FONDATION POUR LES ÉTUDES ET RECHERCHES SUR LE DÉVELOPPEMENT INTERNATIONAL

Working Paper 340 April 2024 Development Policies

Navigating international taxation: the effects of a carbon levy on shipping

Vianney Dequiedt, Audrey-Anne De Ubeda,
Édouard Mien

Vianney Dequiedt, FERDI and Université Clermont Auvergne, CNRS, IRD, CERDI, Clermont-Ferrand, France.

Audrey-Anne De Ubeda, FERDI, Clermont-Ferrand, France.

Édouard Mien, FERDI, Clermont-Ferrand, France.

Abstract

This paper quantifies the effects of a hypothetical $40 per ton of CO2 tax on maritime transport implemented worldwide. Calculations are based on trade data covering the 2012-2018 period for 185 countries and on a multisector structural gravity model designed to isolate seaborne trade and to incorporate marine fuel price in trade cost variables. We focus on the effects of the tax on 2018 trade flows at a disaggregated HS2 sector level. …/…

JEL: F18, F64, Q56, H87.
Keywords: international trade, maritime transport, carbon tax, structural gravity.

Acknowledgements: The authors are grateful to Simone Bertoli, Céline Carrère, Jaime De Melo, Patrick Guillaumont, Gianluca Orefice and Thomas Zylkin for helpful discussions, and to Issakha Thiam for excellent research assistance. They acknowledge the support received from the Agence Nationale de la Recherche of the French government through the program France 2030 (ANR-16-IDEX-0001). The usual disclaimers apply.

LA FERDI EST UNE FONDATION RECONNUE D'UTILITÉ PUBLIQUE.
CETTE PUBLICATION A BÉNÉFICIÉ D'UNE AIDE DE L'ÉTAT FRANÇAIS AU TITRE
DU PLAN D'INVESTISSEMENT FRANCE 2030 PORTANT LA RÉFÉRENCE ANR-16-IDEX-0001.

.../... The counterfactual analysis estimates an average national purchasing power loss of 0.73% on tradables, corresponding to a global economic cost of 166 billion dollars. While OECD countries would lose on average 0.37% of purchasing power, Least Developed countries would lose on average 1.11% highlighting the inequitable distribution of effects. Such a tax, representing 29% of the baseline price, would reduce the emissions from maritime transport by approximately 1.75%, but its impact on global carbon emissions would be offset by the redirection of trade flows towards more carbon intensive transport modes such as air or road. Finally, the tax revenue is estimated in a range from 19.6 to 59.5 billion dollars, much lower than the economic cost resulting from the effects of the tax on trade.

1 Introduction

At the confluence of the climate and development agendas, international taxation of maritime transport is a longstanding issue that has garnered significant attention in current international discussions. Pressured by the international community, the International Maritime Organization mentions the introduction of a greenhouse gas emissions pricing mechanism for the maritime sector in its revised strategy adopted in 2023 as a possible measure to reduce emissions in the medium term.[1] The launch of a task force on international taxation[2] by Antigua and Barbuda, Barbados, France, Kenya and Spain, announced during COP28 in Dubai has also given new political impetus to the maritime carbon taxation project. Many developing countries, including Small Island Developing States (SIDS), advocate for the adoption of a carbon tax on maritime transport. As an example, Fiji, a country that is particularly vulnerable to the impacts of climate change, has called for stronger action to address emissions from maritime transport and supports the adoption of a carbon tax as part of a comprehensive strategy to combat climate change. This stance might appear counter-intuitive from an economic point of view, considering that any rise in maritime transport costs would disproportionately impact states, such as most SIDS, which heavily rely on long-distance maritime transport for their economic activities.

Our objective in this paper is to provide quantitative inputs to these international discussions, to document how much countries would be impacted by a possible carbon tax on maritime transport and to analyze its potential effect on carbon emissions. Since maritime transport is essentially the transport of material goods, we focus on the effect of the tax on international trade flows. We do not discuss what should be done with the tax proceeds and we do not explicitly model the environmental externalities induced by carbon emissions. We consider a carbon levy on maritime transport that is implemented independently of carbon taxation of other international transport modes since this corresponds to the status of current international discussions that treat maritime and aviation carbon taxes almost separately and generally restrict a potential aviation tax to passengers transportation. We base our simulations on panel data covering bilateral trade flows at the HS2 level of disaggregation for 185 countries over the period 2012-2018. We develop a multisector structural gravity model that isolates seaborne trade and incorporates marine fuel costs as a component of bilateral trade costs. We analyse the effects of a maritime transport carbon levy if it were implemented in 2018 by scrutinizing the general equilibrium impacts of an increase in fuel price that year.

Our main results highlight that on average poorer countries would be more negatively impacted than richer ones since both welfare losses and national consumer price index increases are negatively correlated with GDP per capita. More specifically, assuming a 40$ per ton of CO_2 carbon levy, we estimate that on average OECD countries will bear a 0.37% purchasing power (i.e. welfare) loss on tradables while Least Developed Countries will be subject to a 1.11% purchasing power loss.[3] This certainly is an inequitable pattern of differentiated effects that we can attribute both to the

---

[1] `https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/annex/MEPC80/Annex15.pdf`.

[2] `https://www.elysee.fr/admin/upload/default/0001/15/91b013291db03bcc5f2f6b84de39a81ae0c04c7d.pdf`.

[3] These figures correspond to simple averages.

remoteness of least developed countries from the world markets but also to their specific import and export baskets composition. Beyond this aggregate effect on welfare, our structural approach allows us to document the effect of a carbon tax on all bilateral trade flows and how it would affect the whole geography of trade. We estimate that the average distance traveled at sea by 1$ of merchandise would be reduced by 2.59% with the tax, leading to a reduction in maritime transport carbon emissions of 1.75% approximately. Because maritime trade is less carbon intensive than other modes such as road or air, and because a carbon tax on marine fuel would redirect some trade flows towards those more carbon intensive transport modes, the overall effect of the tax on global carbon emissions from trade is more modest and estimated between -0.72% to $+0.12\%$. Finally, we also compute the tax potential. Carbon intensity largely depends on the type and size of vessels which are difficult to assess with precision, so we provide the results as a range of estimates between 19.6 and 59.5 billion dollars. This revenue should be compared to the economic cost related to the effects of the tax on trade which we estimate at 166 billion dollars worldwide. Taken together, our results suggest that it is difficult to justify a tax on international shipping on fairness, efficiency or Pigouvian grounds.

Internationally, material goods are transported by air, train, road or sea. Seaborne trade is largely dominant in volume, but not that much in value. Unfortunately, accurate data on transport mode is scarce and an important aspect of our analysis relates to how we deal with the absence of disaggregated data on maritime transport with worldwide coverage. Isolating maritime trade is crucial in order to assess the effect of a tax that would increase the price of marine fuel without impacting the price of other transport mode fuels. Indeed, the world has no experience of such a tax and we need to rely on variations in marine fuel price to conduct a counterfactual analysis. But prices of diverse types of fuel have been highly correlated in the past, raising the concern that what we capture is the effect of a broader increase in the costs associated to all modes of transport. We tackle this issue by isolating seaborne trade flows and by ensuring that in our model the tax only affects trade costs for these flows.

In a first step we analyse U.S. trade data at the HS6 level to identify goods that are (sufficiently) or are not (sufficiently) traded by sea. We use this information to spot "maritime" and "non-maritime" goods on worldwide bilateral trade data. We aggregate worldwide flows of "maritime" HS6 goods at the HS2 level, while we regroup all identified "non-maritime" HS6 goods in a single additional "non-maritime" sector. Then we estimate a panel gravity system of equations in which maritime transport costs is captured by a multiplicative variable $Sea\ Distance_{ij} \times Marine\ fuel\ price_t$ which value is dyadic (country pair ij) and time (year t) specific. We estimate one equation for each sector and allow the partial equilibrium elasticities of trade with respect to transport costs to be sector specific in order to account for different value-to-volume or value-to-weight ratios as well as different types of vessels with different fuel consumption carrying different types of goods. Those elasticities indeed take values ranging from -0.92 to -0.02 with a somewhat bimodal distribution exhibiting peaks both around -0.60 and -0.30 therefore justifying our analysis at a disaggregated (HS2) level.

To simulate the effect of a marine fuel tax, we perform a rigorous comparative statics exercise and compute the counterfactual equilibrium in a structural Armington-type gravity model that matches the estimated gravity equation. This is done by assuming that the effect of the tax is the same as the effect of a counterfactual increase in marine fuel price. We also develop an algorithm that computes general equilibrium effects in Armington-type multisector gravity models and fully takes into account the interdependencies across sectors. This algorithm produces variations in welfare as well as variations in consumer price indices as outputs which allow us to rank countries according to the impact of the tax on their consumers' purchasing power as well as on price increases.

With our model we recover all counterfactual trade flows. We can then analyse how the tax would reduce the distance traveled by goods and would reorganize the geography of trade in each sector. The reduction in average distance is a key parameter that we use to compute the tax potential, i.e. the expected revenue from the marine fuel carbon tax. We also use those counterfactual trade flows to estimate what could be the reduction in carbon emissions. This is done by converting trade flows in value into sectoral transport volumes measured in ton.kilometers and applying sector-specific carbon intensity factors to compute global emissions related to international trade.

Our main contributions are the following. We contribute to the literature on transportation costs by proposing a parsimonious approach to isolate maritime trade and estimate the elasticities of trade with respect to marine fuel cost. We also contribute to the literature on carbon taxation by providing a structural analysis of an international carbon tax on maritime transport and estimating its fiscal potential, its economic cost and its impact on carbon emissions. We further contribute to the literature on multisector structural gravity models by providing a suitable algorithm to perform a general equilibrium analysis and recover all counterfactual trade flows at the HS2 level for 185 countries including least developed countries and small island developing states. Finally, we transparently inform the current policy debate on an international tax on maritime transport by conducing our analysis with publicly available data only.

We review the relevant literature and some stylized facts about maritime transport in section 2. Data sources are presented in section 3 where we also set forth the preliminary analysis performed on U.S. trade data and construct our baseline sample. Estimation of the system of gravity equations is the subject of section 4. Section 5 is devoted to the counterfactual analysis and to the presentation of our main results about the differentiated effects of the tax. Section 6 offers additional results about the geography of trade, tax potential and reduction in carbon emissions. A detailed presentation of dataset construction is provided in Appendix A. The multisector structural gravity model underlying our empirical approach and the computation of its counterfactual equilibrium is postponed to Appendix B. Additional Tables and Figures are grouped in Appendix C.

2 Literature review and stylized facts

2.1 Transportation costs, seaborne trade and carbon taxation

Hummels (2007, [31]) investigates the role of transportation costs for explaining international trade patterns. Over the period 1974-2004, he finds that the average elasticity of transportation costs with respect to freight costs is much higher in ocean trade (ranging from 0.23 to 0.33) than in air trade (ranging from 0.06 to 0.26). Hummels and Schaur (2013, [32]) discuss the role of transportation duration on trade. In particular, they argue that time enters the mode choice decision of firms engaged in international trade as an additional cost, leading to a trade-off between fast but expensive air transport and slow but cheaper ocean transport. Since the optimal mode of transportation for a given product is determined by comparing the direct cost of transportation and the cost of time, a change in the cost of ocean transportation will have different effects on different products depending on their time sensitivity. More recently, Brancaccio et al. (2020, [12]; 2023, [13]) apply a structural gravity model of trade to investigate the impact of oil price shocks on maritime transport costs, using gains and losses in maritime fuel efficiency as the main explanatory variable. Due to data limitations, however, their study is restricted to bulk shipping. These authors find fuel cost elasticities ranging from 0.1 to 1.2, with an average of about 0.35, very similar to the average partial equilibrium elasticity of 0.35 that we obtain in section 4.2 below.

A growing strand of literature attempts to simulate the effects of a global tax on marine fuel and understand its impact on trade flows, CO_2 emissions and/or welfare (see for instance Parry et al., 2018, [42]; Sheng et al., 2018, [47]). Some articles in this strand are based on a gravity model of international trade. Mundaca et al. (2021, [40]) estimate the impact of carbon taxation on the combination of trade volumes and the average distance these products travel. Based on data for 2009-2017 and distinguishing between different types of industries, they find that a tax of 40$ per ton of CO_2 would lead to an average reduction in CO_2 emissions of almost 8% compared to the "business as usual" scenario. Cariou et al. (2023, [16]) also use a gravity model of trade to examine the impact of a carbon tax on trade volumes and carbon emissions. They focus on trade in grain and soybeans for a limited dataset of 36 grain exporters, 25 soybean exporters, and 84 importing countries for the year 2016. They find moderate impacts of a $50 per ton CO_2 tax, ranging from almost zero to a reduction in total exports of about 4%, depending on the ability of shipowners to pass on the tax to final consumers. By restricting the analysis to partial equilibrium elasticities, these two studies miss the potential effect of a carbon tax on the multilateral resistances to trade and are likely to overestimate the effects of the tax.

Shapiro (2016, [45]) is the closest paper to ours. It is one of the few articles to develop a structural gravity model of trade to study carbon taxation. Specifically, he uses a modified version of the Armington model to estimate the potential impact of global or regional carbon taxation on CO_2 emissions and welfare, using data for 128 countries and 13 sectors. Three counterfactuals are studied including a E.U. tax on air transport, a U.S. tax on all transport modes and a global tax on air and sea transport. The estimates conclude that a global carbon tax of 29$ per metric ton of CO_2 would result in a welfare loss from trade of about -6.5%, with largely heterogeneous effects across regions. It is one of the early works that highlight the uneven distribution of the effects of carbon taxation and the disproportionate impact on poor countries. We go beyond this paper by using different, more recent and publicly available datasets which allow us to estimate the trade elasticities on a much larger sample. We also compute all counterfactual flows and not only welfare and price statistics so that we are able to analyse the counterfactual geography of trade, tax revenue and carbon emissions at a disaggregated level. Finally, we isolate the effect of a worldwide tax on maritime transport only and therefore focus on what is plausibly a more accessible policy target in the current international negotiations.

2.2 Comparative statics in structural gravity models

Following seminal works by Anderson and van Wincoop (2003, [3]) and Eaton and Kortum (2002, [23]) that provide structural foundations for the gravity equation, many authors have performed compelling comparative static exercises to evaluate the effects of policy measures that impact bilateral trade costs. As detailed by Head and Mayer (2014, [29]) this type of exercise must go beyond looking at partial equilibrium elasticities given by estimated coefficients in the gravity equation and take fully into account the effect of the policy on the multilateral resistances to trade. Comparative statics exercises usually follow Dekle et al. (2007, [21]; 2008, [22]) who show how in these gravity models many useful statistics can be expressed in a simple way as functions of ratio variables (counterfactual value over baseline value) without having to recover all the structural parameters of the model. Different packages have been developed to estimate general equilibrium effects in a large class of gravity models via simple fixed point algorithms. Anderson et al. (2018, [2]) developed the *GEPPML* procedure while Baier et al. (2019, [8]) developed the *ge_gravity* package. A *gegravity* package has also been developed by Herman (2021, [30]). All these packages are suited for one-sector models only and we go beyond these by developing a program adapted to multisector models. Such a program is based on a multisector general equilibrium model similar to the one developed by Shapiro (2016, [45]; 2021, [46]).

2.3 Maritime transport - stylized facts

In 2018-2019, 11 billion tons of merchandise were internationally traded via maritime transport (UNCTAD, 2020 [48]). This volume has been steadily increasing until the Covid-19 crisis, almost doubling from 6 billion tons in 2000. According to the International Chamber of Shipping, a professional organization, these maritime flows amounted to 14 trillion U.S.$ in 2019, representing approximately 74% of all international trade flows in value[4]. However, the accuracy and source of this estimate remains unclear. Indeed, despite the importance of the previous figures, detailed information on the value of seaborne trade is scarce and available at a disaggregated level only for a very limited number of countries and rarely over long periods of time. According to U.S. Census data, before the Covid-19 crisis, seaborne trade represented about 45% of the total value of U.S. imports and 35% of their exports. For the European Union, seaborne trade during the same period represented slightly more than 45% of its external trade (with non-E.U. members) in value, but about 75% in volume[5].

For non-adjacent countries, trade usually occurs via maritime or air transport. Feyrer (2019, [25]) or Hummels and Schaur (2013, [32]) describe the choice between those two alternative modes as a trade-off between diverse efficiency parameters and the value of time to final consumers.

---

[4] `https://www.ics-shipping.org/shipping-fact/shipping-and-world-trade-driving-prosperity/`

[5] `https://www.emsa.europa.eu/eumaritimeprofile`

When buyers and sellers attach great value to fast delivery, air transport is an attractive option. In particular, Hummels ad Schaur estimate for the U.S. that each additional day in transit costs the equivalent of an ad-valorem tariff ranging from 0.6% to 2.1%. As a consequence, air transport has become prominent for high-value perishable products as well as for parts and components in supply chains. This explains why the share of air transportation in total international flows is usually much higher in value than in volume. Maritime transport costs encompass various components that are extensively discussed in the literature (see for instance Hummels, 2007 [31]; Rojon et al., 2021 [43]; or Ardelean et al., 2022 [5]). They result from the combination of (*i*) ship running costs, including operating costs (crew, consumables, insurance), fuel costs (which represent approximately 50 percent[6] of these ship running costs) and capital costs, (*ii*) costs related to port infrastructures, including cargo handling costs in ports, port infrastructure performance, customs efficiency, all determining time in port, and (*iii*) market specific factors including margins due to market power on the supply and demand sides. Among these, fuel costs are roughly proportional to distance, some costs are specific to destination or origin (e.g. port infrastructure performance, customs efficiency), while others are product specific (e.g. price margins).

Characteristics of maritime trade are heterogeneous across products. More precisely, ocean shipping can be divided into broad categories according to the type of vessels used for transportation. Tankers carry crude oil, liquid gas and other chemicals; bulk carriers are used for dry bulk cargo such as grains, iron ore, cement, or coal; while container ships carry most consumer goods. In 2019, tankers transported approximately 3 billion tons of liquids while dry cargo, regrouping the two other categories, represent approximately 8 billion tons. Each type of vessel possesses its own technical characteristics including the level of fuel consumption and the markets corresponding to the above three categories of ocean shipping present very distinct organizational structures, as documented by Hummels (2007, [31]). In addition, products differ by the distance they travel at sea. In 2019, grains travel on average 7000 nautical miles, other dry bulk travel on average 5000 nautical miles while containers travel on average 4700 nautical miles and oil products on average 4300 nautical miles (UNCTAD, 2023 [49]).[7] These figures suggest that the impact of a carbon taxation scheme on maritime fuel is likely to be heterogeneous across goods and therefore heterogeneous across HS2 sectors.

3 Data and preliminary analysis

3.1 Data sources

For the purpose of this research we gather publicly available data from diverse sources. Data on trade flows come from the BACI database provided by the CEPII (Gaulier and Zignago, 2010 [27]) that describes harmonized bilateral trade flows at the HS6 product level among 226 countries and territories. From this, we only keep data for 185 independent countries. We use a set of control

---

[6] `https://maritime-professionals.com/will-shipping-costs-ever-drop/`

[7] Our own estimates of average distance computed from BACI data are lower presumably because we average over all flows including some terrestrial flows with neighbors, see Table C.2 in Appendix C.

variables that are common in the international trade literature and that we obtain from the CEPII gravity dataset (Conte et al., 2022 [17]). We also complement information on international trade flows with intranational trade data from the Trade and Production dataset (Mayer et al., 2023 [37]).

The maritime distance variable comes from the CERDI-Seadistance database (Bertoli et al., 2016 [11]). To construct this variable, each country has been assigned a port of reference (or two different ports for countries with access to two different seas / oceans), and maritime distance between the ports of references have been assigned as the measure of maritime distance between countries. For landlocked countries, the port of reference is defined as the foreign port with the shortest road distance to its capital city.

Marine fuel prices come from the French National Institute of Statistics and Economic Studies (INSEE). They correspond to the average annual price of maritime fuel in the European port of Rotterdam. Even though the price of maritime fuel can vary across ports and regions, it is very likely that its variations over time are common to all regions and therefore that the variations of the Rotterdam price are a good proxy for the variations of global prices.

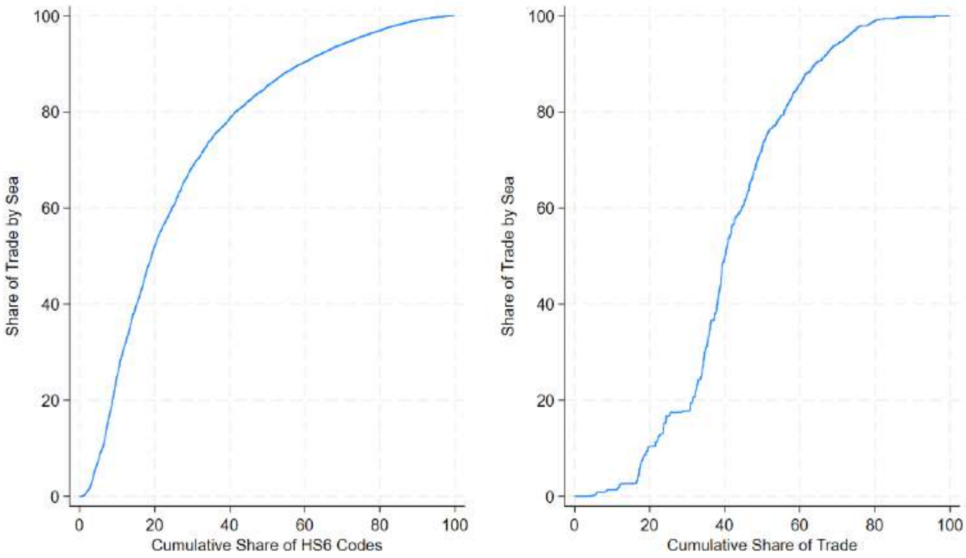
The remoteness and landlockedness measure in the Economic Vulnerability Indicators is retrieved from UN Department of Economic and Social Affairs. Other remoteness indicators will be computed from the BACI dataset. Data on GDP per capita are from the World Bank's world development indicators. Sector-level trade elasticities are from Fontagné et al. (2022, [26]). Carbon intensities of different type of transport mode are from the French Ministry of Ecological Transition (2018, [38]). Finally we also analyse U.S. trade data made available by the U.S. Census Bureau.

3.2 U.S. maritime trade flows

In order to study the impact of a maritime fuel tax on international trade flows it is crucial to be able to track seaborne trade. Unfortunately, there is no complete database of international maritime trade flows at the sectoral level. With a view to establishing for each product whether it is more likely to be transported by sea or by other transportation routes such as air, railway or road, we exploit U.S. trade data provided by the U.S. Census Bureau. These data cover, at the HS6-digit level of disaggregation, all bilateral export flows from and all bilateral import flows to the United States, and document the value share of air and sea transport for each flow. Thus, for each U.S. trading partner and for each commodity, we gather information on the sum all U.S. exports and imports over the period 2012-2018 (ending up with a cross-sectional dataset) and can extract the relative value of seaborne trade.

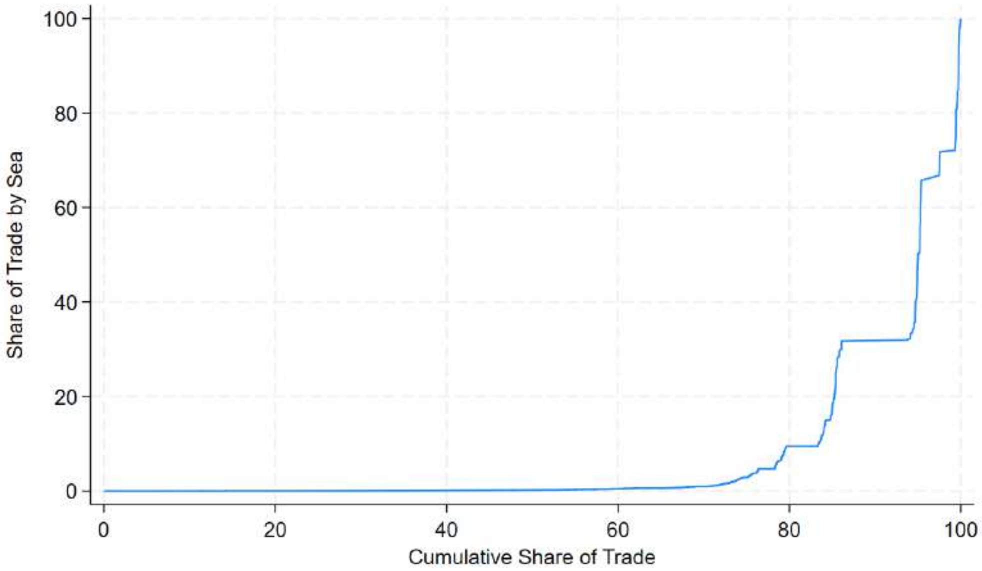
In 2018, total U.S. imports from the rest of the world amounted to \$2.54 trillion, while U.S. exports amounted to \$1.67 trillion, making it the world's second exporter and first importer. U.S. trade appears to be concentrated in a small number of products as for the period 2012-2018 10% of HS6-digit products account for about 80% of total U.S. trade in value. Over that same period, maritime flows accounted for 48% of all U.S. imports and 35% of exports. However, non-maritime flows include both air (to and from the rest of the world) and land (rail and road) transportation, mostly to and from Canada and Mexico. If trade flows with Canada and Mexico are excluded, maritime flows account for 62% of U.S. imports and 50% of exports, with the remainder consisting mainly of air trade. In Figure 1, on the left graph, we plot for each HS6 code the share of maritime trade in total trade (excluding Canada and Mexico), where trade is calculated as the sum of exports and imports, and where the HS6 codes are ordered from "least maritime" to "most maritime". In the graph on the right, we draw a similar curve, but with the width of the HS6 codes proportional to their flow value. In this latter graph, we can read on the horizontal axis the proportion of trade (in value) for which the share of maritime trade in total trade, measured at HS6 level, does not exceed the percentage read on the vertical axis. It is clear from these two curves that the mode mix can be very different from one HS6 product category to another. Looking at the data and to give just a few examples, petroleum gases, grain, gypsum or automobiles are traded almost exclusively by sea, while cut flowers, electronic integrated circuits or diamonds are traded almost exclusively by air. The general shape of the right-hand side curve and its steepness at intermediate percentiles illustrate the fact that at HS6 level and for most goods, trade is either largely seaborne or largely not seaborne. The steepness of the left-hand side curve is less pronounced, implying that U.S. trade for HS6 codes in the middle percentile range is less important in value terms than U.S. trade for HS6 codes in the low or high percentile ranges. These characteristics suggest a separating property with respect to mode choice and are used below to identify maritime trade.

Figure 1: Shares of U.S. seaborne trade excl. Canada and Mexico (in value, 2012-2018)



If we focus on trade with neighboring countries with which the U.S. shares a common land border, i.e. trade with Canada and Mexico, a very different picture emerges. Exports to Canada and Mexico together accounted for about 34% of total U.S. exports between 2012 and 2018, while imports from Canada and Mexico accounted for 27% of total U.S. imports. Trade with these two countries is primarily overland. In fact, seaborne exports accounted for 8.6% of total exports to Canada and Mexico over our period, while seaborne imports accounted for 7.3% of total imports from Canada and Mexico. This is consistent with calculations by Hummels (2007,[31]), who emphasized that about a quarter of the world's trade by value is between countries that share a common land border, and that less than 10 percent of trade with neighbors is by air or sea. Figure 2 provides a graph similar to the right-hand side graph in Figure 1, but restricted to trade flows with Canada and Mexico. The shape of the curves is completely different between the two Figures. Restricting attention to trade with Canada and Mexico, it can be seen that for HS6 codes that account for 70% of the value of trade with these two countries, maritime transport is negligible and that HS6 codes for which the share of maritime trade is higher than 60% account for no more than 5% of total trade in value.

Figure 2: Shares of U.S. seaborne trade with Canada and Mexico (average 2012-2018)



Certainly, U.S. trade is specific. The share of airborne trade observed in U.S. data is probably higher than for the vast majority of other countries, partly due to idiosyncrasies of the U.S. market, but also due to the composition of export and import baskets. U.S. international trade in goods is also largely unbalanced over the 2012-2018 period. In 2018 for instance, the U.S. exported $1.67 trillion of goods and imported $2.54 trillion, by far the largest trade deficit in the world. However, we are confident that the U.S. data provides useful information on the mode of transport that can be used to identify maritime trade out-of-sample, i.e. for all country pairs.

3.3 Isolating maritime trade

Based on the analysis of U.S. trade data, we spot seaborne trade by disregarding in the BACI data trade flows corresponding to HS6 codes for which U.S. trade data report a seaborne share of less than 60% of the total flow (excluding flows with Canada and Mexico). Alternative scenarios, obtained by considering a threshold of 70 or 50%, or by excluding intermediate and perishable products, based on the procedure proposed by Hummels and Schaur (2013, [32]) (hereafter referred to as the H&S procedure)[8] are also considered as robustness checks. In our baseline model (i.e., using the 60% threshold), seaborne trade discards 1264 products, which represent 24% of all HS6-digit level products. In comparison, it discards 981 products (19% of all products) with the 50% threshold, 1621 codes (31% of total) with the 70% threshold and 754 (14%) with the modified H&S procedure.

Our approach to selecting relevant trade flows aims to isolate maritime trade flows from global flows in a dataset that does not contain systematic information on transport mode. It also aims to be consistent with a structural gravity framework applied to sectoral data. The ability to exclude trade by modes other than maritime is important for our empirical analysis, in order to identify the effect of a marine fuel tax on bilateral trade flows. Indeed, in what follows we will use variations in fuel prices to mimic the effect of a tax. However, marine fuel prices are highly correlated with kerosene or diesel prices, which prevents us from including these other energy prices as controls in our estimations. Therefore, it is possible that a tax on marine fuel has an impact on air or road transport simply due to an omitted variable bias, leading to an overestimation of the effect of the tax if we keep global trade flows in our left-hand side variable. Our approach to the selection of relevant trade flows also aims at proposing a simple, sparing with data, yet convincing way to deal with the issue of mode choice by importers and exporters. It is based on the separation property mentioned above and on the idea that for many bilateral flows there is one mode of transport that is superior to the others, so that a tax on sea transport will not affect the choice of mode of transport for that good in that bilateral flow. Therefore, at the HS6 level and for a given pair of countries, we decide either to consider the entire flow as maritime or to consider the entire flow as non-maritime. In the general equilibrium comparative statics exercise that we perform below, all HS6 codes that are considered as non-maritime are aggregated into an additional sector whose transport costs will not be affected by the tax (see Appendix A for details). Bilateral flows between neighboring countries sharing a terrestrial border are mostly non-maritime. We come back later on how this is taken into account in our analysis.

3.4 Modified BACI dataset description

To construct the final dataset, we start with the BACI database at the HS6 level. We first isolate in a “non-maritime” category all bilateral flows corresponding to HS6 codes that do not comply with the 50, 60 or 70% threshold rule for maritime share on U.S. data as described above or corresponding to HS6 codes identified by the H&S procedure (different scenarios, 60% share being our baseline). Then we aggregate “maritime” trade flows at the HS2 sector level and aggregate all “non-maritime” trade flows in a single additional sector. Descriptive statistics of the BACI

---

[8] The procedure implemented by Hummels and Schaur consists in identifying product descriptions at HS10 level containing the words “fresh”, “parts” and “components” and associating them with air transport. Although interesting, this methodology appears to be far too restrictive in its definition of non-maritime flows and is likely to lead to an overestimation of the share of maritime flows in total international trade flows. In the following, and when referring to the H&S procedure, we apply a similar methodology using the description at the HS6 level, but with the exclusion from maritime flows of products whose description contains the words “frozen”, “live”, “edible” and “medicinal” in addition to “fresh”, “parts” and “components”. Therefore, we analyze the descriptions at the HS6 level, and if one of the seven keywords is detected, we consider the corresponding flows as non-maritime.

Table 1: Modified dataset descriptive statistics

Variable	Unit	Obs.	Mean	Std. Dev.	Min.	Max.	Source
Total Flows	1,000 USD	22,999,200	19,921	2,338,679	0	2.30e+09	CEPII
Maritime Flows (>50%)	1,000 USD	22,999,200	16,048	1,918,369	0	1.77e+09	CEPII + Auth.
Maritime Flows (>60%)	1,000 USD	22,999,200	15,342	1,848,347	0	1.77e+09	CEPII + Auth.
Maritime Flows (>70%)	1,000 USD	22,999,200	14,606	1,794,767	0	1.76e+09	CEPII + Auth.
Maritime Flows (H&S)	1,000 USD	22,999,200	16,852	2,092,543	0	2.06e+09	CEPII + Auth.
Fuel Price (1.0% sulph.)	USD/ton	7	450	155	240	664	INSEE
Fuel Price (3.5% sulph.)	USD/ton	7	400	155	193	613	INSEE
Seadistance	km	34,225	10,069	5,385	0	23,247	CERDI
Border	Binary	34,225	0.02	0.15	0	1	CEPII
Language	Binary	34,225	0.15	0.36	0	1	CEPII
Colonization	Binary	34,225	0.01	0.11	0	1	CEPII
FTA	Binary	239,575	0.16	0.36	0	1	CEPII
Custom	Binary	239,575	0.05	0.21	0	1	CEPII
EU	Binary	239,575	0.02	0.15	0	1	CEPII
WTO	Binary	239,575	0.67	0.47	0	1	CEPII
Home	Binary	239,575	0.01	0.07	0	1	Authors

Table 2: Spotted international flows descriptive statistics

Variable	Global International Flows 2012-2018 (1,000 USD)	% of Total Flows	% of non-Zero Flow
Total Flows	4.58e+11	100%	22%
Y_{50}	3.69e+11	81%	20%
Y_{60}	3.53e+11	77%	20%
Y_{70}	3.36e+11	73%	19%
$Y_{H\&S}$	3.87e+11	84%	21%

database adjusted by elimination of non-maritime trade flows are presented in Table 1 at the HS2 level.

We detail in Table 2 the value share of worldwide trade that is considered as maritime[9] in our different scenarios. This share is 69% in our baseline, and ranges from 84% (H&S procedure) to 65% (in the case of a more restrictive 70% threshold). We also report in Table 2 the share of non-zero flows in our different scenarios. While it is logically lower than in the BACI database with total flows, the percentage of non-zero flows does not decrease too much because we aggregate flows at the HS2 level.

3.5 Computing intra-national trade flows

The structural gravity approach that we adopt in this paper requires information on all bilateral trade flows to provide unbiased estimates, including flows from one country to itself, i.e. intranational trade flows. To our knowledge, there are currently two main databases available on intranational trade flows: The International Trade and Production Database for Estimation (ITPD-E) from the United States International Trade Commission, and the CEPII Trade and Production (Trade Prod) database (Mayer et al., 2023 [37]). We use the latter for two reasons. First, while available

---

[9] Notice that “maritime” trade flows are not necessarily seaborne since they are defined at the HS6 level and include flows between neighbors which are unlikely to be seaborne. In fact, “maritime” trade is the complementary set of “non maritime” trade which corresponds to HS6 codes for which trade is assumed to be never seaborne.

at a much more disaggregated level, the ITPD-E database has many missing observations for intranational trade. Second, trade data are often treated to deal with differences in mirror data (when trade outflows reported by the exporting country do not match with trade inflows reported by the importing countries) and to avoid double counting of trade flows arising from re-exports. As our main international trade database comes from the CEPII, we prefer to use intranational trade estimations from the same institution to ensure a comparability of treatment across the two datasets.

However, the Trade Prod database also suffers from some limitations. In particular, to avoid having missing observations, intranational flows are estimated at an aggregate industry level, much coarser than the HS2-digit classification. To estimate intranational trade flows at the HS2-digit level, we therefore proceed as follows (more details are given in Appendix A.3) :

i) for each industry in the Trade Prod database, year and exporting country, we compute the ratio of intra- to international trade flows (i.e. we calculate the ratio of production oriented toward domestic consumption over exports),[10]

ii) for each product at the HS2-digit level, we associate a specific industry in the Trade Prod classification (see Table A.3 in Appendix A.3),

iii) we attribute to each product of the HS2 classification the intra- to international trade ratio of the aggregated industry it has been associated to and compute the intranational flow from the international flow accordingly.

Another limitation is that for 45 countries of the sample, individual data for intranational trade are not available. In the Trade Prod Database, these countries are classified as “Rest of the World” (see Table A.2 in Appendix A.3 for a list of these countries). In that case, we implement the same steps as described above for the “Rest of the World” category and attribute to each country the ratios associated with this category.

3.6 Sea distance and marine fuel price

Our main variable of interest, the trade costs, will be precisely defined below in section 4. It is computed from the product of the maritime distance between the two trading countries and the price of marine fuel.

The maritime distance between two countries is extracted from the CERDI-SeaDistance database (Bertoli et al., 2016 [11]). In this dataset, there is only one reference port for each country in the world, unless the country has access to different seas/oceans, in which case the country has a reference port in each sea/ocean it has access to. The sea distance variable measures the bilateral sea distance between each country’s port of reference (or between the two nearest ports of reference if a country has more than one port of reference). If a country is landlocked, its reference port is the foreign port closest to its capital. Therefore, two countries can have a sea distance equal to 0

---

[10] There are a few countries for which one or several years of inter- and/or intra-national trade data are missing. We detail in Appendix A.3 how we reconstruct the missing ratios based on the years for which data are available.

if (i) they are both landlocked and share the same port of reference (located in a third country), or (ii) one country is landlocked and its port of reference is located in the other country. In either case, trade between the two countries is most likely to take place by land. For example, Botswana and Lesotho are both landlocked and their port of reference is in South Africa: therefore, the sea distance is zero for the pairs Botswana-South Africa, Lesotho-South Africa and Botswana-Lesotho. Importantly, since trade between two neighboring countries is likely not to be seaborne, we modify the original SeaDistance variable by replacing it with zero for pairs of countries sharing a common terrestrial border. By doing so we ensure that trade costs between those two countries will not be directly impacted by a tax on marine fuel.[11]

Marine fuel prices are computed for each year in the sample by using data on the average price of heavy fuel oil in the port of Rotterdam from the French National Institute of Statistics (INSEE). Doing so is justified on the ground that variations in the price of heavy fuel oil in the port of Rotterdam are representative of variations in the price of heavy fuel oil in other areas of the world. Although this assumption is debatable, this variable is arguably a much better proxy for maritime trade costs than the use of crude oil prices, which is quite common in the literature. It should be noted that the price of fuel also depends on its sulfur content, which is subject to international regulations. Usual maximal sulphur contents are 1.0% and 3.5%. Before 2012, the maximum sulfur content allowed by international standards for marine fuel was 4.5%, but it was reduced to 3.5% in 2012 and then to 0.5% in 2020 (IMO 2020 regulation). Therefore, there has been no change in international regulations during our reference period (2012-2018). However, lower limits have been introduced in some regional areas, which means that different ships may use fuels with different sulfur content depending on their trade routes. The month-by-month evolutions of maritime fuel prices (both 1.0% and 3.5%) are plotted in Figure C.1 in Appendix C. Since the two prices, while distincts, are strongly correlated with a correlation coefficient superior to 0.99, we decide to focus on heavy maritime fuel at 1% sulphur only. Its price was on average equal to 441$ per metric ton over the period 2012-2019, ranging from 240$ in 2016 to 664$ in 2012.

4 Empirical analysis

4.1 Econometric specification

The empirical analysis is based on a gravity model which delivers sound theoretical foundations for studying international trade. Properly designed it will allow us to perform the comparative statics exercise needed to analyse the effects of a carbon tax on maritime trade. More precisely, our econometric specification is based on the Armington-Constant Elasticity of Substitution model (Armington, 1969 [6]; Anderson, 1979 [1]; Anderson and Van Wincoop, 2003 [3]) that provides a demand side structural justification for the gravity equation. Details on how to relate the different variables of interest in our gravity equation to structural parameters in the Armington model are given in Appendix B.

---

[11] This is admittedly an approximation since two countries sharing a terrestrial border may trade by sea as it is certainly the case e.g. for Peru and Brazil.

Because the effects of trade frictions due to transportation costs are likely to be sector specific, we conduct our empirical analysis at the sectoral HS2 level, exploiting the so-called *separability* property of structural gravity outlined for instance by Larch and Yotov (2016, [36]). We therefore estimate a panel gravity set of equations:

$$Y_{ijkt} = \exp\left[\beta_k C_{ijt} + \gamma_k . X_{ijt} + F_{ikt} + G_{jkt}\right] \epsilon_{ijkt} \tag{1}$$

where Y_{ijkt} is the value of exports of sector k goods, from exporting country i to importing country j, during year t. This variable is calculated at the HS2 level of aggregation from HS6 flows after the selection procedure described in section 3, i.e. Y_{ijkt} is the value of flows from country i to country j in year t for HS2 category k, once we remove the value of flows of HS6 codes that are considered as "non maritime" in this HS2 category.[12] For each sector k, estimation is performed on a squared dataset, i.e. including intranational flows Y_{iikt} as is required by the structural gravity model (see for instance Yotov et al., 2016 [50]). C_{ijt} is a maritime transport cost variable, X_{ijt} is a vector of control variables defined at the dyadic (importer-exporter) level, most of them, but not all, being time invariant. Its different components are detailed below. F_{ikt} and G_{jkt} are respectively exporter.product.year and importer.product.year fixed effects. With the inclusion of these latter fixed effects, our specification accounts for the effect of any factor that is country.product.year specific, which de facto includes factors that are country.year (e.g. GDP, efficiency of customs), country.product (e.g. structural characteristics of supply or demand) and product.year (e.g. world price) specific. Country.product.year specific factors include for instance cyclical characteristics of national supply and demand. These fixed effect, combined with a Poisson PML estimation (Gourieroux et al., 1984 [28]), also consistently account for the multilateral resistance indices pioneered by Anderson and van Wincoop (2003, [3]) (see Fally, 2015 [24] for details).

The maritime transport cost variable is defined as:

$$C_{ijt} = \ln(1 + SeaDist_{ij} \,.\, p_t) \tag{2}$$

where $SeaDist_{ij}$ is the maritime distance between country i and country j and p_t is the average price of heavy fuel oil in the port of Rotterdam in year t. This C_{ijt} variable does not cover all the aspects of maritime transportation costs detailed in section 2. It corresponds to ship running fuel costs and complements other types of costs already captured by the fixed effects in equation (1) such as port infrastructure performance or customs efficiency, transportation market structure and price margins. The cost variable C_{ijt} is independent of sector k but we allow for its effect on flows to be sector specific since the coefficients β_k can take different values for different sectors k. This is an important aspect of our analysis as products in different sectors may be characterized by different value-to-weight or value-to-volume ratios, be transported by different types of vessels with different fuel consumptions. Therefore, even after controlling for the distance traveled, the impact of ship running fuel costs on trading flows is expected to be product specific.

---

[12] For later use, we regroup all non-maritime trade flows in an additional sector that will become important in next section but for which we do not need to perform the estimation of a gravity equation.

Using $SeaDist_{ij}$, the maritime distance, instead of the geodesic distance between capitals or centroids of economic activity in the different countries, for the definition of C_{ijt} in equation (2) is important in order to capture the effect of maritime transport costs on trade flows. With the formula above, we also guarantee that the fuel price p_t has no impact on trade costs when $SeaDist_{ij}$ is equal to zero which is a desirable property because $SeaDist_{ij} = 0$ in our sample whenever trade between country i and country j is considered not to be seaborne.

For the vector of control variables X_{ijt} we follow standard approaches in the trade literature (see for instance Yotov et al., 2016 [50], or de Sousa et al., 2012 [20]) and include in the vector X_{ijt} the following variables, most of them obtained from the CEPII dataset ([17]):

- $Border_{i,j}$: Binary variable equal to 1 if the exporting and the importing country share a common terrestrial border ("contig"). We modify this variable so that this variable equals 1 for countries sharing a common port of reference in the Seadistance database (i.e. countries with Seadistance = 0), even if they do not share a terrestrial border.
- $Language_{i,j}$: Binary variable equal to 1 if the exporting and the importing country share a common language spoken by at least 9% of the population (variable "comlang_ethno").
- $Colonization_{i,j}$: Binary variable equal to 1 if the exporting and the importing country have been a pair in a colonial relationship post-1945 ("col45").
- $Custom_{i,j,t}$: Binary variable equal to 1 if the exporting and the importing country are engaged in a common Custom Union (based on "rta_type") in year t.
- $FTA_{i,j,t}$: Binary variable equal to 1 if the exporting and the importing country are engaged in a common Custom Union or a Free Trade Agreement (based on "rta_type") in year t.
- $EU_{i,j,t}$: Binary variable equal to 1 if the exporting and the importing country are both members of the European Union ("eu") in year t.
- $WTO_{i,j,t}$: Binary variable equal to 1 if the exporting and the importing country are both members of the World Trade Organization ("wto") in year t.
- $Home_{i,j}$: Binary variable equal to 1 for intranational trade flows (if $i = j$).

We set $Border$, $Language$, $Colonization$, $Custom$, and FTA to 1 and $SeaDist$ to 0 for intranational trade flows.

4.2 Estimation by sector and partial equilibrium elasticities

The system of gravity equations (1) is estimated with Poisson Pseudo Maximum Likelihood (PPML) with country-year fixed effects, as proposed by Santos Silva and Tenreyro (2006, [44]). Indeed, PPML estimators have been proven to perform much better than ordinary least-squares (OLS) estimates for structural gravity models because of two main reasons. First, PPML is a way to estimate the model in its multiplicative form, and does not require a logarithmic transformation of the outcome, contrary to OLS estimates. Second, PPML estimations appear to be more robust to heteroscedasticity biases arising from the log-linear transformation of the gravity equation. Therefore, PPML methods have been proven to be more efficient than OLS estimators when the share of zeros is large (Yotov et al., 2016, [50]). Table 3 provides summary statistics for the coefficients of the different components of trade costs, i.e. maritime transport cost and control variables. Table 4 describes in more details the partial equilibrium elasticities of trade with respect to our maritime cost variable C_{ijt}. The sectors are ranked from the most negative elasticity to the less one. In that Table, the last two columns report by sector the sum of the bilateral 2018 flows in our baseline scenario (Y_{60}), i.e. once HS6 flows that are considered as non-maritime are removed, and the 2018 total value of trade (Y_{tot}), i.e. if we keep all HS6 flows. For the first-ranked sector, live animals, we notice that Y_{60} represents less than one half of Y_{tot}, meaning that this sector is predominantly traded by non maritime transport modes. Cereals (HS2 code 10), coal, oil and gases (HS2 code 27) or iron and steel (HS2 code 72) are mostly traded via maritime transport mode, represent a large volume of trade (in value) and exhibit among the most negative partial equilibrium elasticities. Except for artwork (HS2 coded 97) for which we cannot compute elasticity since no trade is considered as maritime, all partial equilibrium elasticities are negative, as expected. The β_k are non significantly different from 0 at 5% in eight sectors. In section 5, these non-significant β_k will be replaced by zeros.

Table 3: Results of main PPML estimations

Variable	Min.	Max.	Mean	Median
Cost	-0.93	-0.02	-0.38	-0.39
Border	-9.77	0.57	-4.22	-4.37
Language	-1.12	1.49	0.56	0.58
Colonization	-1.39	1.79	0.33	0.42
FTA	-0.61	1.84	0.53	0.54
Custom	-0.37	3.28	1.03	0.92
EU	-2.49	5.95	0.02	0.08
WTO	0.16	6.26	2.22	2.06
Home	-0.21	3.85	1.81	1.85

Table 4: List of HS2 products, partial elasticities, maritime and total flows (1,000 USD)

HS2	Definition	β_k	Y_{60}	Y_{tot}
1	Live Animals	-0.9260***	5.94E+07	1.30E+08
26	Ores, Slag, Ashes and Residues	-0.6450***	8.05E+08	8.11E+08
7	Vegetables	-0.6202***	6.80E+08	7.98E+08
96	Brushes, Pens, and Lighters	-0.5978***	1.32E+08	1.42E+08
90	Optical Products	-0.5851***	4.22E+07	1.38E+09
10	Cereals	-0.5801***	1.09E+09	1.09E+09
27	Coal, Oil and Gases	-0.5427***	1.19E+10	1.23E+10
41	Hides, Skins and Leather	-0.5423***	3.47E+07	6.10E+07
35	Glues and Enzymes	-0.5294***	9.48E+07	1.25E+08
8	Fruits and Nuts	-0.5265***	1.12E+09	1.18E+09
33	Cosmetics and Perfumes	-0.5255***	2.91E+08	4.64E+08
79	Zinc	-0.5214***	6.66E+07	6.66E+07
29	Hydrocarbons, Alcohols, Ethers, and Similar Compounds	-0.5147***	1.56E+09	2.18E+09
72	Iron and Steel	-0.5126***	2.08E+09	2.10E+09
60	Knitted or Crocheted Fabrics	-0.5039***	8.06E+07	8.13E+07
6	Plants	-0.4980***	4.71E+07	1.21E+08

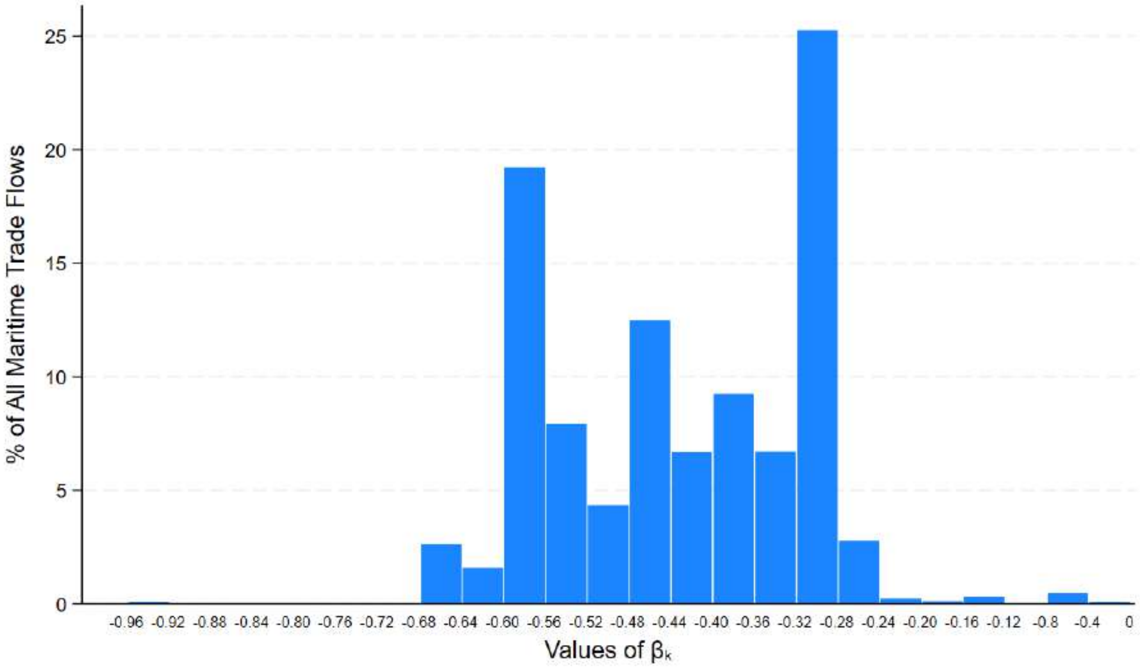
HS2	Definition	β_k	Y_{60}	Y_{tot}
68	Marble, Stones, Plaster, and Similar	-0.4879***	3.61E+08	4.25E+08
28	Gases, Acids, Oxides, and Similar Compounds	-0.4861***	6.94E+08	7.53E+08
25	Sands, Clays, and Minerals	-0.4842***	8.16E+08	8.17E+08
34	Soaps, Waxes, and Lubricating preparations	-0.4829***	2.47E+08	2.47E+08
32	Dyes and Paints	-0.4801***	3.16E+08	3.51E+08
51	Wool and Fabrics	-0.4760***	2.89E+07	4.37E+07
57	Carpets and Textile Floors	-0.4737***	3.89E+07	3.89E+07
23	Residues from Food Products	-0.4633***	7.05E+08	7.05E+08
47	Wood Pulp	-0.4630***	2.43E+08	2.43E+08
16	Meat and Fish Preparations	-0.4571***	6.20E+08	6.24E+08
78	Lead	-0.4556***	3.57E+07	3.72E+07
38	Chemicals	-0.4527***	6.98E+08	9.02E+08
11	Flour	-0.4495***	1.47E+08	1.48E+08
48	Paper	-0.4491***	7.32E+08	7.63E+08
39	Plastics	-0.4457***	2.53E+09	2.95E+09
61	Knitted or Crocheted Clothes	-0.4436***	5.00E+08	5.32E+08
74	Copper	-0.4431***	6.46E+08	6.59E+08
17	Sugars	-0.4418***	3.57E+08	3.57E+08
58	Other Ornemental Fabrics	-0.4377***	1.48E+07	2.60E+07
56	Nonwovens, Twine, Cordage or Rop	-0.4374***	6.04E+07	6.12E+07
19	Food Preparations of Flour	-0.4336***	5.11E+08	5.11E+08
15	Fats and Oils	-0.4268***	7.06E+08	7.08E+08
80	Tin	-0.4248***	1.62E+07	1.88E+07
64	Footwear	-0.4187***	3.47E+08	3.71E+08
2	Meat	-0.4161***	7.12E+08	7.13E+08
21	Sauces, Soups, Extracts, Essences and Concentrates	-0.4057***	6.62E+08	6.62E+08
14	Other Vegetable Products	-0.4006***	1.74E+07	1.74E+07
44	Wood	-0.3996***	6.01E+08	6.01E+08
22	Beverages	-0.3966***	7.69E+08	7.69E+08
20	Fruits and Vegetables Preparations	-0.3925	7.16E+08	7.16E+08
63	Other Linen	-0.3890***	1.79E+08	1.80E+08
70	Glass	-0.3854***	5.00E+08	6.00E+08
52	Coton Yarn and Fabrics	-0.3852***	1.21E+08	1.30E+08
66	Umbrellas	-0.3834***	9606367	9606367
46	Plaiting	-0.3795***	1.46E+07	1.46E+07
24	Tobacco	-0.3780***	3.14E+08	3.44E+08
94	Seats and Bedroom Furnitures	-0.3764***	6.46E+08	6.54E+08
31	Fertilizers	-0.3742***	3.65E+08	3.65E+08
37	Photographic and Cinematographic Products	-0.3712***	2.80E+07	6.64E+07
54	Synthetic Yarn and Synthetic Fabrics	-0.3702***	1.21E+08	1.28E+08
12	Seeds	-0.3664***	8.82E+08	9.68E+08
59	Textile products and articles for technical uses	-0.3654***	5.00E+07	5.64E+07
76	Aluminium	-0.3629***	9.70E+08	9.85E+08
9	Spices	-0.3567***	4.76E+08	4.87E+08
18	Cocoa	-0.3559***	2.80E+08	2.80E+08
71	Precious Stones and Precious Metals	-0.3558***	5.97E+07	2.28E+09
73	Iron and Steel Products	-0.3452***	1.89E+09	1.98E+09
45	Cork	-0.3424**	7958401	8142269
62	Non-Knitted Nor Crocheted Clothes	-0.3374***	4.54E+08	5.45E+08
69	Bricks, Blocks and Tiles	-0.3203***	4.63E+08	4.93E+08
49	Printed or Illustrated Products	-0.3194***	1.09E+08	1.94E+08
53	Yarn	-0.3172*	5415980	9753613
85	Electrical Equipment	-0.3085***	1.43E+09	6.12E+09
30	Medicaments and Pharmaceutical Products	-0.3040***	1.05E+08	1.69E+09
55	Synthetic Fibres and Fabrics	-0.2991***	9.74E+07	1.01E+08
91	Clocks and Watches	-0.2950***	5760578	8.78E+07
87	Vehicles and Parts	-0.2926***	5.16E+09	5.18E+09
75	Nickel	-0.2844***	7.04E+07	1.02E+08
3	Fish	-0.2776***	1.15E+09	1.40E+09
84	Machinery	-0.2774***	3.15E+09	5.90E+09
95	Games and Sport Equipment	-0.2735***	2.73E+08	3.47E+08
83	Safety and Ornament Metal Based Products	-0.2703***	4.26E+08	4.87E+08
4	Dairy	-0.2670***	3.96E+08	4.15E+08
65	Hats	-0.2564***	2.80E+07	2.92E+07
86	Railway or Tramway Locomotives	-0.2520***	1.56E+08	1.56E+08
40	Rubber	-0.2501***	8.25E+08	8.84E+08
92	Musical Instruments	-0.2369***	1.46E+07	1.92E+07
89	Vessels	-0.2235***	4.79E+08	6.76E+08
43	Furskins	-0.2225**	1054215	1.17E+07

HS2	Definition	β_k	Y_{60}	Y_{tot}
50	Silk	-0.1994	291330.5	6088256
82	Hand Tools	-0.1882***	2.32E+08	4.34E+08
36	Pyrotechnic Products	-0.1768**	6022965	1.81E+07
5	Non-Edible Animal Products	-0.1747***	1.62E+08	1.69E+08
67	Artificial Hair and Artificial Vegetals	-0.1365	1.80E+07	1.91E+07
81	Other Metals	-0.1037	8.30E+07	1.48E+08
13	Vegetable Saps and Extracts	-0.1023	6.30E+07	1.19E+08
88	Spacecrafts and Parts	-0.1005	2.55E+07	1.00E+09
42	Leather Products	-0.0598	1.45E+08	1.97E+08
93	Firearms and Ammunitions	-0.0198	1.14E+07	3.93E+07
97	Artworks	NA	0	7.34E+07

* Significant at 10%; ** Significant at 5%; *** Significant at 1%.

Overall, partial elasticities range from -0.0198 for “Firearms and Ammunitions” to -0.9260 for “Live Animals”, with an average value of -0.35. However, despite a few extreme values, the coefficients tend to be relatively concentrated, as 76 partial elasticities out of 95 (hence 80%) take values between -0.56 and -0.24 (see Figure C.2 in Appendix C). It is also noticeable that the coefficients with the most extreme values tend to be associated with products with very low flows (maritime flows associated with “Live Animals” and with “Firearms and Ammunitions” represent both less than 0.1% of total maritime flows). In addition, looking at the distribution of β_k across shares of maritime trade in value (Figure 3) reveals that the distribution of β_k looks bimodal with large shares of trade subject to β_k both around -0.30 and around -0.60.

Figure 3: Distribution of partial elasticities (% of maritime flows in value)



Note: Here we dropped flows between countries sharing a common border or a common port of reference.

5 Simulating the general equilibrium effects of a carbon tax

The world has no experience of an international tax on maritime fuel. Therefore, the simulation of the effects of an international carbon tax on maritime transport cannot easily exploit some natural experiment. Because the main direct effect of an international carbon tax will be an increase in the maritime fuel price, we use information from past variations in the fuel price to simulate the effect of the tax. More precisely, we assume that the effect of a carbon tax on maritime transport can be estimated by looking at the effect of an increase in the heavy fuel oil price in our structural gravity model. In what follows we focus on year 2018, the last year in our sample, and look at the trade flows that our model predicts for that year, had the fuel price variable taken a higher value.

This approach relies on the assumption that if a carbon tax on maritime transport were implemented in 2018, it would have only affected the fuel price level and not the structural parameters of the gravity model such as the representative consumer preferences, the sector.country endowments or the country specific relative trade imbalances (see Appendix B.1 for details on these structural parameters). This approach therefore takes a short term perspective and does not take into account how a carbon tax could lead to a technological transformation of the impacted sectors or to a change in consumers' tastes.

For a specific marine fuel tax T, we assume that the heavy fuel oil price p_t increases worldwide by $\tilde{T}$ to become $p_t^c = p_t + \tilde{T}$, the counterfactual price level. The variation $\tilde{T}$ might not be identical to T, depending on the pass-through of the tax on prices which depends on the marine fuel market structure. The academic literature on international fuel cost pass-through is scarce and we are not aware of any convincing estimation of marine fuel cost pass-through. We therefore assume that $\tilde{T} = T$ and that with a specific marine fuel tax T, the maritime transport cost variable C_{ijt} becomes

$$C_{ijt}^c = \log(1 + SeaDist_{ij}(p_t + T)). \tag{3}$$

To calibrate the specific tax rate T, we use information provided by Olmer et al. (2017, [41]) on the carbon intensity of bunker fuel consumption and asssume that consuming 1 ton of fuel corresponds to emitting 3.12 tons of CO_2. Fixing $T = \$124.8$ per ton of fuel therefore corresponds to a carbon tax of \$40 per ton of CO_2. Compared to the actual heavy fuel oil price in the Port of Rotterdam which averaged at \$426 in 2018, the carbon tax that we envision would have implied then a price increase of around 29%. This is a substantial increase. However, it must be noted that with such a tax, the average price of heavy maritime fuel oil would have been approximately \$551 per ton of fuel, which remains below its maximum value (without tax) over our period of interest of \$664 reached in 2012.

Due to the functional form of C_{ijt}, increasing the price from p_t to $p_t + T$ is equivalent to multiplying $SeaDist_ij$ by a factor $\frac{p_t+T}{p_t} > 1$ for all country pairs. So it is important for the accuracy of our results that the elasticity of trade with respect to C_{ijt} corresponds to the fuel cost elasticity and not to other types of transport costs elasticities. Time costs in particular, which certainly depend on the distance traveled at sea, could be confounding and lead us to overestimate the impact of the tax on trade if they were not to vary with price p_t and were influencing the elasticities measured by the estimation of equation (1). Three arguments should be put forward here. First, it is well established that vessels speed influences fuel consumption so that it should be adapted to the price of fuel in a cost-minimizing decision, with reduced speed when price is higher, so that the tax T would indeed increase transport time as well as transport fuel costs. Second, transport duration is a key element of transport costs for goods that are time sensitive. But the goods that are time sensitive the most are precisely those that we regroup in our "non maritime" sector and for which we do not estimate equation (1). Third, maritime route duration is only a part of transport duration, with time in ports (e.g. for customs inspection or handling) being also an important part already captured in our fixed effects F_{ikt} or G_{jkt}.

Looking solely at the cost elasticities β_k obtained from the estimation of equation (1) as exposed in section 4 above is nevertheless insufficient in order to properly assess the effect of the specific tax T on trade. Indeed, any modification of the marine fuel price will affect trade costs for all country pairs and will have an impact on the multilateral resistances to trade captured in the fixed effects F_{ikt} and G_{jkt}. We cannot assume that these fixed effects remain constant in the counterfactual scenario. Therefore we turn below to a general equilibrium analysis, as coined by Head and Mayer (2014, [29]), i.e. we use the structural foundations of equation (1) to compute the new equilibrium of the gravity model in a rigorous comparative statics exercise.

The identification of the relevant structural parameters is detailed in Appendix B.3 where we adapt the exact hat algebra approach (Dekle et al., 2007 [21], 2008 [22] and Anderson and Yotov, 2016 [4]) to our Armington-type multisector model. We also provide in Appendix B.4 an algorithm designed to compute general equilibrium effects in multisector gravity models. This algorithm extends the *ge_gravity* algorithm built by Baier et al. (2019, [8]) for one sector models. It is important to notice that in multisector models, interdependencies across sectors exist despite the so-called *separability* property that only states that gravity equations can be estimated sector by sector. These interdependencies appear for instance via the budget constraint of the representative consumer for a demand side model as ours. Therefore it would be incorrect to aggregate results obtained by running a one sector algorithm on each sector. The approach developed in Appendices B.3 and B.4 consistently takes into account these interdependencies across sectors. It is similar to the model developed by Shapiro (2016, [45]; 2021, [46]) to study trade policy and the environment, with the additional feature that it computes all counterfactual flows and not only welfare and price statistics.

More specifically, our algorithm only requires baseline (i.e. absent the tax) sector by sector bilateral trade flows in value, sector by sector ratio of transport costs (counterfactual over baseline) which themselves necessitate results from the estimation of the β_k coefficients in equation (1)[13], as well as the representative consumer's elasticity of substitution parameters σ_k.[14] These latter elasticity parameters may differ from one sector to the other. In our analysis we borrow the values estimated by Fontagné et al. (2022, [26]) at the HS6 level and take an average at the HS2 level. These average values are reported in Table A.4 in Appendix A.5. They are broadly consistent with

---

[13] The eight values of β_k not significant at 5% are replaced by 0 in the following estimations.

[14] See Appendix B.1 for the precise definition of these σ_k.

the elasticities outlined by Costinot and Rodriguez-Clare (2014, [18]) in their survey.

When computing general equilibrium effects, we reintroduce the “non maritime” sector obtained by aggregating all non seaborne trade flows. In this sector, baseline and counterfactual trade costs are identical so that their ratio is equal to 1. This sector will nevertheless be impacted by the tax through the interdependencies mentioned above and its existence will in return influence how other sectors are impacted by the tax. The elasticity of substitution for this non maritime sector is taken as the average of the relevant HS6 elasticities estimated by Fontagné et al. (2022, [26]).

For the comparative statics exercise, relevant statistics include welfare and consumer price index in each country. Welfare is measured as the purchasing power of the representative consumer in the country. Variations in welfare due to the implementation of the tax combine effects channeled via variations in exports as well as effects channeled via variations in imports. Welfare variations are the relevant indicator to assess which countries are impacted the most by the tax. Variations in consumer price index provide information on price changes at the national level that would be due to the tax. In this comparative statics exercise we do not scrutinize how the proceeds from the tax could be used or shared among countries. While this use or sharing is certainly an important aspect of international discussions about such a tax, our approach is equivalent to assuming that the tax is used for the production of a global public good which benefits all countries uniformly. Under that circumstance, what precisely this use is would not change the rankings of countries that we detail below.

Welfare loss due to the tax is on average 0.73% (simple average, one observation by country) with standard deviation 0.72. Table 5 provides the complete list of countries and the percentage change in welfare due to the tax (see also the world map of Figure C.3 in Appendix C). Unsurprisingly, Small Island Developing States such as Sao Tome and Principe, Comoros, Cuba or Haiti are among the most affected countries. Least Developed Countries are also over-represented in the group of most affected countries with Comoros and Haiti again, as well as Gambia, Djibouti, Yemen or Guinea-Bissau. From these figures, we can calculate the average percentage loss in welfare by groups of countries. For OECD countries it is 0.37% while it reaches 1.11% for Least Developped Countries. Figure 4 offers a clear visualization of the inequitable distribution of effects. There, it appears that countries with low GDP per capita are on average more negatively impacted by the tax than richer countries. A simple descriptive linear regression gives

$$Welfare\,Loss = 0.8802154 - 8.32e^{-06}\,GDPpc$$

from which we deduce for instance that the average impact on a country with a GDP per capita of \$3,000 (in PPP) is a loss of 0.86% while the average impact on a country with a GDP per capita of \$40,000 would be a loss in welfare of 0.55% only.

Table 6 and Figure 5 offer similar information for the effect on the consumer price indices. Notice that since our general equilibrium simulation is performed while assuming as a normalization the total nominal value of production constant, it is not surprising to obtain a positive effect on prices for some countries and a negative effect for others. Again, it appears that countries with low GDP per capita are on average more negatively impacted by the tax than richer countries. A simple

Table 5: Welfare loss / gain by country (% change)

Country	Change	Country	Change	Country	Change	Country	Change
Sao Tome and Principe	-3.56	Egypt	-0.87	Sweden	-0.44	Indonesia	-0.23
Gambia	-3.22	Belize	-0.86	Dem. Rep. of Congo	-0.43	Portugal	-0.23
Djibouti	-3.20	Andorra	-0.83	Eritrea	-0.42	United Arab Emirates	-0.22
Somalia	-3.01	Seychelles	-0.81	Hungary	-0.42	Viet Nam	-0.21
Libya	-2.99	Bahamas	-0.80	Paraguay	-0.41	Chile	-0.19
Comoros	-2.94	Burkina Faso	-0.80	Namibia	-0.41	Canada	-0.19
Nauru	-2.63	Mozambique	-0.80	Bulgaria	-0.40	USA	-0.18
Maldives	-2.49	Chad	-0.76	Pakistan	-0.40	Niger	-0.17
Cook Isds	-2.41	Dominican Rep.	-0.76	Japan	-0.40	Ecuador	-0.16
Palau	-2.35	Zambia	-0.75	North Macedonia	-0.39	South Africa	-0.16
Cabo Verde	-2.25	Nicaragua	-0.73	Marshall Isds	-0.39	Bolivia	-0.16
Samoa	-2.14	Solomon Isds	-0.71	Morocco	-0.38	Kuwait	-0.15
Yemen	-2.10	Suriname	-0.71	Slovakia	-0.37	Azerbaijan	-0.14
Guinea-Bissau	-2.04	Guatemala	-0.71	Equatorial Guinea	-0.37	Bahrain	-0.12
Grenada	-2.02	Tanzania	-0.71	Croatia	-0.37	Iran	-0.12
Antigua and Barbuda	-1.93	Madagascar	-0.70	Finland	-0.36	Argentina	-0.11
Cuba	-1.80	Malta	-0.70	Botswana	-0.35	India	-0.11
St Lucia	-1.75	Tunisia	-0.69	Romania	-0.34	China	-0.11
Tuvalu	-1.69	Zimbabwe	-0.69	Serbia	-0.34	Australia	-0.10
St Kitts and Nevis	-1.62	Cote d'Ivoire	-0.68	Malaysia	-0.34	Georgia	-0.10
Timor-Leste	-1.56	New Zealand	-0.67	Cameroon	-0.34	Mexico	-0.09
Benin	-1.53	El Salvador	-0.67	Kyrgyzstan	-0.34	Russia	-0.09
St Vincent and the Gr.	-1.48	Philippines	-0.66	Rep. of Korea	-0.34	Lesotho	-0.08
Vanuatu	-1.40	Guinea	-0.66	Singapore	-0.33	Belarus	-0.06
Jamaica	-1.33	Honduras	-0.66	Nepal	-0.33	Myanmar	-0.06
Central African Rep.	-1.30	Burundi	-0.65	Brunei Darussalam	-0.32	Rep. of Congo	-0.05
Haiti	-1.30	Albania	-0.64	Oman	-0.32	Uruguay	-0.05
Dominica	-1.26	Norway	-0.63	Nigeria	-0.32	Brazil	-0.02
Afghanistan	-1.24	Qatar	-0.63	Lithuania	-0.32	Cambodia	0.03
Syria	-1.23	Montenegro	-0.61	Saudi Arabia	-0.31	Mongolia	0.04
Kiribati	-1.23	Slovenia	-0.60	Greece	-0.31	Peru	0.09
Ethiopia	-1.21	Israel	-0.60	Colombia	-0.30	Ukraine	0.10
Mali	-1.16	Jordan	-0.59	Rwanda	-0.30	Eswatini	0.11
San Marino	-1.16	Panama	-0.59	Rep. of Moldova	-0.30	Lao PDR	0.24
Angola	-1.15	Guyana	-0.57	Spain	-0.30	Armenia	0.30
Uganda	-1.14	Sri Lanka	-0.57	Gabon	-0.29		
Barbados	-1.13	Ireland	-0.56	Italy	-0.29		
Fiji	-1.12	Kenya	-0.54	Belgium	-0.28		
Sierra Leone	-1.12	Liberia	-0.54	Czech Rep.	-0.28		
FS Micronesia	-1.10	Bosnia Herzegovina	-0.54	Latvia	-0.28		
Lebanon	-1.09	Mauritania	-0.54	Kazakhstan	-0.27		
Iceland	-1.06	Costa Rica	-0.52	Austria	-0.27		
Mauritius	-1.01	United Kingdom	-0.51	Germany	-0.27		
Togo	-0.99	South Sudan	-0.51	France	-0.26		
Tajikistan	-0.94	Turkmenistan	-0.50	Thailand	-0.26		
Cyprus	-0.91	Bhutan	-0.49	Luxembourg	-0.26		
Sudan	-0.91	Denmark	-0.46	Poland	-0.26		
Algeria	-0.91	Niue	-0.46	Turkey	-0.25		
Senegal	-0.88	Estonia	-0.45	Switzerland	-0.25		
Malawi	-0.88	Netherlands	-0.44	Ghana	-0.24		

descriptive linear regression gives

$$Price\,Increase = 1.324022 - 0.0000123\,GDPpc$$

from which we deduce that the average impact on a country with a GDP per capita of \$3,000 (in PPP) would be a price increase of 1.29% while the average impact on a country with \$40,000 of GDP per capita corresponds to an increase in domestic prices of approximately 0.83%.

While the result that poorer countries will be more negatively impacted by the effect of the

Figure 4: Impact of a carbon tax on welfare by countries depending on GDP per capita

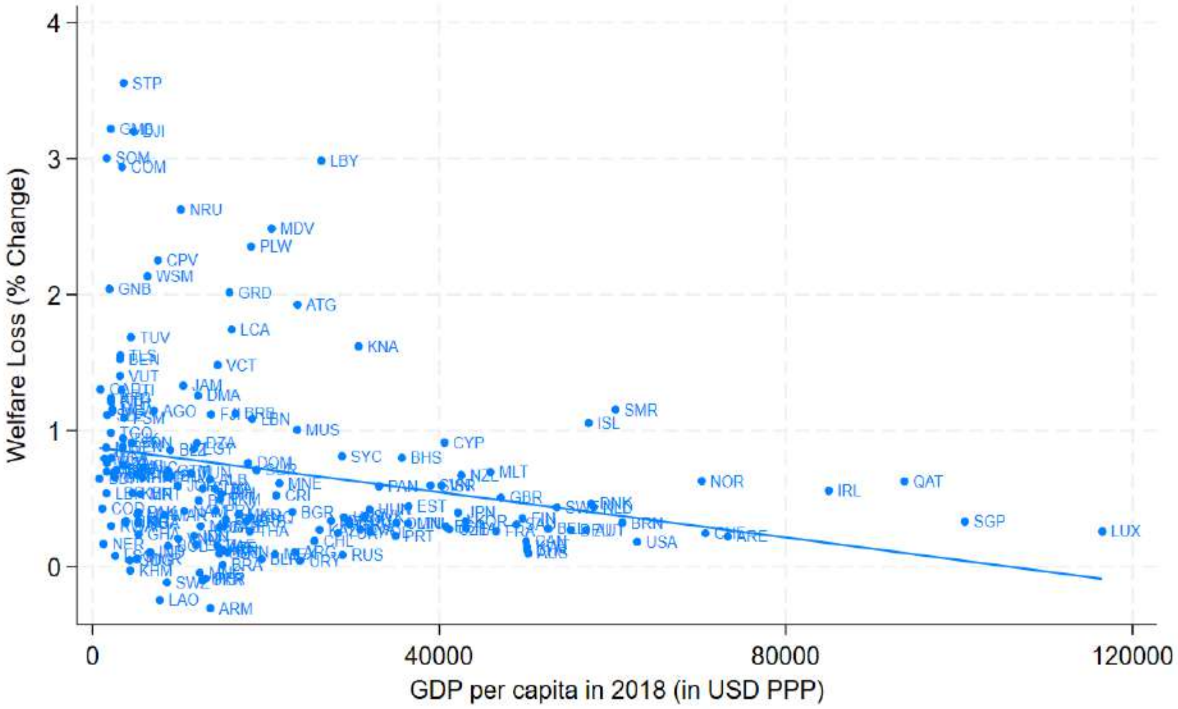


Figure 5: Impact of a carbon tax on consumer price index by countries

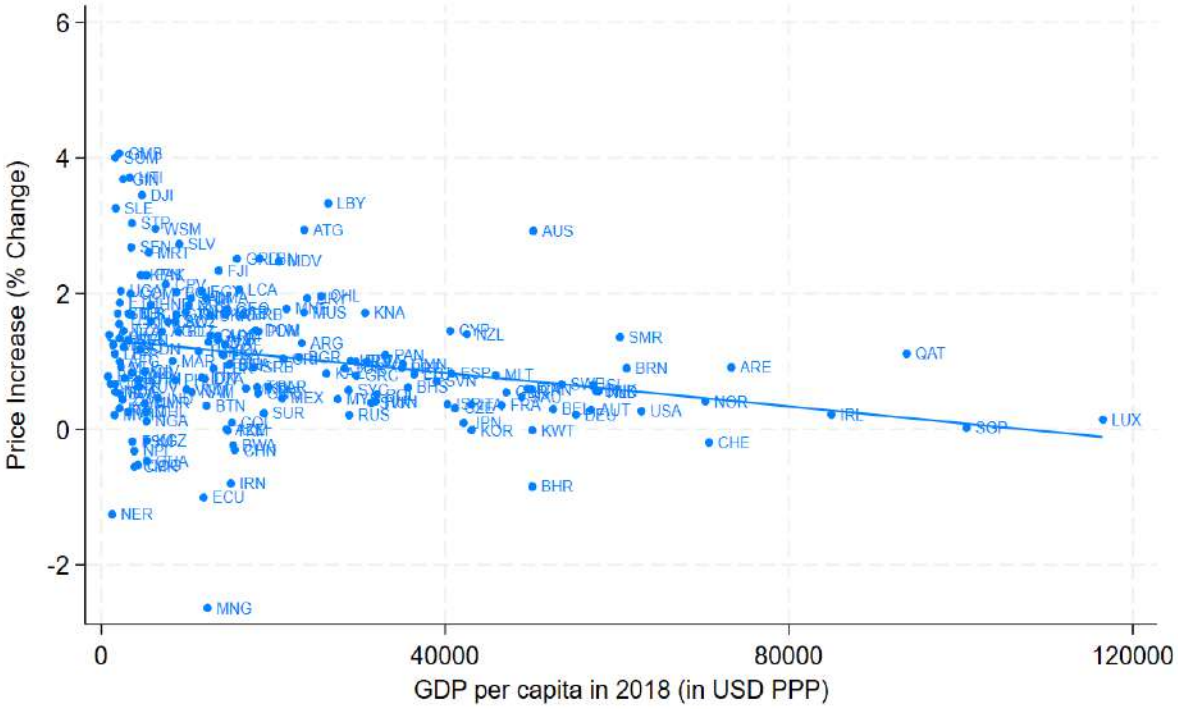


Table 6: Price Increase / Decrease by Country (% Change)

Country	Change	Country	Change	Country	Change	Country	Change
Eritrea	5.72	Nicaragua	1.59	South Sudan	0.85	Kiribati	0.31
Gambia	4.07	Eswatini	1.59	Zambia	0.83	Belgium	0.30
Somalia	4.01	Lao PDR	1.59	Estonia	0.83	Austria	0.29
Yemen	3.96	Togo	1.56	Spain	0.82	USA	0.27
Haiti	3.71	Dominican Rep.	1.46	Kazakhstan	0.82	Marshall Isds	0.27
Guinea	3.69	Tanzania	1.45	Lithuania	0.81	Vanuatu	0.26
Djibouti	3.45	Cyprus	1.45	Malta	0.80	Suriname	0.24
Libya	3.33	Palau	1.45	Greece	0.79	Germany	0.22
Sierra Leone	3.26	Angola	1.44	Burundi	0.78	Ireland	0.22
Sao Tome and Principe	3.04	Belize	1.44	Indonesia	0.76	Malawi	0.21
Samoa	2.96	New Zealand	1.40	Solomon Isds	0.76	Russia	0.21
Syria	2.95	Central African Rep.	1.39	Algeria	0.75	Luxembourg	0.15
Antigua and Barbuda	2.94	Guyana	1.39	Cambodia	0.74	Nigeria	0.12
Australia	2.93	Armenia	1.38	Philippines	0.73	Colombia	0.10
El Salvador	2.73	San Marino	1.36	Slovenia	0.71	Japan	0.10
Senegal	2.69	Cook Isds	1.36	Dem. Rep. of Congo	0.67	Singapore	0.03
Mauritania	2.61	Rwanda	1.34	Chad	0.67	Azerbaijan	0.00
Lebanon	2.52	Albania	1.32	Sweden	0.67	Rep. of Korea	-0.01
Grenada	2.52	Benin	1.32	Iceland	0.65	Kuwait	-0.01
Maldives	2.48	Rep. of Moldova	1.29	Tuvalu	0.63	Turkmenistan	-0.02
Fiji	2.34	Argentina	1.27	Belarus	0.62	Kyrgyzstan	-0.17
Kenya	2.28	South Africa	1.25	Thailand	0.62	FS Micronesia	-0.18
Pakistan	2.28	Mozambique	1.25	Bahamas	0.62	Switzerland	-0.19
Cabo Verde	2.14	Lesotho	1.21	North Macedonia	0.60	Niue	-0.20
St Lucia	2.06	Sudan	1.18	Finland	0.59	Botswana	-0.23
Uganda	2.04	Tunisia	1.15	Viet Nam	0.59	China	-0.31
Egypt	2.03	Qatar	1.12	Canada	0.59	Nepal	-0.32
Bolivia	2.02	Liberia	1.12	Seychelles	0.58	Ghana	-0.47
Comoros	2.00	Sri Lanka	1.11	Denmark	0.56	Rep. of Congo	-0.53
Chile	1.96	Panama	1.10	Netherlands	0.56	Cameroon	-0.55
Dominica	1.94	Paraguay	1.10	Madagascar	0.55	Iran	-0.80
Uruguay	1.93	Bulgaria	1.06	Namibia	0.55	Bahrain	-0.85
Jamaica	1.93	Costa Rica	1.04	United Kingdom	0.55	Ecuador	-1.01
Ethiopia	1.87	Croatia	1.01	Equatorial Guinea	0.53	Niger	-1.25
Honduras	1.83	Morocco	1.01	Burkina Faso	0.53	Mongolia	-2.63
Nauru	1.83	Latvia	1.00	Poland	0.51		
Montenegro	1.78	Romania	1.00	Saudi Arabia	0.48		
Georgia	1.78	Afghanistan	1.00	Mexico	0.46		
Cuba	1.74	Brazil	0.97	India	0.46		
Jordan	1.73	Oman	0.96	Malaysia	0.45		
Mauritius	1.73	Bosnia Herzegovina	0.95	Zimbabwe	0.44		
Gabon	1.72	Mali	0.92	Hungary	0.41		
St Kitts and Nevis	1.72	Serbia	0.92	Norway	0.41		
Guinea-Bissau	1.71	United Arab Emirates	0.91	Slovakia	0.40		
Timor-Leste	1.71	Portugal	0.91	Myanmar	0.38		
Tajikistan	1.70	Brunei Darussalam	0.90	Israel	0.37		
Guatemala	1.70	Turkey	0.90	Italy	0.37		
St Vincent and the Gr.	1.70	Peru	0.90	France	0.36		
Barbados	1.69	Cote d'Ivoire	0.86	Bhutan	0.35		
Ukraine	1.68	Andorra	0.85	Czech Rep.	0.31		

tax on trade than richer countries may not come as a surprise, our analysis provides a rigorous justification and a quantification for what was mostly an intuitive argument in the international debate. Robustness checks of the decreasing relationship between GDP per capita and either welfare or price index corresponding to the Y_{50}, Y_{70} and Y_{HS} scenarios are provided in Figure C.4 in Appendix C.

To elaborate on the distinctive features of our approach, one can start from the intuition that the effects of a carbon tax on maritime transport should be magnified on countries that are remote from world markets, especially when they rely on sea transport for trade. Remoteness has long been considered as an important factor of economic vulnerability and several remoteness indices have been proposed in the academic literature (see for instance Brun et al., 2005 [14]) as well as by international institutions.[15] However, our approach for ranking the countries according to the magnitude of the effects of a carbon tax on maritime transport goes beyond the simple computation of a maritime distance remoteness index in at least three distinct aspects. First, our multisector model allows us to take into consideration the different elasticities of trade in different sectors and therefore adjust our measure to the export and import basket composition of each country. Second, by looking at welfare and price indices we go beyond the computation of an average maritime distance weighted by the share of imports and/or exports and do take into account the evolution of national prices. Third, by computing general equilibrium effects we take into account how multilateral resistances to trade react to the tax and are able to capture how, for each country, the whole geography of direct and indirect trade partners is affected. For comparison with the rankings of Tables 5 and 6, Table C.3 in Appendix C provides the list of the 30 most remote countries according to UNDESA and according to a maritime remoteness index based on the average sea distance to trading partners weighted by the sum of exports and imports.[16]

To complement the results showing the welfare effects of the tax, we can measure the monetary equivalent of the country-by-country welfare losses: the so-called *equivalent variation in income* from standard microeconomics textbooks. This is done by computing the budget loss, measured at baseline prices, equivalent to the welfare loss. Details are given in Appendix B.3 and, in our CES-utility representative consumer model, lead to equation (B.22) which gives a worldwide economic cost related to the effect of the tax on trade equal to \$166 billion. The country-by-country decomposition of this aggregate amount is given in Table 7.

6 Environmental effects of a carbon tax

6.1 Geography of trade

Beyond the two statistics detailed in section 5, welfare and price index, our general equilibrium algorithm produces the counterfactual values of all trade flows (i.e. the bilateral trade flows with the tax, see Appendix B.4 for details) and therefore provides all the information we need to analyze how the geography of trade is impacted by the tax. Intuitively, implementing a tax on maritime fuel will make distance more costly for trade and should lead to a redistribution of trade flows

---

[15] The remoteness and landlockedness component of the Economic Vulnerability Index (EVI) computed by the United Nations Department of Economic and Social Affairs is a landmark. In the EVI, remoteness and landlockedness measure the average distance of a country to the world market. More precisely, it is constructed as the average geographic distance of a country to the actual or potential trade partners that represent one-half of the world trade (exports+imports). In addition, a premium is given to landlocked countries. The same component is named *low connectivity* in the UN Multidimensional Vulnerability Index (See details at `https://www.un.org/ohrlls/mvi`) where it is aimed at capturing the low capacity to integrate with international markets.

[16] We compute such a sea remoteness index for country i from the baseline trade flows as

$$SeaRemote_i = \sum_j \frac{\sum_k Y_{ijk} + Y_{jik}}{\sum_{l,k} Y_{ilk} + Y_{lik}} SeaDist_{ij}.$$

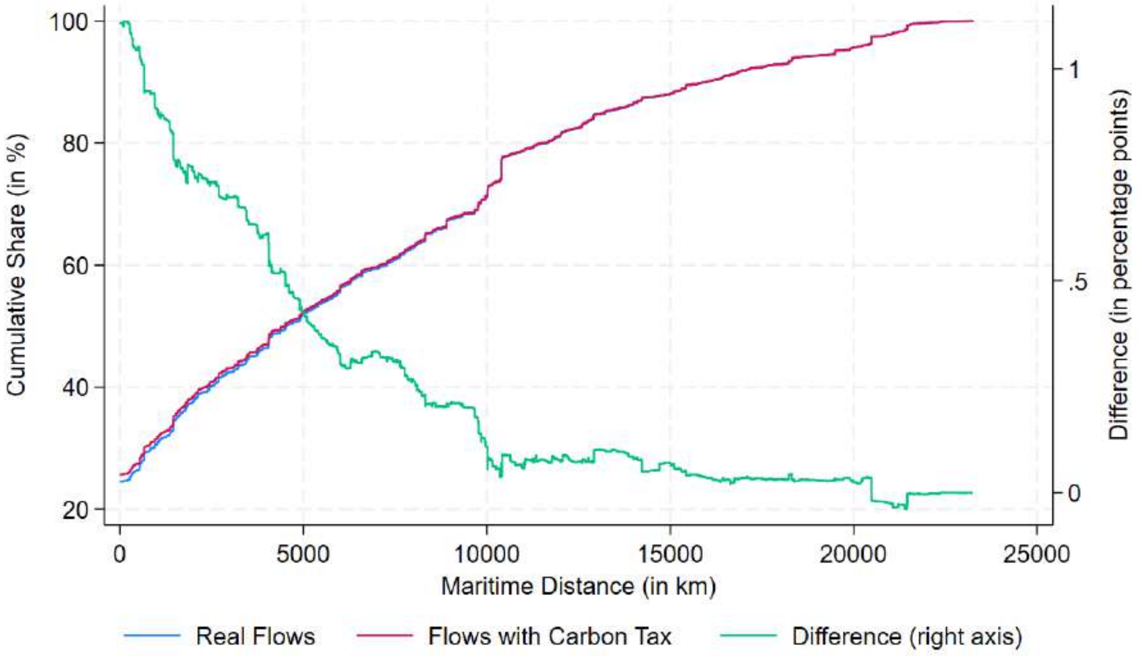
Table 7: Economic cost of the tax by country (Billion U.S.$)

Country	Loss	Country	Loss	Country	Loss	Country	Loss
USA	-20.07	Sudan	-0.55	Paraguay	-0.15	Solomon Isds	-0.02
China	-20.01	Ghana	-0.55	Zimbabwe	-0.14	Comoros	-0.02
Japan	-13.26	Lebanon	-0.54	Burkina Faso	-0.13	Guinea-Bissau	-0.02
Germany	-7.97	Dominican Rep.	-0.52	Malta	-0.13	South Sudan	-0.02
Rep. of Korea	-7.75	Slovakia	-0.51	Kyrgyzstan	-0.13	Belize	-0.02
United Kingdom	-6.87	Angola	-0.49	Jamaica	-0.13	Georgia	-0.02
Italy	-4.43	Libya	-0.49	El Salvador	-0.12	Andorra	-0.01
France	-4.19	Portugal	-0.48	Bosnia Herzegovina	-0.12	Vanuatu	-0.01
Netherlands	-3.93	Kenya	-0.46	Syria	-0.12	Uruguay	-0.01
Saudi Arabia	-3.14	Cote d'Ivoire	-0.42	Luxembourg	-0.11	Samoa	-0.01
Spain	-3.02	Argentina	-0.42	Madagascar	-0.11	Grenada	-0.01
Russia	-2.86	Yemen	-0.42	Malawi	-0.10	Central African Rep.	-0.01
India	-2.53	Guatemala	-0.37	Guinea	-0.10	Timor-Leste	-0.01
Algeria	-2.33	Qatar	-0.37	Bahamas	-0.10	Kiribati	-0.01
Singapore	-2.17	Oman	-0.36	Mauritius	-0.09	St Vincent and the Grenadines	-0.01
Canada	-2.11	Tunisia	-0.36	Namibia	-0.09	Bhutan	-0.01
Philippines	-2.04	Costa Rica	-0.36	Nepal	-0.09	FS Micronesia	-0.01
Iran	-2.03	Bulgaria	-0.35	Latvia	-0.09	Cook Isds	-0.01
Egypt	-1.96	Kazakhstan	-0.35	Mauritania	-0.09	St Kitts and Nevis	-0.01
Turkey	-1.95	Ethiopia	-0.34	Tajikistan	-0.08	Sao Tome and Principe	-0.01
Belgium	-1.91	Jordan	-0.34	Maldives	-0.08	San Marino	-0.01
Malaysia	-1.84	Sri Lanka	-0.34	Myanmar	-0.08	Palau	-0.01
Indonesia	-1.76	Slovenia	-0.33	North Macedonia	-0.08	Dominica	-0.01
Nigeria	-1.71	Zambia	-0.33	Turkmenistan	-0.07	Eritrea	-0.01
Thailand	-1.56	Bahrain	-0.31	Fiji	-0.07	Nauru	0.00
Poland	-1.55	Tanzania	-0.31	Haiti	-0.07	Tuvalu	0.00
United Arab Emirates	-1.51	Panama	-0.30	Botswana	-0.07	Lesotho	0.00
Sweden	-1.43	Benin	-0.29	Rwanda	-0.07	Niue	0.00
Switzerland	-1.35	Senegal	-0.28	Belarus	-0.07	Eswatini	0.01
Viet Nam	-1.32	Brazil	-0.28	Albania	-0.06	Cambodia	0.02
Norway	-1.28	Afghanistan	-0.27	Gambia	-0.05	Armenia	0.03
Israel	-1.24	Cameroon	-0.26	Liberia	-0.05	Lao PDR	0.06
Colombia	-1.14	Mozambique	-0.22	Brunei Darussalam	-0.05	Ukraine	0.15
Kuwait	-0.94	Croatia	-0.22	Bolivia	-0.04	Peru	0.19
Austria	-0.92	St Lucia	-0.21	Rep. of Moldova	-0.04	Mongolia	0.22
Mexico	-0.91	Cyprus	-0.20	Niger	-0.04		
Ireland	-0.87	Azerbaijan	-0.20	Rep. of Congo	-0.04		
Denmark	-0.86	Honduras	-0.19	Marshall Isds	-0.04		
Czech Rep.	-0.85	Djibouti	-0.19	Seychelles	-0.04		
New Zealand	-0.83	Dem. Rep. of Congo	-0.19	Cabo Verde	-0.04		
Australia	-0.81	Serbia	-0.19	Equatorial Guinea	-0.04		
Hungary	-0.77	Iceland	-0.18	Gabon	-0.04		
Pakistan	-0.76	Cuba	-0.18	Suriname	-0.04		
Romania	-0.73	Uganda	-0.18	Sierra Leone	-0.04		
Finland	-0.67	Estonia	-0.17	Burundi	-0.04		
Greece	-0.62	Togo	-0.17	Montenegro	-0.03		
Morocco	-0.59	Nicaragua	-0.17	Guyana	-0.03		
Ecuador	-0.59	Lithuania	-0.17	Chad	-0.03		
Chile	-0.59	Mali	-0.16	Barbados	-0.02		
South Africa	-0.57	Somalia	-0.16	Antigua and Barbuda	-0.02		

towards closer trade partners. Figure 6 illustrates the reduction in distance traveled by goods at the aggregate level and highlights that for any maritime distance, the share of trade that travels less than this maritime distance always increases with the tax, i.e. a first-order stochastic reduction in traveled sea distance. On average and at an aggregate level, the maritime distance traveled by 1 dollar of good is 1298 kilometers at baseline and 1264 kilometers with the tax, which corresponds to a 2.59% reduction (see Appendix B.5 for calculation details).

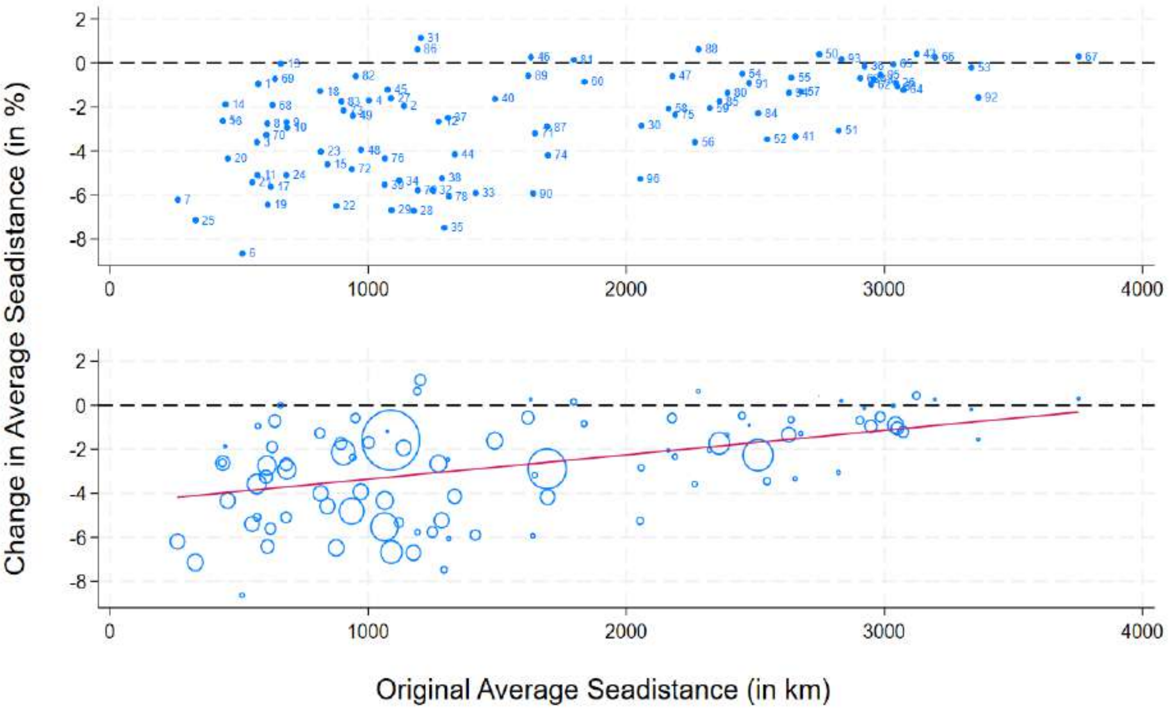
If one scrutinizes what occurs at the sectoral level, it appears that goods from different sectors travel different average distances and are also diversely impacted by the tax (see Table C.2 in

Figure 6: Maritime distance traveled by international trade flows



Note: The blue line represents the cumulative share of actual observed trade flows (in %). The red line represents the cumulative share of predicted flows with marine fuel taxation (in %). The green line represents the difference between predicted and real cumulative shares of flows (i.e. the difference between these red and blue curves, in percentage points, scale on the right-axis).

Figure 7: Change in average seadistance traveled by sector (% change)



Note: The same observations are represented in the two graphs. The upper graph gives the HS2 codes while the circle sizes in the lower graph are proportional to the value of the sectoral flows at baseline. The red line represents the linear relationship between the original average sea distance and the change in average sea distance, weighted by the value of the sectoral flow at baseline.

Appendix C). If average distance declines with the tax for almost all sectors, the relative decline seems to be more pronounced in sectors with low baseline average distance as one can see on Figure 7 where we plot each HS2 sector average sea distance at baseline (horzontal axis) and relative decline in sea distance that would be due to the tax (vertical axis). The information provided by this Figure 7 complements that of the sectoral partial equilibrium elasticities given in Table 4. It helps better understand what would be the most impacted sectors and how the reaction of demand to the tax would translate into a reduced distance traveled by goods.

6.2 Tax potential and reduction in carbon emissions

Building on the analysis of distances traveled, we can estimate the fiscal potential of the maritime tax and the predicted reduction in CO_2 emissions. To determine the tax revenue, we begin by expressing trade flows in volume (i.e., tons) rather than value. For the baseline, the information on volume is provided by the BACI database. For the counterfactual it is necessary to take into account price variations, so we exploit a basic property of Armington endowment models to obtain counterfactual volumes from baseline volumes and values together with counterfactual values (see Appendix B.5 for details). To estimate the potential tax revenue, we then need to assign to each product transported by sea an average carbon intensity, expressed in grams of CO_2 emitted per kilometer per ton transported. Such a carbon intensity depends on the type of product, mainly because different products are transported by different types of ships with different fuel consumption. In addition, even for vessels transporting the same category of goods, the carbon intensity varies with the size of the vessel (the larger the vessel, the lower its carbon intensity per ton of goods transported). Therefore, we assign each product to a specific type of ship (bulk carrier, container ship, oil tanker, chemical tanker, or ro-ro ship) based on previous literature and online research (see section A.6 for more details). Then, we extract estimates of carbon intensity for each type of vessel from an official report published by the French Ministry of Ecological Transition (2018, [38]) to serve as a guide in applying current environmental regulations. Finally, since we cannot know the size of the vessel used for each specific loading, we estimate two scenarios: (i) a minimum scenario, where we assign to each vessel the minimum carbon intensity of that type of vessel, and (ii) a maximum scenario, where we assign to each vessel the maximum carbon intensity of that type of vessel.

Based on these values, we compute for each sector the actual pre-tax level of CO_2 emissions, the predicted post-tax level, and the subsequent tax-induced change in maritime emissions under the minimum and maximum scenarios. Based on this methodology, we conclude that the baseline CO_2 emissions from maritime shipping ranged from 499 million tons of CO_2 in the lowest carbon intensity scenario to 1.513 billion tons of CO_2 in the highest carbon intensity scenario. These results are consistent with the IMO (2020, [33]) estimate of 1.056 billion tons of CO_2 emissions in 2018.[17] After the implementation of the carbon tax, we find new estimates of CO_2 emissions ranging from 491 million tons of CO_2 in the low carbon intensity scenario to 1.487 billion tons in the high carbon intensity scenario. This corresponds to a decrease in CO_2 emissions from maritime transport of -1.76% and -1.74%, respectively.[18] Since we examine in this paper the effects of a carbon tax of \$40 per ton of CO_2, we simply multiply the predicted post-tax level of CO_2 emissions by 40 to obtain an approximation of the tax revenues under the low and high carbon intensity scenarios. We obtain an estimate of revenues ranging from \$19.6 billion to \$59.5 billion. For comparison, Parry et al. (2018, [42]) conclude that a tax of \$75 per ton of CO_2 in 2030 would allow for the collection of \$75 billion, while Baresic et al. (2022, [9]) estimate that revenues collected from a \$100 tax would range from \$40 to \$90 billion. Our results are reported in Table 8. Overall, they suggest a large revenue from such a tax scheme, but a rather small reduction in CO_2 emissions from shipping, which is be due to the low elasticity of shipping to changes in marine fuel prices.[19]

The tax potential range from \$19.6 billion to \$59.5 billion can be compared with the economic cost of \$166 billion outlined in section 5 above. This comparison does not exactly yield a marginal cost of funds estimate since we do not model environmental externalities, however it provides relevant information on what the magnitude of these environmental externalities should be in order for the tax to be efficient. The ratio cost/revenue ranges from 2.78 to 8.47 which is far above standard estimations of the marginal cost of public funds, even in developing countries. Auriol

---

[17] This consistency is also an additional and indirect validity check for our approach to spot maritime trade.

[18] The discrepancy between the 1.74 or 1.76 % decrease in emissions and the 2.59 % decrease in average traveled distance obtained above is related to the different carbon intensities of transport for different types of goods.

[19] The \$40 per ton of CO_2 tax in 2018 is equivalent to a 29 % price increase.

Table 8: Revenue collection and change in CO_2 emissions

	Scenario 1: Lowest CI of Vessels and land transport by road	Scenario 2: Highest CI of Vessels and land transport by rail
Pre-tax CO_2 Emissions (billion tons)	0.499	1.513
Post-tax CO_2 Emissions (billion tons)	0.491	1.487
Change in Maritime Transport Emissions	-1.76%	-1.74%
Revenues Collected ($ billion)	19.624	59.476
Change in Total Transport Emissions	+0.12%	-0.72%

and Warlters (2012, [7]) for instance estimate at 1.2 the average marginal cost of public funds in 38 African countries for five different tax instruments. While a high cost/revenue ratio is not necessarily problematic for a tax that aims at modifying behaviors and not only raise revenues, it is nevertheless a significant warning when combined with our result on the small magnitude of the effect of the tax on maritime transport emissions.

So far, we have limited our attention to maritime emissions. However, under a maritime taxation scheme, some bilateral trade flows may be redirected towards more carbon intensive transport modes, notably because flows between neighboring countries are likely to increase. Therefore, to properly estimate the reduction in CO_2 emissions from international transport, we must consider possible changes in CO_2 emissions from air and land transport.

Goods transported by sea must also be transported (most likely by land) from (or to) the port to (or from) the rest of the country. Most of the time this intranational transportation is by land. Even if sea transport is the least carbon intensive mode, replacing an international seaborne flow by an international terrestrial flow does not necessarily increase emissions if the associated land transport distance decreases.[20] Taking the multimodal aspect of transportation into account is important in order to properly assess the effect on carbon emissions of a redirection of trade towards closer neighbors.

We add now three sources of carbon emissions related to international trade flows. First, for seaborne trade flows we approximate land transport emissions by the road distance between each national capital and the reference port (from the CERDI-Seadistance database) multiplied by the carbon intensity of land transport times the volume of the flow. Second, for all trade flows between countries sharing a terrestrial border, we approximate emissions by the geodesic distance between capitals multiplied by the carbon intensity of land transport times the volume of the flow. Third, for "non-maritime" sector flows between non-neighboring countries, we approximate emissions by the geodesic distance between the exporting and importing capitals (from CEPII) multiplied by the carbon intensity of air transport times the volume of the flow. All carbon intensities that we use are reported in Table A.5 in Appendix A. Land transport can be by road or by rail with carbon intensity of rail transport depending on the energy mix. Instead of trying to assess precisely what

---

[20] Take for instance a flow to a distant partner replaced by a flow to a neighbor, with the road distance from the place of production to the place of consumption even smaller than the road distance from the place of production to the port of reference.

is the average carbon intensity of land transport worldwide, we consider two extreme scenarios with all land transport by road (scenario 1) or all land transport by rail with a European energy mix to produce electricity (scenario 2).

With this approach, we can estimate the changes in CO_2 emissions from international transport due to the tax. The results are reported in Table 8, last row. They highlight that in the best case (i.e. the high carbon intensity scenario for vessels and all land transportation by electric train with a European energy mix) CO_2 emissions would decrease by less than 0.72%, while in the worst case (i.e. the low carbon intensity scenario for vessels and all land transportation by road) they could even increase slightly by 0.12%. This possible increase in CO_2 emissions is due to a reallocation effect from low CO_2-emitting maritime transport to more polluting land and air means of transportation.[21]

7 Conclusion

In this paper we have evaluated the effects of a carbon tax on maritime transport with the help of a multisector structural gravity model. Disaggregating trade flows at HS2 sector level appeared to be important in order to take into account the fact that trade elasticities with respect to fuel costs are sector specific and that different goods are conveyed by different types of vessels with different carbon footprint. We have devoted some effort to carefully isolate trade flows that would be impacted by the tax, i.e. that correspond to seaborne trade, to minimize the risk that we overestimate the impact of the tax on trade. We have also fully taken into account the impact of the tax on multilateral resistances to trade by going beyond a partial equilibrium analysis of elasticities and by providing an algorithm suited for comparative statics in multisector Armington-type gravity models.

Our results highlight the fact that a maritime transport carbon levy would be inequitable in the sense that it would have a higher negative impact on purchasing power in developing countries compared to developed countries. It would redirect trade flows towards closer partners and reduce the average distance traveled by goods. However its impact on carbon emissions would be modest, with a small reduction in emissions from maritime transport but also a redirection of seaborne trade towards other transport modes with a higher carbon footprint. Finally, the ratio economic cost/ tax revenue is likely to be much higher with this tax compared to other fiscal instruments. The double dividend narrative therefore seems inappropriate for an international tax on maritime transport implemented alone.

The implications of this work for policy and the current international discussions on carbon taxation are important. First, by quantifying precisely the impacts on CO_2 emissions of a 40$ per ton of CO_2 tax on maritime transport, we demonstrate that such a tax is not a silver bullet if the objective is to drastically reduce maritime sector emissions and that it should be accompanied by other steps. Second, by documenting how the tax could redirect maritime trade flows towards more polluting transport modes, we draw attention on the fact that a maritime transport carbon levy

---

[21] Robustness checks for this section are provided in Table C.4 in Appendix C.

should not be considered independently from a more global carbon tax that includes for instance international aviation with the objective to set a uniform price of carbon across air, sea or road transport. Finally, by simulating the effects of the tax at the country level for 185 countries, we provide a complete picture of potential winners and losers from the tax and help identify who should benefit the most from the tax proceeds if one wants the international negotiations to succeed.

References

[1] J. E. Anderson. A theoretical foundation for the gravity equation. *The American Economic Review*, 69(1):106–116, 1979.

[2] J. E. Anderson, M. Larch, and Y. V. Yotov. GEPPML: General equilibrium analysis with PPML. *The World Economy*, 41(10):2750–2782, 2018.

[3] J. E. Anderson and E. van Wincoop. Gravity with Gravitas: A Solution to the Border Puzzle. *American Economic Review*, 93(1):170–192, 2003.

[4] J. E. Anderson and Y. V. Yotov. Terms of trade and global efficiency effects of free trade agreements, 1990-2002. *Journal of International Economics*, 99:279–298, 2016.

[5] A. Ardelean, V. Lugovsky, A. Skiba, and D. Terner. Fathoming Shipping Costs. An Exploration of Recent Literature, Data, and Patterns. Policy Research Working Paper 9992, World Bank Group, Washington, D.C., 2022.

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

[7] E. Auriol and M. Warlters. The marginal cost of public funds and tax reform in africa. *Journal of Development Economics*, 97(1):58–72, 2012.

[8] S. L. Baier, Y. V. Yotov, and T. Zylkin. On the widely differing effects of free trade agreements: Lessons from twenty years of trade integration. *Journal of International Economics*, 116:206–226, 2019.

[9] D. Baresic, I. Rojon, A. Shaw, and N. Rehmatulla. Closing the Gap: An Overview of the Policy Options to Close the Competitiveness Gap and Enable an Equitable Zero-Emission Fuel Transition in Shipping. Technical report, UMAS, London, 2022.

[10] D. M. Bernhofen, Z. El-Sahli, and R. Kneller. Estimating the Effects of the Container Revolution on World Trade. *Journal of International Economics*, 2016.

[11] S. Bertoli, M. Goujon, and O. Santoni. The CERDI-seadistance database. *Etudes et Documents*, 7, 2016.

[12] G. Brancaccio, M. Kalouptsidi, and T. Papageorgiou. Geography, Transportation, and Endeogenous Trade Costs. *Econometrica*, 88(2):657–691, 2020.

[13] G. Brancaccio, M. Kalouptsidi, and T. Papageorgiou. The Impact of Oil Prices on World Trade. *Review of International Economics*, 3(2):444–463, 2023.

[14] J.-F. Brun, C. Carrère, P. Guillaumont, and J. de Melo. Has Distance Died? Evidence from a Panel Gravity Model. *The World Bank Economic Review*, 19(1):99–120, 2005.

[15] F. Cantu-Bazaldua. Remote but well connected? Neighboring but isolated? Measuring remoteness in the context of small island developing states. UNCTAD Research Paper 67, UNCTAD, 2009.

[16] P. Cariou, R. A. Halim, and B. J. Rickard. Ship-owner response to carbon taxes: Industry and environmental implications. *Ecological Economics*, 212, 2023.

[17] M. Conte, P. Cotterlaz, and T. Mayer. The CEPII Gravity Database. CEPII Working Paper 2022-05, CEPII, 2022.

[18] A. Costinot and A. Rodríguez-Clare. Trade Theory with Numbers: Quantifying the Consequences of Globalization. In *Handbook of International Economics*, volume 4. 2014.

[19] A. Cristea, D. Hummels, L. Puzzello, and M. Avetisyan. Trade and the greenhouse gas emissions from international freight transport. *Journal of Environmental Economics and Management*, 65:153–173, 2013.

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

[21] R. Dekle, J. Eaton, and S. Kortum. Unbalanced Trade. *The American Economic Review*, 97(2):351–355, 2007.

[22] R. Dekle, J. Eaton, and S. Kortum. Global Rebalancing with Gravity: Measuring the Burden of Adjustment. *IMF Staff Papers*, 55(3), 2008.

[23] J. Eaton and S. Kortum. Technology, geography, and trade. *Econometrica*, 70:1741–1779, 2002.

[24] T. Fally. Structural gravity and fixed effects. *Journal of International Economics*, 97(1):76–85, 2015.

[25] J. Feyrer. Trade and Income—Exploiting Time Series in Geography. *American Economic Journal: Applied Economics*, 11(4):1–35, 2019.

[26] L. Fontagné, H. Guimbard, and G. Orefice. Tariff-based product-level trade elasticities. *Journal of International Economics*, 137:103593, 2022.

[27] G. Gaulier and S. Zignano. BACI: International Trade Database at the Product-Level. The 1994-2007 Version. CEPII Working Paper 2010-23, CEPII, 2010.

[28] C. Gourieroux, A. Monfort, and A. Trognon. Pseudo Maximum Likelihood Methods: Applications to Poisson Models. *Econometrica*, 52(3):701–720, 1984.

[29] K. Head and T. Mayer. Gravity Equations: Workhorse, Toolkit, and Cookbook. In *Handbook of International Economics*, volume 4, pages 131–195. Elsevier, 2014.

[30] P. R. Herman. gegravity: General Equilibrium Gravity Modeling in Python. Economics Working Paper Series 2021-04-B, U.S. International Trade Commission, Washington, D.C., 2021.

[31] D. Hummels. Transportation Costs and International Trade in the Second Era of Globalization. *The Journal of Economic Perspectives*, 21(3):131–154, 2007.

[32] D. Hummels and G. Schaur. Time as a Trade Barrier. *American Economic Review*, 103(7):2935–2959, 2013.

[33] IMO. Fourth IMO GHG Study 2020. Technical report, International Maritime Organization, London, 2020.

[34] M. Isaacson and H. Rubinton. Shipping Prices and Import Price Inflation. *Federal Reserve Bank of St. Louis Review*, 2023.

[35] S. Lagouvardou, H. N. Psaraftis, and T. Zis. Impacts of a bunker levy on decarbonizing shipping: A tanker case study. *Transportation Research Part D*, 106, 2022.

[36] M. Larch and Y. V. Yotov. General equilibrium trade policy analysis with structural gravity. CESifo Working Papers 6020, CESifo, Munich, 2016.

[37] T. Mayer, G. Santoni, and V. Vicard. The CEPII Trade and Production Database. CEPII Working Paper 2023-01, CEPII, 2023.

[38] Ministère de la Transition Ecologique et Solidaire. Information GES des Prestations de Transport - Guide Méthodologique. Technical report, Ministère de la Transition Ecologique et Solidaire, Paris, 2018.

[39] D. Mirza and H. Zitouna. Oil Prices, Geography and Endogenous Regionalism: Too Much Ado About (Almost) Nothing. CEPII Working Paper 26, CEPII, 2009.

[40] G. Mundaca, J. Strand, and I. R. Young. Carbon pricing of international transport fuels: Impacts on carbon emissions and trade activity. *Journal of Environmental Economics and Management*, 110, 2021.

[41] N. Olmer, B. Comer, B. Roy, X. Mao, and D. Rutherford. Greenhouse Gas Emissions from Global Shipping. Technical report, The International Council on Clean Transportation, 2017.

[42] I. Parry, D. Heine, K. Kizzier, and T. Smith. Carbon Taxation for International Maritime Fuels: Assessing the Options. IMF Working Paper 203, IMF, Washington, D.C., 2018.

[43] I. Rojon, N.-J. Lazarou, N. Rehmatulla, and T. Smith. The impacts of carbon pricing on maritime transport costs and their implications for developing economies. *Marine Policy*, 132:104653, 2021.

[44] J. M. C. Santos Silva and S. Tenreyro. The Log of Gravity. *The Review of Economics and Statistics*, 88(4):641–658, 2006.

[45] J. S. Shapiro. Trade Costs, CO2, and the Environment. *American Economic Journal: Economic Policy*, 8(4):220–254, 2016.

[46] J. S. Shapiro. The Environmental Bias of Trade Policy. *Quarterly Journal of Economics*, 136(2):831–886, 2021.

[47] Y. Sheng, X. Shi, and B. Su. Re-analyzing the economic impact of a global bunker emissions charge. *Energy Economics*, 74:107–119, 2018.

[48] UNCTAD. Handbook of Statistics. Technical report, United Nations Conference on Trade and Development, Geneva, 2020.

[49] UNCTAD. Review of Maritime Transport 2023. Technical report, United Nations Conference on Trade and Development, Geneva, 2023.

[50] Y. V. Yotov, R. Piermartini, J.-A. Monteiro, and M. Larch. An Advanced Guide to Trade Policy Analysis: The Structural Gravity Model. Technical report, World Trade Organization, Geneva, 2016.

A Appendix: Construction of the dataset

In this section, we present the complete methodology used to construct our final database and describe all of the data sources, their limitations, and the methodology we implemented to work around these limitations.

A.1 The initial BACI database for international trade

The original BACI dataset used here covers bilateral trade flows at the 6-digit level (HS6 rev. 12 classification) for 226 countries or territories and for about 5200 products starting in 2012 (see Gaulier and Zignano, 2010, [27] for a detailed description of the dataset). At the 2-digit level, these products correspond to 96 different categories. We keep all official independent countries (recognized by the U.N.) in this database and end up with 193 countries. The 33 unrecognized countries and territories excluded from this database are listed in Table A.1.

Table A.1: List of excluded territories (BACI database)

Not included: Aruba, Anguilla, American Samoa, French Southern Antarctic Territory, Bonaire, St Barthelemy, Bermuda, Cocos Isds, Curacao, Christmas Isds, Cayman Isds, Gibraltar, Greenland, Guam, Hong Kong, British Indian Ocean Territory, Macao, Northern Mariana Isds, Montserrat, New Caledonia, Norfolk Isds, Pitcairn, State of Palestine, French Polynesia, St Helena, St Pierre and Miquelon, St Maarten, Taiwan, Turks and Caicos Isds, Tokelau, British Virgin Isds, Wallis and Futuna.

A.2 Isolating maritime trade

Unfortunately, there is no complete database of international maritime trade flows at the sectoral level. To estimate for each product whether it is more likely to be transported by sea, by land or by air, we use U.S. trade data provided by the U.S. Census Bureau. These data cover, at the HS6-digit level of disaggregation, all bilateral export flows from the United States and all bilateral import flows to the United States, and document the value share of air and sea transport for each flow. Based on this dataset, we implement the following procedure.

First, for each U.S. trading partner and for each commodity, we sum all U.S. exports and imports over the 2012-2018 period, and do the same for U.S. maritime exports and imports. We then subtract from these values all flows to and from Canada and Mexico to remove what is mostly road and rail transport from our analysis. We end up with a cross-sectional dataset that includes, for each HS6-digit product, the value of exports (maritime and total separately) plus imports between the United States and the rest of the world (excluding Canada and Mexico) between 2012 and 2018. Third, for each product, we estimate the share of that trade that is seaborne. If this share is greater than 60% in our baseline specification, we define that product as "maritime", and we define it as "non-maritime" otherwise.[22] Finally, in the full BACI database, we compute the

---

[22] Note that for 7 products, all trade flows to/from the U.S. are only with Canada and/or Mexico, which means we cannot know if they should be defined as "maritime". To avoid dropping too many observations, we assume that these products are mainly exported by sea and keep them in our final dataset.

value of maritime flows at the HS2-digit level by summing all HS6-digit flows associated with HS6-digit products defined as "maritime". After aggregation, our dataset covers 95 commodities[23]. All remaining flows (i.e., the values associated with HS6-digit products defined as "non-maritime") are then grouped into a specific category numbered 99. We thus end up with a sample of 95 maritime flows, corresponding to the "maritime" trade of each HS2-level category labeled from 1 to 96 (there is no category 77 in the latest HS2 classifications), plus a category 99 that includes all estimated "non-maritime" flows from all other categories. This last category is not used in the PPML estimation of the gravity equation, but is included in the counterfactual analysis based on the multisector structural gravity model (see section B.1).

As a robustness check, we apply the same procedure but using alternative thresholds of 50% and 70% instead of 60%. In addition, we also apply an alternative procedure inspired by Hummels and Schaur (2013, [32]), but modified to include more categories of goods. First, at the HS6-digit level, we identify all products which description contains the words "edible," "fresh," "frozen," "live," or "medicinal" (to capture perishable products), as well as "parts" or "components" (to capture intermediate products involved in lean manufacturing production). In the BACI database, we drop all these products from the sample and then aggregate all HS6-digit categories to the HS2-digit level to construct maritime flows. Finally, we also drop category number 97 (artworks) from the sample as this category is more likely to be transported by air (in line with U.S. trade data).

A.3 Estimation of intra-national trade

To estimate the value of intra-national trade by country and product, we use the CEPII Trade and Production (TradeProd) database, which provides data on both international and domestic flows for 9 industrial sectors from 1966 to 2018. While international trade data are extracted from Comtrade, domestic trade is estimated in this dataset using the UNIDO Industrial Statistics database (see Mayer et al., 2023, [37] for more details on the methodology). Despite the quality of the TradProd dataset, we had to deal with three issues. First, the TradeProd database does not cover all countries in our panel. More precisely, it provides country-level information for 152 countries over the period 2012-2018, and adds data for all other countries and territories that are grouped into a common "Rest of the World" category. Table A.2 lists all countries and territories grouped in this category. Second, the industry classification that is used in TradeProd is much coarser than the HS2-digit level classification. Finally, there is at least one missing year (up to six missing years) for 19 countries in the database. We describe below our methodological approach and the procedure used to deal with these issues.

We start by aggregating international exports by exporting country, year, and industry, and dividing intra-national flows by this value. We thus end up with a variable that indicates the average ratio of intra- to international flows at the country-year-industry level. For all countries

---

[23] In reality, 96 goods are defined at the HS2-digit level in our original dataset. However, all HS6 products are defined as maritime for the HS2-digit category number 97, which includes artworks, such as paintings, sculptures, antiques, and similar collections. This is not surprising as these products tend to be expensive and fragile, and are therefore likely to be exported by air. Moreover, it is not a problem to consider these flows as maritime and to exclude them from our regressions, since they represent less than 0.1% of all global flows over our period of interest.

Table A.2: List of countries defined as "Rest of the World" (Trade Prod database)

Rest of the World: American Samoa, Andorra, Anguilla, Antigua and Barbuda, Aruba, Bhutan, Bonaire, British Indian Ocean Territory, British Virgin Isds, Caymans Isds, Chad, Christmas Isds, Cocos Isds, Comoros, Cook Isds, Curacao, Dem. People's Rep. of Korea, Dem. Rep. of Congo, Djibouti, Dominica, Equatorial Guinea, Falkland Isds, French Southern Antarctic Territory, French Polynesia, Federated States of Micronesia, Gibraltar, Greenland, Grenada, Guam, Guinea, Guinea-Bissau, Guyana, Kiribati, Mali, Marshall Isds, Mauritania, Montserrat, Northern Mariana Isds, Nauru, New Caledonia, Niue, Norfolk Isds, Palau, Panama, Pitcairn, St Helena, St Kitts and Nevis, St Maarten, St Pierre and Miquelon, St Vincent and the Grenadines, Samoa, San Marino, Sao Tome and Principe, Seychelles, Sierra Leone, Solomon Isds, South Sudan, Timor-Leste, Togo, Tokelau, Turkmenistan, Turks and Caicos Isds, Tuvalu, Wallis and Futuna.

classified as "Rest of the World", we assign to this variable the average ratio of the rest of the world. We then associate each HS2-digit code with a specific industry (see Table A.3). Note that within each HS2 code, there may be HS6-digit products belonging to different industries. However, we always assign the HS2 code to the industry that has the highest number of HS6-digit products belonging to that industry. We then merge our BACI database with the ratios obtained and multiply, for each HS2-digit code, the sum of all the country's exports and the ratio of intra- to international trade. The values obtained for each country-year-product correspond to the value of intra-national trade for that country-year-product. Note that even if all countries classified as "Rest of the World" share the same ratios (which vary by year and industry), the sum of all exports still varies by country (and by year and product). Therefore, the final values of intra-national trade by year and product vary across "Rest of the World" countries.[24] Finally, we have to deal with the 19 countries for which at least one year is missing in the original Trade Prod dataset. For 12 of them, there is only one missing year (the year 2018)[25]. For these 12 countries, we estimate the missing value using the known value for the year 2017 and attribute to them the same trend of the ratio between 2017 and 2018 as for the "Rest of the World" (i.e., we estimate $CountryRatio_t = (RoWRatio_t / RoWRatio_{t-1}) * CountryRatio_{t-1}$). The 7 other countries with more than one missing year are dropped from the sample[26]. After all these modifications, we end up with a balanced panel of 185 countries.

A.4 Computation of trade costs

The sea distance between pairs of countries is extracted from the CERDI-SeaDistance database (Bertoli et al., 2016, [11]). It is constructed by assigning to each country a reference port used for international maritime trade. In that database, there is only one reference port for each country in the world, unless the country has access to different seas/oceans, in which case the country has a reference port in each sea/ocean to which it has access. The sea distance variable measures the bilateral sea distance (in kilometers) between each country's reference port (or between the two closest reference ports if a country has more than one reference port). If a country is landlocked,

---

[24] It should be noted that the ratio for product 99 (which includes all "non-maritime" flows) corresponds to the average of all ratios of all "non-maritime" products weighted by their relative share in total "non-maritime" flows.

[25] The Bahamas, Bosnia and Herzegovina, Algeria, Greece, Jordan, Kyrgyzstan, Lithuania, the Republic of North Macedonia, Myanmar, Namibia, Sudan, and Slovakia

[26] Bangladesh, Iraq, Papua New Guinea, Tonga, Trinidad and Tobago, Uzbekistan, and Venezuela

Table A.3: List of industries and equivalences HS2-digit products (rev.12) - Industry classification from Trade Prod database

Trade Prod Classification	HS2-digit Classification (rev. 12)
Food and Animal Products (ISIC 15; 16)	1 to 24
Textiles (ISIC 17; 18; 19)	41 to 43; 50 to 65
Wood and Paper (ISIC 20; 21; 22)	44 to 49
Chemicals (ISIC 23; 24; 25)	27 to 35; 37 to 40
Minerals (ISIC 26)	25; 68 to 70
Metals (ISIC 27; 28)	26; 71 to 76; 78 to 83
Machines (ISIC 29; 30; 31; 32; 33)	84; 85; 90; 91; 93
Vehicles (ISIC 34; 35)	86 to 89
Other (ISIC 36)	36; 66; 67; 92; 94 to 97

Note: There is no category 77 in the HS2-digit revision 12 Classification.

its reference port is the foreign port closest to its capital. Therefore, two countries can have a sea distance equal to 0 if (i) one country is landlocked and its reference port is located in the other country, or (ii) they are both landlocked and share the same reference port (located in a third country). In both cases, trade between the two countries is most likely to take place by land. For example, Botswana and Lesotho are both landlocked and their port of reference is located in South Africa: thus, the sea distance is zero for the pairs Botswana-South Africa, Lesotho-South Africa, and Botswana-Lesotho[27]. Finally, since trade costs between two neighboring countries are unlikely to be directly affected by a tax on marine fuel, we modify the original variable by replacing it with zero for pairs of countries that share a common land border.

Marine fuel prices are estimated annually using the average price of heavy fuel oil in the port of Rotterdam, obtained from the French National Institute of Statistics (INSEE). Since we are interested in the effect of variations in transportation costs, we assume that variations in the price of heavy fuel oil (HFO) in the port of Rotterdam are representative of variations in the price of heavy fuel oil in other areas of the world. Although this assumption is debatable, this variable is arguably a much better proxy for maritime trade costs (rather than land or air transport costs) than the use of crude oil prices, which is quite common in the literature. It should be noted that the price of fuel also depends on its sulphur content, which is subject to international regulations. Prior to 2012, the maximum sulphur content allowed by international standards for marine fuel was 4.5%, but this was reduced to 3.5% in 2012 and then to 0.5% in 2020 (IMO 2020 regulation). Therefore, there has been no change in international regulations during our reference period (2012-2018), so using the price of the same type of marine fuel over the entire period of interest is not an issue here. In addition, the price of HFO with 1% sulfur content and the price of HFO with 3.5% sulfur content are highly correlated (see Figure C.1), with a correlation coefficient of 0.9995 over 2012-2018, suggesting that using one or the other price is unlikely to affect our results. We therefore use the price of 1% sulphur HFO in the port of Rotterdam as our measure for global marine fuel price.

---

[27] Unfortunately, no data were available for South Sudan. However, since it is a landlocked country, we have simply reconstructed the sea distance variable by considering its reference port to be in Kenya.

A.5 Sector specific elasticities

To estimate our multisector structural gravity model of trade, we need a calibration of the trade elasticity for each product (the σ_k variable, see Appendix B.1 for more details). We use the CEPII database of tariff-based product elasticities (Fontagné et al., 2022, [26]). To construct this database, the authors estimated the trade elasticity of products to changes in bilateral tariffs up to 2016 at the HS4 and HS6 levels with worldwide coverage. We simply average all available values for products at the HS6 level to determine the elasticity for each HS2 category. For "non-maritime" flows, which are grouped into the additional sector 99, we simply use the simple average of all available elasticities. The values that we assign to each HS2 category are presented in Table A.4.

Table A.4: Elasticity of substitution by sector

HS2	Definition	σ_{50}	σ_{60}	σ_{70}	σ_{HS}
1	Live Animals	7.34	9.11	9.11	NA
2	Meat	8.72	8.72	8.72	5.98
3	Fish	8.11	7.44	7.16	13.59
4	Dairy	7.76	7.76	7.76	7.68
5	Non-Edible Animal Products	4.41	4.48	4.49	11.90
6	Plants	7.51	7.51	5.06	7.51
7	Vegetables	6.66	6.81	6.73	5.10
8	Fruits and Nuts	8.82	8.82	8.81	NA
9	Spices	5.09	5.09	5.09	5.94
10	Cereals	6.28	6.28	6.28	6.28
11	Flour	6.52	6.52	6.52	6.53
12	Seeds	6.62	6.62	6.62	7.05
13	Vegetable Saps and Extracts	5.45	5.82	5.82	5.45
14	Other Vegetable Products	7.96	7.96	7.96	7.96
15	Fats and Oils	9.48	9.48	9.48	9.54
16	Meat and Fish Preparations	8.36	8.36	8.36	8.28
17	Sugar	6.21	6.21	6.21	6.21
18	Cocoa	11.95	11.95	11.95	11.95
19	Food Preparations of Flour	7.41	7.41	7.33	7.41
20	Fruits and Vegetables Preparations	6.46	6.46	6.46	6.45
21	Sauces, Soups, Extracts, Essences, and Concentrates	6.68	6.68	6.63	6.68
22	Beverages	4.05	4.05	4.05	4.12
23	Residues from Food Products	11.27	11.27	11.27	11.27
24	Tobacco	3.28	3.29	3.29	3.28
25	Sands, Clays, and Minerals	14.84	15.07	15.07	14.74
26	Ores, Slag, Ashes, and Residues	22.69	22.69	22.69	22.69
27	Coal, Oil, and Gases	26.64	26.64	27.22	28.89
28	Gases, Acids, Oxides, and Similar Compounds	12.30	12.25	12.17	13.00
29	Hydrocarbons, Alcohols, Ethers, and Similar Compounds	13.76	13.86	14.06	13.40
30	Medicaments and Pharmaceutical Products	9.26	7.41	7.92	6.88
31	Fertilizers	16.68	16.68	16.68	16.68
32	Dyes and Paints	6.65	6.57	6.03	6.98
33	Cosmetics and Perfumes	7.08	6.89	6.69	7.08
34	Soaps, Waxes, and Lubricating Preparations	9.44	9.44	9.56	9.44
35	Glues and Enzymes	4.71	4.91	4.91	5.96
36	Pyrotechnic Products	11.09	11.09	11.09	8.35
37	Photographic and Cinematographic Products	5.84	6.42	8.08	6.50
38	Chemicals	8.23	8.28	8.23	8.16
39	Plastics	9.64	9.93	10.31	9.61
40	Rubber	9.22	9.36	8.76	9.12
41	Hides, Skins, and Leather	8.07	8.75	8.23	7.79
42	Leather Products	3.39	3.34	2.51	3.74
43	Furskins	3.83	3.83	4.28	8.08
44	Wood	10.50	10.43	10.44	10.63
45	Cork	5.50	5.50	6.05	6.96
46	Plaiting	3.61	3.61	3.35	3.61
47	Wood Pulp	17.27	17.27	17.27	17.27

HS2	Definition	σ_{50}	σ_{60}	σ_{70}	σ_{HS}
48	Paper	10.00	10.03	10.07	9.91
49	Printed or Illustrated Products	8.03	7.94	6.68	9.62
50	Silk	5.75	5.75	5.75	5.75
51	Wool and Fabrics	20.93	21.33	22.02	18.48
52	Coton Yarn and Fabrics	10.13	10.41	10.86	9.97
53	Yarn	16.15	17.66	17.66	16.15
54	Synthetic Yarn and Synthetic Fabrics	10.53	10.93	11.51	10.35
55	Synthetic Fibres and Fabrics	9.95	10.10	10.49	9.93
56	Nonwovens, Twines, Cordage, or Rops	7.25	7.43	7.43	7.14
57	Carpets and Textile Floors	5.31	5.31	5.44	5.31
58	Other Ornemental Fabrics	6.02	5.78	6.15	5.56
59	Textile Products and Articles for Technical Uses	9.56	10.03	11.00	9.56
60	Knitted or Crocheted Fabrics	6.39	6.34	6.55	6.39
61	Knitted or Crocheted Clothes	5.54	5.77	5.75	5.15
62	Non-Knitted nor Crocheted Clothes	3.50	3.69	3.79	3.37
63	Other Linen	5.14	5.09	5.05	5.05
64	Footwear	4.71	4.71	4.86	4.96
65	Hats	3.48	4.52	4.52	4.13
66	Umbrellas	7.24	7.24	7.24	7.24
67	Artificial Hair and Artificial Vegetals	2.42	2.42	2.23	3.23
68	Marble, Stones, Plaster, and Similar	9.04	9.41	9.32	9.19
69	Bricks, Blocks, and Tiles	5.79	5.86	6.35	5.80
70	Glass	7.47	7.20	7.16	7.14
71	Precious Stones and Precious Metals	24.85	24.85	25.43	16.71
72	Iron and Steel	13.08	13.08	13.17	13.10
73	Iron and Steel Products	7.09	7.22	7.24	7.35
74	Copper	14.32	14.32	14.62	14.42
75	Nickel	20.11	18.68	20.52	16.79
76	Aluminium	9.91	9.85	10.08	10.16
78	Lead	12.02	11.54	13.17	12.02
79	Zinc	22.35	22.35	22.35	22.35
80	Tin	24.35	27.21	27.21	24.35
81	Other Metals	15.08	14.95	12.13	13.69
82	Hand Tools	4.46	4.43	4.56	5.02
83	Safety and Ornament Metal Based Products	4.89	4.87	4.88	4.79
84	Machinery	7.16	7.22	7.33	7.33
85	Electrical Equipment	6.26	6.41	6.46	6.72
86	Railway or Tramway Locomotives	20.55	20.55	21.05	18.45
87	Vehicles and Parts	9.21	9.21	9.32	10.28
88	Spacecrafts and Parts	14.81	14.81	NA	9.70
89	Vessels	8.56	9.01	9.01	8.02
90	Optical Products	5.46	4.52	4.77	6.20
91	Clocks and Watches	3.68	3.68	3.76	7.43
92	Musical Instruments	8.34	8.34	6.71	7.77
93	Firearms and Ammunitions	5.82	6.25	5.92	8.05
94	Seats and Bedroom Furnitures	7.68	7.70	7.90	8.08
95	Games and Sport Equipment	5.56	5.62	5.91	5.94
96	Brushes, Pens, and Lighters	3.75	3.90	4.05	4.19
97	Artworks	NA	NA	NA	NA
99	Airborne Products	8.49	8.04	7.95	7.57

Source: CEPII, Fontagné et al., 2022, [26]

A.6 Estimation of fiscal revenues and carbon emissions

Carbon intensity per type of vessel is taken from the French Ministry of Ecological Transition (2018, [38]), which estimates the average level of CO_2 emissions per ton (of goods) per kilometer traveled for different modes of transportation. This official report provides several estimates for each type of ship (bulk carrier, container ship, oil tanker, chemical tanker, ro-ro ship, etc.) as well as for air (plane) and land (truck and train) transport. We associate each HS2 product with one type of vessel, based on the nature of the product. However, the average carbon intensity per kilometer of a ton of goods also depends on the size of the ship transporting it. Since we cannot know for each bilateral flow what the average size of the vessel used for transport is, we create two extreme scenarios: (i) a minimum scenario, where we assign to each ship the minimum carbon intensity value of that ship type, and (ii) a maximum scenario, where we assign to each ship the maximum carbon intensity value of that ship type. One issue arises with product 1 ("live animals"). In fact, live animals are usually transported on special ships that are much more carbon intensive than conventional container ships, but no data are available in the report for live animal cargo. To solve this problem, we assign product 1 the carbon intensity (CI) of container ships in the minimum CI scenario and the value of ro-ro ships (the most carbon intensive ships) in the maximum CI scenario. It should be noted, however, that this choice is unlikely to affect our final estimates due to the very small share of live animals transported by sea in total maritime flows (less than 0.1%).

Products in the "non-maritime" sector are associated with air transport for flows between non-neighboring countries. For air transport, the carbon intensity per kilometer depends primarily on the average distance traveled (due to emissions from takeoff, the average carbon intensity per kilometer decreases as the number of kilometers increases), and values are reported in this report by distance categories (less than 1,000 kilometers, between 1,000 and 4,000 kilometers, etc.). Since the average distance traveled by air in our database is estimated to be about 1,600 kilometers, we attribute the average value of the 1,000-4,000 km category (which is 1,065 grams of CO_2 per ton.kilometer) to air transportation.

All flows between neighboring countries are associated with land transport. For this type of transport we use the estimate of 85 grams of CO_2 per ton-kilometer traveled for scenario 1 where we assume that all land transport is by road (i.e., by truck), while we use the estimate of 13.5 grams of CO_2 per ton-kilometer traveled for scenario 2 where we assume that all land transport is by rail. Notice that in this latter case, the carbon intensity corresponds to that of electric trains with a European energy mix. It is very likely to be a lower bound on carbon intensity of land transport, just as scenario 1 is likely to be a higher bound on carbon intensity of land transport. Data on the type of vessel assigned to each product, as well as the minimum and maximum carbon intensity per vessel, are provided in Table A.5.

Finally, we use the CERDI-SeaDistance database to obtain estimates of the road distance between the capital of each country and its (domestic or foreign) port of reference. For countries where the capital is also the reference port (mostly small islands), this distance is zero. Based on this variable, we estimate the road distance for each pair of countries by summing the capital - port of reference distance for the exporting and importing country[28].

---

[28] Unfortunately, road distance data are missing for three countries in the sample: South Sudan, the Democratic Republic of the Congo, and Ukraine. For these countries, we estimated the road distance between the capital city and the port using a simple Google query. We obtain 1617 km for South Sudan (distance Juba - Mombasa), 346 km for DR Congo (Kinshasa - Matadi), and 475 km for Ukraine (Kyiv - Odessa).

Table A.5: List of vessels, sectors, and carbon intensities

Vessel	HS2 sectors	Min. CI	Max. CI
Bulk Carrier	02; 03; 07; 08; 10; 11; 12; 13; 14; 15; 22; 23; 25; 26; 31; 44	3.65	11.10
Container Ship	01; 04; 05; 06; 09; 16; 17; 18; 19; 20; 21; 24; 30; 37; 39; 40; 41; 42; 43; 45-85; 89; 90; 91; 92; 93; 94; 95; 96	10.02	21.90
Oil Tanker	27	3.36	18.70
Chemical Tanker	28; 29; 32; 33; 34; 35; 36; 38	14.70	54.70
Ro-Ro Ship	01; 86; 87; 88; 89	103	
Plane	99	1065	
Truck	All Products if $Border = 1$	85	
Train	All Products if $Border = 1$	13.5	

Note: Carbon Intensity (CI) is expressed in $gCO2.ton^{-1}.km^{-1}$. There is no category 77 in the HS2-digit revision 12 classification.
Source: Ministère de la Transition écologique et solidaire (2018) and authors.

B Appendix: Structural gravity and computations

B.1 Multisector model

We consider a multisector Armington model along the lines of Larch and Yotov (2016, [36]). On the demand side, for each sector k consumer preferences are assumed to be identical across countries and represented by a Constant Elasticity of Substitution (CES) utility function given, for country j, by :

$$U_{jk} = \left\{ \sum_{i=1}^{N} \beta_{ik}^{\frac{1-\sigma_k}{\sigma_k}} c_{ij}^{\frac{\sigma_k - 1}{\sigma_k}} \right\} \tag{B.1}$$

where N is the number of countries in the world, $\sigma_k > 1$ is the elasticity of substitution among different varieties in sector k, i.e. goods produced in different countries, β_{ik} is a parameter characterizing in sector k the preference for goods produced in country i, while c_{ijk} denotes the consumption in country j of the sector k variety produced in country i. These sectoral preferences are nested in a Cobb-Douglas function to define the aggregate preferences of the representative consumer in country j :

$$U_j = \Pi_{k=1}^{K} \left\{ \sum_{i=1}^{N} \beta_{ik}^{\frac{1-\sigma_k}{\sigma_k}} c_{ij}^{\frac{\sigma_k - 1}{\sigma_k}} \right\}^{\alpha_{jk}}$$

where K is the total number of sectors, and the parameters α_{jk} can be country specific and sum up to 1, i.e. verify $\sum_{k=1}^{K} \alpha_{jk} = 1$ for all country j.

On the supply side, each country i produces a fixed quantiy Q_{ik} in sector k that is sold at (endogenous) factory gate price p_{ik} so that the value of sector k production in country i is $Y_{ik} = p_{ik} Q_{ik}$. The representative consumer in country j maximizes (B.1) subject to the budget constraint

$$\sum_{i=1}^{N} p_{ijk} c_{ijk} = E_{jk}$$

where E_{jk} is the total expenditure dedicated to sector k in country j, p_{ijk} is the delivered price in country j of sector k goods produced in country i, with $p_{ijk} = p_{ik} t_{ijk}$. In the latter equality $t_{ijk} \geq 1$ is the iceberg bilateral trade cost from country i to country j that applies to sector k. It represents the quantity of sector k good to be bought in country i for one unit of that good to be consumed in country j. Solving for the consumer's constrained optimization problem yields

$$Y_{ijk} = \left(\frac{\beta_{ik} p_{ik} t_{ijk}}{P_{jk}} \right)^{1-\sigma_k} E_{jk} \tag{B.2}$$

where Y_{ijk} is the amount spent by country j to buy sector k goods produced by country i and

$$P_{jk} = \left(\sum_{i=1}^{N} (\beta_{ik} p_{ik} t_{ijk})^{1-\sigma_k} \right)^{\frac{1}{1-\sigma_k}} \tag{B.3}$$

can be interpreted as a consumer price index for sector k in country j. The next step consists in imposing market clearance in each sector for goods from each origin :

$$Y_{ik} = \sum_{j=1}^{N} Y_{ijk} = \sum_{j=1}^{N} \left(\frac{\beta_{ik} p_{ik} t_{ijk}}{P_{jk}} \right)^{1-\sigma_k} E_{jk} \tag{B.4}$$

In this model, we allow for trade imbalances and assume that

$$\sum_{k=1}^{K} E_{ik} = \phi_i \left(\sum_{k=1}^{K} Y_{ik} \right)$$

where the left hand-side represents the aggregate expenditures by country i while the term in parenthesis in the right-hand side represents the aggregate value of sales by country i. When $\phi_i > 1$ country i exhibits a trade deficit, while $\phi_i < 1$ corresponds to a positive trade balance. It is worth noticing that in this Armington model, the ϕ_i are parameters and will be considered as fixed in the forthcoming counterfactual exercise. Exploiting a property of Cobb-Douglas preferences, we know that the share of expenditures in each sector k by consumers in country i is given by the parameter α_{ik}, so we can deduce that

$$E_{ik} = \alpha_{ik} \phi_i Y_i$$

where $Y_i = \sum_{k=1}^{K} Y_{ik}$. Next, we can rearrange the terms in equation(B.4) to obtain

$$(\beta_{ik} p_{ik})^{1-\sigma_k} = \frac{Y_{ik}}{\Pi_{ik}^{1-\sigma_k}} \tag{B.5}$$

where $\Pi_{ik}^{1-\sigma_k} = \sum_{j=1}^{N} \left(\frac{t_{ijk}}{P_{jk}} \right)^{1-\sigma_k} E_{jk}$. We can then use the expression obtained in equation(B.5) for $\beta_{ik} p_{ik}$ to subsitute in equations (B.2) and (B.3) to obtain the structural gravity system

$$Y_{ijk} = \left(\frac{t_{ijk}}{P_{jk} \Pi_{ik}} \right)^{1-\sigma_k} Y_{ik} E_{jk} \tag{B.6}$$

$$P_{jk}^{1-\sigma_k} = \sum_i \left(\frac{t_{ijk}}{\Pi_{ik}}\right)^{1-\sigma_k} Y_{ik} \tag{B.7}$$

$$\Pi_{ik}^{1-\sigma_k} = \sum_j \left(\frac{t_{ijk}}{P_{jk}}\right)^{1-\sigma_k} E_{jk} \tag{B.8}$$

$$E_{ik} = \alpha_{ik}\phi_i Y_i \tag{B.9}$$

A normalization is required to pin down a unique solution in simulations. In the counterfactual exercise, we will follow Anderson and Yotov ([4]) and assume that nominal resources are held constant so that

$$\sum_{i=1}^{N} Y_i = Y = \bar{Y} \tag{B.10}$$

B.2 Maritime distance and trade costs

Adapting equation (B.6) to a panel data setting, we can write

$$Y_{ijkt} = \left(\frac{t_{ijkt}}{P_{jkt}\Pi_{ikt}}\right)^{1-\sigma_k} Y_{ikt}E_{jkt} \tag{B.11}$$

We define iceberg trade costs t_{ijkt} to be equal to 1 plus some trade frictions, some of which related to maritime transport variable costs. Specifically we assume that

$$t_{ijkt}^{1-\sigma_k} = \exp[\beta_k C_{ijt} + \gamma_k.X_{ijt}]$$

where X_{ijt} is a vector of control variables, defined at the dyadic (i.e. importer - exporter) level, that influence trade costs such as contiguity, common language, former colonial ties, etc. and where

$$C_{ijt} = \ln(1 + SeaDist_{ij}.p_t) \tag{B.12}$$

is the component of trade costs related to maritime transport variable costs which are proportional to the maritime distance between country i and country j (measured by $SeaDist_{ij}$). In the expression above, p_t is the average maritime fuel price in year t. The specific expression of C_{ijt} ensures that iceberg trade costs t_{ijkt} can always be computed even when $SeaDist_{ij} = 0$ which occurs for adjacent countries or countries that share a common port of reference. Notice also that $C_{ijt} = 0$ whenever $SeaDist_{ij} = 0$ and t_{ijkt} is not impacted by p_t in that case. Coming back to equation (B.11), we can replace t_{ijkt} and obtain

$$Y_{ijkt} = \exp\left[\beta_k \ln(1 + SeaDist_{ij}.p_t) + \gamma_k.X_{ijt} + \ln(I_{ikt}) - \ln(\Pi_{ikt}^{1-\sigma_k}) + \ln(E_{jkt}) - \ln(P_{jkt}^{1-\sigma_k})\right]$$

which brings our central econometric specification (equation (1) in section 4)

$$Y_{ijkt} = \exp\left[\beta_k \ln(1 + SeaDist_{ij}.p_t) + \gamma_k.X_{ijt} + F_{ikt} + G_{jkt}\right]\epsilon_{ijkt} \tag{B.13}$$

where F_{ikt} is an exporter.product.time fixed effect capturing the outward multilateral resistance to trade while G_{jkt} is an importer.product.time fixed effect capturing the inward multilateral resistance to trade.

Our counterfactual exercise consists in looking at the consequences of imposing a specific international tax T on maritime fuel. Assuming full pass-through of the specific tax, the actual (C_{ijt}, t_{ijkt}) and counterfactual (C^c_{ijt}, t^c_{ijkt}) transport cost variables verify the following :

$$C^c_{ijt} = \ln(1 + SeaDist_{ij}.(p_t + T)) = C_{ijt} + \ln\left(\frac{1 + SeaDist_{ij}.(p_t + T)}{1 + SeaDist_{ij}.p_t}\right).$$

and

$$t^c_{ijkt} = \exp\left[\left(\frac{1}{1-\sigma_k}\right)\beta_k \ln\left(\frac{1 + SeaDist_{ij}.(p_t + T)}{1 + SeaDist_{ij}.p_t}\right)\right] t_{ijkt}$$

or

$$\hat{t}_{ijkt} = \frac{t^c_{ijkt}}{t_{ijkt}} = \left(\frac{1 + SeaDist_{ij}.(p_t + T)}{1 + SeaDist_{ij}.p_t}\right)^{\frac{\beta_k}{1-\sigma_k}}. \tag{B.14}$$

B.3 Exact hat algebra with multiple sectors

In this subsection we build upon the "*exact hat algebra*" approach pioneered by Dekle et al. ([21], [22]) and adapted to the one-sector Armington model by Anderson et al. ([2]) or Baier et al. ([8]). We extend the analysis to the multiple sector setting. We want to compare two situations for which the structural gravity system (B.6) to (B.10) holds : a baseline situation (Y_{ijk}, t_{ijk}) in which trade flows Y_{ijk} are observed and for wich trade costs t_{ijk} can be estimated ; and a counterfactual situation (Y^c_{ijk}, t^c_{ijk}) in which trade costs t^c_{ijk} can be computed from the baseline t_{ijk} and result from the implementation of a specific international tax T on maritime fuel. As in equation (B.14) above, superscript c will be used for counterfactual values, baseline values will not be indexed, while hat variables will be defined as the ratio of the counterfactual value over the value at baseline.

In our fixed endowment setting,

$$\frac{Y_{ik}}{p_{ik}} = \frac{Y^c_{ik}}{p^c_{ik}} \text{ so that } \hat{p}_{ik} = \hat{Y}_{ik}.$$

Let us denote

$$\lambda_{ijk} = \frac{Y_{ijk}}{E_{jk}} \tag{B.15}$$

the share of country j's sector k expenditures on good produced by country i. Exploiting the fact that equations (B.2) and (B.3) are verified both at baseline and for the counterfactual we can write that

$$\lambda_{ijk} = \frac{(\beta_{ik}p_{ik}t_{ijk})^{1-\sigma_k}}{\sum_{l=1}^{N}(\beta_{lk}p_{lk}t_{ljk})^{1-\sigma_k}} \text{ and } \lambda^c_{ijk} = \frac{(\beta_{ik}p^c_{ik}t^c_{ijk})^{1-\sigma_k}}{\sum_{l=1}^{N}(\beta_{lk}p^c_{lk}t^c_{ljk})^{1-\sigma_k}},$$

and from the equality on the left,

$$\frac{1}{\sum_{l=1}^{N}(\beta_{lk}p_{lk}t_{ljk})^{1-\sigma_k}} = \frac{\lambda_{ijk}}{(\beta_{ik}p_{ik}t_{ijk})^{1-\sigma_k}},\ \forall i, 1 \leq i \leq N,$$

so that

$$\hat{\lambda}_{ijk} = \frac{\left(\hat{Y}_{ik}\hat{t}_{ijk}\right)^{1-\sigma_k}}{\sum_{l=1}^{N}\lambda_{ljk}\left(\hat{Y}_{lk}\hat{t}_{ljk}\right)^{1-\sigma_k}}.$$

We can further exploit the fact that counterfactual income levels Y^c_{ik} verify

$$Y^c_{ik} = \sum_{j=1}^{N}\lambda^c_{ijk}\alpha_{jk}\phi_j Y^c_j$$

in order to obtain that

$$\hat{Y}_{ik}Y_{ik} = \sum_{j=1}^{N}\frac{\lambda_{ijk}\left(\hat{Y}_{ik}\hat{t}_{ijk}\right)^{1-\sigma_k}}{\sum_{l=1}^{N}\lambda_{ljk}\left(\hat{Y}_{lk}\hat{t}_{ljk}\right)^{1-\sigma_k}}\alpha_{jk}\phi_j\hat{Y}_j Y_j$$

which can be equivalently rewritten

$$\hat{Y}_{ik} = \left[\frac{1}{Y_{ik}}\sum_{j=1}^{N}\frac{\lambda_{ijk}\left(\hat{t}_{ijk}\right)^{1-\sigma_k}}{\hat{P}^{1-\sigma_k}_{jk}}\alpha_{jk}\phi_j\hat{Y}_j Y_j\right]^{\frac{1}{\sigma_k}}$$

The computation of the general equilibrium effects of the counterfactual trade costs t^c_{ijk} can be computed from the following system of equations:

$$\hat{Y}_{ik} = \left[\frac{1}{Y_{ik}}\sum_{j=1}^{N}\frac{\lambda_{ijk}\left(\hat{t}_{ijk}\right)^{1-\sigma_k}}{\hat{P}^{1-\sigma_k}_{jk}}E^c_{jk}\right]^{\frac{1}{\sigma_k}} \tag{B.16}$$

$$\hat{Y}_{ik} = \hat{Y}_{ik}\frac{Y}{\sum_{j=1}^{N}\sum_{l=1}^{K}\hat{Y}_{jl}Y_{jl}} \tag{B.17}$$

$$\hat{P}_{jk} = \left[\sum_{l=1}^{N}\lambda_{ljk}\left(\hat{Y}_{lk}\hat{t}_{ljk}\right)^{1-\sigma_k}\right]^{\frac{1}{1-\sigma_k}} \tag{B.18}$$

$$E^c_{jk} = \alpha_{jk}\phi_j\hat{Y}_j Y_j \tag{B.19}$$

The solution of this system (which is what we are looking for) can be obtained by a fixed point iterative procedure that starts with $E^c_{jk} = \sum_{i=1}^{N} Y_{ijk}$ and $\hat{P}_{jk} = 1$ and then uses baseline flows and shares together with counterfactual trade costs and equation (B.16) to update $\hat{Y}_{ik}$, equation (B.17) to renormalize trade flows, then equation (B.18) to update $\hat{P}_{jk}$ and equation (B.19) to update E^c_{jk}, until convergence. The algorithm is depicted in more details in next subsection. Notice that the presence of equations (B.17) and (B.19) in this system implies that general equilibrium effects cannot be computed sector by sector and then aggregated.

As in a one sector model, we remark here that in order to compute the general equilibrium effects of a counterfactual experiment (e.g. the specific tax T in this paper) we only need to know the baseline flows Y_{ijk}, the parameters σ_k and the ratio of the counterfactual trade costs over the baseline trade costs. As it appears clearly in equation (B.14), computing such a ratio a priori requires the estimation of baseline trade costs : in our case it requires having estimated the β_k coefficients from equation (B.13).

The parameters ϕ_i can be computed from the baseline flows via the defining identity $\phi_i = \frac{E_i}{Y_i}$, while the parameters α_{ik} can also be computed from the baseline flows as $\alpha_{ik} = \frac{E_{ik}}{E_i}$.

In this multisector model, welfare in country i is measured by the real consumption in that country. The aggregate price index that needs to be taken into account for country i is

$$P_i = \Pi_{k=1}^{K} P_{ik}^{\alpha_{ik}} \tag{B.20}$$

so that welfare in country i is measured by the ratio

$$W_i = \frac{\sum_{k=1}^{K} E_{ik}}{\Pi_{k=1}^{K} P_{ik}^{\alpha_{ik}}} = \frac{E_i}{P_i}$$

And the change in welfare is given by

$$\hat{W}_i = \frac{\hat{E}_i}{\hat{P}_i} = \frac{\hat{Y}_i}{\hat{P}_i} \tag{B.21}$$

where the latter equality comes from $E_i = \phi_i Y_i$, and ϕ_i is a parameter not affected by the tax. It is then possible to quantify in monetary terms for each country the economic cost related to the effect of the tax on trade by computing

$$(1 - \hat{W}_i)E_i.$$

That amount is the representative consumer budget loss, evaluated at baseline prices, which corresponds to the welfare loss due to the tax. We can then aggregate over all countries to obtain a monetary equivalent of the welfare losses incurred worldwide.

$$\sum_i (1 - \hat{W}_i)E_i. \tag{B.22}$$

The amount resulting from this last formula will be compared to the tax potential in order to evaluate the marginal cost of funds raised by the maritime tax.

B.4 Algorithm for computing equilibrium in the multisector model

We provide in this subsection more details on the algorithm used to compute the general equilibrium effects. It extends the algorithm used by the package *ge_gravity* developped by Tom Zylkin for the one sector Armington model (Baier et al. [8]). [29]

Entries[30]

$$\begin{cases} N := \cdot & \text{number of countries} \\ K := \cdot & \text{number of sectors} \\ \sigma_k := \cdot & \text{vector } 1 \times K, \text{sectoral elasticities of substitution} \\ Y_{ijk} := \cdot & \text{tensor } N \times N \times K \text{ of baseline trade flows in value} \\ \hat{t}_{ijk} := \cdot & \text{tensor } N \times N \times K \text{ of transport costs ratios - counterfactual/baseline} \end{cases}$$

Preliminary computations

$$\begin{cases} Y_{ik} & = \sum_{j=1}^{N} Y_{ijk} & \text{matrix } N \times K, \text{check : } Y_{ik} > 0 \\ Y_i & = \sum_{k=1}^{K} Y_{ik} & \text{vector } 1 \times N, \text{ total revenue in country } i \\ Y & = \sum_{i=1}^{N} Y_i & \text{number, total nominal value of trade} \\ E_{jk} & = \sum_{i=1}^{N} Y_{ijk} & \text{matrix } N \times K, \text{check : } E_{jk} > 0 \\ E_j & = \sum_{k=1}^{K} E_{jk} & \text{vector } 1 \times N, \text{ total expenditures of country } j \\ \lambda_{ijk} & = \frac{Y_{ijk}}{E_{jk}} & \text{tensor } N \times N \times K, \text{ share of country } j \text{ expenditures} \\ & & \text{ devoted to country } i \text{ - for sector } k \\ \phi_i & = \frac{E_i}{Y_i} & \text{vector } 1 \times N, \text{measure of trade imbalances in country } i \\ & & \text{- will not be affected by the tax} \\ \alpha_{ik} & = \frac{E_{ik}}{E_i} & \text{matrix } N \times K, \text{ calibration of the Cobb-Douglas utility function} \\ & & \text{of country } i \text{ representative consumer} \end{cases}$$

Initialisation

$$\begin{cases} \hat{P}_{ik}^{(0)} & = 1, & \forall i, k & \text{matrix } N \times K, \\ E_{ik}^{c(0)} & = E_{ik}, & \forall i, k & \text{matrix } N \times K, \\ \hat{Y}_{ik}^{(0)} & = 1, & \forall i, k & \text{matrix } N \times K, \\ \tilde{Y}_{ik}^{(0)} & = 1, & \forall i, k & \text{matrix } N \times K. \end{cases}$$

Iterative step n

$$\begin{cases} \tilde{Y}_{ik}^{(n)} & = \left[\frac{1}{Y_{ik}} \sum_{j=1}^{N} \frac{\lambda_{ijk} \left(\hat{t}_{ijk} \right)^{1-\sigma_k}}{(\hat{P}_{jk}^{(n-1)})^{1-\sigma_k}} E_{jk}^{c(n-1)} \right]^{\frac{1}{\sigma_k}} & \forall i, k, \\ \hat{Y}_{ik}^{(n)} & = \tilde{Y}_{ik}^{(n)} \frac{Y}{\sum_{j=1}^{N} \sum_{l=1}^{K} \tilde{Y}_{jl}^{(n)} Y_{jl}} & \forall i, k, \\ \hat{P}_{jk}^{(n)} & = \left[\sum_{l=1}^{N} \lambda_{ljk} \left(\hat{Y}_{lk}^{(n)} \hat{t}_{ljk} \right)^{1-\sigma_k} \right]^{\frac{1}{1-\sigma_k}} & \forall j, k, \\ E_{jk}^{c(n)} & = \alpha_{jk} \phi_j \sum_{l=1}^{K} \hat{Y}_{jl}^{(n)} Y_{jl} & \forall j, k. \end{cases}$$

---

[29] see `http://www.tomzylkin.com/uploads/4/1/0/4/41048809/help_file.pdf`

[30] To avoid division by zero issues we set a minimal value of 1 \$ for intranational flows and replace $Y_{iik} = 0$ by $Y_{iik} = 1\$$ when necessary.

Stopping condition

$$\left|\frac{\hat{Y}_{ik}^{(n)}-\hat{Y}_{ik}^{(n-1)}}{\hat{Y}_{ik}^{(n-1)}}\right| \leq \epsilon = 0,001, \quad \forall i, k.$$

Final computations

$$\begin{cases} \hat{Y}_{ik} & := \hat{Y}_{ik}^{(n)} & \forall i, k, \\ \hat{P}_{jk} & := \hat{P}_{jk}^{(n)} & \forall j, k, \\ E_{jk}^{c} & := E_{jk}^{c(n)} & \forall j, k. \end{cases}$$

and

$$\begin{cases} E_i^c & = \sum_{k=1}^{K} E_{ik}^c, & \forall i, \\ \hat{\lambda}_{ijk} & = \frac{\left(\hat{Y}_{ik}\hat{t}_{ijk}\right)^{1-\sigma_k}}{\sum_{l=1}^{N} \lambda_{ljk}\left(\hat{Y}_{lk}\hat{t}_{ljk}\right)^{1-\sigma_k}}, & \forall i, j, k, \\ \hat{P}_i & = \Pi_{k=1}^{K}(\hat{P}_{jk})^{\alpha_{ik}}, & \forall i, \\ \hat{W}_i & = \frac{E_i^c}{E_i}\frac{1}{\hat{P}_i}, & \forall i, \\ Y_{ijk}^c & = \hat{\lambda}_{ijk}\frac{E_{jk}^c}{E_{jk}} Y_{ijk}, & \forall i, j, k. \end{cases}$$

Output

$$\begin{cases} \hat{W}_i & \text{vector } 1 \times N & \text{welfare (purchasing power) variation in country } i \text{ ,} \\ \hat{P}_i & \text{vector } 1 \times N & \text{consumer price index variation in country } i \text{ ,} \\ Y_{ijk}^c & \text{tensor } N \times N \times K & \text{counterfactual trade flows in value.} \end{cases}$$

B.5 Distances and carbon emissions

B.5.1 Maritime distances

The multisector model can be used to obtain quantitative results by products. We can compute

$$\hat{Y}_k = \frac{Y_k^c}{Y_k} = \frac{\sum_{i=1}^{N} \hat{Y}_{ik} Y_{ik}}{\sum_{i=1}^{N} Y_{ik}}$$

which is the ratio of total value of production in sector k in the counterfactual over the total value of production in sector k in the baseline. It is a measure of how a given sector is impacted by the tax. Notice that since we keep the total value of production constant in our model, $\hat{Y}_k$ will take values below and above 1 : the value of production in some sectors will increase with the tax while it will decrease in others.

The tax redistributes trade flows and trading partners. On average, it will likely reduce the distance that goods travel. To document this distance reduction we compute the average distance traveled by 1 dollar of goods in sector k as

$$AverageSeaDist_k = \frac{\sum_{i=1}^{N} \sum_{j=1}^{N} Y_{ijk} SeaDist_{ij}}{\sum_{i=1}^{N} \sum_{j=1}^{N} Y_{ijk}}$$

and its variation as

$$\widehat{AverageSeaDist_k} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\hat{Y}_{ijk}Y_{ijk}SeaDist_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{N}Y_{ijk}SeaDist_{ij}}\frac{1}{\hat{Y}_k} \tag{B.23}$$

This indicator (likely taking values between 0 and 1) is also a measure of how a given sector is affected by the tax. When we are interested in average distance at an aggregate level as in section 6.1 we compute

$$AverageSeaDist = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{K}Y_{ijk}SeaDist_{ij}}{\bar{Y}}$$

and its variation as

$$\widehat{AverageSeaDist} = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{K}\hat{Y}_{ijk}Y_{ijk}SeaDist_{ij}}{\sum_{i=1}^{N}\sum_{j=1}^{N}\sum_{k=1}^{K}Y_{ijk}SeaDist_{ij}} \tag{B.24}$$

B.5.2 Reduction in emissions from maritime transport

In order to evaluate how the tax will reduce emissions we proceed as follows. First, we compute variations of flows in quantities (instead of variations in value) where quantities are given by $Q_{ijk} = \frac{Y_{ijk}}{p_{ik}}$. Since Q_{ik} is constant in our fixed endowment Armington model we deduce that

$$\hat{p}_{ik} = \hat{Y}_{ik} \tag{B.25}$$

and therefore

$$\hat{Q}_{ijk} = \frac{\hat{Y}_{ijk}}{\hat{Y}_{ik}}$$

From the BACI database, we know what is the volume in metric tons of every bilateral trade flow at the HS6 level of disaggregation. Therefore, at the HS2 level, we know the baseline quantities Q_{ijk}, from which we can compute the counterfactual quantities as

$$Q^c_{ijk} = \hat{Q}_{ijk}Q_{ijk} = \frac{\hat{Y}_{ijk}}{\hat{Y}_{ik}}Q_{ijk}$$

The total ton.kilometers transported by vessel in the baseline in (“maritime”) sector k is

$$\sum_{i=1}^{N}\sum_{j=1}^{N}Q_{ijk}SeaDist_{ij},$$

while in the counterfactual it is

$$\sum_{i=1}^{N}\sum_{j=1}^{N}\hat{Q}_{ijk}Q_{ijk}SeaDist_{ij}.$$

The reduction (likely to be positive for all sectors) in tons.kilometers due to the tax is therefore

$$\Delta Dist_k = \sum_{i=1}^{N}\sum_{j=1}^{N}(1-\hat{Q}_{ijk})Q_{ijk}SeaDist_{ij} \tag{B.26}$$

To each sector we can match a type $C(k)$ of carrier (tanker, container ship, bulk carrier, etc., see Table A.5). For each type of carrier it is possible to obtain information on the carbon intensity $CarbonInt_C$ (in gram of CO_2 per ton.kilometer, see also Table A.5) The reduction in the maritime sector emissions is then given by

$$\Delta Emissions = \sum_{k=1}^{K} \Delta Dist_k CarbonInt_{C(k)}.$$

and the relative reduction is

$$\frac{\Delta Emissions}{Emissions} = \frac{\sum_{k=1}^{K} \Delta Dist_k CarbonInt_{C(k)}}{\sum_{k=1}^{K} \left(\sum_{i=1}^{N} \sum_{j=1}^{N} Q_{ijk} SeaDist_{ij}\right) CarbonInt_{C(k)}}$$

which can be written

$$\frac{\Delta Emissions}{Emissions} = \frac{\sum_{k=1}^{K} \left(\sum_{i=1}^{N} \sum_{j=1}^{N} (1 - \frac{\hat{Y}_{ijk}}{\hat{Y}_{ik}}) Q_{ijk} SeaDist_{ij}\right) CarbonInt_{C(k)}}{\sum_{k=1}^{K} \left(\sum_{i=1}^{N} \sum_{j=1}^{N} Q_{ijk} SeaDist_{ij}\right) CarbonInt_{C(k)}}. \tag{B.27}$$

C Appendix: Additional tables and figures

Figure C.1: Evolution of heavy fuel oil price in the port of Rotterdam

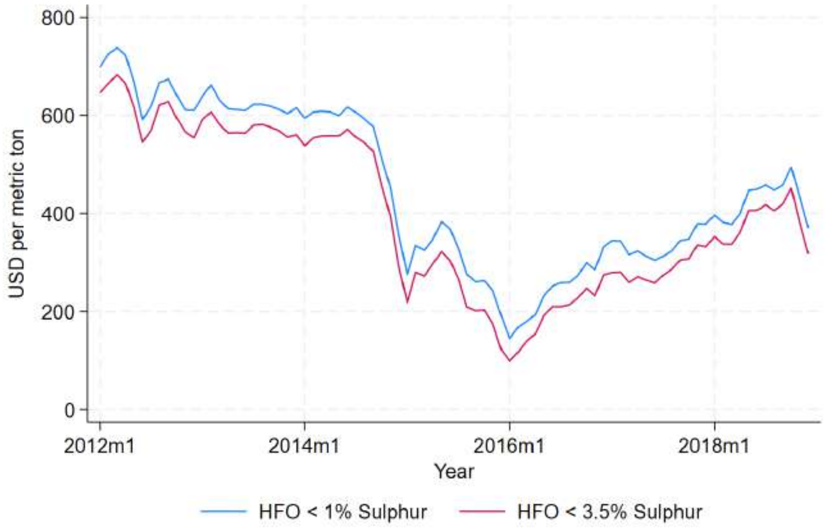


Table C.1: List of partial elasticities by sectors

Code	Definition	β_{50}	β_{60}	β_{70}	β_{HS}
1	Live Animals	-0.9964	-0.9260	-0.9259	NA
2	Meat	-0.4160	-0.4161	-0.4161	-0.6914
3	Fish	-0.2890	-0.2776	-0.2775	-0.4110
4	Dairy	-0.2720	-0.2670	-0.2668	-0.2488
5	Non-Edible Animal Products	-0.1761	-0.1747	-0.1793	-0.3593
6	Plants	-0.4980	-0.4980	-0.3464	-0.3574
7	Vegetables	-0.6049	-0.6202	-0.6174	-0.5174
8	Fruits and Nuts	-0.5265	-0.5265	-0.5235	NA
9	Spices	-0.3567	-0.3567	-0.3567	-0.3586
10	Cereals	-0.5801	-0.5801	-0.5801	-0.5801
11	Flour	-0.4495	-0.4495	-0.4495	-0.4516
12	Seeds	-0.3653	-0.3664	-0.3664	-0.3489
13	Vegetable Saps and Extracts	-0.1387	-0.1023	-0.1023	-0.1387
14	Other Vegetable Products	-0.4006	-0.4006	-0.4006	-0.4006
15	Fats and Oils	-0.4268	-0.4268	-0.4268	-0.4273
16	Meat and Fish Preparations	-0.4571	-0.4571	-0.4571	-0.4558
17	Sugars	-0.4418	-0.4418	-0.4418	-0.4418
18	Cocoa	-0.3559	-0.3559	-0.3559	-0.3559
19	Food Preparations of Flour	-0.4336	-0.4336	-0.4334	-0.4336
20	Fruits and Vegetables Preparations	-0.3925	-0.3925	-0.3925	-0.4042
21	Sauces, Soups, Extracts, Essences and Concentrates	-0.4057	-0.4057	-0.4075	-0.4057
22	Beverages	-0.3966	-0.3966	-0.3966	-0.3961
23	Residues from Food Products	-0.4633	-0.4633	-0.4633	-0.4633
24	Tobacco	-0.3746	-0.3780	-0.3780	-0.3746
25	Sands, Clays, and Minerals	-0.4842	-0.4842	-0.4842	-0.4842
26	Ores, Slag, Ashes and Residues	-0.6450	-0.6450	-0.6450	-0.6519
27	Coal, Oil and Gases	-0.5427	-0.5427	-0.5474	-0.5649
28	Gases, Acids, Oxides, and Similar Compounds	-0.4712	-0.4861	-0.4863	-0.4665
29	Hydrocarbons, Alcohols, Ethers, and Similar Compounds	-0.5042	-0.5147	-0.5203	-0.4904
30	Medicaments and Pharmaceutical Products	-0.3291	-0.3040	-0.3547	-0.3324
31	Fertilizers	-0.3742	-0.3742	-0.3742	-0.3742
32	Dyes and Paints	-0.4762	-0.4801	-0.4869	-0.4892
33	Cosmetics and Perfumes	-0.5547	-0.5255	-0.5572	-0.5547
34	Soaps, Waxes, and Lubricating preparations	-0.4829	-0.4829	-0.4893	-0.4829
35	Glues and Enzymes	-0.4910	-0.5294	-0.5294	-0.4900

Code	Definition	β_{50}	β_{60}	β_{70}	β_{HS}
36	Pyrotechnic Products	-0.1768	-0.1768	-0.1768	-0.3165
37	Photographic and Cinematographic Products	-0.3691	-0.3712	-0.3738	-0.3830
38	Chemicals	-0.4529	-0.4527	-0.4519	-0.4490
39	Plastics	-0.4432	-0.4457	-0.4415	-0.4448
40	Rubber	-0.2517	-0.2501	-0.2484	-0.2521
41	Hides, Skins and Leather	-0.5838	-0.5423	-0.6073	-0.5941
42	Leather Products	-0.0295	-0.0598	-0.0679	-0.0641
43	Furskins	-0.2225	-0.2225	0.5957	-0.3764
44	Wood	-0.3997	-0.3996	-0.3994	-0.4002
45	Cork	-0.3424	-0.3424	-0.3528	-0.3441
46	Plaiting	-0.3795	-0.3795	-0.3544	-0.3795
47	Wood Pulp	-0.4630	-0.4630	-0.4630	-0.4630
48	Paper	-0.4465	-0.4491	-0.4490	-0.4475
49	Printed or Illustrated Products	-0.3453	-0.3194	-0.3982	-0.3220
50	Silk	-0.1635	-0.1994	-0.1994	-0.3997
51	Wool and Fabrics	-0.4907	-0.4760	-0.4956	-0.4470
52	Coton Yarn and Fabrics	-0.3865	-0.3852	-0.3758	-0.3899
53	Yarn	-0.3203	-0.3172	-0.3176	-0.3369
54	Synthetic Yarn and Synthetic Fabrics	-0.3706	-0.3702	-0.3465	-0.3700
55	Synthetic Fibres and Fabrics	-0.3006	-0.2991	-0.2839	-0.3051
56	Nonwovens, Twine, Cordage or Rop	-0.4332	-0.4374	-0.4374	-0.4333
57	Carpets and Textile Floors	-0.4737	-0.4737	-0.5028	-0.4737
58	Other Ornemental Fabrics	-0.4361	-0.4377	-0.4371	-0.4193
59	Textile products and articles for technical uses	-0.3651	-0.3654	-0.3644	-0.3650
60	Knitted or Crocheted Fabrics	-0.5041	-0.5039	-0.5018	-0.5041
61	Knitted or Crocheted Clothes	-0.4348	-0.4436	-0.4514	-0.4283
62	Non-Knitted Nor Crocheted Clothes	-0.3317	-0.3374	-0.3361	-0.3205
63	Other Linen	-0.3889	-0.3890	-0.3877	-0.3892
64	Footwear	-0.4187	-0.4187	-0.3844	-0.3519
65	Hats	-0.2554	-0.2564	-0.2460	-0.2593
66	Umbrellas	-0.3834	-0.3834	-0.3834	-0.3719
67	Artificial Hair and Artificial Vegetals	-0.1365	-0.1365	-0.1307	-0.3502
68	Marble, Stones, Plaster, and Similar	-0.4599	-0.4879	-0.5059	-0.4261
69	Bricks, Blocks and Tiles	-0.3155	-0.3203	-0.3190	-0.3182
70	Glass	-0.3812	-0.3854	-0.3827	-0.3976
71	Precious Stones and Precious Metals	-0.3558	-0.3558	-0.5292	-0.3678
72	Iron and Steel	-0.5126	-0.5126	-0.5135	-0.5114
73	Iron and Steel Products	-0.3425	-0.3452	-0.3466	-0.3200
74	Copper	-0.4431	-0.4431	-0.4480	-0.4588
75	Nickel	-0.3041	-0.2844	-0.2983	-0.2914
76	Aluminium	-0.3619	-0.3629	-0.3718	-0.3675
78	Lead	-0.4486	-0.4556	-0.4563	-0.4486
79	Zinc	-0.5214	-0.5214	-0.5214	-0.5214
80	Tin	-0.4612	-0.4248	-0.4248	-0.4612
81	Other Metals	-0.1332	-0.1037	-0.1106	-0.2166
82	Hand Tools	-0.2282	-0.1882	-0.1783	-0.2470
83	Safety and Ornament Metal Based Products	-0.2730	-0.2703	-0.2756	-0.2731
84	Machinery	-0.2772	-0.2774	-0.2902	-0.2560
85	Electrical Equipment	-0.3289	-0.3085	-0.2613	-0.3606
86	Railway or Tramway Locomotives	-0.2520	-0.2520	-0.2537	-0.3020
87	Vehicles and Parts	-0.2923	-0.2926	-0.2923	-0.2896
88	Spacecrafts and Parts	-0.1005	-0.1005	NA	-0.1324
89	Vessels	-0.2429	-0.2235	-0.2235	-0.2610
90	Optical Products	-0.4570	-0.5851	-0.3339	-0.4084
91	Clocks and Watches	-0.2961	-0.2950	-0.3009	-0.1249
92	Musical Instruments	-0.2454	-0.2369	-0.2865	-0.2301
93	Firearms and Ammunitions	-0.0614	-0.0198	-0.0272	0.2147
94	Seats and Bedroom Furnitures	-0.3764	-0.3764	-0.3826	-0.3840
95	Games and Sport Equipment	-0.3056	-0.2735	-0.2378	-0.3101
96	Brushes, Pens, and Lighters	-0.5937	-0.5978	-0.6072	-0.5901
97	Artworks	NA	NA	NA	NA

NA means that all HS6-digit products included in the HS2-digit sector are transported by air.

Figure C.2: Distribution of partial elasticities (% of HS2 codes)

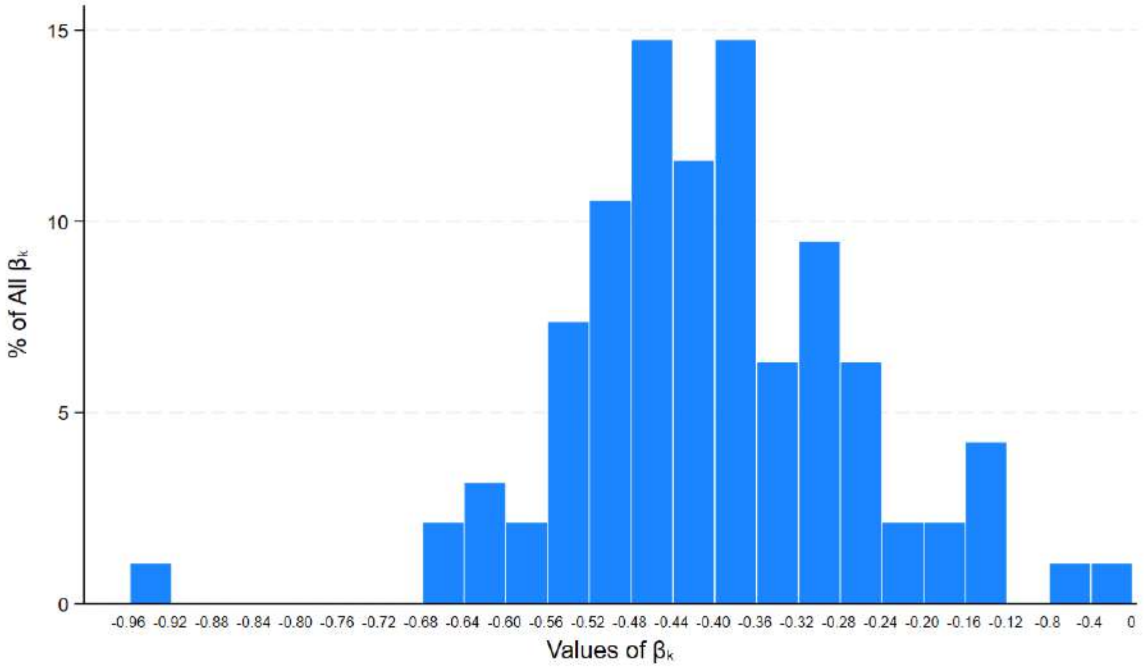


Table C.2: List of HS2 sectors and variation in average sea distance

HS2	Definition	Change (in %)	Baseline distance (in km)
6	Plants	-8.63	512
35	Glues and Enzymes	-7.47	1294
25	Sands, Clays, and Minerals	-7.13	330
28	Gases, Acids, Oxides, and Similar Compounds	-6.70	1175
29	Hydrocarbons, Alcohols, Ethers, and Similar Compounds	-6.67	1090
22	Beverages	-6.48	876
19	Food Preparations of Flour	-6.41	609
7	Vegetables	-6.19	261
78	Lead	-6.06	1311
90	Optical Products	-5.92	1638
33	Cosmetics and Perfumes	-5.90	1415
79	Zinc	-5.76	1191
32	Dyes and Paints	-5.76	1249
17	Sugar	-5.60	621
39	Plastics	-5.52	1063
21	Sauces, Soups, Extracts, Essences, and Concentrates	-5.40	550
34	Soaps, Waxes, and Lubricating Preparations	-5.33	1119
96	Brushes, Pens, and Lighters	-5.25	2053
38	Chemicals	-5.23	1285
24	Tobacco	-5.09	682
11	Flour	-5.08	570
72	Iron and Steel	-4.81	936
15	Fats and Oils	-4.58	842
20	Fruits and Vegetables Preparations	-4.33	455
76	Aluminium	-4.33	1064
74	Copper	-4.17	1695
44	Wood	-4.14	1335
23	Residues from Food Products	-4.00	816
48	Paper	-3.93	971
3	Fish	-3.58	568
56	Nonwovens, Twines, Cordage, or Rops	-3.58	2265
52	Coton Yarn and Fabrics	-3.45	2545

HS2	Definition	Change	Baseline distance
41	Hides, Skins, and Leather	-3.34	2654
70	Glass	-3.25	604
71	Precious Stones and Precious Metals	-3.18	1646
51	Wool and Fabrics	-3.06	2822
10	Cereals	-2.93	685
87	Vehicles and Parts	-2.89	1693
30	Medicaments and Pharmaceutical Products	-2.84	2058
8	Fruits and Nuts	-2.74	608
9	Spices	-2.68	683
12	Seeds	-2.66	1272
16	Meat and Fish Preparations	-2.63	437
5	Non-Edible Animal Products	-2.62	435
37	Photographic and Cinematographic Products	-2.48	1308
49	Printed or Illustrated Products	-2.38	940
75	Nickel	-2.34	2189
84	Machinery	-2.27	2510
73	Iron and Steel Products	-2.14	904
58	Other Ornemental Fabrics	-2.06	2162
59	Textile Products and Articles for Technical Uses	-2.03	2322
2	Meat	-1.94	1137
68	Marble, Stones, Plaster, and Similar	-1.90	628
14	Other Vegetable Products	-1.88	446
85	Electrical Equipment	-1.74	2360
83	Safety and Ornament Metal Based Products	-1.73	894
4	Dairy	-1.69	1002
40	Rubber	-1.61	1490
27	Coal, Oil, and Gases	-1.59	1088
92	Musical Instruments	-1.55	3363
80	Tin	-1.35	2391
94	Seats and Bedroom Furnitures	-1.34	2629
57	Carpets and Textile Floors	-1.29	2676
18	Cocoa	-1.27	813
64	Footwear	-1.21	3073
45	Cork	-1.19	1075
61	Knitted or Crocheted Clothes	-1.06	3050
62	Non-Knitted nor Crocheted Clothes	-0.96	2948
1	Live Animals	-0.94	573
91	Clocks and Watches	-0.91	2475
26	Ores, Slag, Ashes, and Residues	-0.90	3043
60	Knitted or Crocheted Fabrics	-0.85	1837
43	Furskins	-0.73	2957
69	Bricks, Blocks, and Tiles	-0.72	638
63	Other Linen	-0.69	2905
55	Synthetic Fibres and Fabrics	-0.66	2639
47	Wood Pulp	-0.59	2177
82	Hand Tools	-0.59	951
89	Vessels	-0.57	1619
95	Games and Sport Equipment	-0.53	2984
54	Synthetic Yarn and Synthetic Fabrics	-0.48	2448
53	Yarn	-0.19	3336
36	Pyrotechnic Products	-0.13	2922
65	Hats	-0.04	3034
13	Vegetable Saps and Extracts	-0.01	661
81	Other Metals	0.15	1796
93	Firearms and Ammunitions	0.19	2832
66	Umbrellas	0.27	3196
46	Plaiting	0.27	1629
67	Artificial Hair and Artificial Vegetals	0.30	3752
50	Silk	0.41	2746
42	Leather Products	0.43	3124
86	Railway or Tramway Locomotives	0.64	1190
88	Spacecrafts and Parts	0.64	2279
31	Fertilizers	1.14	1202

Figure C.3: World map of countries by welfare loss / gain

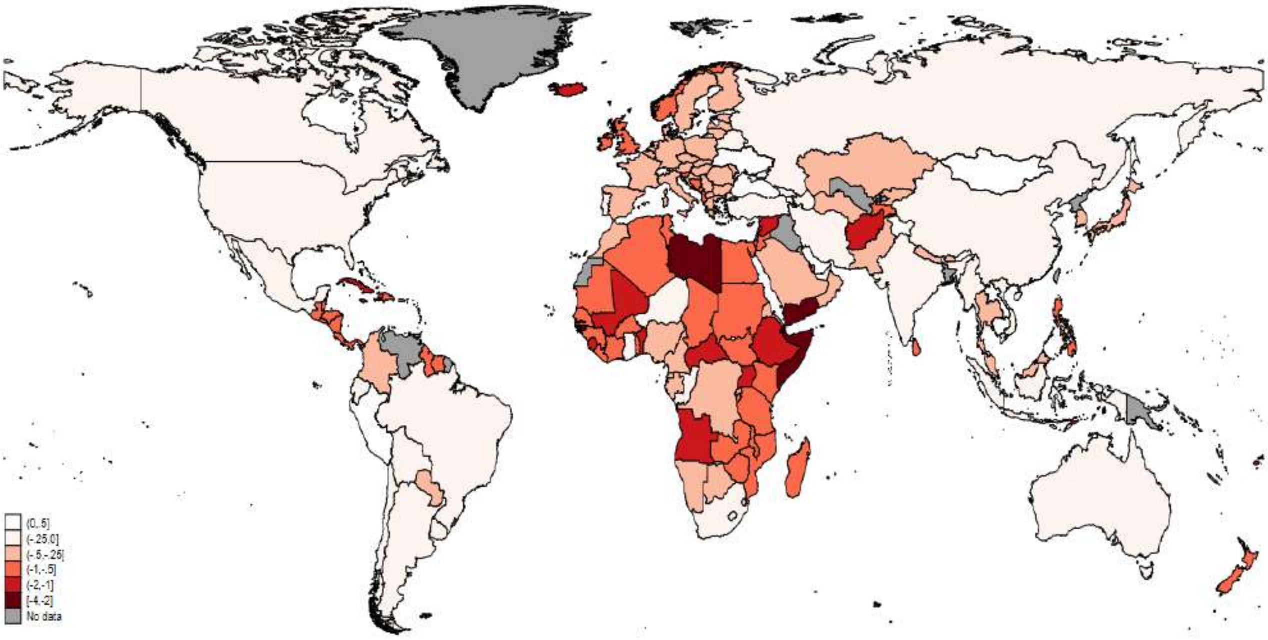


Table C.3: Most remote countries according to Sea Remoteness and REM

Sea Remoteness Index (2018)			**REM Index (2018)**		
Rank	Country	Index	Rank	Country	Index
1	Liberia	14622	1	Paraguay	100.00
2	Guinea	14070	2	Lesotho	98.70
3	Gabon	13689	3	Bolivia	97.71
4	Equatorial Guinea	13470	4	Eswatini	96.68
5	Angola	13143	5	Botswana	95.45
6	Chile	13000	6	Tonga	93.25
7	Brazil	12710	7	Fiji	91.48
8	Rep. of Congo	12708	8	Zimbabwe	90.35
9	Benin	12654	9	Vanuatu	90.04
10	Ghana	11808	10	Chile	89.94
11	Sierra Leone	11724	11	Samoa	89.02
12	Dem. Rep. of Congo	11698	12	Argentina	88.32
13	Chad	11401	13	Uruguay	88.11
14	Nigeria	11373	14	Zambia	88.06
15	Gambia	11208	15	Tuvalu	88.03
16	New Zealand	10876	16	Malawi	87.29
17	Australia	10866	17	Solomon Isds	84.69
18	Cameroon	10716	18	South Africa	83.16
19	Mauritania	10712	19	Kiribati	83.10
20	Niger	10687	20	Nauru	82.67
21	Marshall Isds	10682	21	Marshall Isds	80.15
22	China	10294	22	Papua New Guinea	79.47
23	Uruguay	10137	23	Brazil	79.36
24	Argentina	10055	24	Peru	78.82
25	Central African Rep.	10002	25	Mozambique	77.70
26	Peru	9836	26	Burundi	76.25
27	Suriname	9795	27	FS Micronesia	76.11
28	Cuba	9612	28	Rwanda	74.82
29	South Africa	9573	29	Namibia	74.63
30	Togo	9450	30	Mauritius	74.57

Source: Authors for Sea Remoteness Index and UNDESA for REM Index.

Figure C.4: Relation between Welfare / Price change and GDPpc - Robustness checks

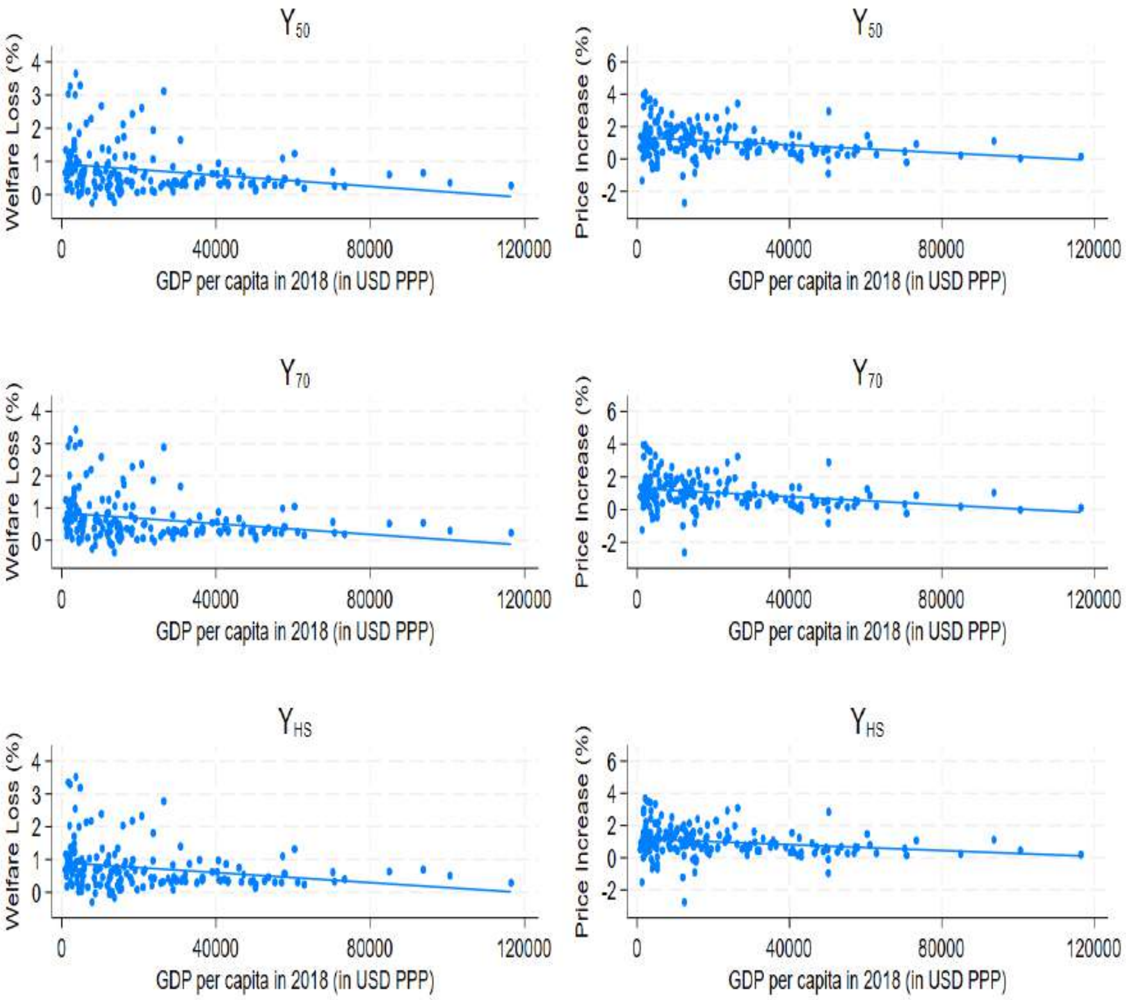


Table C.4: Results for all alternative scenarios and robustness checks

		Y_{50}	Y_{60}	Y_{70}	Y_{HS}
Change in Welfare (%)	Average Effect	-0.77	-0.73	-0.69	-0.77
	Range	[-3.66; +0.24]	[-3.56; +0.30]	[-3.45; +0.37]	[-3.53; +0.29]
	Most Impacted	Sao Tome & Pr.	Sao Tome & Pr.	Sao Tome & Pr.	Sao Tome & Pr.
	Least Impacted	Lao PDR	Armenia	Armenia	Lao PDR
Change in Price (%)	Average Effect	+1.13	+1.11	+1.06	+1.03
	Range	[-2.69; +5.70]	[-2.63; +5.72]	[-2.60; +5.76]	[-2.73; +5.81]
	Most Impacted	Eritrea	Eritrea	Eritrea	Eritrea
	Least Impacted	Mongolia	Mongolia	Mongolia	Mongolia
Change in Average Seadistance traveled (%)		-2.65	-2.59	-2.52	-2.75
Change in Emissions from Sea Trade (%)	Low CI Scenario	-1.77	-1.76	-1.75	-1.57
	High CI Scenario	-1.74	-1.74	-1.66	-1.48
Tax Revenues ($bn)	Low CI Scenario	19.753	19.624	19.012	18.761
	High CI Scenario	59.785	59.476	57.335	58.818
Change in Emissions from Trade (%)	Low CI + Road	+0.06	+0.12	-0.20	+0.28
	Low CI + Rail	-0.37	-0.19	-0.49	-0.11
	High CI + Road	-0.37	-0.30	-0.40	-0.07
	High CI + Rail	-0.88	-0.72	-0.69	-0.51

Note: In the “Low CI” scenario, we assign the lowest carbon intensity to all ships. In the “High CI” scenario, we assign the highest carbon intensity to all ships. In the “Truck” scenario, we assume that international trade between neighboring countries and intra-national port-to-capital transport is done by truck. In the “Rail” scenario, we assume that international trade between neighboring countries and intra-national port-to-capital transport are carried out by rail with a European electricity mix.

“ Sur quoi la fondera-t-il l’économie du monde qu’il veut gouverner ? Sera-ce sur le caprice de chaque particulier ? Quelle confusion ! Sera-ce sur la justice ? Il l’ignore. ”

Pascal

FERDi

Créée en 2003, la **Fondation pour les études et recherches sur le développement international** vise à favoriser la compréhension du développement économique international et des politiques qui l’influencent.

Contact
www.ferdi.fr
contact@ferdi.fr
+33 (0)4 43 97 64 60