Carbon pricing of international transport fuels:

Impacts on carbon emissions and trade activity

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Abstract

We study impacts of carbon pricing for international transport fuels on fuel consumption and carbon emissions, trade activity, and welfare, 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 on bunker fuel consumption 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 elasticities ranging from -0.0028 up to -0.64. 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 a global \$40 per ton CO_2 tax on carbon emissions from ships will reduce carbon emissions from the global shipping fleet by about 4% for the goods categories considered.

1. Introduction

To avoid continuing to experience increasing 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, while minimizing the mitigation costs. No international transport activity today faces any meaningful emission taxes or charges. This has at least three adverse consequences in for example the shipping sector. The *first* is a higher than optimal activity in international shipping (types of vessels, the routes they take, and the types of goods they transport), as the sectors do 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 critical problem for many low-income countries with low tax revenues (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.

This paper analyzes, theoretically and empirically, the relationship between fuel costs and international trade of goods, and global greenhouse gas (GHG) emissions from the maritime sector. Our study considers the bunker price per ton fuel to represent the unit fuel cost. A report from UNCTAD (UNCTAD (2009)) indicate that fuel costs account for as much as 50% to 60% of total operating costs depending on the type of ship and service. The effects on trade of changes in bunker prices allow us to make prediction about how an implementation of 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 possible impacts of changes in bunker fuel prices on the structure of *global* international trade (extensive and intensive margins), on *global* carbon emissions derived from this trade, and on economic welfare from changes in this trade activity and carbon emissions using a comprehensive panel dataset for products at the 6-digit HS level of aggregation.

The 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 share 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 emission levels that are derived from the maritime transport sector at both the country and product levels, but also how to quantify how the current emissions from the maritime transport of internationally traded goods can be affected by implementing carbon pricing. To this end, it is indispensable that we analyze how fuel prices (carbon pricing) affect international trade at the highest possible disaggregation. We think that our work contributes to overcome the 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, in order to suggest policies that are directed to the industries and countries/regions that emit high levels of CO_2.

Impacts of carbon pricing on carbon emissions from international goods freight are known to be of three main types: 1) via changes between and within modes of transport, where international goods freight is composed by three main modes: sea, air and land transport; 2) changes in the weight and structure of trade using each of these three transport modes; and 3) changes in energy use per unit of transport for each 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 pairs of countries that trade products at the 6-digit HS level of aggregation. It focus on three main topics. *First*, we will analyze theoretically and empirically the impacts of increasing bunker prices per ton of fuel (and fuel costs per ton-km) on the structure of international trade: traded weight (intensive margin); the number of traded goods (extensive margin); and the number of country-pair trading partners (extensive margin). *Second*, we will show, both theoretically and empirically, the degree of "pass-through" of changes in the prices or costs of fuel (which will represent carbon pricing) to import–export prices. *Third*, we will calculate the impact on carbon emissions due to changes in the structure of the international goods' trade that follows from increases in carbon pricing (i.e. inferred from changes in bunker prices).

International Climate Agreements, including the Paris Agreement, have not paid enough attention to how and how much CO_2 emissions result from international maritime transport. The Third International Maritime Organization (IMO) GHS Study (Smith et al. (2015a, 2015b) estimates that international transportation by sea produced annually and globally approximately one billion tons of CO_2 emission, between 2007 and 2012. The IMO GHS Study has revised its estimates and finds that these emissions will increase 35% - 210% by 2050 under a business-as-usual scenario (CE Delft (2017)). 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)).

GHG emissions from international transport has recently become a central issue of interest, for various reasons. *First*, the adverse consequences mentioned above are increasingly becoming recognized, by more countries and other international stakeholders. *Secondly*, such emissions are now embedded in the Paris Agreement (PA) and were not part of the Kyoto Protocol. In April 2018, the International Maritime Organization (IMO) decided 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 in specifying the mechanisms by which this target can be reached (see IMO (2018)). In 2017, IMO already implemented new vessel carbon intensity standards for technical efficiency. Our project aims to contribute to better understanding how and to what degree emissions from international transport could be reduced due to carbon pricing.

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. It should be however noted that if carbon pricing is implemented via carbon taxation, this scheme could potentially raise substantial revenues some of which can be transferred directly to individual trading countries. These revenue transfers can serve to compensate the poorest and most remote countries with high and increased trade costs (e.g. fewer product varieties, lower trade quantities); and/or support global climate finance purposes. Offset or other cap-and-trade schemes are less likely to provide similar revenues. Our analysis forms a basis for reimbursement of carbon tax revenues to individual countries, which could be related to transport costs for the countries' exports and imports.

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.

We should mention that 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 carbon emission friendly according to the transported product; or iii) give boost to technological improvements in the quality and more environmentally friendly fuel. The first issue is important for impacts of trade on carbon emissions, as average carbon emissions per ton-km of transported goods are up to about 100 times as high from air transport as from sea transport. Point ii) could be important as fuel consumption per ton-kilometer varies substantially between types of ships, their speeds and their load factors. Point iii) is becoming increasingly relevant as availability of alternative fuels (including biofuels) is becoming more relevant, and more abundant.

In the continuation we present a literature review in Section 2 while the theoretical background to our paper is 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 sums up and concludes.

2. Literature review

The background literature dealing directly with the main research topics for our proposal is limited. Cristea et al. (2013), Shapiro (2016) and Schim et al. (2018) are central works to this paper. The main objectives of Cristea et al. (2013) were to compute GHG emissions from both production and transport of internationally traded goods, focusing only on the year 2004. Their paper did not study econometrically the impacts of higher transport costs 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 40 regions (1,600 bilateral pairs) — i.e., 28 individual countries and 12 regional groupings — and 23 traded merchandise sectors and 6 non-traded service sectors based on the Global Trade Analysis Project (GTAP) data base. They aggregated sectors with similar transport characteristics. They specified a formula to quantify emissions for each product category depending on volume and value of trade flows between country-pairs, distance traveled, modes of transport, and emissions by the transportation mode. They also assessed the likely growth in emissions in response to changes in global trade arising from tariff liberalization and unevenly distributed GDP growth. For 35 percent of the trade value, no direct data on mode use were found. Modal shares were then estimated (imputed) as a function of geography, country, and product characteristics, using data for countries with high quality information on these variables.

Cristea et al. (2013) calculated shipping emissions for 6 ship categories, with average emissions from 4.5 (bulk) to 16 g CO_2/ton-km (LNG ships). For aviation emissions, they used data on the Boeing 747-400 (552 g/ton-km), and other higher figures (493–1,934 g; California Climate Change; 963 g based on the Air Transport Association of America). Their final assessments were between 552 g (lower bound) and 959 g (higher bound). Truck freight was found to be, on average, approximately 10 times as carbon intensive per ton-km as was sea freight, and air freight was found to be 10 times as carbon intensive as was truck freight. Whether goods are transported by sea, air, or land was then found to have a high impact on carbon emissions from trade. Note that, though air freight in 2004 represented only 4% of US exports in ton-km, more than 60% of US export-related carbon emissions were from air freight.

Cristea et al. (2013) compared their "bottom-up" approach to calculating international transport emissions for a given trade flow to the ITF's "top down" approach and found good correspondence. The bottom-up approach consists of calculating the kg-km of each mode for each origin–destination–product trade flow and multiplying by the average emissions per kg-km for each mode. The best estimate for 2004 emissions was 1,205 million tons CO_2 (145 g per dollar of world trade; higher than ITF's "top down" estimate of 910 million tons, which ignores land-based transport), with a lower bound of 941 million tons of CO_2.

Emissions from transport of international trade were obtained by considering:

- 35,880 individual trade flows (40 exporters x 39 importers x 23 traded goods' sectors)
- International trade emissions = aggregate transport emissions for each industry by summing over all country pairs.
- Transport emission intensity for each industry = ratio of transport emissions for each industry to value of trade.

They found large variation in emissions across industries and countries and large imbalances in the emissions between importers and exporters. In particular, the US relies heavily on-air cargo for exports.

In this study, in contrast to Cristea et al. (2013), we estimate econometrically how GHG emissions can be reduced when the carbon price increases and affects international trade activity. To do this, we first analyze, theoretically and empirically: i) how international trade structure (intensive and extensive margins) is impacted by carbon pricing; ii) the "pass-through" of carbon pricing to import-export price; and iii) the welfare effects from changes in the structure of the international trade when carbon prices increase. We use the World Integrated Trade Solution (WITS) database, which was 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 approximately 6 million records for each of the years 2002–2016, a large number of trading country pairs, and more than 6,000 commodities at the 6-digit HS level.

Shapiro (2016) estimates fuel demand elasticities from a gravity model in which *trade value* depends on *transport costs*, using quarterly reports of transportation costs and trade values for all 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. Shapiro's numbers on CO_2 emissions are not derived from international trade dynamics, but come from outside sources: CO_2 from production come from GTAP for 2007, and uniform CO_2 emission rates for airborne trade come from IATA, and maritime trade come from IMO. Notably, Shapiro does not distinguish aircraft and ship types.

In Shapiro (2016), transport costs contain several elements such as insurance rates, tariffs, border effects, oil price, among other costs. With this approach, considering the impacts of total transportation costs, it is difficult to single out the effect of carbon taxes/fuel prices on trade (value). On the basis of these data, Shapiro calculates effects of carbon tax counterfactual on welfare from trade and environmental costs. Shapiro follows Armington's (1969) modelling which assumes that each country produces only one goods variety per sector, and varieties are different across countries.

We will in contrast estimate the elasticities of *traded weight times distance* (which is directly related to fuel consumption) with respect to, not total transport costs, but first, *bunker prices per ton of fuel*, and second *fuel cost per ton-km* of maritime transported cargo and vessel type. Our estimates cover the period 2002-2017, and products at the 2-digit and 4-digit HS levels of aggregation, that are traded between all country pairs in the world. We follow this approach to estimate the true global CO_2 emissions considering all countries and traded products (their weights) to obtain the effects of carbon pricing on trade and CO_2 emissions *by product*. Our proposed analysis is richer because we also consider the effect of fuel price or cost on not only the intensive margin (weight), but also on extensive margins of trade, the unit value of trade (i.e. pass-through from fuel pricing) per product, and on welfare.

Shapiro's approach is closer to Cristea et al (2013) than to ours. Shapiro's paper does not present the impacts of the counterfactual carbon tax on CO_2 emissions. We will in contrast estimate how fuel prices or costs impact CO_2 emissions as a result of changes in the margins of trade per product type, vessel type, and country partners, for each of the years 2002 to 2017, and with projections for later years. In addition, our analysis of the effect of carbon pricing on trade and CO_2 emissions, for the universe of 2- and 4-digits products and country pairs, will consider different data subsets such as the products that are the heaviest, that traveled the most, by regions, etc. See Section 4.1 in this Proposal.

To calculate the carbon tax counterfactual effects on welfare, Shapiro uses a single emissions intensity rate, 9.53 grams CO2/ton-km. We however know that emission intensities vary substantially with the weight classes of transported goods, product type, and vessel type. We will use a detailed ship type and product type classification with average emissions intensities varying from 4 g to 35 g CO2/(ton-km). Taking into account these distinctions in the emission intensities will reduce dramatically the CO_2 emissions of heavy weight product types and increase these emissions for high-valued goods (most exports from HICs), relatively to the results obtained by Shapiro. Thus, the use of our methodology will substantially reduce (increase) the average carbon costs for LICs (HICs). For the same reasons, Shapiro's conclusions that a carbon tax is not beneficial for LICs, is no longer obvious. We will evaluate his conclusions using our methodology and data.

The approach used by Schim et al. (2018) builds on a method of calculating emissions per vessel and per journey developed by members of the University College London (UCL) team and endorsed by the International Maritime Organization (IMO). The approach makes it possible to allocate shares of these emissions to individual commodity shipments, and thus to 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 it a proportional share of the ship's emissions on each leg of the journey. The approach is applied to all individual Brazilian exports in the year 2014 – around 520 million tons of cargo. The authors do not address carbon pricing, and its possible effects on international maritime trade.

With respect to other literature, we first consider the literature on the contributions of shipping and aviation to global GHG emissions. According to Eyring et al (2005), fuel consumption in shipping more than quadrupled between 1950 and 2001, going from 65 to 280 million tons (equivalent to 840 million tons of CO_2 emissions). Psaraftis and Kontovas (2008) found wide variations by vessel type and size for 2004, with much lower emission intensities per freight ton-km for oil tankers and cargo ships than for container ships. Olmer et al. (2017) and Johansson et al. (2017) later found somewhat lower CO_2 emission intensities by the shipping industry. Johansson et al. (2017) found that emissions from container ships, cargo ships (including bulk carriers), and oil tankers represent 82.6% of CO2 emissions from ships, with container ships accounting for 35% of total emissions.

For aviation emissions, the climate forcing impact is approximately 1.5 times that of the CO_2 impact, as emissions at high altitudes are more damaging than are those at sea level; see IPCC (1999), Azar and Johansson (2011), and Dessens et al. (2014).

Determining what the "globally optimal" carbon prices for sea and air transport should be is challenging when there are no taxation schemes at all in shipping and no widespread application of VAT in international aviation. Keen and Strand (2007) find the second-best optimal carbon price for aviation to be 100–250% of the Pigou tax. However, Keen, Parry, and Strand (2013) have estimated the Pigou tax for shipping and found it to be the optimal carbon price. Given a carbon tax of \$50/ton CO_2, this increases average sea freight costs by approximately 15% and could reduce carbon emissions from sea freight by approximately 12%. Two recent papers discuss the role of Pigou taxes in shipping based on modeling exercises. Lee et al. (2013) consider the impacts of different levels of Pigou taxes charged to container ships up to US\$90/t CO2, using the GTAP-E model and global trade data. They find that the impacts on the global economy are negligible unless the tax is high, 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). They use a global recursive dynamic CGE model and find that global GDP is reduced by approximately -0.5%. Meanwhile, traded weight and patterns are affected, but only moderately.

Lower average ship speeds can reduce fuel consumption and GHG emissions for given weight and transport distances, as the fuel consumption of ships is close to a third power function of vessel speed (Faber et al., 2017; Lindstad and Eskeland, 2015). Reductions in average vessel speeds were observed over the 2012–2014 period, when the bunker price was very high; speeds increased again in 2015, when the bunker price fell sharply. We will take into consideration these estimations on the effect of the vessel speeds in our estimates of GHG emissions from international shipping.

Some related literature analyzes how trade patterns can change due to increased trading costs. Martínez et al. (2015) and Ong and Sou (2015) show that increased transport costs reduce trade volume of commodities for the same monetary trade values, and that such impacts differ by countries, goods types, and trading routes. Bachmann (2017), de Jong et al. (2017), and Johansen and Hansen (2016) find that increased transport costs can have large impacts on international trade activity and can make trade for high–cost countries unattractive for importers. However, none of these works provide either econometric or statistical analysis on the basis of historical data, which is one of our main targets in this project. Thus, in contrast with this literature, we will analyze, both theoretically and empirically, the effect of carbon pricing on the structure of international trade, as we have indicated above.

Almost all recent literature on fuel consumption and carbon emissions impacts from carbon pricing in the shipping sector has virtually ignored impacts on trade composition, trade values and volumes, and instead focused on issues such as fuel switching and technological vessel developments. An exception is Limão and Venables (2001) who studied the effect of transportation costs on volume of international 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. If we keep in mind that fuel costs represent as much as 50-60% of total ship operating costs, depending on the type of ship and service, and that fuel price increase has significant impact on transport cost by ship (higher than by train and truck) (Gohari et al. (2018)), the above results indicate that it can be significant and consequently highly relevant to analyze the impacts of carbon pricing on the shipping activities and their carbon emissions.

Finally, we shall mention that there are works that make projections of future GHG emissions from shipping over a longer future period as a result of implementing carbon pricing and technological improvement in alternative fuels and vessels. IMO (2015) assumes business-as-usual (BAU) policies, and projects CO_2 emissions from international shipping by 2050 to be twice the 2015 level. These projections deviate dramatically from the IMO's own policy target, which is to halve current carbon emissions by 2050 based on new motor technologies and alternative fuels. A growing body of literature [International Maritime Organization (2015), CE Delft (2012), Eide et al. (2013), International Transport Forum (2016), Bouman et al. (2017)] projects transport demand, fuel efficiency improvements, and substitution by alternative fuels in international shipping toward 2050. Schuitmaker (2016) considers 5 measures 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. See also ITF (2016) for analysis of alternative ways to reduce carbon emissions in international aviation up to 2050. Smith et al. (2016) and Halim et al. (2018) simulate dynamic transport models and find high potential for reducing carbon emissions from shipping, although their projections vary substantially. According to Halim et al. (2019), carbon pricing of shipping in the range of \$10–\$50 per ton CO2 has limited negative impacts on the global economy.

Tavasszy et al. (2016) assert that a \$50 per ton CO2 carbon charge on transport fuels reduces global trade flows by only approximately 1%, although the figure is higher for heavy products. Similar results are found from other recent models, including from the IMF (Parry et al., 2018), where reduced trade activity is found to only comprise 4% of the total reduction in ships' fuel consumption in the long run. Note that results from these studies are all based on numerical modeling and not on statistical estimates of trade responses to increases in transport fuel costs, and they do not represent any stringent empirical analysis of the impacts of carbon pricing on international trade activities, which will be our main approach.

3. Background to the theoretical model

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 and extensive margins of international trade and on carbon emissions. We remark in this context that none of the studies cited and discussed in the previous section, 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.

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 will also study by how much, and how quickly, carbon price changes affect markup prices, that is the degree of pass-through from carbon prices to prices of traded goods. Our approach is also 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 quantity of trade of products at the 6-digit HS levels, and not aggregate flows of trade at the country level. We do consider however 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 countries as determining the aggregate level of trade of products at the 6-digit HS level. Thus, in our framework, countries have some product varieties to choose from when importing. This theoretical approach is more appropriate and useful than Armington's (1969) approach (also considered in Shapiro (2016)) in which each country produces one variety per sector and where varieties are differentiated by country of origin. Some of the reasons are that such modeling does not reflect the reality of the world; and secondly and more importantly, we intend to determine what product varieties that are traded between the different country pairs could be most affected by the implementation of carbon pricing, which of these products are the highest emitters of CO_2, and which are the countries that trade such products the most. This approach is crucial in order to attribute as correctly as possible the responsibility of CO_2 emissions by country, industry, company, and commodity type.

Bernard, Redding, and Schott (2010, 2011) pioneered the modelling of asymmetries between products on the demand side. Before deciding to enter international markets, firms consider their productivity levels and product–market–specific demand shocks. The latter determine a firm's scale and scope of sales in different markets, which imply that its price and output profiles are always negatively correlated. By contrast, Eckel and Neary (2010) emphasize asymmetries between products on the cost side (of producing different varieties), which imply that price and output profiles are always positively correlated. We here integrate demand and supply approaches by assuming that the costs of producing a variety of products and total fuel costs (which at the same time depend on the geographical location of importers and exporters, the weight of the merchandise, type of vessel, and the bunker fuel price) determine the scale and scope of international trade.

Our main contribution to the theoretical literature is to consider each importing country as maximizing a three-level utility function that depends on the country's consumption levels (weight) of product varieties, from different industries, and from a portfolio of exporting countries. Our model involves countries that export multi-products from different industries taking into account the costs of producing differentiated products. We follow closely Eckel and Neary (2010) and Mayer et al. (2014) by 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 assume that there are cost linkages across product varieties and trading partners. Thus, exporting countries' trading decisions about weight and number of product varieties will here depend on, besides bunker fuel price changes, the costs of producing these product varieties for different importers. Consequently, when for example the bunker price increases, countries will produce more products closer to their core competence and will have incentives to trade more goods of these types of goods.

On the other hand, importing countries make decisions about country trading exporting partners (and, consequently, the distances that the traded goods will travel), the weights of the traded goods of different varieties, the economic value of the differentiated imported goods, the number of product varieties, bunker fuel prices, and final prices of the traded goods to maximize welfare.

Thus, in the presence of carbon pricing, exporting countries with profit maximizing firms will produce more products closer to their core competence. Countries may either add or drop products for import due to changes in bunker prices and value of the imported product. It is crucial for importing countries to choose exporting countries that are closer geographically and product varieties that have less weight to save on fuel costs, to maximize households' utility functions. These effects have important implications for the profile of prices and will be strongly dependent on what we could call "cost-based" and "fuel efficiency-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 fuel costs on to consumers by charging higher prices.

How are the extensive margins of trade and the fuel-price pass-through related? Consider first a model where two countries (A and B) face fixed export costs. Country B produces a large number of differentiated products for export to country A and has firms that set lower prices when their marginal production costs are lower. If the bunker fuel price increases, country B's exports become less competitive in country A. Country B could even stop exporting the highest-cost (-price) product varieties to country A and exit the markets for such product varieties as a result of rises in the bunker price. This effect will be reinforced if the distance traveled by the traded goods is uneconomically large because of higher fuel costs. Thus, certain product varieties will become too costly to produce and export to country A. If the number of products that exit markets is sufficiently high, and if only the varieties produced and exported by country B that have low marginal costs survive, country A will then face lower import prices. Higher fuel prices could then lead to a negative pass-through rate from the fuel prices to import prices. Import prices will then depend on exporting countries' production costs (core competence), traveled distance by traded goods, exported weight, and the fuel prices. Empirically, we will study such relationships by considering products at the 6-digit HS level of aggregation that are traded between country pairs.

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 or cost changes affect trade and consequently CO_2 emissions at the product level (2- and 4-digit HS levels of disaggregation).

To sum up, our theoretical model considers the impacts of changes in the bunker price per ton of fuel or fuel costs per ton-km per type of product and vessel on: i) the traded weight of each product (intensive margin); ii) the number of country destinations (extensive margin); and iii) the number of product varieties (extensive margin). Thereafter, bunker prices, transport distances for the traded products, weights of these products, the varieties of goods, and the vessel type used for transporting the different products determine in our model the levels of fuel consumption and, consequently, carbon emissions.

4. The theoretical model

Importing countries buy different product-variety in the international market from different exporting countries. In this model, changes in bunker prices, resulting from carbon taxes, will affect international trade in differentiated products between countries. Products at the 6-digit HS level are considered to be traded between all possible country pairs worldwide. We will leave for future research the analysis of firm-to-firm, instead of country-to-country, relationships.

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 there are production costs that differ with the variety of the exporting goods. A marginal cost increases as the exported product variety to a specific country moves away from the "core competence" (e.g. importing country-product specialization) of the exporting country at which its marginal cost is lowest. Indeed, this synergy of this "core-competence" plays a crucial role for the net effect that bunker prices per ton fuel (or fuel per ton-km) have on the structure of trade and finally on carbon emissions.

For the demand side, we consider m importing countries. Each country maximizes a three-level utility function that depends on the country' consumption levels $q(i;j;k)$ of the N_{jk} varieties produced in each industry j from exporting country k. We have $i \in [1,N_{jk}]$, where N_{jk} is the measure of product variety i; while j and k change over the interval [0,1] respectively. The two upper levels are additive functions of a continuum of sub-utility functions, each corresponding to one type of exporting industry in a specific exporting country:

At the lower level, the importing country has an additive function of a continuum of quadratic sub-utility functions obtained from buying a variety of products from *a specific industry j in a specific 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 the exporting country *k*. The utility parameters *a, b* and ξ are assumed to be identical for all consumers in importing country *m*. These parameters denote the consumers' maximum willingness to pay, the inverse market size, and the inverse degree of product differentiation, respectively. If $\xi=1$, the goods are homogeneous (perfect substitutes), so that demand only depends on aggregate output in the industry. On the other hand, $\xi=0$ describes the monopoly case, where the demand for each good is completely independent of other goods. Consumers then give increasing weight to the distribution of consumption levels across varieties.

The two-upper utility levels are then obtained by adding continuously each of the sub-utility functions of the importing country (equation (1)) such as $u[q(0;j;k)\}\ \ldots,\ u(N_{jk};j;k)]$ across all product varieties, across all industries and all countries that participate in the export market. Thus, the two-upper utility levels represent the importing country's welfare from consuming a variety of products from *each of the industries j, in each of the many 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 typical importing country will maximize its welfare by maximizing equations (1) and (2) subject to the budget constraint (3):

$$\int_0^1\int_0^1\int_0^{N_{jk}} p(i)_{j,k}\, q(i,j,k)di\,dj\,dk \le E; \quad (3)$$

where E denotes the expenditure by the typical importing country on the set of differentiated products from different industries in different exporting countries.

We will derive the individual inverse demand function for each product variety i from each industry j in each exporting country k by the typical importing country. We denote this inverse demand by $x_{j;k}(i)$. $p_{j;k}(i)$ is the price of the good i in terms of the currency in the importing country.

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

$$U[u\{q(0;j;k)\},...,u\{q(N_{jk};j;k)\}] = \int_{k=0}^{1}\int_{j=0}^{1}\left\{a\int_{0}^{N_{jk}} q(i,j,k)di - \frac{1}{2}b\left[(1-\xi)\int_{0}^{N_{jk}} q(i,j,k)^2 di + \xi\left\{\int_{0}^{N_{jk}} q(i,j,k)di\right\}^2\right]\right\}dj\,dk \quad ; \tag{4}$$

subject to:

$$\int_0^1\int_0^1\int_0^{N_{jk}} p_{j,k}(i)q(i,j,k)di\,dj\,dk \le E. \tag{5}$$

To take into account the exporting country's maximization problem, we model the exporting country k as producing a variety of products (in each of its industries j) and denoted by δ_Z, and to export these varieties to a portfolio of countries denoted by δ_W.

Profits are equal to:

$$\pi_{Z,V,W} = \int_0^{\delta_W}\int_0^{\delta_V}\int_0^{\delta_Z}\left[\left\{p_{Z;V;W}(i;j;m)/ExcRate_{mk}\right\} - BP - c_{Z;V;W}(i;j;m)\right]x_{Z;V;W}(i;j;m)\,didjdm - F_{i,j,m}; \tag{6}$$

where F is a fixed cost independent of the scale and scope (product variety and importing country portfolio); $p_{Z;V;W}(i;j;m)$ is the price of the good i from industry j in terms of the currency in the importing country m. *ExcRate* and *BP* stand for the exchange rate (i.e. the value of the importing country currency in terms of the exporter country currency) and the bunker fuel costs, respectively. $C_{Z;V;W}(i,j;m)$ is the marginal cost that industry j faces to produce variety i and export it to country m. These marginal costs are constant with respect to the quantity produced, but differ with the core-competitiveness to produce a specific variety and to export it to a specific importing country. This marginal cost will be lowest for the core competence variety, because it uses the industry's most efficient production process. The industry can produce more varieties as part of its production line via flexible manufacturing, which describes its ability to produce additional varieties. Note that the production of more varieties requires the firm to make some modifications and incur higher marginal production costs, even when its marginal production costs of existing products remain unchanged.

Solving from (4), (5) and (6) will allow us to determine the price and quantities of equilibrium.

5. 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 are available at: http://www.bunkerindex.com/prices/bixfree_0903.php?priceindex_id=4.

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

6. The econometric analysis

6.1 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.[1] 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. In order to have more bunker price variation within each of our cross-sectional data over time, our empirical relationship also includes as explanatory variable per product variety and year, the interaction between the bunker price and the value of this product variety that is traded between a country pair. This strategy will also allow us to answer the following question: how would the effect of higher bunker fuel price on the weight

[1] 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).

of a specific product variety traded between two countries be influenced by the value of that product variety.

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 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).

6.2 The econometric model

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 products imported 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 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 (in ton-kilometers) of traded goods. This work will be extended to also consider the effect of changes in the bunker price on: 1) the number (variety) of traded goods; 2) the number of trading partner pairs; 3) the fuel price/cost pass-through to the final price of internationally traded goods; and 4) the reduction of CO2 emissions per product category and vessel type that follows from changes in these trade activities.

When we consider the bunker price per ton fuel, our proposed econometric model for the bilateral trade between a pair of countries of 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:

$$\begin{aligned}\ln q_{ijkmt} = \alpha_{11} + \beta_{11} \ln(Bunker\ price_t) + \lambda_{11} \ln(Exchange\ Rate_t) + \beta_{12} C_{kt} * \ln(Bunker\ price_t) + \\ \gamma_{11} M_{mt} + \delta_{11} X_{kt} + \mu_{ijkm} + \varphi_{ijkmt}.\end{aligned} \tag{7a}$$

We will also consider in the revised version of this paper, how the unit cost of fuel per ton-km will be affected by changes in the bunker price per ton fuel, using the following relationship:

$$\begin{aligned}\ln p_{ijkmt} = \alpha_{11} + \beta_{11} \ln(Bunker\ price_t) + \lambda_{11} \ln(Exchange\ Rate_t) + \beta_{12} C_{kt} * \ln(Bunker\ price_t) + \\ \gamma_{11} M_{mt} + \delta_{11} X_{kt} + \mu_{ijkmt} + \varphi_{ijkmt}.\end{aligned} \tag{7b}$$

In equations (7a) and (7b), at time t, q_{ijkmt} is 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}	It is the (log) of sales value of a 6-digit HS level product, traded between two countries.
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).

6.3 Estimation results for changes in weight for 6-digit HS level product categories that are the heaviest

We will start the discussion of our empirical results by considering the effects of changes in the global average bunker price and the weight of 6-digit HS level products with the heaviest trade weights in each of the years 2009 - 2017. These chosen product categories 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 trade transported by shipping.

The empirical results are shown in Table 2. We here concentrate on presenting the most important estimates of equation (7a), such as the average 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 the heaviest and are traded bilaterally. These products turned out to be from 21 industries (i.e. from 21 product at the 2-digit HS level of aggregation). These elasticities are shown in column 2 in Table 2. We do not present the estimates of all the background variables (e.g. M_{nt}, X_{kt}) as they are not so consequential for our ultimate objective of this paper: the analysis of the effect of carbon pricing on trade structure and on carbon emissions.[2] Note that we have grouped the 6-digit HS products within each industry (i.e. 2-digit HS level) into 10 categories according to their monetary import values, and have derived the elasticities for each of these categories of products and industries. We however only present in Table 2, the estimates for 3 categories of products that have: i) between the 10 and 25 *low* percentile value; ii) the median value; and iii) between the 25 and 10 percentile *highest* value.

We also estimated the parameters accompanying the variable representing the interaction between the bunker price and the value of this product variety that is traded between a country pairs. Column 3 in Table 2 presents the estimates for the 3 categories mentioned above, which show how the effect of changes in bunker fuel prices on the weight-distance of a specific product variety traded between two countries is influenced by the value of that product variety. The sum of the pure elasticities (column 2) plus the estimates of the interactive variable (column 3) provide the total effect of changes in the bunker price on weight-distance, after correcting for the value of the imported good. We call this sum, the *"net"* elasticities and these are shown in column 4 in Table 2.

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

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)*

Product Category *2 HS level*	**lnBunkerPrice**	**lnBunkerPrice* lnSalesValue**	**Net Elasticity**
(1)	**(2)**	**(3)**	**(4)**
10: Cereals			
10-25 percentile	-0.0403968	0.1600924	-0.12232
	(0.0211903)	(0.002747)	
Median	-0.1897024	0.1507654	-0.08069
	(0.022811)	(0.00485)	
75-90 percentile	-0.6943085	0.1543607	-0.11925
	(0.023972)	(0.003325)	
12: Miscel. grains			
10-25 percentile	-0.0468156	0.1607933	-0.10969
	(0.020438)	(0.002801)	
Median	-0.2242817	0.1663386	-0.13632
	(0.027165)	(0.00841)	
75-90 percentile	-0.4482542	0.13924	-0.02175
	(0.01841)	(.004123)	
15: Animal-Vegetable oils			
10-25 percentile	-0.1287205	0.1550637	-0.15434
	(0.019130)	(0.00301)	
Median	-0.2563184	0.1433961	-0.15522
	(0.017540)	(0.005033)	
75-90 percentile	-0.4273014	0.1229405	-0.06439
	(0.015479)	(0.003615)	
23: Animal fodder			
10-25 percentile	-0.074572	0.1641996	-0.15118
	(0.020458)	(0.003624)	
Median	-0.205357	0.1594204	-0.11266
	(0.016583)	(.0046371)	
74-90 percentile	-0.481850	0.1416685	-0.05921
	(0.015909)	(0.00303)	
25: Salt, stones, cement			
10-25 percentile	0.1595976	0.1606017	-0.08728
	(0.016539)	(0.002971)	
Median	0.048033	0.1543708	-0.04408
	(0.013308)	(0.005256)	
75-90 percentile	-0.369934	0.1658231	-0.06855
	(0.016456)	(0.004069)	

26: Ores	-0.178658	0.1409837	-0.24656
10-25 percentile	(0.033089)	(.0042726)	
Median	-0.346726	0.1433522	-0.18939
	(0.032888)	(0.005486)	
75-90 percentile	-1.004093	0.1544254	-0.30830
	(0.036704)	(0.004474)	
27: Mineral fuels			
10-25 percentile	-0.237314	0.1608234	-0.20958
	(0.020018)	(0.002594)	
Median	-0.597128	0.1597445	-0.31181
	(0.019326)	(0.003137)	
75-90 percentile	-1.616535	0.1734115	-0.64967
	(0.025197)	(0.002352)	
28: Inorganic chemical prod.			
10-25 percentile	0.0286131	0.1534404	-0.10664
	(0.012112)	(0.003345)	
Median	-0.086629	0.1525265	-0.08129
	(0.014832)	(0.007029)	
75-90 percentile	-0.450888	0.1555083	-0.11084
	(0.013048)	(0.003361)	
29: Organic chemical prod.			
10-25 percentile	-0.266395	0.1469172	-0.25008
	(0.009133)	(.0018195)	
Media	-0.370081	0.1391294	-0.23167
	(0.008358)	(0.002366)	
75-90 percentile	-0.644196	0.1446705	-0.20325
	(0.016808)	(0.003782)	
31: Fertilizers			
10-25 percentile	0.0461656	0.1555548	-0.074143
	(0.020985)	(0.002330)	
Median	-0.1555168	0.1519224	-0.115598
	(0.0168491)	(0.004069)	
75-90 percentile	-0.6882685	0.1633246	-0.226636
	(0.0162698)	(0.002614)	
38: Miscellaneous chemical prod.			
10-25 percentile	-0.0493162	0.1346475	-0.05552
	(0.0155726)	(0.004602)	
Median	-0.2023574	0.1429652	-0.08181
	(0.0213986)	(0.008277)	
75-90 percentile	-0.5256218	0.1560869	-0.06115
	(0.0186372)	(.0048044)	

39: Plastics			
10-25 percentile	-0.2268569 (0.0099024)	0.1539678 (.0023289)	-0.18051
Median	-0.2833303 (0.0108861)	0.1469674 (0.004278)	-0.12125
75-90 percentile	-0.5817368 (0.0082638)	0.1489865 (0.002108)	-0.12709
44: Wood			
10-25 percentile	0.0458854 (0.0160431)	0.1581739 (.0026332)	-0.06769
Median	-0.0860982 (0.01246)	0.1627062 (0.004711)	-0.05245
75-90 percentile	-0.4312786 (0.0094593)	0.1608621 (0.002467)	-0.04222
47: Pulp of wood			
10-25 percentile	0.094163 (0.019023)	0.1530974 (0.002316)	-0.05995
Median	-0.068043 (0.012578)	0.1498387 (0.002576)	-0.03680
74-90 percentile	-0.587105 (0.011483)	0.162444 (0.00179)	-0.07705
48: Paper			
10-25 percentile	-0.047969 (0.010325)	0.152779 (0.001547)	-0.10487
Median	-0.138020 (.0080244)	0.158454 (0.002815)	-0.06266
75-90 percentile	-0.418680 (0.00855)	0.153982 (0.002613)	-0.04627
72: Iron & steel			
10-25 percentile	-0.156211 (0.009027)	0.145849 (0.001069)	-0.21501
Median	-0.286602 (0.006422)	0.139396 (0.001462)	-0.21209
75-90 percentile	-0.701455 (0.007142)	0.162642 (0.001216)	-0.24921
73: Iron & steel products			
10-25 percentile	-0.189148 (0.014659)	0.145851 (0.002659)	-0.16544
Median	-0.239192 (0.013563)	0.140816 (.0040844)	-0.09998
75-90 percentile	-0.510604 (0.013379)	0.148868 (0.002826)	-0.08736

74: Cooper and cooper prod.			
10-25 percentile	-0.337588 (0.023504)	0.135052 (0.00255)	-0.17744
Median	-0.429721 (0.018661)	0.127027 (0.003562)	-0.19010
75-90 percentile	-0.643666 (0.044887)	0.121502 (0.007902)	-0.16891
76: Aluminum			
10-25 percentile	-0.220222 (0.01549)	0.142608 (0.002238)	-0.13117
Median	-0.263494 (0.013761)	0.141418 (.0038676)	-0.06889
75-90 percentile	-0.616893 (0.012225)	0.165193 (0.002243)	-0.06052
87: Vehicles			
10-25 percentile	-0.226669 (0.015531)	0.145313 (0.003875)	-0.03312
Median	-0.323704 (0.014751)	0.144694 (0.004444)	-0.00282
75-90 percentile	-0.716692 (0.013946)	0.156409 (0.00267)	-0.01275
94: Furniture			
10-25 percentile	-0.159325 (0.016366)	0.151632 (0.004937)	-0.06024
Median	-0.260353 (0.024838)	0.156411 (0.010856)	-0.03214
75-90 percentile	-0.4120202 (0.0168201)	0.1071084 (0.004093)	-0.04186

The results presented in Table 2 indicate that the "net" elasticities of traded weight-distance with respect to the bunker price and "corrected" for the value of the imported product vary greatly depending on which industry the 6-digit products belongs to and the value of the imported good. In general, the higher the value, the lower the net elasticity. For example, these net elasticities can vary from -0.00282 (for 6-digit HS products in the automobile industry) and -0.02175 (for 6-digits product in grains such as soya beans), to -0.31 (for 6-digit HS products in the ores category) and -0.64 (for 6-digit HS products in the mineral fuels category). Given these results, a 10% increase in the bunker price would reduce the overall traded weight for 6-digit products by between 0.03% and 6.4%. 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 trade activity, as we will show in the next section.

Figure 1 illustrates the *"net"* average elasticities of our heaviest products at the 6-digit HS level by industry group (i.e. 2-digit HS level).

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

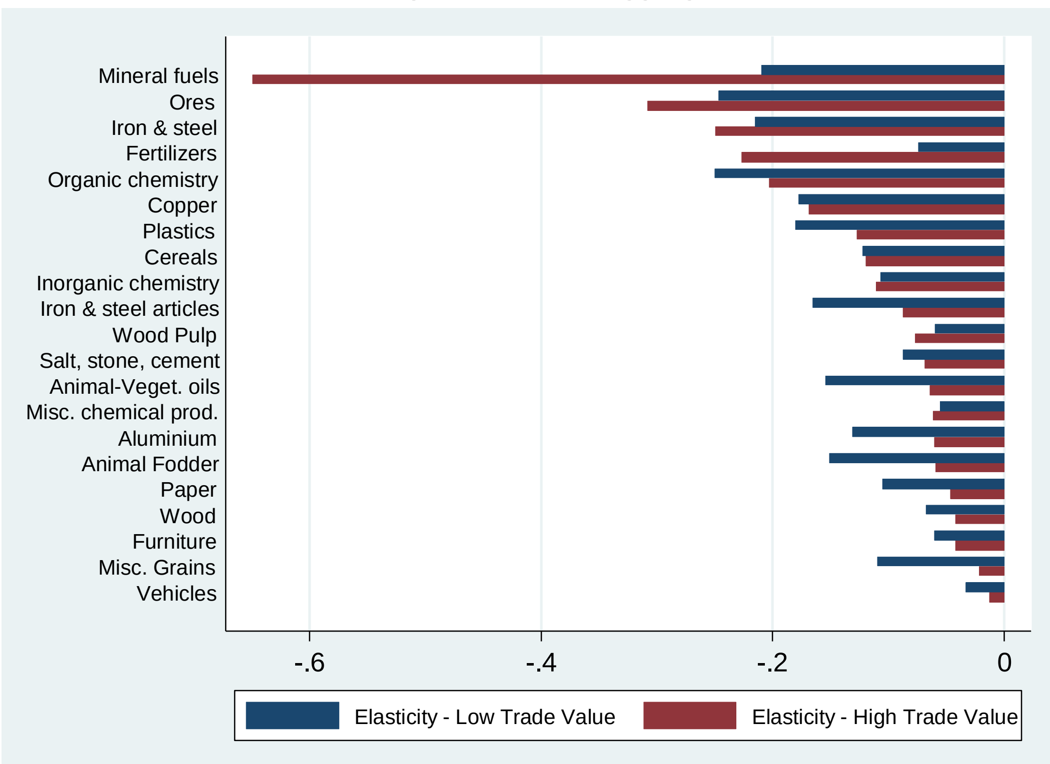

Figure 1 shows the net response of traded weight-distance to changes in the bunker fuel price, whichfor almost all sectors declines as the sales value of the 6-digit level products traded between two countries rises (see the estimate for *logBunkerPrice*logSalesValue* in column 3). The relationship between the bunker price and the weight-distance weakens between 25% and 40% as the traded product becomes more valuable. The exceptions are for mineral fuels, ores, iron and steel, and fertilizers.

We also find for example that a depreciation of the importing country's currency decreases the weight-distance of traded goods; while increases in the population in the importing country increases the weight-distance of trade products.

7. 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 from International Transport Forum (ITF) at the OECD (ITF (2018)) on 8 types of vessels and fuel consumption intensity per ton-kilometer for each type of vessel. See Table 3. The ITF/OECD provides emissions data for every 5 years, historical data since 2000, and projected figures up to 2050. These calculations have taken into account the average emissions rates, weight categories and various other characteristics for each ship category. There are also data on emissions rates by vessel size for each vessel type. However, in our estimations, we will concentrate on the average size per vessel type to estimate the average emission rates per vessel type (see Table 3). We do not have information about what product variety is transported by ship size between country pairs.

We consider a constant relationship (α) between fuel consumption and carbon emissions (i.e. one ton of bunker fuel consumption corresponds to emitting 3 tons of CO_2, thus $\alpha = 3$. 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 consumption intensity per ton-kilometer of the vessel that the given product uses. As mentioned, our calculations of CO_2 emissions take into account the fuel consumption intensity data per vessel type given in Table 3.

Table 3: Sea freight and average freight emissions by vessel category (grams CO_2 per ton-kilometer)

Type of ship	Types of goods transported	Emissions rates by 2020, grams CO2/t-km
Bulk carriers	Bulk agriculture, forestry, mining, minerals, non-ferrous metals, coal products	4.5
Container ships	Processed food, textiles, wearing apparel, leather products, wood products, paper, iron and steel, transport equipment, electronic equipment, machinery and equipment, other manufactures	18.2
General cargo	Food products, fish, livestock	13.0
Oil tankers	Oil	4.0
LNG ships	Gas	13.6
Products tankers	Petroleum	13.2
Chemical ships	Chemical products	9.6
Vehicle carriers	Vehicles (automobiles)	35.4

Note: Total emissions, and emissions changes due to carbon taxes, are calculated using the OECD/ITF table for emissions rates in grams per ton-kilometer, in 2020 and 2030 relative to 2010.
Source: International Transport Forum (ITF) (2018)

To calculate the reduction in carbon emissions resulting from a carbon tax, say $40 per ton CO_2, note first that such a carbon tax implies an increase in the bunker price of ($40 times 3 =) $120 per ton, since burning one ton of bunker fuel will release 3 tons of CO_2. If we assume a bunker price of $450 per ton (as the approximate level today, in December 2019), this carbon tax then leads to a relative increase in the bunker price of 120/450 = 0.27, or 27%. Our econometric results yield elasticities of the trade weight times transported distance (assumed to be proportional to bunker fuel consumption for a given vessel type), in response to an increase in the bunker fuel price (some of these elasticities are shown in column 2 in Table 2). We also estimated how this effect of changes in bunker fuel prices on the weight-distance of a specific product variety traded between two countries is influenced by the value of that product variety (some of these elasticities are shown in column 3 in Table 2). The sum of these two estimates (e.g. column 2 plus column 3) provide the total effect of changes in the bunker price on weight-distance, after correcting for the value of the imported good. We call this sum, the *"net"* elasticities and some of these are shown in column 4 in Table 2, and denote by β, which we expect to be negative. The expected relative impact on carbon emissions (and bunker fuel consumption), resulting from a carbon tax of $40 per ton CO_2, will be a reduction in carbon emission equal to *0.27* times β. For example, if this elasticity is -0.2 (so that a 1% increase in the bunker fuel price leads to 0.2% reduction in traded weight times transported distance), the carbon emissions are reduced by a fraction 0.27 times 0.2, or 5.4%.

We see from Table 3 that the average CO_2 emissions rates by vessel type, in grams per ton-kilometer of freighted goods for 2020, varies substantially from a low value of 4 grams for oil tankers, to a high value of 35.4 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.

From our bottom-up calculations using data for ton-kilometers by goods category, and the average carbon intensities given in the OECD/ITF table for the ship types used by the different goods types, we find that total annual carbon emissions from transport of our heaviest 6-digit products at the HS level of aggregation which come from 21 2-digit goods categories, were about 457 million tons of CO_2 over the 2009-2017 period, or somewhat more than half of total emissions from the entire international shipping over the same period (see e.g. IMO (2015)). By 2020, CO_2 emissions from the same trade volume is expected to be reduced to 426 million tons, and to 397 million tons by 2030, due to predicted improvements in the average fuel efficiency of ships over the same period.

Our estimates indicate that a global carbon tax of \$40 per ton CO_2 on all bunker fuels reduces the total number of ton-kilometers in international shipping, and the resulting carbon emissions, by about 4%, for our heaviest 6-digit HS products which are part of 21 sectors. There are however substantial differences in the impact by sector. By far the greatest reduction is estimated to take place for the freight of petroleum products (by oil tankers), whose emissions of CO_2 are predicted to go down by around 10 million tons (or about 7%) due to this carbon tax. Other sectors with substantial reductions in carbon emissions are iron and steel, ores, and cereals.

Table 4 gives estimates of projections for total carbon emissions both under "business-as-usual" (with no carbon tax), as well with changes in carbon emissions resulting from a \$40 per ton CO_2 carbon tax, for the heaviest 6-digit HS products in each of the 21 sectors considered in our estimations. For these calculations, we simply assume that the overall activity levels in international trade (in ton-kilometers) in 2020 and 2030 is the same than the average trade for the period between 2009 and 2017, for all 6-digit HS products in the 21 sectors in our study. The average carbon emissions are calculated using the average carbon intensities of sea transport (in grams of CO_2 per ton-kilometer of freight) for years 2020 and 2030, taking into consideration the ship type by which each of our product types are transported. Since these carbon intensities fall over time, we find that carbon emissions (in grams of carbon per ton-kilometer) from the average level between 2009 and 2017 could be reduced in 2020, and even more up in 2030, when using the OECD/ITF carbon intensity estimates (Table 4). Thus, the BAU carbon emissions, shown in Table 4 will be lower for all good categories in 2020 than the average for the 2009-2017 period, and will be reduced further by 2030.

Table 4: Estimated "business-as-usual" carbon emissions due to sea transport of goods by sector in 2020 and 2030, and estimated reductions in carbon emissions due to a $40/t CO_2 carbon tax in the same years. 1000 tons CO_2 per year.

Sector	Sector number	BAU carbon emissions, 2020	Reductions in carbon emissions from a $40 carbon tax, 2020	BAU carbon emissions, 2030	Reductions in carbon emissions from a $40 carbon tax, 2030
Cereals	10	22 000	786	20 500	733
Seeds	12	19 600	512	18 300	478
Vegetable oils	15	8 840	88	8 210	82
Animal feed	23	16 700	265	15 600	247
Stone/Cement	25	11 200	472	10 500	440
Ores	26	50 700	918	47 300	857
Petroleum and coal	27	142 000	10 600	133 000	9 890
Inorganic chem	28	7 530	108	7 030	101
Organic chemicals	29	7 600	315	7 090	294
Fertilizers	31	6 740	448	6 290	418
Chemical products	38	4 770	72	4 450	67
Plastics	39	15 900	293	14 800	273
Wood	44	11 900	79	11 100	74
Pulp	47	7 280	42	6 790	39
Paper	48	8 330	123	7 770	115
Iron and steel	72	22 500	1310	21 000	1220
Iron and steel prod	73	11 200	186	10 500	174
Copper	74	2 080	60	1 940	56
Aluminum	76	3 850	128	3 590	115
Vehicles	87	19 700	50	18 400	47
Furnitures	94	25 600	132	23 900	119
Total		426 000	17 090	397 000	15 900

Note: It is assumed that the "BAU" activity level for each sector corresponds to the average activity levels over the period 2009-2017.

Table 5 provides estimates for 2030 which are similar to those in Table 5, except that we now assume that the overall activity level in international sea transport has developed, and changed, by 2030. To calculate this activity change, we estimated the average annual change in traded weight in our heaviest 6-digit HS products in each of the 21 sectors over our period of analysis (2009-2017). We then estimated the future total growth in trade from 2013 (the mean year of our period of study) up to 2030, and use this figure to project the possible trade in 2030. Column 3 in Table

5, gives the growth rate in trade activity in terms of weight for each sector over this period, and under these assumptions. We find positive growth in weight for all sectors, but the growth rate varies by type of product. We found the growth rate to be particularly high for fertilizers, wood products, animal feed, and plastics.

On this basis we find the estimated carbon emissions by sector in 2030 in column 4. We find in column 5 reductions in carbon emissions from a $40 per ton CO_2 tax on emissions in that year, assuming that the average elasticity with respect to the carbon price is the same as before for each sector. These figures are now higher than those in Table 4. These figures are then all proportionately higher than those in Table 4, by the growth factor in column 3.

Table 5: Estimated carbon emissions due to sea transport of goods by sector in 2030, and estimated reductions in carbon emissions due to a $40/t CO_2 carbon tax in the same year, assuming historical increase in transported weight by 2-digit sector. 1000 tons CO_2 per year.

Sector	Sector number	Relative activity increase up to 2030	Estimated carbon emissions 2030	Reduction in carbon emissions from a $40 carbon tax, 2030
(1)	**(2)**	**(3)**	**(4)**	**(5)**
Cereals	10	0.4489598	29 700	1060
Seeds	12	0.4837333	27 100	709
Vegetable oils	15	0.5393352	12 600	126
Animal feed	23	0.726971	26 900	427
Stone/Cement	25	0.4109291	14 700	621
Ores	26	0.3980465	66 100	1200
Petroleum and coal	27	0.4858804	197 000	14 700
Inorganic chemicals	28	0.5070046	10 600	152
Organic chemicals	29	0.4477069	10 300	426
Fertilizers	31	0.8823221	11 800	787
Chemical products	38	0.443989	6 430	97
Plastics	39	0.6217019	24 100	443
Wood	44	0.8199083	20 200	134
Pulp	47	0.4264773	8 690	56
Paper	48	0.1384463	8 850	131
Iron and steel	72	0.3121353	27 500	1600
Iron and steel prod	73	0.1665133	12 200	202
Copper	74	0.3305072	2 580	75
Aluminum	76	0.5458207	5 550	185
Vehicles	87	0.5213798	28 000	71
Furnitures	94	0.5292832	36 500	330
TOTAL			588 000	23 500

Note: These calculations assume the same annual sectoral increases in transported weights by 2-digit sector up to 2030, as was found on an annual basis for the period 2009-2017.

Shippers may start to phase in faster alternative fuel technologies (biofuels; hydrogen; electric motors in vessels), which may contribute to greater reductions in carbon emissions from the shipping fleet than the ones we have here estimated. We recognize that this can be potentially important factors behind reduced transport-related carbon emissions due to carbon pricing.

8. Conclusions

The objective of this paper has been to estimate the impacts of changes in bunker fuel prices on bunker fuel consumption and carbon emissions for the global international shipping sector. We take as basis the WITS data set for all 6-digit goods categories within 21 2-digit goods categories of particularly heavy goods traded by sea.

We first present a theoretical 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. The exporting and importing countries face also varying production costs across products and country destinations. In our model, changes in bunker prices, resulting from carbon pricing, will affect the structure of international trade of differentiated products between countries.

We then estimate our model based on 6-digit HS level trade data, and data for global bunker fuel prices, for the period 2009-2017, and 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 an equally large carbon tax on bunker fuels. In our econometric analysis, we model the weight of the exports, the number of goods varieties and of trading partnerships, and export prices, 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 the heaviest product at the 6-digit HS level of aggregation that are part of 21 industries (i.e. 2-digit HS level). With a few exceptions, these elasticities are found to have lower (absolute) values for product categories with higher import values. Elasticities differ substantially, from low values of about -0.0028 to a high value of about -0.64.

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 and this reduces the bunker fuel consumption and carbon emissions from international shipping. A rough estimate is that a global and uniform carbon tax of $40 per ton CO_2 will reduce fuel consumption, and carbon emissions, by about 4% in total for the 21 industries here considered, and whose 6-digit HS products are the heaviest. 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 present two types of calculations of the predicted carbon emissions impacts by 2030. In the first calculation, we assume that the average activity level by weight remains the same over that period as it was in the period of our data (2009-2017). In the second calculation, we assume an annual growth rate for traded weights by goods category, equal to the average growth rate for the 2009-2017 period, found to be positive for all goods categories studied.

From our calculations, a carbon tax of $40 per ton CO_2 is found to reduce CO_2 emissions from transport of our considered goods categories by about 20 million tons by 2020. The predicted impact in 2030 is found to be somewhat smaller than this level given that traded weights are kept constant in a "baseline" case with no carbon taxation; and somewhat greater than this level when traded weights keep increasing up to 2030 at the same rates as during the 2009-2017 period. The impact on carbon emissions however varies substantially between sectors. This impact is found to be particularly large for petroleum and coal, but also large for iron and steel, ores, and cereals.

A $40 per ton CO_2 tax on bunker fuels at a global level would also generate substantial tax revenues, and give room for redistributions benefitting low-income countries, or general climate action that could also lead to higher global welfare.

As far as we know, 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 on detailed data for carbon emissions intensities for different types of ships transporting different goods categories. Our analysis strongly indicates that a $40 per ton CO_2 on bunker fuel will have substantial impacts both on carbon emissions from the international maritime sector, and on the volume and structure of international trade. Our estimated reduction in carbon emissions from the shipping sector by 2020 and 2030 from such a carbon tax due to reduced or altered trade activity, about 4%, is much larger than other recent assessments of similar impacts. In particular, in a recent IMF study (Parry et al 2018), the reduction in carbon emissions due to reduced shipping ton-kilometers, that is expected to result from such a carbon tax, is assessed at only 0.3%. We show that changed trade relations can be an additional important factor behind future reduced carbon emissions from international shipping, alongside with other factors such as improved technical efficiency of ships, and the substitution of standard bunker fuels with renewable fuels (the two measures of greatest importance in the IMF study).

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.

References

Antweiler, W., B. R. Copeland and M. S. Taylor (2001), Is free trade good for the environment? *American Economic Review,* 91, 877–908.

Arellano M. and O. Bover (1995). Another look at the instrumental variables estimation of error-components models. *Journal of Econometrics* 68, 29 – 51.

Arkolakis, C. and M.-A. Muendler (2010). The extensive margin of exporting products: a firm-level analysis. NBER Working Paper # 16641.

Arkolakis, C, A. Costinot and A. Rodriguez-Clare (2012). New Trade Models, Same Old Gains? *American Economic Review,* 102(1), 94 – 130.

Armington, P. (1969). A Theory of Demand for Products Distinguished by Place of Production." *IMF Staff Papers* 16(1), 159 – 178.

Azar, C. and D. Johansson (2011). Valuing the non-CO_2 climate impacts of aviation. *Climatic Change* 111, 559-579.

Bachmann, C. (2017). Modeling the impacts of free trade agreements on domestic transportation gateways, corridors, and ports. *Transportation Research Record: Journal of the Transportation Research Board* 2611, 1-10.

Baumeister C. and J.D. Hamilton (2019). Structural Interpretation of Vector Autoregressions with Incomplete Identification: Revising the Role of Oil Supply and Demand Shocks. *American Economic Review* 109(5), 1837 – 1910.

Behar A. and A. J. Venables (2011). "Transport Costs and International Trade," in Handbook of Transport Economics, Chapter 5. Edward Elgar Publishing.

Bergstrand, Jeffrey H. 1985. "The Gravity Equation in International Trade: Some Microeconomic Foundations and Empirical Evidence." *Review of Economics and Statistics* 67(3):474–81.

Bernard, A., S. Redding and P.K. Schott (2010). Multiple-product firms and product switching. *American Economic Review* 100, 70 – 97.

Bernard, A., S. Redding and P.K. Schott (2011). Multi-product firms and trade liberalization. *Quarterly Journal of Economics* 126, 1271 – 1318.

Bernard A.B., E. Dhyne, G. Magerman, K. Manova and A. Moxnes (2017). The origins of firm heterogeneity: a production network approach. Tech. Rep., Eur. Cent. Adv.Res. Econ. Stat., Brussels.

Bernard A.B., E.A. Bøler and S. Dhingra (2018). Firm-to-firm connections in Colombian imports. In *World Trade Evolution*, ed. L.Y. Ing, M. Yu. Oxford, U.K.:Routledge. In press.

Bernard A.B. and A. Moxnes (2018). Network and Trade. *Annual Review of Economics* 10, 65 – 85.

Blundell R. and S. Bond (1998). Initial conditions and moment restrictions in dynamic panel data models. *Journal of Econometrics* 87, 115 – 143.

Bougheas, S. and others. 1999. "Infrastructure, Transport Costs, and Trade." *Journal of International Economics* 47:169–89.

Bouman, E. A., E. Lindstad, A. I. Rialland and A. H Strømman (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. *Transportation Research* Part D 52, 408-421.

CE Delft (2012). The fuel efficiency of marine transport: Potential for improvement an analysis of barriers. Consultancy report. Delft, the Netherlands: CE Delft

Cristea, A., D. Hummels, L. Puzzello and M. Avetisyan (2013). Trade and the greenhouse gas emissions from international freight transport. *Journal of Environmental Economics and Management*, 65, 153-173.

Deardorff, A. V. 1998. "Determinants of Bilateral Trade: Does Gravity Work in a Neoclassical World?" In J. A. Frankel (ed.), The Regionalization of the World Economy. Chicago: University of Chicago Press.

De Hoyos, R.E. and V. Sarafidis. (2006). "Testing for cross-sectional dependence in panel-data models." *The Stata Journal* 6(4), 482 – 496.

De Jong, G., R. Tanner, J. Rich, M. Thorhauge, O.A. Nielsen and J. Bates (2017). Modelling production-consumption flows of goods in Europe. *Journal of Shipping and Trade*, 2:5.

Delft, C.E., (2017). Update of Maritime Greenhouse Gas Emission Projections. CE Delft, Delft.

de Sousa, J., T. Mayer and S. Zignago (2012). Market access in global and regional trade. *Regional Science and Urban Economic* 42(6), 1037 – 1052.

Dessens, O., M. O. Köhler, H. L. Rogers, R. L. Jones and J A. Lyle (2014). Aviation and climate change. Working Paper, University College London.

Eckel C., L. Iacovone, B. Javorcik and Neary, J.P. (2015). Multi-product firms at home and away: Costs-versus quality-based competence. *Journal of International Economics*, 95, 216 – 232.

Eckel C. and Neary P. (2015). Multi-product firms and flexible manufacturing in the global economy. *Review of Economic Studies*, 77, 188 – 217.

Eide, M. S., C. Chryssiakis and Ø. Endresen (2013). CO_2 abatement potential towards 2050 for shipping including alternative fuels. *Carbon Management*, 4, 275-289.

European Environment Agency (2016), EMBP/EEA air pollutant emission inventory guidebook, 2016. EEA Report 21/2016.

Eyring, V., H. W. Köhler, J. van Aardenne and A. Lauer (2005). Emissions from international shipping: The last 50 years. *Journal of Geophysical Research* 110.

Faber, J., D. Nelissen, G. Hon, H. Wang and M. Tsimplis (2012). Regulated slow steaming in maritime transport: An assessment of options, costs and benefits. Delft, NL: CE Delft.

Faber, J, T. Huigen and S. Nelissen (2017). Regulating speed – a short-term measure to reduce maritime GHG emissions. Delft, the Netherlands: CE Delft.

Feenstra, R. C. (2010). *Product variety and the gains from international trade*. Cambridge, MA: MIT Press.

Franc, P. and L. Sutto (2014). Impact analysis on shipping lines and European ports or a cap-and-trade system on CO2 emissions in maritime transport. *Maritime Policy Management* 41, 61-78.

Frankel, Jeffrey A. 1997. *Regional Trading Blocs in the World Economic System*. Washington, D.C.: Institute for International Economics

Giannouli, M. and G. Mellios (2005). Overall Energy Efficiency and Specific CO2 Emissions for Passenger and Freight Transport. European Environmental Agency, 2005 TERM200527EEA32.

Gohari, A., N. Matori, K. Wan Yusof, I. Toloue, and K. Cho Mying (2018). Effects of the Fuel Price Increase on the Operating Costs of Freight Transport Vehicles. E3S Web of Conferences 34. https://doi.org/10.1051/e3sconf/20183401022

Halim, R. A., L. Kirstein, O. Merk and L. M. Martinez (2018~~a~~). Decarbonization pathways for international maritime transport: A model-based policy impact assessment. *Sustainability*, 10, 2243.

Halim, R. A., T. Smith and D. Englert (2019~~8b~~). Understanding the economic impacts of GHG mitigation policies on shipping. What is the state of the art of current modeling approaches? ~~Unpublished,~~Policy Research Working Paper WPS8695. Washington DC: The World Bank.

International Civil Aviation Organization (2016). Carbon Offsetting and Reduction Scheme for International Aviation. https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

International Maritime Organization (2015). Third IMO greenhouse gas study, 2014. London: International Maritime Organization.

International Maritime Organization (2018). Initial IMO Strategy for Reduction of GHG Emissions from Ships. http://www.imo.org/en/MediaCentre/HotTopics/GHG/Pages/default.aspx

International Transport Forum (2016). Reduced CO_2 emissions from international aviation. Policy options to 2050. ITF: Global dialogue for better transport. Paris 2016.

International Transport Forum (2018). CO2 emissions by ship type used in international trade. Excel data sheets. Paris: International Transport Forum, OECD, 2018.

IPCC (1999). *Aviation and the Global Atmosphere: A Special Report of IPCC Working Groups I and III*. Inter-Governmental Panel on Climate Change.

Johansen, B. G. and W. Hansen (2016). Predicting market allocations, user benefits and wider economic impacts of large infrastructure investments for freight transportation. *Transportation Research Procedia*, 16, 146-157.

Johansson, L., J.-P. Jalkanen and J. Kukkonen (2017). Global assessment of shipping emissions in 2015 on a high spatial and temporary resolution. *Atmospheric Environment* 167, 403-415.

Keen, M., I. Parry and J. Strand (2013). Planes, boats and taxes: Charging for international aviation and maritime emissions. *Economic Policy*, October 2013, 701-749.

Keen, M. and J. Strand (2007). Indirect taxes on international aviation. *Fiscal Studies* 28, 1 – 41.

Kilian, L. and D. P. Murphy (2012). Why Agnostic Sign Restrictions Are Not Enough: Understanding the Dynamics of Oil Market VAR Models. *Journal of the European Economic Association* 10(5), 1166 – 1188.

Kilian, L. and D. P. Murphy (2014). The Role of Inventories and Speculative Trading in the Global Market for Crude Oil. *Journal of Applied Econometrics* 29(3), 454 – 478.

Kågeson, P. (2009). Environmental Impacts of International Transport: Making International Transport Pay Its Climate Bill. International Transport Forum, Transport for a Global Economy. 26-29 May, Leipzig.

Lee, T., Y. Chang and P. T. W. Lee (2013). Economy-side impact analysis of a carbon tax on international container shipping. *Transportation Research* Part A 58, 87-102.

Limão, N. and A. J. Venables (2001). Infrastructure, geographical disadvantage, transport costs, and trade. *World Bank Economic Review*, 15 (3), 451-479.

Lindstad, H., G. S. Eskeland (2015). Low carbon maritime transport: How speed, size and slenderness amounts to substantial capital energy substitution. *Transportation Research* Part D 41, 244-256.

Lindstad, H., G. S. Eskeland, H. Psaraftis, I. Sandaas and A. H. Strømman (2015). Maritime shipping and emissions: A three-layered, damage-based approach. *Ocean Engineering* 110, 94-101.

Martínez, L, M. et al (2015). International freight and related carbon dioxide emissions by 2050: New modeling tool. *Transportation Research Record: Journal of the Transportation Research Board*, 2477, 58-67.

Mayer, T., M. Melitz, and G. Ottaviano (2014). Market size, competition, and the product mix of exporter. *American Economic Review* 104, 495 – 536.

Mundaca, B. G., J. Strand and H. Bofinger (2019). Carbon pricing of international transport fuels: Impacts on carbon emissions and trade activity. Unpublished, the World Bank

Newell, R. G. (2015). The role of energy technology policy alongside carbon pricing. In I. Parry, A. Morris and R. Williams (eds.): *Implementing a US carbon tax: Challenges and debates*. London: Routledge.

Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., (2017). The activity based methodology to assess ship emissions - a review. *Environ. Pollut.* 231, 87-103.

Olmer, N., B. Comer, R. Biswajoy, M. Xiaoli and D. Rutherford (2017). Greenhouse gas emissions from global shipping, 2013-2015. Report, International Council on Clean Transportation.

Ong, G. P. and W. S. Sou (2015). Modeling commodity value-weight trends between the United States and its trading partners. *Transportation Research Record: Journal of the Transportation Research Board*, 2477, 93-105.

Parry, I. A., D. Heine, K. Kizzier and T. Smith (2018). Carbon Taxation for International Maritime Fuels: Assessing the Options. IMF Working Paper, WP/18/203. Washington DC: International Monetary Fund.

Peters, G. P. and E. G. Hertwich (2008). CO2 embodied in international trade with implications for global climate policy. *Environmental Science and Technology* 42 (5), 1401–1407.

Psaraftis, H. N. and Kontovas, C. A. (2008). *Ship Emissions Study*. Report, National Technical University of Athens, May 2008.

Rodriguez-Lopez, J.A. (2011). Prices and Exchange Rates: A Theory of Disconnect. *The Review of Economic Studies* 78(3), 1135 – 1177.

Roodman, D. (2009). "How to do xtabond2: An introduction to difference and system GMM in Stata." *The Stata Journal* 9(1), 86 – 136.

Schim van der Loeff, W., Godar, J. and Prakash, V. (2018). A spatially explicit data-driven approach to calculating commodity-specific shipping emissions per vessel. *Journal of Cleaner Production*. DOI: 10.1016/j. jclepro.2018.09.053

Schuitmaker, R. (2016). Evolution of global maritime freight energy demand and CO_2 emissions: A BAU and 2DS scenario. Master Thesis, Utrecht University.

Shapiro, J. S. (2016). Trade Costs, CO_2, and the Environment. *American Economic Journal: Economic Policy* 8(4), 220 – 254.

Sheng, Y., S. Xunpeng and B. Su (2018), Re-analyzing the economic impact of a global bunker emissions charge. *Energy Economics* 74, 107-119.

Smith, T.W., et al. (2015a). Third IMO GHG Study 2014. IMO, London.

Smith, T.W.P., Prakash, V., Aldous, L., Krammer, P. (2015b). The Existing Shipping- Fleet's CO2 Efficiency. International Maritime Organisation, London, UK.

Smith, T. et al. (2016). CO_2 emissions from international shipping. Possible reduction targets and their associated pathways. UMAS, London.

Tavasszy, L. A. et al. (2016). Effect of a full internalization of external costs of global supply chains on production, trade and transport. In C. Blanquart, U. Clausen & B. Jacob (Eds.), *Towards Innovative Freight and Logistics*. Hoboken, New Jersey: John Wiley & Sons.

UNCTAD (2018). Handbook of Statistics. Geneva, Switzerland.

University of Maryland National Consortium for the Study of Terrorism and Responses to Terrorism (2019). Global Terrorism Database. University of Maryland at College Park, USA.

Weitzman, M. (1974). Prices versus Quantities. *Review of Economic Studies*, 41, 477-491.

Winnes, H., L. Styhre and E. Fridell (2015). Reducing GHG emissions from ships in port areas. *Research in Transportation Business & Management* 17, 73–82.