduce carbon emissions from global shipping fleet by about 7% for the heaviest traded products; and by most so for goods with particularly high weight-to-value ratios such as fossil fuels and ores.

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1. Introduction

To limit increased 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, while minimizing the mitigation costs. No international transport activity today faces any meaningful emission taxes or charges. 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, 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 activity. The *second* is too high fuel consumption (and too polluting fuels), and consequently too high carbon emissions. The *third* is low fiscal revenue raised from international shipping transport, a common and critical problem for many low-income countries with relatively low tax revenues collection (see Keen and Strand (2007) and 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%. According to Cristea et al. (2013), 51% of carbon emissions from international trade in 2004 resulted from sea freight, 27% from air freight, and 22% from land (road and rail) transport. Note that the average carbon emissions per ton-km of transported goods are up to 100 times as high for air transport as for sea transport.

This paper aims to contribute to better understanding of how and to what degree emissions from international transport can be reduced due to carbon pricing. It analyzes, theoretically and empirically, the relationship between fuel costs, and international goods trade and global greenhouse gas (GHG) emissions from the maritime sector. Our study considers the bunker price per ton of fuel to represent the unit fuel cost, and changes in the bunker price to represent impacts of (and serve as a proxy for) carbon taxation. A report from UNCTAD (2009) indicates that fuel costs account for as much as 50% to 60% of total ship operating costs depending on the type of ship and service (see also Gohari et al. (2018)).

Thus, the effects on trade of changes in bunker prices allow us to predict how implementing carbon pricing in the maritime sector will impact on different attributes of trade structure, and on the CO_2 emission from this sector.

As far as we are aware, this is the first research study that theoretically and empirically attempts to infer impacts of changes in bunker fuel prices on *global international trade* and on *global* *carbon 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.

A main objective of this work is 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 pricing could reduce CO_2 emissions. We estimate not only CO_2 emissions levels from maritime transport at both the country and product levels, but also how these emissions can be affected by carbon pricing. It is then indispensable that we analyze how changes in fuel prices (through carbon pricing) affect international trade, at the highest possible level of disaggregation. We think that our work contributes to overcoming a lack of information about the CO_2 emissions in the maritime sector by traded product types and categories, and not just the aggregate levels of CO_2. Our work can also help to suggest policies directed at industries and countries/regions whose maritime transport results in high levels of CO_2 emissions.

Carbon pricing can impact on carbon emissions from international goods freight in three main ways: 1) via changes between and within modes of transport, where international goods freight is composed of three main modes: sea, air and land transport; 2) changes in the structure of trade including the weight of shipped goods and the choice of trading partners and good types, for each transport mode; 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.

This study considers all possible worldwide country pairs that trade products at the 6-digit HS level of aggregation. It focuses on three main topics. *First*, we analyze theoretically and empirically the impacts of increasing bunker prices per ton of fuel on the traded weight (intensive margin). *Second,* we study, both theoretically and empirically, the degree of "pass-through" of changes in fuel prices (which will represent carbon pricing) to final prices of the traded goods. *Third,* we will calculate the impact on carbon emissions due to changes in the structure of the international goods' trade that follow from carbon pricing (i.e. inferred from changes in bunker prices).

GHG emissions from international transport have recently become a central issue of interest, for various reasons. *First*, the adverse consequences mentioned above are increasingly being recognized, by more countries and other international stakeholders. *Secondly*, such emissions are now embedded in the Paris Agreement (PA) but were not part of the Kyoto Protocol. In April 2018, the International Maritime Organization (IMO) decided on a plan to reduce the GHG emissions from international shipping transport to half the 2008 levels (1,135 million tons) by 2050, but this plan needs to be developed further to specify the mechanisms by which this target can be reached (see IMO (2018)). In 2017, the IMO already implemented new vessel carbon intensity standards for technical efficiency.

International Climate Agreements, including the PA, have however so far not paid enough attention to CO_2 emissions resulting from international maritime transport, and how they can be affected. The Third IMO GHG Study (Smith et al. (2015a, 2015b) estimates that international transportation by sea resulted annually and globally in approximately one billion tons of CO_2 emissions between 2007 and 2012. These figures have more recently been revised, by CE Delft (2017), which predicts that these emissions will increase by between 35% and 210% by 2050 under a business-as-usual scenario. Moreover, shipping emissions continue being omitted from national GHG emissions accounts, as they are only referred to as supplementary information in national inventories for communication to the UNFCCC (Nunes et al. (2017)).

There are two main alternatives for implementing a carbon price for transport of traded goods: i) *carbon taxation* (with 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 will be established to represent the marginal cost of carbon emissions related to bunker fuel consumption by the maritime sector. If carbon pricing is implemented via carbon taxation, this scheme could raise substantial revenues some of which can be transferred back to individual countries. These revenue transfers can serve to compensate 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 support global climate finance purposes. Offset or other cap-and-trade schemes are less likely to provide similar revenues.

In our study we consider "carbon pricing" more generally; therefore, all our results and conclusions will be considered to 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 scheme.

Due to lack of data, we do not in this paper study how carbon pricing can: i) shift trade between transport modes (air and sea transport) for goods where both modes can be relevant; ii) induce the use of shipping modes that are more technologically efficient and less carbon intensive; and iii) give boost to develop more environmentally friendly fuels.

In the continuation we present a literature review in Section 2, while the theoretical background to our paper is found in section 3; our theoretical model in section 4; a discussion to our data in section 5; and the empirical analysis and results in section 6. Section 7 presents the estimations on the potential reductions in carbon emissions that could result from implementing carbon taxation to shipping international trade. Section 8 includes the analysis of the effect of carbon pricing on the prices of the traded goods. Section 9 sums up and concludes.

2. Literature review

The background literature dealing directly with the main research topics of our paper is limited. Cristea et al. (2013), Shapiro (2016), Schim et al. (2018), and Parry et al (2018) are central works and will be discussed carefully here.

Cristea et al. (2013) computed GHG emissions from both production and transport of internationally traded goods, focusing on one year, 2004, using dataset from the Global Trade Analysis Project (GTAP). Their paper did not study econometrically the impacts of higher transport costs (i.e. fuel or carbon pricing) on the weight and structure of international trade, which is the main objective in this project. They created a database of output and transport emissions associated with origin–destination–product trade flow, considering 28 individual countries and (own-defined) 12 regions; and 23 traded merchandise sectors and 6 non-traded service sectors, all based on the Global Trade Analysis Project (GTAP) data base. They aggregated sectors with similar transport characteristics. They assessed the likely growth in emissions in response to changes in global trade due to tariff liberalization and unevenly distributed GDP growth. They calculated shipping emissions for 6 ship categories and other transport modes (air, rail and trucks). They found large differences in emissions across their selected industries and countries, and their selected imported and exported goods.

Shapiro (2016) estimated fuel demand elasticities based on a gravity model in which *trade values* depend on *transport costs*, using quarterly reports of transportation costs and trade values for only US and Australian imports over the period 1991–2010. The US data report trade at the 10-digit HS level, while the Australian data report trade at the 6-digit HS level. Shapiro aggregates these data to 13 sectors. In contrast to our present work, Shapiro's numbers on CO_2 emissions are not derived from international trade dynamics, but rather from separate sources: CO_2 from production comes from GTAP for 2007, and single CO_2 emission rates for airborne trade (IATA) and maritime trade (IMO). Notably, Shapiro does not distinguish emissions by aircraft and ship types, as we do here for shipping. Transport costs comprise insurance rates, tariffs, border effects, and bunker oil price. It is therefore difficult to single out the effect of carbon taxes/fuel prices on trade (value). Shapiro considers a carbon tax counterfactual, assuming a single emissions intensity rate, 9.53 grams CO2/ton-km for the maritime sector, to estimate the effect on welfare of this tax. We, by contrast, take into account the widely different emission intensity rates by ship type. This is important because goods are transported in different types of ships. Shapiro followed Armington's (1969) modeling which assumes that each country produces only one goods variety, and varieties differ across countries. His paper does not either present the impacts of the counterfactual carbon tax on CO_2 emissions, as we analyze here.

Schim et al. (2018) calculate carbon emissions per vessel and per journey for Brazilian export shipments in 2014. Their approach allocates shares of these emissions to individual commodity shipments, and their exporters, importers, traders and owners. They trace the complete journey of a cargo consignment from the port of export to its final destination port and allocate a proportional share of the ship's emissions to each leg of the journey. They apply this approach to all individual Brazilian export shipments in the year 2014 – around 520 million tons of cargo. The authors found that most of Brazil's exports consist of raw materials with low value per weight unit. China is the largest recipient (41%) followed by Japan and Netherlands (6% each). Total emissions related to Brazilian exports in 2014 were found to be 26 million tons of CO_2, most from export of ores (14.7 million tons), and agricultural products (6 million tons). The authors do not address carbon pricing nor its possible effects on international maritime trade, as we do here.

A recent study by the IMF, Parry et al. (2018), considers impacts on carbon emissions from international shipping due to a carbon tax which rises gradually to $75 per ton CO_2 by 2030, and to $150 per ton in 2040. Their model assumes that carbon emissions from shipping can be reduced from a carbon tax through four factors: 1) ships' technical efficiency improvements (e.g. ship modification to less polluted fuels, higher propulsion efficiency, optimal ship size); 2) ships' operational efficiency improvements (e.g. speed, route lengths, maintenance, load factor); and 3) optimal ton-kilometers of trade transport activity. They find that such a carbon tax will cause reductions in carbon emissions by 14% by 2030, and by 23% by 2040. 4% of these reductions are derived from a decrease in the traded volume measured in ton-kilometers.

Schuitmaker (2016) considers 5 measures that can contribute to reduce emissions: avoid heavy freight (oil, gas, and coal); use larger ships; improve the efficiency of new and old ships; and shift fuel demand to LNG and biofuels. Together, these measures could reduce carbon emissions from international shipping to 710 million tons CO2 by 2050; relative to IMO's BAU scenario of approximately 2 billion tons. McCollum et al. (2010) assess in a similar study that shipping emissions can be retained at today's level, about 1 billion tons of CO_2, by 2050 (versus their BAU emissions assessment of 2.75 billion tons), through similar measures.

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 global trade data. They find that the impacts on the global economy are negligible but more significant if the tax is US$90/ton of CO^2, with the greatest relative impacts on China. They also find that certain distant trade routes are discouraged by high carbon taxes. Sheng et al. (2018) consider more modest carbon pricing (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) studied the effect of transport costs on volume of bilateral trade using gravity models. They do not analyze specifically the effect of fuel prices on trade. They however find that doubling transport costs from their median value reduces trade volumes by 45 percent. In addition, they indicate that moving from the median value of transport costs to the 75th percentile cuts trade volumes by two-thirds.

Peters and Hertwich (2008) argue that cooperation in designing optimal trade policies among trading countries can substantially reduce fuel consumption and carbon emissions from international trade, and gives better opportunities for exploiting trade as a means for reducing emissions. They however do not consider carbon taxation as a mechanism for inducing such collaboration, which is our aim here.

Note that the results from most of these studies mentioned above are all based on numerical modeling and not on statistical estimates of trade responses to increases in transport fuel costs, and thus do not represent any stringent empirical analysis of the impacts of carbon pricing on international trade activities, which is our approach. We here estimate econometrically how GHG emissions can be reduced by implementing the carbon pricing on international trade activity. We historical data for trade activity, and for bunker prices, taking the bunker price change as a proxy for carbon pricing on bunker fuels. We analyze, theoretically and empirically, i) how international trade structure (intensive margin) is impacted by carbon pricing (i.e. elasticities of *traded weight times distance* with respect to *bunker prices per ton of fuel*); and ii) the "pass-through" of carbon pricing to import-export prices. 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 dataset consists of approximately 2.5 million observations for the period 2009–2017, including worldwide trading country partners, and more than 6,000 commodities at the 6-digit HS level. We only consider the products that have had the highest weight during our period of study. We thus estimate the true global CO_2 emissions considering all possible countries and traded products (their weights) to obtain the effects of carbon pricing on trade and CO_2 emissions *by product*. We also take into consideration that emission intensities vary substantially by vessel type and the type of product vessels transport, which is much in contrast with Shapiro (2016) and Parry et al. (2018).

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 assessment of the impact of changes in the bunker price per ton of fuel on the intensive margin of international trade and on carbon emissions. We remark in this context that none of the studies cited and discussed in the previous section analyzing the effect of carbon pricing on international maritime trade and CO_2 emissions, except for the work of Shapiro (2016) with the caveats addressed above, are based either on economic theory or on econometric analysis of panel data for international trade of goods, which is our approach.

We will not focus on exporting firms from different countries that sell a variety of products to importing firms in different countries. We neither focus on the dynamics of the connections nor focus on networking between firms on both sides of a trade transaction. See Bernard and Moxnes (2018), Bernard et al. (2018), Bernard et al. (2017) for further details on the new trade literature on networking in international trade and firms' behavior in such environments. Such an approach for our project is excluded, as the complete data for all firms participating in international trade in all countries are not available; and, in any case, such an approach would not be computationally feasible within the scope of this project.

Our main focus is to analyze how all countries make relevant decisions when they trade products at the 6-digit HS levels of aggregation related to trade adjustments (i.e. margins of trade) in response to carbon price changes. On this basis, we study, both theoretically and empirically, how changes in fuel prices affect trade dynamics (margins of trade) and the degree of fuel price pass-through from carbon pricing to international prices of goods.

Our approach is somewhat related to gravity modeling which is a standard analytical framework to analyze bilateral trade flows. Gravity models closely related to our work are the studies analyzing the effect of transport costs on trade volumes [see Bergstrand (1985), Deardorff (1998), Bougheas et al. (1999), Limão and Venables (2001), and Behar and Venables (2011)]. One of the main distinctions between our work here and these works is that we consider the effect of carbon pricing 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. Exporters chose not only the export quantity and the distance of its importing countries in order to minimize transportation fuel costs. There is also one practical reason why we need to estimate 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 total carbon emissions from maritime transport then requires the measure of ton-kilometers for each product category. We also consider several of the variables that are usually used in the estimation of gravity models.

Even though our analysis and empirical implementation will focus on countries instead of firms, our model follows closely the theoretical underpinnings of activities of multi-product firms in international trade (see Bernard, Redding, and Schott (2010, 2011); Eckel and Neary (2010); Mayer et al. (2014); and Eckel et al. (2015)). One reason is that we model exporting countries as determining the level of trade of each of the products at the 6-digit HS level that they produce. Thus, in our framework, importing countries have also some product varieties to choose from..

Our theoretical approach is more appropriate than Armington's (1969) approach (also considered in Shapiro (2016)) because it considers that each country produces only one variety, and varieties are differentiated by country of origin. We think that such modeling does not reflect the reality of the world; and secondly and more importantly, our goal is 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 carbon pricing; and ii) which of these products are the highest emitters of CO2. This approach is crucial in order to attribute as correctly as possible the responsibility of CO2 emissions by industry, and product type.

Bernard, Redding, and Schott (2010, 2011) pioneered the modelling of asymmetries between products on 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 costs of producing a variety of products and fuel costs determine the scale and scope of international trade, including the distances of the trading partners.

Our main contribution to the theoretical literature is to consider each importing country as maximizing a three-level utility function for the importing country that depends on the country's consumption levels (weight) of product varieties, from different industries, and from a portfolio of exporting countries, and prices of the traded products. Our model also involves countries that make decisions about i) exporting multi-products from different industries taking into account the costs of producing differentiated products; and 2) the distance to the importing countries. We follow Eckel and Neary (2010) and Mayer et al. (2014) when considering that countries that produce several product varieties, will face "product ladder" costs. This means that each country has a core product (its "core competence"), with lower efficiency (higher costs) for products further away from this core. We thus assume that there are cost linkages across product varieties and trading partners. Thus, an exporting country's trading decisions about weight of product varieties and importing-country distances here depend on bunker fuel price changes, and how close its exporting products are to its core competence.

As widely recognized in the trade literature, increased competition (including oligopolistic competition) between firms, both within and across countries, tends to reduce markup rates [see, for example, Rodriguez-Lopez (2011) and Arkolakis et al. (2012)]. We here instead consider how the profile of traded product prices are dependent on what we could call "cost-based" competence (how far is the exported product to the core competence of its exporting country), and "fuel cost-based" competence. The former implies that a country's core products are sold at lower prices, passing on their lower production costs to consumers (importers). The second can have the opposite effect, as exporting countries pass increased bunker fuel costs (and carbon price changes) on to consumers by charging higher prices.

One important aspect to mention here is partial- versus general-equilibrium analysis. Eckel and Neary (2010) highlight general-equilibrium adjustments through factor markets as an important channel for transmission of external shocks. To study the labor markets will require to consider firms' decision about employment and wages and how these firms interact with each other. Our available data will not allow us to ascertain how factor prices and employment at our product level of disaggregation will be affected by general-equilibrium adjustments, to changes in fuel prices/costs. Thus, we focus on a partial-equilibrium model (and reduced-form) analysis of how bunker price changes (or carbon pricing) affect trade and consequently CO2 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 categories of 6-digit products; ii) CO_2 emissions after taken into consideration that ships specialize in transporting different products and have different carbon emission intensities; and iii) prices of the traded 6-digit products.

3.2 The model

On the demand side, consumers in the importing countries buy different product varieties (i.e. products at the 6-digit HS level of aggregation) in the international market from different exporting countries. We consider *m* importing countries. Each consumer in each importing countries maximizes a three-level utility function that depends on the country' consumption levels $q(i;j;k)$

of the N_{jk} varieties (i.e. 6-digit products) produced in industry *j* (2-digit) from exporting country *k*. We have product variety $i \in [1, N_{jk}]$, where N_{jk} is the measure of product variety *i*; while *j* and *k* change over the interval [0,1] respectively.

At the lower level, consumers in the importing country has an additive function of a continuum of quadratic sub-utility functions obtained from buying a variety of products from *industry j and exporting country k:*

$$u[q(0;j;k),...,q(N_{jk};j;k)] = a\int_0^{N_{jk}} q(i,j,k)di - \frac{1}{2}b\left\{(1-\xi)\int_0^{N_{jk}} q(i,j,k)^2 di + \xi\left[\int_0^{N_{jk}} q(i,j,k)di\right]^2\right\}. \quad (1)$$

$\int_0^{N_{jk}} q(i,j,k)di$ is here the consumption of all varieties from industry *j* in exporting country *k*. The utility parameters *a, b* and ξ are assumed to be identical for all consumers in importing country *m,* and non-negative. These parameters denote the consumers' maximum willingness to pay, the inverse market size, and the inverse degree of product differentiation, respectively. If ξ =1, the goods are homogeneous (perfect substitutes), so that demand only depends on aggregate output in the industry. On the other hand, ξ=0 describes the monopoly case, where the demand for each good is completely independent of other goods. Thus, the last two terms in equation (1) indicates that consumers give increasing weight to the distribution of consumption levels across varieties.

The two-upper utility levels for each of the consumers in our importing countries are obtained by adding continuously each of the sub-utility functions of the importing country (equation (1)) such as $u[q(0;j;k)\}$ …, $u(N_{jk};j;k)]$ across all product varieties, across all industries and exporting countries that our importing country imports from. . Thus, the two-upper utility levels represent the typical consumer's welfare of the importing country from consuming a variety of products from *each of the industries j, from possible countries k that export products* to this importing country:

$$U[u\{q(0;j;k)\},...,u\{q(N_{jk};j;k)\}] = \int_{k=0}^{1}\int_{j=0}^{1} u\{q(0;j;k),...,q(N_{jk};j;k)\}djdk. \quad (2)$$

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

$$U[u\{q(0;j;k)\},...,u\{q(N_{jk};j;k)\}] = \int_{k=0}^{1}\int_{j=0}^{1}\left\{a\int_{0}^{N_{jk}} q(i,j,k)di - \frac{1}{2}b\left[(1-\xi)\int_{0}^{N_{jk}} q(i,j,k)^2 di + \xi\left\{\int_{0}^{N_{jk}} q(i,j,k)di\right\}^2\right]\right\}dj\,dk \quad ; \tag{3}$$

subject to the following budget constraint:

$$\int_0^1\int_0^1\int_0^{N_{jk}} p(i,j,k) * q(i,j,k)di\,dj\,dk \le E; \tag{4}$$

where *p(i,j,k)* is the price of the 6-digit product from industry *j* and from exporting country *k* in terms of the importing country currency[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 we use Lagrange multiplier method, to obtain the following linear demand functions for the different 6-digit products that a country chooses to import to maximize its utility, where λ is the Lagrangian multiplier (i.e. marginal utility of income):

$$\lambda p(i,j,k) = a - b\left[(1-\xi)q(i,j,k) + \xi\int_0^{Nj,k} q(i,j,k)di\right] \tag{5}$$

The inverse demand will be:

$$p(i,j,k) = a' - b'\left[(1-\xi)x(i,j) + \xi\int_0^{Nj,k} q(i,j,k)di\right]. \tag{6}$$

In equation (6), a'=a/λ; b'=b/k); and $\int_0^{Nj,k} q(i,j,k)di$ is the total demand for product variety *i* from a given industry *j*.

On the supply side, we assume that there are asymmetries in the marginal costs associated with the production of the export good varieties. This asymmetry arises because the production costs are close associated to the exported-good varieties A marginal cost increases as the exported product variety moves away from the "core competence" of the exporting country at which its marginal cost is lowest. Indeed, this synergy of this "core-competence" plays a crucial role for the

[1] An importer may buy different amounts of product variety *i* from different exporters.

net effect that bunker prices per ton fuel (or fuel per ton-km) have on the structure of trade and finally on carbon emissions.

We model an exporting country *k* as producing a variety of products equal to ρ_Z, from its ρ_V number of industries, and to be exported to its chosen portfolio of country-distances so that countries are associated with their distances to the exporting country and denoted by δ_M. Now, for the exporter's point of view, it is not the number of countries that are per se important but rather their distances to the exporter's country. δ_M is therefore a distance value associated to the distance between the importing and exporting country. This is especially crucial when exporters face changes in bunker fuel prices (i.e. carbon pricing), which makes it necessary to the exporters to optimally minimize the distance to the country partners to also minimize fuel costs, while taking into consideration the core competence or marginal cost of the product variety, as explained above.

Exporting countries whose firms export product variety *i* from industry *j*, maximize the following profits when selling abroad product variety *i*:

$$\begin{aligned}\pi_{Z,V,M} = & \int_0^{\delta_M}\int_0^{\rho_V}\int_0^{\rho_Z}\left[\left\{p_{Z;V;M}(i,j,m)/ExcRate_{mk}\right\} - BP_{ijm}\right]*F(q_{Z;V;M}(i,j,m);D_M)\,didjdm - \\ & \int_0^{\rho_V}\int_0^{\rho_Z} c_{Z;V}(i,j)*q_{Z;V;M}(i,j,m)didj - F\end{aligned} \quad ; \qquad (7)$$

where *F* is a fixed cost independent of the scale and scope (product variety and importing country portfolio), i.e. a sunk cost to participate in international markets; $p_{Z;V;W}\,(i;j;m)$ is the price of the good *i* from industry *j* in terms of the currency in the importing country *m*; and the function *F(q, D)* denotes the individual demands $q_{Z;V;W}\,(i;j;m)$ (equation (5)) for product variety *i* from different importers and their distances D_M . *ExcRate* is the exchange rate (i.e. the value of the importing country currency in terms of the exporter country currency). BP_{ijm} is the fuel cost per unit of the exported product that incorporate the type of ship that is used to transport the product variety *i*. $C_{Z;V}(i,j)$ is the marginal cost that industry *j* faces to produce variety *i*. These marginal costs are not related to the quantity produced (Eckel and Neary (2010), Eckel et al. (2015)), but differ, as mentioned, with the core-competitiveness to produce a specific variety. This marginal cost will be lowest for the core competence variety, because it uses the industry's most efficient production process.

We solve for the product variety *i* for any given industry *j*, to be exported to each country partner, taking into account the distance that exported products need to travel needs to be minimized. We can then focus on the exporter's decision making about exports volume and traveled distance for these products. Solving the derivative of equation (7) with respect to the different individual demands *q(i,j,m)* from each importing countries and their *distances* D_M for any industry, we find that:

$$\frac{\partial \pi_{Z,V,W}}{\partial q(i;j;m)} = \int_0^{\delta_M}\int_0^{\rho_Z} \frac{\partial F(q_{Z;V;M}(i,j,m);D_M)}{\partial q(i;j;m)} * \left[\left\{p_{Z;V;W}(i;j;m)/ExcRate_{mk}\right\} - BP_{ijm}\right] didm - \int_0^{\rho_Z} \frac{\partial p(i;j;m)}{\partial q(i;j;m)} q(i;j;m)di - c_{Z;V}(i;j) = 0 \quad (8)$$

Equation (8) is the solution of choosing the optimal volume of one variety *i* from a given industry *j* to export to a set of given importing countries, and their corresponding distance between the exporter and its country partners. We use equation (6) to solve equation (8) using the Leibniz integral rule and to obtain the first-order condition with respect to *q(i,j,k)*:

$$\frac{\partial \pi_{Z,V,W}}{\partial q(i;j;m)} = \left[\int_0^{\delta_M} F(q_{Z;V;M}(i,j,m);D_M)dm + \int_0^{\rho_Z} F(q_{Z;V;M}(i,j,m);D_M)di\right] * \left[\left\{p(i;j;m)/ExcRate_{mk}\right\} - BP_{ijm}\right] - \int_0^{\rho_Z} \frac{\partial p(i;j;m)}{\partial q(i;j;m)} q(i;j;m)di - c_{Z;V}(i;j) = 0 \quad (9)$$

From equation (9), we can solve for any given industry *j*, the prices (p(i;j;m)) and quantities (q(i;j;m)) for each product variety *i* for each importing country.

4. Data

Our most important dataset for our analysis is the World Integrated Trade Solution (WITS) database, set up by the World Bank, and contains *bilateral international trade in terms of weight and value by product and year*, at 2-digit, 4-digit and 6-digit HS levels. It consists of about 6 million records for each of the years 2002-2016, a large number of trading country pairs, and data for more than 6,000 commodities at the 6-digit HS level.

Using this WITS dataset, we analyze among other things, how the trade structure of products (intensive and extensive margins) at the 6-digit HS levels of disaggregation between *country-product pairs (exporting versus importing countries) could change in response to changes in bunker fuel prices*, and also the degree of pass-through of increased carbon prices to the final unit value/price of traded goods.

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. These data will also give us the ability to study the degrees of pass-through of fuel costs to final good costs, by using average price data embedded in the dataset.

Bunker price changes are here interpreted as proxies for changes in bunker fuel taxes. The bunker fuel price data (in $ per metric ton) for the period between 2009 and 2017.

A large number of 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 data for backhaul trade is obtained from UNCTAD (2018) (https://unctadstat.unctad.org/wds/TableViewer/tableView.aspx?ReportId=32363).

5. The econometric analysis

5.1 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 and the bunker price per ton of fuel. An ideal instrumental variable for our two measures of fuel price/cost is one that is highly correlated with these two variables but not with unobserved shocks to traded weight (quantity equation) and price (price equation) of the traded products. However, it is challenging to find the most appropriate and effective instrumental variables. We have chosen as instruments number of terror attacks to oil field, and the level of trade backhaul multiplied by the distance between trading partners. A subsequent version of this paper will consider average wind speed and wave heights in the travelling routes between country pairs trading products internationally using maritime transport.[2] Note that we will 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 will test the validity of the instruments with the Sargan test. When our econometric relation includes the bunker price per metric ton of fuel, the time-fixed effect will be omitted to avoid collinearity problems.

We will also report 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).

5.2 The econometric model to estimate 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. Using the WITS dataset, we analyze how the trade structure of the heaviest products (in each of the years of study) at the 6-digit HS levels of disaggregation between country-product pairs (exporting countries versus importing countries) could change in response to changes in bunker fuel prices.

Our work is the first econometric analysis of the impacts of fuel price changes on trade and emissions from trade. The closest work to our study is the paper of Shapiro (2016) who estimates the elasticities of traded value of imports by only two countries, Australia and the United States, with respect to transportation costs. In Shapiro's (2016) study one cannot directly identify the pure effect of carbon pricing (or fossil fuel price) on the weight of traded products. In our view it is essential to estimate the elasticities of the weight-fuel price, on the basis of data for a widest possible set of countries and not just two countries, in order to calculate the worldwide CO_2

[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).

emissions from maritime transport of traded products. As noted above, all other related studies that we are aware of are instead based on calibration approaches.

Thus, covering the period between 2009 and 2017, we study econometrically the impacts of fuel price changes on the weight *times* freight distance of traded goods (in ton-kilometers). This work will be extended to also consider the effect of changes in the bunker price on: 1) the number (variety) of traded goods; and 2) the number of trading partner pairs.

When we consider the bunker price per ton fuel, our proposed econometric model for the bilateral trade between a pair of countries for a product variety at the *6-digit HS level* will not include time-fixed effects to avoid collinearity problems with the bunker price per ton fuel, and will be represented by the following empirical relation:

$$\ln q_{ijkmt} = \alpha_{11} + \beta_{11}\ln(Bunker\ \ price_t) + \lambda_{11}\ln(Exchange\ \ Rate_t) + \xi_{11}C_{kt} + \gamma_{11}M_{mt} + \delta_{11}X_{kt} + \mu_{ijkm} + \varphi_{ijkmt}. \tag{10}$$

In equation (10), at time t, q_{ijkmt} is the weight-distance measure since the exporter optimizes both quantity and country-partner distance. q_{ijkmt} 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).

We present the results from estimating equation (8), but focusing on analyzing 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 that are traded bilaterally. These chosen 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. These 6-digit HS products belong to 21 industries. The estimated elasticities are reported in Table 2.

The marginal cost C_{kt} as mentioned, is lowest for the core competence product when this product uses the exporting country *k*'s most efficient production. The theory defines a country operating at its highest core of competence either when it uses its most efficient production process or with the minimum costs. 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 that this variety *i* has in terms of its sales value, when compared to all the varieties sold by firm *j* at each year *t*. Thus, for the triplet exporter-product variety-country destination (importer) by year, the product variety with the lowest sales value is the lowest core or the lowest rank (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 considered by Chatterjee, Dix-Carneiro, and Vichyanond (2013). The parameters β_{11} and ξ_{11} should be negative and positive respectively, according to our model. We do not present the estimates of all the background variables (e.g. M_{nt}, X_{kt}, *exchange rate*) as they are less consequential for our ultimate objective of this paper: the analysis of the effect of carbon pricing on trade structure and carbon emissions.[3]

We have grouped the core-competence of the products for each exporting country in each year, into 4 different ranking groups: from group 1 which are the products closest to the core competence of the exporting country, to group 4, the products furthest away (lowest sales value) from this core competence. Thus, products in group 1 for example are the ones with the lowest marginal costs, C_{kt}. We estimated equation (10) for each of these 4 core-competence ranking groups 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 the bunker fuel price on the weight-distance of traded

[3] These estimates can be obtained by request from the authors.

product *i* varies according to the exporting country's marginal cost of producing and exporting this product *i*. All these empirical results are shown in Table 2.

These average elasticities of the weight – distance with respect to the bunker fuel price (across core-competence ranking groups) can vary from -0.03 (for 6-digit HS products in the automobile industry) and -0.095 (for 6-digits product in grains such as soya beans), to -0.37 (for 6-digit HS products in the ores category) and -0.52 (for 6-digit HS products in the fossil fuels category). These results indicate that the elasticities of traded weight-distance with respect to the bunker price vary greatly depending on which industry the 6-digit products belongs to.

Table 2. The effect on trade weight-distance of changes in bunker prices. Heaviest Products at the 6-digit HS level of aggregation. *(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	-.2259165	-.1340677	-.0475471	-.169546	-.096066	-.363544	-.428729	-.1165603
	(.0222622)	(.0180333)	(.0178846)	(.008872)	(.012348)	(.019629)	(.018543)	(.008987)
Category 2	-.2066948	-.1541526	-.1939408	-.151313	-.0893179	-.381815	-.542399	-.137764
	(.0210279)	(.037522)	(.0204747)	(.020146)	(.028269)	(.032708)	(.026595)	(.031191)
Category 3	-.1344393	-.2779322	-.1018606	-.0960679	-.09904	-.4331261	-.599935	-.131478
	(.065977)	(.0356521)	(.0383166)	(.027934)	(.030534)	(.048778)	(.025817)	(.044325)
Category 4	-.1935967	-.0365099	-.686941	-.0970478	-.045958	-.330697	-.548737	-.439043
	(.0320208)	(.0074625)	(.0028311)	(.033187)	(.039995)	(.043254)	(.047958)	(.016101)
Elasticity lnSalesValue								
Category 1	.7706389	.6525852	.3176365	.7719075	.698961	.913218	.782951	.594808
	(.0416075)	(.053771)	(.0413574)	(.021945)	(.03767)	(.027688)	(.027405)	(.030203)
Category 2	.8692895	.8052071	.8941689	.7198861	.7907954	.976679	.852992	.744040
	(.0228566)	(.049786)	(.0260403)	(.036571)	(.043419)	(.027071)	(.02866)	(.041297)
Category 3	.8916678	.8615971	.774393	.7303565	.900656	.972993	.988067	.817315
	(.0442497)	(.026832)	(.0246695)	(.052096)	(.038509)	(.026569)	(.018204)	(.042722)
Category 4	.9201535	.6512115	.9032104	.7018992	.877312	1.03166	.858565	.640672
	(.010703)	(.004104)	(.0020785)	(.039139)	(.037915)	(.023268)	(.038503)	(.014785)

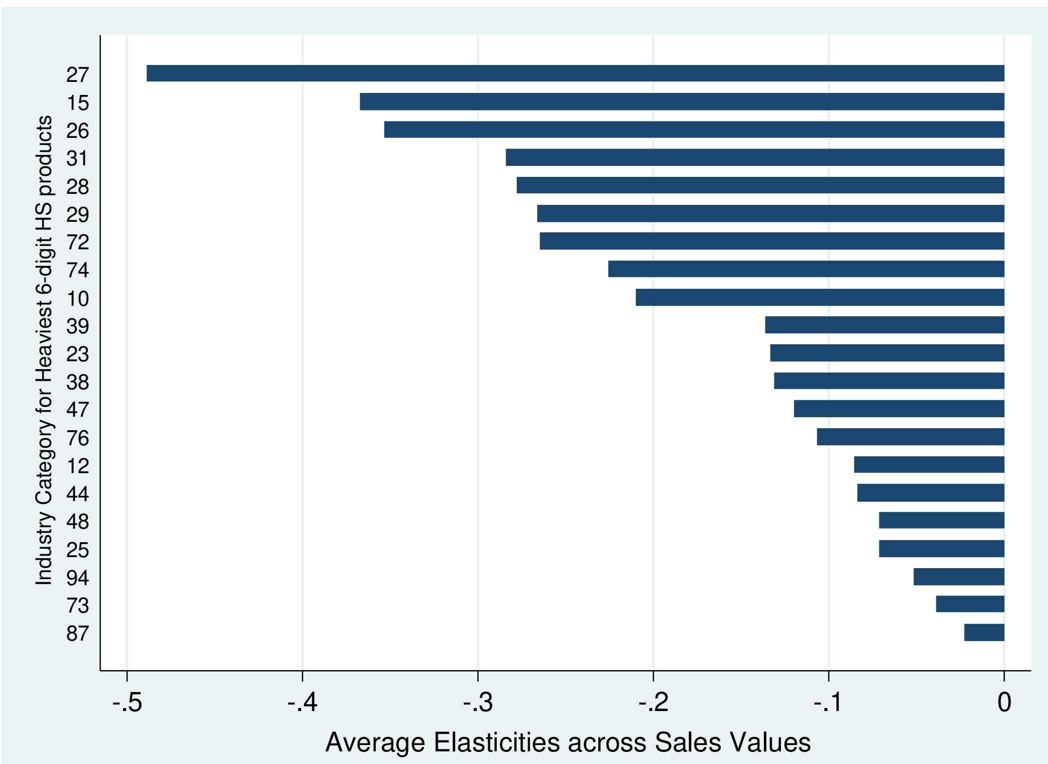
	Industry Category of the 6-digit HS products							
	29: Organic chemicals	**31: Fertilizers**	**38: Other chemicals**	**39: Plastics**	**44: Wood**	**47: Wood pulp**	**48: Paper**	**72: Iron & steel**
	(9)	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**
Elasticity lnBunkerPrice								
Category 1	-.157166	-.201595	-.095873	-.135548	-.096122	-.139786	-.059624	-.124433
	(.009296)	(.016563)	(.009597)	(.005743)	(.010385)	(.007163)	(.007639)	(.010772)
Category 2	-.224847	-.168728	-.087062	-.086914	-.105272	-.163713	.054295	-.20884
	(.021606)	(.025198)	(.019298)	(.014079)	(.022738)	(.016969)	(.025705)	(.021925)
Category 3	-.297066	-.223588	-.121762	-.142658	-.036811	-.130172	-.032741	-.310945
	(.025571)	(.028508)	(.022836)	(.021682)	(.045361)	(.016542)	(.037318)	(.018559)
Category 4	-.375145	-.366109	-.166157	-.13666	-.071323	-.099739	-.083001	-.404808
	(.020019)	(.036956)	(.027562)	(.015749)	(.03261)	(.014691)	(.039826)	(.019569)
Elasticity lnSalesValue								
Category 1	.445546	.688643	.521395	.538013	.59344	.804188	.419195	.399388
	(.023733)	(.039743)	(.030749)	(.019609)	(.034182)	(.018455)	(.026548)	(.021162)
Category 2	.754422	.841058	.557763	.347239	.670599	.847589	.459106	.687103
	(.027473)	(.024265)	(.046647)	(.039767)	(.053235)	(.021277)	(.041829)	(.024929)
Category 3	.877244	.949931	.890059	.549311	.594932	.993154	.589004	.863271
	(.020983)	(.020878)	(.036525)	(.047097)	(.086853)	(.017306)	(.039069)	(.01177)
Category 4	.930755	1.04605	.951564	.7057473	.688947	.919201	.7194904	.930942
	(.008016)	(.020611)	(.036355)	(.025052)	(.045392)	(.012104)	(.031035)	(.011247)

	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	-.0838076	-.118374	-.1096042	-.065746	-.074476
	(.012165)	(.023408)	(.015446)	(.008256)	(.010539)
Category 2	-.034486	-.272317	-.138285	-.065287	-.070694
	(.028032)	(.033882)	(.019313)	(.012954)	(.020411)
Category 3	-.090278	-.247315	-.192589	-.053405	-.068804
	(.034305)	(.027507)	(.015754)	(.022546)	(.028367)
Category 4	.0063154	-.332863	-.103560	.020351	-.028484
	(.036263)	(.018259)	(.029993)	(.031627)	(.0288)
Elasticity lnSalesValue					
Category 1	.467884	.389069	.526222	.626458	.606633
	(.03379)	(.04766)	(.050724)	(.026008)	(.040515)
Category 2	.491135	.710575	.595592	.687608	.428608
	(.04788)	(.037259)	(.040752)	(.033694)	(.065325)
Category 3	.562141	.646595	.811167	.608604	.558436
	(.052888)	(.025927)	(.019719)	(.04561)	(.069768)
Category 4	.589748	.907760	.742077	.517198	.471648
	(.048256)	(.018365)	(.031080)	(.054161)	(.071662)

Figure 1 illustrates these differences when considering the average elasticities across the different core competence of the products.

Given these results, a 10% increase in the bunker price would reduce the overall traded weight for 6-digit products by between 0.3% and 5.2%. Considering that the heaviest goods categories by 6-digit sectors constitute almost 75% of total traded weight, this also implies a very substantial impact of fuel taxation on fuel consumption and carbon emissions for the entire maritime trade activity for these heaviest products, as we will show in the next section

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

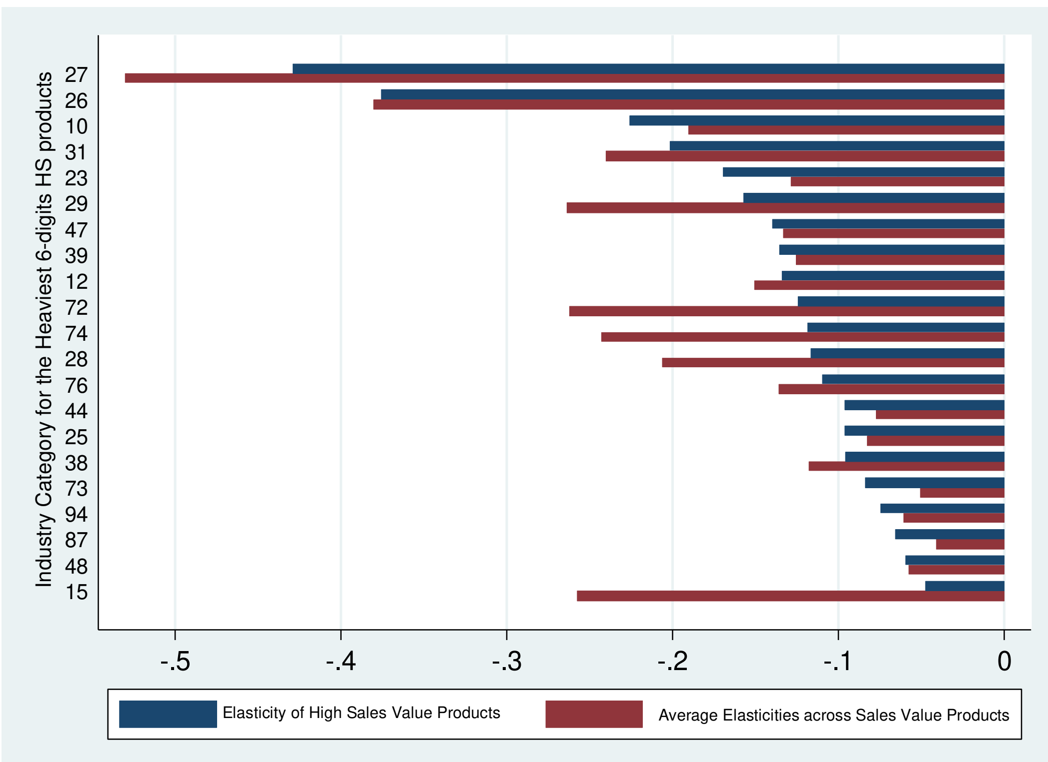


Note also that the elasticities of traded weight-distance with respect to the bunker price vary greatly not only with the industry the 6-digit products belongs to, but also with the core competence of the traded good. In most cases, the closer is the product to the core competence of the country's product portfolio, the lower the net elasticity. Figure 2 illustrates the average elasticities of our heaviest products at the 6-digit HS level by industry category (illustrated in Figure 1), and the corresponding elasticities for the core products (highest sales values).

The empirical results also indicate that regarding the elasticity of the weight – distance with respect to the marginal cost, it is the case that for certain products, the further away the traded product is from the core competence of its country's product portfolio (high marginal cost), the greater is the change in the weight – distance that is traded. Lower value products likely rely on higher export volumes to maximize their revenues. This is the case for 6-digit products in industries such as animal and vegetable oils, organic chemicals, fertilizers, plastics, paper, iron and steel, copper, and aluminum.

We also find for example that 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. These results are not reported but are available from the authors.

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



6. Estimation of changes in carbon emissions due to carbon pricing

The CO_2 emissions, and changes in such emissions as a result of increases in carbon prices, will depend on the type of product and the type of vessel with which the different products are transported. To estimate CO_2 emissions, we consider data on fuel carbon intensity per ton-kilometer (i.e. grams CO2 per ton-km) for 8 types of vessels and 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, historical data since 2000, and projected figures up to 2050. These estimates take into account the average emissions rates, weight categories, speed and various other characteristics for each ship category. There are also data on carbon intensities by *vessel size* for each vessel type. In our estimations, we will however concentrate on the *average size* per vessel type to estimate the average emission rates per vessel type (see Table 3). The reason is because there is not data on what product variety is transported by ship size.

6.1 Methodology to calculate carbon emissions

We consider a constant relationship (α) between fuel consumption and carbon emissions (i.e. one ton of bunker fuel consumption corresponds to emitting 3.11 tons of CO_2 (see Olmer et al 2017) thus $\alpha = 3.11$. The CO_2 emissions resulting from the trade of a given product from country B to country A are obtained by multiplying the product of the *weight of the exported commodity (in tons)* times *the distance between countries A and B (in kilometers)*, and the fuel carbon intensity per ton-kilometer of the vessel that the given traded product uses. The latter is given in Table 3.

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) (2018)

We see from Table 3 that the average CO_2 emissions rates by vessel type, in grams per ton-kilometer of freighted goods for 2030, varies substantially from a low value of 3.7grams for oil tankers, to a high value of 33 grams for vehicle carriers. This implies that assuming a common emissions rate for all ship types (as in Shapiro 2016) will lead to very large errors when calculating the carbon emissions implications of particular goods categories. Such errors will be avoided in our study.

Determining the "globally optimal" carbon prices for sea transport is challenging when shipping is subject to hardly any taxation, and there is no widespread application of VAT or other activity taxes. Our estimations of CO_2 emissions will assume a carbon tax of US$ 40, which is 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)).

The absolute increase in the bunker fuel price resulting from a carbon tax of for example US$40 per ton CO_2 would be equal to *US$124.4* per ton of fuel (= 3.11 (carbon content of 1 ton of bunker fuel) *times* $40). If we assume a bunker price of $450 per ton of fuel (as by December 2019), the increase in the bunker price will be 124.4/450 = *0.27644* (or 27.64%) as a result of the US$ 40 of carbon tax.

Our econometric results yield elasticities of the trade weight–transported distance (which is proportional to bunker fuel consumption for a given vessel type), with respect to the bunker fuel price. We have shown above that the effect of changes in the bunker fuel price on the weight–distance of a traded product between two countries (i.e. the elasticities) varies 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.

A possible annual average carbon emissions reductions between 2009 and 2017 from a carbon tax of $40 per ton CO_2, would be equal to *0.2764 times* the elasticity of ton-km relative to bunker prices (i.e. β_{11}) *times* the annual average CO_2 (BAU) emissions. For an elasticity β_{11} equal to -0.2 (i.e. 1% increase in the bunker fuel price leads to 0.2% reduction in traded weight– distance); an annual BAU emissions of 20 mill ton of CO_2; and a carbon tax of US$ 40, would reduce carbon emissions by 1.1 mill ton of CO_2 (=-0.2 x 20 mill ton CO_2 x 0.2764)[4].

[4] Recall that 0.2764 is the relative increase in the bunker price resulting from a carbon tax of US$40.

6.2 Carbon emissions in the maritime sector: BAU and with carbon pricing

Table 4 presents our bottom-up carbon emissions calculations using data for both the average annual weight–distance (ton-km) by industry (to which the 6-digit products belong), and the average carbon intensities for the type of ship used to transport the different product category (column 3), for the period we here study (2009 – 2017). We remark that the results by industry in Table 4 are averages from i) taking into account the elasticities of the weight– distance of its traded 6-digit products between two countries with respect to the bunker fuel price; and ii) that these elasticities vary according to the core competence of the traded 6-digit product.

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. 1000 tons CO_2

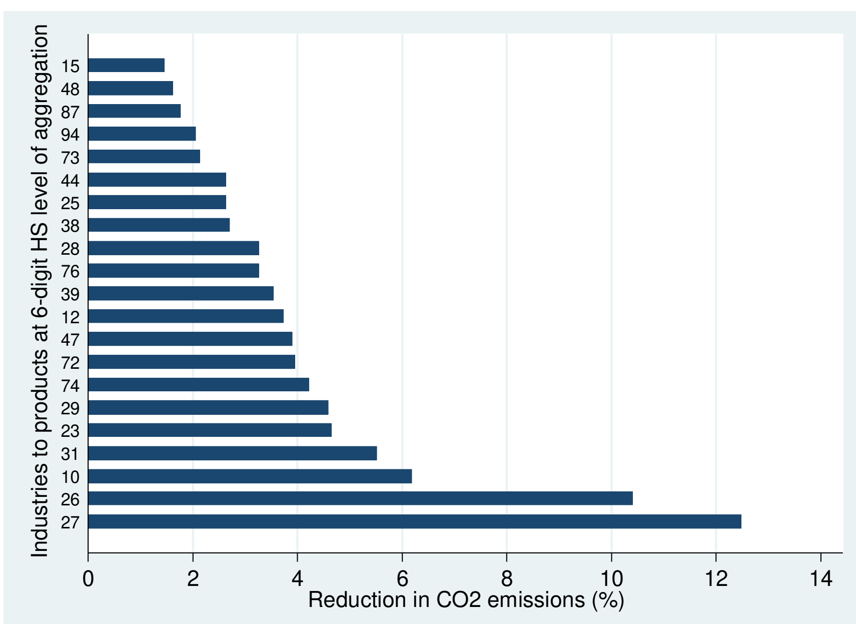
6-digit HS products per industry (1)	Industryc category (2)	Average Carbon emissions intensities: 2010 - 2015 (gram per ton-km)* (3)	BAU CO_2 emissions (4)	CO_2 emissions reduction from BAU from a $40 carbon tax (5)	Percent CO_2 reduction due to a $40 carbon tax from BAU (6)
Cereals	10	11.98	23189	-1434	6.18
Seeds	12	19.23	20623	-768	3.73
Vegetable oils	15	19.23	9319	-135	1.45
Animal feed	23	19.23	17640	-821	4.65
Salt/stone/cement	25	4.71	12883	-340	2.64
Ores	26	4.71	53338	-5553	10.41
Fossil fuels	27	4.245	148679	-18382	12.36
Inorganic chemicals	28	10.12	7947	-260	3.27
Organic chemicals	29	10.12	8007	-368	4.59
Fertilizers	31	7.42	7108	-392	5.51
Chemical products	38	19.23	5023	-136	2.70
Plastics	39	19.23	16632	-589	3.54
Wood	44	11.98	12494	-329	2.64
Pulp	47	11.98	7658	-299	3.91
Paper	48	19.23	8794	-142	1.62
Iron and steel	72	11.98	23621	-934	3.93
Iron and steel products	73	19.23	11825	-252	2.14
Copper	74	19.23	2153	-91	4.23
Aluminum	76	19.23	4020	-131	3.21
Vehicles	87	37.28	20741	-365	1.76
Furniture	94	19.23	26954	-553	2.05
Total			**448648**	**-32275**	**7.20**

* International Transport Forum (ITF) (2018). **Note:** It is assumed that the "BAU" activity level for each sector corresponds to the average activity levels over the period 2009-2017.

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 industry categories) were about 448 million tons of CO_2 (see column 4). This estimate is about half of total emissions from the entire international shipping over the same period (see e.g. IMO (2015)).

We also estimate what would have been the annual average CO_2 emissions and reductions from the BAU, if a global carbon tax of $40 per ton CO_2 on all bunker fuels would have been implemented between 2009 and 2017. See respectively columns 5 and 6 in Table 4. Assuming no change in ship technology (i.e. using the average carbon intensities for 2010 – 2015), we find that there will be a reduction in CO_2 emissions, by about 7.2% from the BAU, again for our heaviest 6-digit HS products which are part of 21 industries (see column 6). There are however substantial differences in the impact by sector. By far the greatest reduction is estimated to take place for the freight of fossil fuel products (by oil tankers), whose emissions of CO_2 are predicted to go down by around 18 million tons (or about 12%) due to this carbon tax. Other sectors with substantial reductions in carbon emissions are ores (10%) and cereals (6%). See Figure 3. 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 that would have resulted from 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).

Figure 3. Estimated average carbon emissions reduction from a US$ 40/ton CO_2 to the heaviest products at the 6-digit HS level of aggregation by industry type during 2009 - 2017



6.3 Projections of carbon emissions: 2030 and 2050

In Table 5 we follow the same methodology as for the results presented in Table 4, to estimate how carbon emissions would be reduced in 2030 by considering i) only technological progress in the maritime sector up to 2030; and ii) both this shipping technological progress and a carbon tax of US$ 40. We assume that the annual average maritime trade (weight – distance) from 2009 – 2017 will remain unchanged after 2017. Note however, that the emissions by product/industry category will increase proportionally to any possible increase in trade, if it happens.

Table 5: Estimated carbon emissions and emissions reductions in 2030, due to a $40/t CO_2 carbon tax and shipping technology improvements. 1000 tons CO_2 per year

6-digit HS products per industry	Carbon emissions intensities in 2030 (grams per ton-km)* (1)	CO_2 emissions from shipping technological progress in 2030. *No carbon tax* (2)	Reduction in CO_2 emissions from *only* technology progress in 2030 (3)	Reduction in CO_2 emissions due to CO_2 tax & technology progress in 2030 (4)	CO_2 reduction from both CO_2 tax & technology progress in 2030 (%) (5)
Grains	10.60	20542	-2648	-1270	16.8
Seeds	17.03	18268	-2355	-680	14.7
Vegetable oils	17.03	8256	-1064	-120	12.7
Animal feed	17.03	15632	-2014	-727	15.5
Salt/stone/cement	4.17	11417	-1471	-301	13.8
Ores	4.17	47245	-6091	-4919	20.6
Fossil fuels	3.96	131960	-16979	-16470	22.5
Inorganic chemicals	8.96	7037	-908	-230	14.3
Organic chemicals	8.96	7091	-914	-326	15.5
Fertilizers	6.57	6295	-812	-347	16.3
Chemical products	17.03	4453	-574	-120	13.8
Plastics	17.03	14730	-1899	-522	14.6
Wood	10.60	11067	-1427	-292	13.8
Pulp	10.60	6783	-874	-265	14.9
Paper	17.03	7786	-1004	-126	12.9
Iron and steel	10.60	20923	-2698	-827	14.9
Iron and steel products	17.03	10471	-1350	-224	13.3
Copper	17.03	1908	-246	-81	15.2
Aluminum	17.03	3559	-459	-116	14.3
Vehicles	33.01	18372	-2369	-323	13.0
Furniture	17.03	23876	-3078	-490	13.2
Total		**397220**	**-51236**	**-28776**	**17.8**

* International Transport Forum (ITF) (2018)

The reduction in carbon emissions due to technological improvements from 2010 – 2015 and up to 2030 are presented in column 3, while the reduction in emissions due to the assumed carbon tax together with the shipping technological progress are shown in column 4. Column 5 presents the percentage reduction in carbon emissions in 2030, due to combined effects of technology improvements and the $40 carbon tax.

We now present carbon emissions projections for 2050 in Table 6. The main difference from Table 5 is that the assessed carbon emissions intensities by 2050, in column 1, are lower due to further technological progress up to 2050. Column 2 as before shows CO_2 emissions calculations resulting from shipping technological progress without imposing the carbon tax, while column 3 displays the CO_2 reductions as a result of technological progress from 2010 – 2015 and up to 2050.

Table 6: Estimated carbon emissions and emissions reductions in 2050, due to a $40/t CO_2 carbon tax and shipping technology improvements. 1000 tons CO_2 per year

6-digit HS products per industry	Carbon emissions intensities in 2050 (grams per ton-km)* (1)	CO_2 emissions from shipping technological progress in 2050. *No carbon tax* (2)	Reduction in CO_2 emissions due to CO_2 tax & technology progress in 2050 (3)	Reduction in CO_2 emissions from *only* technology progress in 2050 (4)	CO_2 reduction from both CO_2 tax & technology progress in 2050 (%) (5)
Grains	9.229	17883	-5308	-1106	27.6
Seeds	14.826	15904	-4721	-592	25.8
Vegetable oils	14.826	7188	-2133	-104	24.0
Animal feed	14.826	13609	-4038	-633	26.5
Salt/stone/cement	3.631	9939	-2949	-262	24.9
Ores	3.631	41131	-12209	-4282	30.9
Fossil fuels	3.448	114882	-34033	-14339	32.5
Inorganic chemicals	7.799	6126	-1819	-200	25.4
Organic chemicals	7.799	6173	-1833	-283	26.4
Fertilizers	5.719	5481	-1627	-302	27.1
Chemical products	14.826	3877	-1150	-105	25.0
Plastics	14.826	12824	-3807	-454	25.6
Wood	9.229	9635	-2860	-254	24.9
Pulp	9.229	5905	-1753	-231	25.9
Paper	14.826	6779	-2013	-110	24.1
Iron and steel	9.229	18215	-5407	-720	25.9
Iron and steel products	14.826	9116	-2707	-195	24.5
Copper	14.826	1661	-493	-70	26.2
Aluminum	14.826	3098	-920	-101	25.4
Vehicles	28.743	15995	-4748	-281	24.2
Furniture	14.826	20786	-6170	-427	24.5
Total		**346206**	**-102696**	**-25052**	**28.5**

* International Transport Forum (ITF) (2018)

Column 4 shows the impacts on carbon emissions from shipping, due to a \$40 per ton CO_2 carbon tax and the technological progress. Column 5 shows the total percentage reductions in carbon emissions due to both technical progress and to the carbon tax. The total reduction in emissions from those in 2017, for our heaviest products is larger than for 2030, 28.4% (versus 17.8%).

Our CO_2 estimates strongly indicate that expected advances in ship technology, combined with moderate carbon pricing (US\$ 40), will be far from sufficient to fulfill the IMO target emissions rate reduction by 2050 which is 50%. Additional instruments and tools are needed. Even a higher carbon tax, for example \$80 per ton CO_2 in 2050 (the high end of the globally optimal range in Stern, Stiglitz and others (2017)) would lead to a total reduction in carbon emissions from international shipping by at most 34% in 2050. And even this reduction is 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 comprehensive 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 fa combination of four factors: improvements in ships' 1) technical efficiency; and 2) 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 fact, only 4% of their total estimated carbon emission reductions (14%), when imposing a US\$ 75 carbon tax, are a result of decreases in volume – country distance of international trade. A crucial difference however between our study and Parry et al. (2018) is that only our study provides estimations on real historical data, while 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. Our heaviest products represent about half of the total carbon emissions from international maritime trade today. Schuitmaker (2016) finds that taking specific measures to reduce emissions, will reduce carbon emissions from total international shipping to 710 million tons CO2 by 2050; relative to IMO's BAU scenario of approximately 2 billion tons.

We here remark that the only possible way to obtain an overall small effect of carbon pricing on trade and consequently in 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% for 2050 relative to its 2008 level. This implies a cut in emissions of 50% of 1,135 million ton by 2050. Note that we have found that only considering the traded heaviest products, one can reduce CO_2 emissions to 321 mill tons (=346 – 25; see Table 6) from the heaviest traded products, but only if one has a combination of a carbon tax of $40 per ton CO_2, plus technological and efficiency improvements in maritime transport, and assume that the average annual trade is going to be equal to the historical average annual trade over the period 2009 – 2017. Recall also, that IMO has not committed yet to any carbon price scheme. Therefore, it is difficult to see how IMO will reach its goals without implementing carbon pricing of at least US$ 40 per ton CO_2. Technology and efficiency progress will not be sufficient. See Smith et al. (2015a, 2016) for similar conclusions.

At least two additional factors point toward our calculations might be *over-estimating* the actual carbon emission reductions that can realistically be achieved from shipping in 2030 or 2050. First, our estimations only embed the approximate half of emissions from the heaviest goods at the 6-digit HS level of aggregation. The rest of international sea freight consists of less heavy and relatively higher-valued goods whose transport volumes are likely to be less responsive to carbon taxation. Secondly, and more importantly, our calculations assume that the aggregate sea freight volume from now and up to 2050 will remain at average annual levels experienced during the years between 2009 and 2017. This may not happen. With further economic growth over the coming 30-year period (in particular among countries currently in the low-income group), trade volumes are likely to increase by 2050.

7. 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.

Carbon emissions for maritime transport of these products in 2030 after imposing a $40 carbon tax are found, from Table 5, as (397.22 – 28.78 =) 368.44 million tons times US$40 per ton = **US$ 14.94 billion**.

Similar figures for 2050 are found from Table 6, namely (346.21 – 25.05 =) 321.16 million tons times US$40 per ton = **US$ 12.85 billion**.

Tax revenues are thus greater in 2030 than in 2050 from our calculations, as carbon emissions 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.

8. Price pass-through of carbon pricing. Heaviest 6-digit HS level products

Our theory explained above indicates that a country that exports multi-products from different industries and takes into account the costs of producing differentiated products, will produce and export products with diverse "core competence". Higher efficient (lower-cost) products will be closer to the core of the country's portfolio of goods it produces. The cost linkages across product varieties affect not only the traded quantity and country distances, but also the prices charged to the importers.

We will here analyze how a carbon price will affect the prices of these traded goods when the exporting country takes into consideration its core-competent products and the distances the products will travel. Alchian and Allen (1964) found that as higher quality goods are more expensive, prices will increase with distance of transport, and more so if cheap and lower quality products exit the export market when transported distance is longer. Chen and Juvenal (2019) indicate that there could be also price discrimination, with higher markups and consequently higher prices, when exporting goods to more distant countries. We will here analyze whether these results will or will not hold in the presence of carbon pricing, and whether they depend on the traded product types at the 6-digit HS level of aggregation.

In our econometric model, the exporting countries' pricing decisions depend on bunker fuel price changes, the costs of producing the product varieties (i.e. lower or higher costs depending on the core competency of the products), and the importing country-partner distances. Note that we do not emphasize the value of the product per se, but rather the cost of producing the traded good relative to others (i.e. the core) within the same industry and country. See Sections 4 and 6.3 for our definition of core competence. Other macroeconomic variables are also considered, but we emphasize the effect of the exchange rate on this price formation.

We estimate the following empirical relationship (11):

$$\ln p_{ijkmt} = \alpha_{12} + \beta_{12}\ln(Bunker\ price_t) + \lambda_{12}\ln(Exchange\ Rate_t) + \phi * distance_{km}$$
$$\gamma_{12}M_{mt} + \delta_{12}X_{kt} + \tilde{\mu}_{ijkm} + \tilde{\varphi}_{ijkmt}. \quad (11)$$

In equation (11), p_{ijkmt} is the unit value of product i from industry j that is exported from country k to importing country m, at time t. The exchange rate is the value of the importing country currency relative to the exporting country currency; and distance is between the importing and exporting countries. Note that the marginal cost, C_{ijkmt}, is not included since p_{ijkmt} has been defined as total sales value divided by total weight. We take of this by estimating equation (11) for 4 different core-competence groups of products at the 6-digit HS level of aggregation per industry, as we did when estimating equation (10) above: products from group 1 are closest to the core competence (highest values) of the exporting country; to products in group 4 are furthest away to this core competence (lowest sales value). With equation (10), we estimated the effect of bunker fuel price on weight-distance of traded 6-digit products.

Estimating 4 different β_{12} for each industry, helps to determine whether the pass-through of changes in the bunker fuel price to the unit value of traded product i varies according to the exporting country's marginal cost of producing and exporting this product i. The most important empirical results are shown in Table 7.

Our estimations indicate that the *average elasticity of markups with respect to carbon pricing* (across different industries and core-competence product types) are positive for all the 6-digit product types we here consider (i.e. the heaviest ones), with magnitudes between 0.08 (furniture) and 0.58 (fossil fuels). When we consider this *elasticity by class of core-competence* we find for a range of industries that the elasticity is significantly larger the further away the exported good is from the core-competence of the exporting country (i.e. higher cost to produce relative to other products that the country exports). This is the case for 6-digit products that are part of the following industries: vegetable-animal oils, fossil fuels, inorganic chemicals, organic chemicals, and copper. This result can be explained by the possibility that some of the low-value products become too costly to produce (and export) and have to be sold at higher prices to remain profitable, before they exit the export markets. For other industries (except for grains, including soy beans[5]), the magnitude of the elasticity is independent of the core competence of the exported good.

The elasticity of markups with respect to distance country by product category, we find for a number of industries in contrast to Chen and Juvenal (2019), that these elasticities are smaller the further away the exported product is from the core competence of the exporting country's product portfolio (with higher costs relative to other products in the exporter's portfolio). Examples are the following industries: stones and sand, ores, inorganic chemicals, and wood. By contrast, these elasticities are larger in magnitude, for 6-digit products further away from the exporting country's core competence in several other industries: cereals, grains, animal-vegetable oils, organic chemicals, fertilizers, organic chemicals, and copper. Remarkably, distance has no systematic effect on the price markup for fossil fuels, plastics, vehicles, and furniture.

To ensure that our empirical results do not depend on possible heterogeneous pricing-to-market behavior of exporters, we have included the *effect of the nominal exchange rate* for each of the country-pair trading partners. We find that for exported products which are close to the competence of their exporting countries, the markups are positively affected by exchange rate depreciation of the importing country, except for automobiles, furniture, chemicals, plastics, and wood, which shows signs of pricing-to-market strategy from the exporting country's side. For most products however, as they move further away from the core competence of their countries (have higher costs and lower values), there is a higher degree of pricing-to-market, except for ores, fossil fuels, automobiles and chemicals.

[5] The elasticity for grains is smaller the further away is the exported product from the core competence of the exporting country.

Table 7. The effect on prices from changes in bunker prices. Heaviest Products at the 6-digit HS level of aggregation. Industry Category of the 6-digit HS products. *(Standard errors in parentheses)*

	10: Cereals	12: Misc.grains (soya, etc.)	15: Animal-Vegetable oils	23: Animal fodder	25: Stones, cement	26: Ores	27: Fossil fuels	28: Inorganic chemicals
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Elasticity lnBunkerPrice								
Category 1	.3350997	.219822	.2410557	.235424	.154182	.399717	.566099	.190376
	(.009525)	(.007659)	(.005338)	(.007054)	(.006874)	(.015088)	(.008319)	(.00411)
Category 2	.271173	.235131	.240755	.2147691	.151442	.357921	.624475	.181587
	(.014179)	(.016614)	(.014978)	(.014019)	(.016653)	(.025049)	(016397)	(.013262)
Category 3	.2514701	.306495	.271381	.148293	.165323	.4355613	.624264	.185812
	(.021656)	(.026901)	(.027754)	(.018741)	(.025750)	(.037071)	(.021515)	(.024663)
Category 4	.2510137	.117566	.579234	.090824	.148293	.364349	.645274	.280659
	(.027271)	(.003277)	(.006771)	(.025541)	(.028330)	(.029345)	(.020616)	(.018855)
Elasticity lnDistance								
Category 1	.0366854	.065814	.0204862	.058103	.277306	.235517	-.0131059	.228831
	(.017564)	(.024687)	(.009033)	(.021965)	(.013036)	(.049430)	(.012949)	(.011821)
Category 2	.077021	.104117	.0317671	.133985	.157124	.255057	.004437	.116384
	(.025371)	(.036577)	(.018405)	(.030394)	(.025336)	(.061639)	(.021464)	(.023879)
Category 3	-.032879	.130229	.091186	.125906	.134739	.075906	.047512	.024591
	(.032490)	(.043333)	(.041487)	(.041604)	(.041938)	(.080992)	(.02729)	(.050257)
Category 4	-.036572	.147415	-.224011	.044108	.110698	.021969	.0329	-.015468
	(.035896)	(.022559)	(.026874)	(.050246)	(.049856)	(.084704)	(.021284)	(.037449)
Elasticity lnExchange Rate								
Category 1	.053342	.036963	.0538068	.061302	.051941	.115346	.085728	-.056328
	(.017249)	(.021362)	(.007786)	(.018671)	(.010707)	(.032441)	(.011387)	(.009402)
Category 2	-.047241	.09433	.0773114	.117558	.045757	.072054	.069409	.032332
	(.018204)	(.037844)	(.013761)	(.024591)	(.016825)	(.037915)	(.015896)	(.017978)
Category 3	.251470	.058263	.0240206	.067641	.042955	.10574	.048313	-.079746
	(.021656)	(.032721)	(.020801)	(.027186)	(.022877)	(.04830)	(.02356)	(.038587)
Category 4	-.087179	-.048612	-.265662	.095503	-.005765	.076543	.074961	.096469
	(.020314)	(.005505)	(.004983)	(.017896)	(.025656)	(.026014)	(.01896)	(.026538)

Industry Category of the 6-digit HS products. *(Standard errors in parentheses)*								
	29: Organic chemicals	**31: Fertilizers**	**38: Other chemicals**	**39: Plastics**	**44: Wood**	**47: Wood pulp**	**48: Paper**	**72: Iron & steel**
	(9)	**(10)**	**(11)**	**(12)**	**(13)**	**(14)**	**(15)**	**(16)**
Elasticity lnBunkerPrice								
Category 1	.312837	.297241	.184473	.2027145	.157176	.170465	.157206	.339818
	(.00331)	(.007165)	(.005482)	(.0027293)	(.004605)	(.005887)	(.002743)	(.002756)
Category 2	.330771	.267282	.185466	.2358718	.1848706	.1596794	.164387	.358170
	(.009613)	(.01524)	(.010293)	(.004388)	(.009279)	(.010831)	(.005736)	(.005432)
Category 3	.384714	.315701	.165770	.249394	.142431	.147156	.163621	.373110
	(.021677)	(.02514)	(.018642)	(.006463)	(.014638)	(.013130)	(.011281)	(.011208)
Category 4	.424995	.338520	.185139	.228687	.1451236	.176149	.186316	.378918
	(.017534)	(.03371)	(.025128)	(.007108)	(.013186)	(.011894)	(.019849)	(.012720)
Elasticity lnDistance								
Category 1	.113878	.053144	.097695	.0026832	.1601022	.225459	-.042085	.0465812
	(.007170)	(.010594)	(.014596)	(.0054483	(.013270)	(.016165)	(.006313)	(.005055)
Category 2	.033852	.049701	.074977	-.0035679	.114252	.162971	-.041834	.052662
	(.016133)	(.016411)	(.023389)	(.007798)	(.019531)	(.031739)	(.010349)	(.008511)
Category 3	.122836	.067835	.248367	.007464	.061278	.0469377	-.021434	.0527108
	(.038961)	(.038146)	(.038439)	(.013683)	(.021773)	(.043892)	(.017782)	(.01478)
Category 4	.248078	.081654	.299495	.008651	.069405	.037137	-.069279	.019951
	(.017637)	(.036117)	(.04375)	(.017952)	(.029641)	(.039329)	(.026404)	(.022179)
Elasticity lnExchange Rate								
Category 1	-.012925	.065504	.048396	-.0346546	.0163421	-.038782	.034328	-.003986
	(.004826)	(.009764)	(.010286)	(.0045619)	(.008858)	(.008865)	(.005003)	(.005346)
Category 2	.039729	.053759	.095870	.0125661	-.0006777	-.072384	.008802	.036806
	(.010703)	(.015906)	(.01478)	(.006684)	(.013088)	(.011734)	(.008154)	(.007598)
Category 3	.033924	.092756	.074868	.0142805	.0246943	-.102927	-.007522	-.008873
	(.022023)	(.028931)	(.023002)	(.009573)	(.018946)	(.014800)	(.012513)	(.01175)
Category 4	-.0455028	-.0153703	.122117	-.008010	.005105	-.066067	-.064278	-.104542
	(.012284)	(.025582)	(.028673)	(.009508)	(.021111)	(.009136)	(.020702)	(.015598)

Industry Category of the 6-digit HS products. *(Standard errors in parentheses)*					
	73: Iron & steel products	**74: Copper**	**76: Aluminum**	**87: Vehicles**	**94: Furniture**
	(17)	**(18)**	**(19)**	**(20)**	**(21)**
Elasticity lnBunkerPrice					
Category 1	.196422	.342810	.17196	.094409	.0916285
	(.004624)	(.005909)	(.005346)	(.00444)	(.005489)
Category 2	.230804	.39152	.19903	.110488	.1008659
	(.009714)	(.013952)	(.00872)	(.007767)	(.010348)
Category 3	.22166	.499713	.229563	.1146478	.103037
	(.016037)	(.019860)	(.011761)	(.010072)	(.014038)
Category 4	.143767	.4277356	.208361	.101579	.076126
	(.017666)	(.013250)	(.010682)	(.011480)	(.012752)
Elasticity lnDistance					
Category 1	-.013541	-.001463	-.031512	.0130307	-.0343691
	(.007838)	(.012191)	(.009583)	(.008426)	(.011879)
Category 2	.052910	.046470	-.044283	.0638318	-.050897
	(.012859)	(.024044)	(.01415)	(.011311)	(.02220)
Category 3	.030218	.115538	-.045246	.069099	.010442
	(.02116)	(.020461)	(.023165)	(.016094)	(.029656)
Category 4	.006415	.069749	-.00769	.036234	-.049605
	(.033684)	(.019835)	(.029934)	(.026743)	(.030998)
Elasticity lnExchange Rate					
Category 1	-.027077	-.014503	.011326	-.076884	-.011536
	(.006423)	(.008778)	(.008945)	(.006726)	(.008449
Category 2	.083221	.005812	.015265	.000648	.000725
	(.010890)	(.014286)	(.014822)	(.009203)	(.011931)
Category 3	.115685	.003644	-.067193	.023416	.013709
	(.018101)	(.016020)	(.018441)	(.010862)	(.014808)
Category 4	.072371	-.012246	-.016655	.0703932	-.026922
	(.022473)	(.008965)	(.014008)	(.021526)	(.017796)

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9. Conclusions

We present a theoretical and an 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 pricing on carbon emissions from global international maritime trade. The exporting countries face differing marginal costs with each product variety.

Our paper is the first to estimate impacts of carbon taxation on global maritime transport activity, using detailed data for emissions intensities by type of maritime vessel used for such transport, which vary substantially by vessel type and transported product. We find high impacts of carbon taxes on maritime trade for the heaviest products.

We estimate our empirical model using the WITS data set with products at the 6-digit HS level of aggregation for the period 2009 – 2017, and global bunker fuel prices. These products are part of 21 industries and consist of particularly heavy products traded by sea. We also use several background variables to correct for global demand fluctuations, taking into consideration the standard variables included in modern gravity models of international trade. Our approach is to consider a given change in the bunker fuel price as equivalent to a carbon tax on bunker fuels. In our econometric analysis, we model the weight-distance of traded products corresponding to our theoretical model specification. As estimation method we use the Systems of General Method of Moments.

We first derive elasticities for weight times traveled distance (assumed proportional to bunker fuel consumption for a given goods category) with respect to changes in the bunker price, for our heaviest product at the 6-digit HS level of aggregation. These elasticities are in most cases found to have lower (absolute) values for exported products that have lower marginal costs. This means that a country that exports a product with lower marginal costs or is closer to its core competence, using its most efficient production process (i.e. at minimum costs), will have a relatively lower response, in terms of changes in ton-kilometers of transport activity, to changes in the bunker prices. It must be then very important for this exporting country to sell his/her more valuable and efficient product, regardless of the size of a carbon tax. Elasticities differ substantially, from low values of about -0.03, to a high value of about -0.52.

We find that increases in bunker fuel prices, taken as proxy for carbon pricing of such fuel, lead to substantial reductions in the total measure of weight *times* distance for internationally traded goods, which reduces the bunker fuel consumption and carbon emissions from international shipping. Considering a global and uniform carbon tax of $40 per ton CO2 will reduce fuel consumption, and carbon emissions, by about 7.2% in total for our heaviest 6-digit HS level products. The products with the highest average reduction in carbon emissions resulting from a $40/ton CO2 carbon tax are fossil fuels (12.36%), followed by ores (10.41%), grains (6.18%), and fertilizers (5.51%). The products with the lowest impacts are vegetable oils (1.45%), paper (1.62%) motor vehicles (1.76%) and furniture (2.05%).

These products together represent about 75% of total weight in international sea freight, and about half of the sector's fuel consumption and carbon emissions.

We also calculated the reductions in carbon emissions from maritime transport of heavy products by 2030 and 2050, due to two factors: i) expected technical and efficiency improvements in such transport, and ii) a tax of US$40 per ton CO2, on such transport, for a given (non-tax) maritime trade activity for these industries. We find that these two factors could reduce the carbon emissions from this transport by 80 million tons CO2 in 2030: from 448 million tons in 2017 to 368 million tons in 2030; and by 127 million tons: from 448 million tons in 2017 to 321 million tons in 2050. This estimates are obtained under the assumption that there is no growth in international trade. Still, our estimated reduction by 2050 is far less than the reduction target set by the IMO, which is to reduce carbon emissions from the maritime sector by 50%, or by about 560 million tons CO2, in 2050 relative to 2008. And notice that emission in 2015 were already 927 mill tons CO2. 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 is clearly necessary.

A $40 per ton CO2 tax on bunker fuels at a global level would generate substantial tax revenues, and give room for redistribution benefitting low-income countries, or general climate action that could also lead to higher global welfare. From our calculations, a carbon tax of US$40 per ton CO2, on maritime transport of the heaviest goods categories studied here, will yield a global tax revenue close to US$15 billion by 2030, and close to US$13 billion by 2050.

As far as we are aware, this is the first theoretical and econometric analysis of impacts of carbon taxes on the shipping sector, and their impacts on bunker fuel prices, on maritime trade activity and carbon emissions from such trade, based on historical trade and bunker price data, and detailed data for carbon emissions intensities for different types of ships transporting different goods categories.

An innovation of our work, relative to other studies of carbon pricing on international trade activity, is simply to be able to integrate the carbon emissions impacts with the trade structure impacts, thus yielding a much richer set of implications of carbon taxation. Numerous extensions of our work can be visualized; we intend to pursue some of these in future work.

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