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We discuss the impact of a carbon tax on the maritime transport sector, which is responsible for approximately 3% of global emissions. The International Maritime Organization (IMO) has set long-term targets to reduce carbon intensity and achieve carbon neutrality, but the impact of the policies to achieve those targets on the global and local economies must be assessed. We use a global and multi-region Computable General Equilibrium (CGE) model - Global Trade Analysis Project Energy-Environmental augmented version (GTAP-E) – to evaluate the environmental and economic effectiveness of a carbon tax of $50/tCO2e on international shipping. GTAP-E does not provide emissions data by transport mode and accurately estimating emissions is crucial to proposing a carbon pricing measure. Therefore, we have applied machine-learning techniques to predict the share of international trade transported by sea by sector, origin and destination countries and calculate ship emissions for each bilateral flow by sector. The findings indicate that while the tax considerably reduced emissions from ships, it also had a negative impact on exports and resulted in mixed impacts on GDP, exacerbating existing inequalities across regions. Our analysis highlights the importance of considering various economic and social variables in impact assessments to identify potential trade-offs and synergies between policy objectives.

Keywords: Carbon Pricing, Carbon Tax, Shipping, Computable General Equilibrium

JEL Codes: Q52, R48, F17, Q56

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Abstract

We discuss the impact of a carbon tax on the maritime transport sector, which is responsible for approximately 3% of global emissions. The International Maritime Organization (IMO) has set long-term targets to reduce carbon intensity and achieve carbon neutrality, but the impact of the policies to achieve those targets on the global and local economies must be assessed. We use a global and multi-region Computable General Equilibrium (CGE) model - Global Trade Analysis Project Energy-Environmental augmented version (GTAP-E) – to evaluate the environmental and economic effectiveness of a carbon tax of $50/tCO2e on international shipping. GTAP-E does not provide emissions data by transport mode and accurately estimating emissions is crucial to proposing a carbon pricing measure. Therefore, we have applied machine-learning techniques to predict the share of international trade transported by sea by sector, origin and destination countries and calculate ship emissions for each bilateral flow by sector. The findings indicate that while the tax considerably reduced emissions from ships, it also had a negative impact on exports and resulted in mixed impacts on GDP, exacerbating existing inequalities across different regions. Our analysis highlights the importance of considering various economic and social variables in impact assessments to identify potential trade-offs and synergies between policy objectives.

1. INTRODUCTION

The IPCC has reported that human activities have already caused a 1°C increase in global average temperature due to greenhouse gas emissions (IPCC, 2018). The maritime transport sector is responsible for almost 3% of global emissions, comparable to emissions from countries such as Germany and Japan (IMO, 2018; OECD, 2019). To reduce emissions, the International Maritime Organization (IMO) adopted an initial strategy in 2018, which includes reducing carbon intensity by 40% in 2030 and 70% in 2050 (compared to 2008 levels), and achieving carbon neutrality by 2050 (IMO, 2018). However, adhering to these goals may affect the local and international economy, which must be evaluated and quantified. The IMO has approved a procedure to assess the impacts of candidate mitigation measures, but no academic literature has undergone studies evaluating market-based measures to date.

To fill this gap, we evaluate the environmental and economic effectiveness of the application of a carbon tax to international shipping at a rate of US$ 50/tCO2e[1]. We employ an energy–environmental version of the Global Trade Analysis Project model (GTAP-E). Our study encompassed all direct and indirect impacts on countries' exports, GDP, maritime transport costs, and maritime emissions. The database includes 2014 information on 141 countries or regions of worldwide coverage, and 65 production sectors, disaggregated at a high level to report results for all potential participants under IMO Governance.

The model assumes competitive markets and constant returns to scale technology and describes the domestic economy for each region. However, as GTAP-E database does not provide information on carbon emissions from ships; therefore, we estimate emissions associated with international shipping. To do that, we first estimate a machine-learning model using data from Cristea et al. (2013) and bilateral trade flows by commodity from UN COMTRADE to predict the transport mode shares of international trade in 2014. Second, we use several datasets, such as shipping distance from Seadistances.org and ship characteristics per bilateral trade flow and sector, to calculate emissions by origin-destination and sector pairs.

As GTAP provides data on shipping costs per transport mode, we use these data combined with the estimated emissions as the basis for the carbon tax shock. Therefore, a carbon tax is modeled by altering maritime transport costs. In this way, the carbon tax implemented changes in relative transport prices, following Lee et al. (2013).

Our results indicate that implementing the carbon tax has led to a reduction of 7% in global emissions from international shipping. However, it has also had a negative impact of 0.20% on global exports. The impact on exports is also very heterogeneous by region, being the global south countries the most negatively affected ones. After accounting for substitution effects from price changes in the model, we find that certain regions experienced positive GDP impacts while others suffered negative impacts. For instance, if we exclude the OECD's member countries, the effect of the proposed carbon tax will be a decrease of 0.13% in GDP. The most penalized regions are in Africa, South America, and the former Soviet Union.

The use of global computable general equilibrium (CGE) models, such as GTAP or GTAP-E extended model, has become popular for analyzing the potential impacts of climate policies on

[1] Based on the Social Cost of Carbon, calculated to 2020 considering the discount rate of 3% per year (Interagency Working Group on Social Cost of Greenhouse Gases – White House (2021)).

international trade and global economic activity. As noted by Hertel (1997), the GTAP model is a widely recognized and transparent tool for conducting economic analysis in the context of climate change policies. Furthermore, the ability of CGE models to capture the general equilibrium effects of policy changes, including the substitution effects due to changes in relative prices, is a key feature for comprehensive impact analysis (Babatunde et al., 2017). This is particularly relevant in the case of climate policy, where changes in the relative prices of goods and services can significantly impact the competitiveness of industries and the welfare of households in different countries and sectors.

In this sense, the use of the GTAP-E model in this study allowed for a global and sectoral analysis of the potential impacts of a maritime carbon tax, providing results for 141 countries/regions and several sectors of the economy. The study also highlights the importance of considering a wide range of economic and social variables in impact assessments, which can help to identify potential trade-offs and synergies between different policy objectives (Babatunde et al., 2017).

Overall, this study presents a comprehensive approach to impact analysis that can provide valuable insights for policymakers and stakeholders in designing and implementing effective climate policies that address the global challenge of reducing greenhouse gas (GHG) emissions while promoting sustainable economic growth and development. Its main scientific contribution is to provide empirical evidence of the economy-wide impacts of a carbon tax on international shipping across regions using a CGE model, accounting for all bilateral trade flows and associated maritime emissions.

The remainder of this paper is organized as follows. Section 2 presents the institutional background regarding the carbon pricing mechanisms and details the discussion at the maritime authority. In Section 3, we provide details on the method and data used to calculate emissions, the carbon tax shock and the impacts on the global economy. Section 4 describes the data. The results are presented and discussed in Section 5. Section 6 concludes.

2. CARBON PRICING MECHANISMS

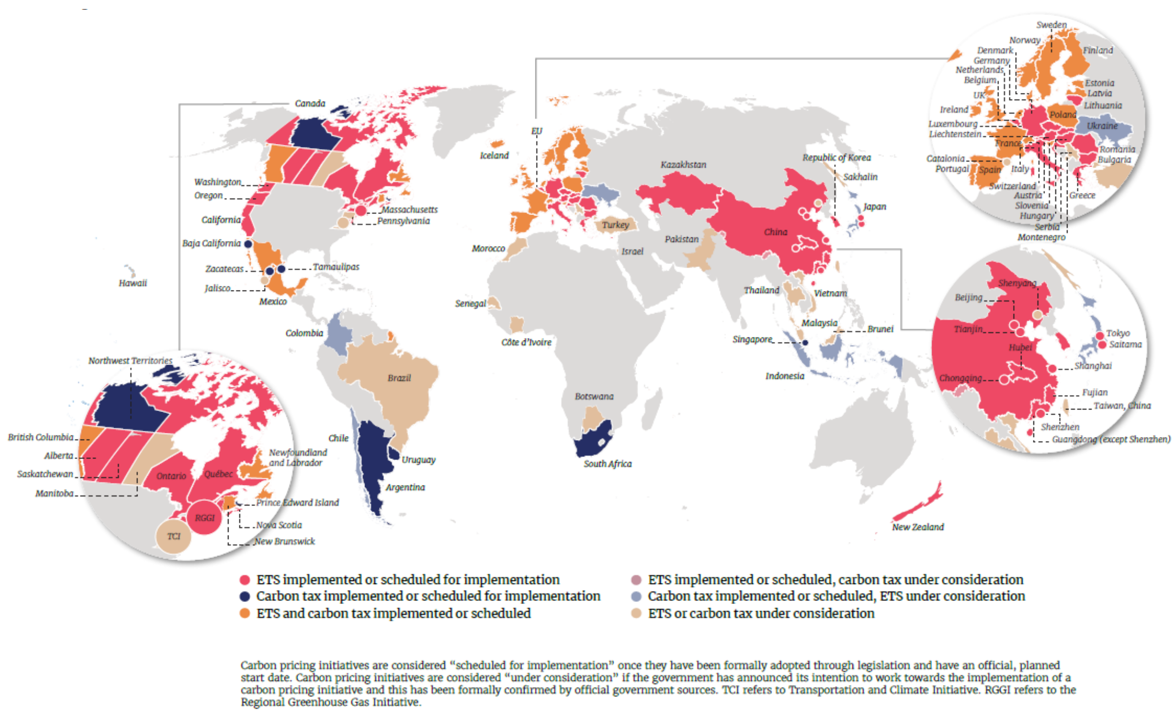
2.1 CARBON PRICING ACROSS THE GLOBE

Carbon pricing mechanism, or market-based mechanisms (MBMs), have gained attention as economic instruments to internalize the external costs of GHG emissions and incentivize investment in energy-saving technologies and alternative fuels (Psaraftis and Kontovas, 2020; Christodoulou et al., 2021). MBMs offer flexibility compared to command-and-control approaches (Nordhaus, 2008; Lagouvardou et al., 2020).

Besides being a way to transit towards a low-carbon economy and reduce emissions, carbon pricing faces challenges such as the free-rider problem in international cooperation, equity concerns for low-income groups, and the impact of global events on energy prices (Schmalensee and Stavins, 2015; Edenhofer et al., 2015). Therefore, its implementation might be accompanied by a complete impact assessment on environmental, economic, and social variables.

The most up-to-date report of the World Bank (The World Bank, 2022) outlines the existence of 37 carbon taxes and 34 emission trading schemes (ETS) initiatives implemented, and three more are scheduled for implementation (Washington state, Indonesia, and Austria). Figure 1 illustrates the global pricing status as of 2022.

Figure 1: Map of Carbon Taxes and ETSs Worldwide



Source: The World Bank (2022).

Figure 1 shows that countries in all regions are establishing a price on carbon as a central component of their efforts to reduce emissions, with different scopes. Yet, the global coverage remains limited, representing approximately 23% of total GHG emissions (The World Bank, 2022). Moreover, the average global carbon price in these initiatives is US$2.48/t$CO_2$ (in 2020), much lower than the 2020 US$ 51/tCO_2 (3% discount rate) reference global Social Cost of Carbon (SCC) calculated by the Interagency Working Group on Social Cost of Carbon (IWG, 2021) and commonly utilized in climate change studies. (Figure 2). SCC is estimated by integrated assessment models (such as DICE[2], developed by Nordhaus 2014, 2017, 2019) and can be defined as the monetary value of the incremental global damage (agricultural productivity, human health, increased risk of flooding, damage to ecosystem services, among others) resulting from the emission of an additional ton of CO_2 into the atmosphere in a given year. In this sense, Figure 2 shows that carbon pricing policies remain modest and less ambitious than they could be.

Figure 2: Average Global Carbon Price (US$/t$CO_2$)

Source: The World Bank (2020) and IWG (2021), considering the discount rate of 3% per year.

2.2 CARBON PRICING IN THE MARITIME CONTEXT

The scientific literature on MBMs examines various options for reducing emissions from international shipping. Many papers in the literature advocate the use of carbon pricing revenues to boost research and development (R&D) and technology deployment (Psaraftis and Lagouvardou, 2019) and help close the competitiveness gap while enabling an equitable transition (Baresic et al., 2022).

[2] Dynamic Integrated Climate and Economy.

The maritime sector can opt to price its carbon content through a tax or levy on the fuel[3], or an ETS (Dominioni et al., 2018). Subsidies[4] also fit into the MBM category (Baresic et al, 2022). Although several variants of a levy are possible, a large body of research refers to the bunker levy as the most suitable instrument to curb ship emissions (Psaraftis, 2019). More specifically, it centers the discussion on the comparison between a bunker levy and an ETS, giving a clear preference for these two MBM proposals (Psaraftis and Lagouvardou, 2019).

A bunker levy system is a fixed-price approach that implies taxing fuel consumption on-board of vessels. Hence, emissions are priced upstream (at the point of sale to the ship) according to the carbon content of that fuel. On the other hand, an ETS sets a cap on emissions and the price of emissions allowances is determined by the market. An ETS is based on the economic idea of "cap-and-trade", where regulated actors choose how to adjust to the mitigation target (cap) and the trading enables the emitter to reduce emissions in the most cost-effective way, generating economic efficiencies (Oliveira et al, 2021).

In the case of ETS, the environmental outcome is certain, but prices are not known in advance. The overall abatement cost of meeting the emission reduction target is reduced to the extent that some shipping companies are able to reduce their emissions below the determined commitment and sell their surplus of emission allowances to others that cannot meet their emission reduction targets (Psaraftis and Lagouvardou, 2019).

The number of allowances that are released into the market annually corresponds to the established cap. In practice, emission allowances would be surrendered for each ton of carbon a ship emits during its operations. Evidence also reveals low environmental effectiveness resulting from the weak price signal caused by the oversupply of emission allowances in the market and price volatility, discouraging reductions beyond the emissions target (Psaraftis and Lagouvardou , 2019).

Dominioni et al (2018) compare the relative performance of various regional measures based on carbon pricing that could be an alternative to a global agreement. A cargo-based measure covering emissions released throughout the whole voyage is found to be more advantageous than other carbon pricing schemes. A sub-global carbon pricing system could be an option, but

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[3] A rebate mechanism has been proposed at the IMO aiming to compensate developing countries from the financial impact of an MBM. It could be used alongside MBMs (Lema et al, 2017).

[4] These are environmental subsidies or transfers aimed at lowering the costs of alternative fuels. For the decarbonization of the maritime sector, three are the possibilities Baresic et al (2022) suggest: a) fuel subsidies, b) production subsidies and c) R&D subsidies.

it comprises economic, legal, and political obstacles such as international law incompatibility and both environmental and competitiveness issues. ETS can be harder to operationalize than a carbon levy due to the large number of ships operating internationally, and because the high variability in the fuel consumption of each ship makes it difficult to allocate credits accurately. Other challenges of a maritime ETS involve deciding how allowances are to be distributed as carbon leakage effects or risk of increased emissions from shipping may arise (Wang et al, 2019). The study of Lema et al (2017) reinforces that ultimately the level of emission reductions will depend on the annual emission growth and the defined cap.

Wu et al (2022) review, identify and synthesize the drivers, challenges and impacts of an ETS on international shipping. Among the drivers, the study highlights the limitations of existing technical and operational solutions and the promise of market-based solutions. However, there are challenges of geographic and sectoral coverage, the share of free emissions, and the carbon trading price as well as management difficulties. Political challenges include conflict between common but differentiated responsibilities and opposition from the shipping sector. In this context, developing a successful ETS required an understanding of the challenges and opportunities while enduring public and political support. The objective of this study is to produce evidence to support the policymakers at IMO.

2.3 CARBON PRICING AT IMO

The IMO took a significant step towards reducing GHG emissions from international shipping in 2018. This was achieved by adopting an initial strategy that aligns with the goals of the Paris Agreement. The strategy aims to reduce the sector's GHG emissions by at least 50% by 2050, compared to 2008 levels.

As part of the strategy, the IMO is considering market-based measures (MBMs) as potential medium- and long-term solutions. However, there is currently a lack of evidence on the most appropriate mechanism and design option for MBMs, as well as their associated effects.

The decision to implement MBMs is a crucial one for the shipping industry, as it would have significant implications for both shipping companies and the wider global economy. Therefore, careful consideration and analysis must be undertaken to ensure that any MBMs implemented are effective, efficient, and equitable.

The IMO has been discussing the implementation of Market-Based Measures (MBMs) since 2010, with further discussions in 2011, 2018, and ongoing talks (MEPC 61/5/39, Sept 2010; MEPC 62/5/7; MEPC 62/5/14; MEPC 63/5/2; MEPC 63/5/11; and MEPC 64/5/10)[5].

More recently, from 2021 on, three MBMs options have been proposed: carbon taxes (MEPC 76/7/12, MEPC 78/7/5, ISWG-GHG 10/5/2, ISWG-GHG 12/3/1 and ISWG-GHG 12/3/17), Emissions Trading Systems (ETS) (MEPC 77/7/16, ISWG-GHG 10/5/6 and ISWG-GHG 12/3/13), and a combination of technical and economic measures (ISWG-GHG 12/3/5). Table 1 summarizes the main elements of the carbon tax proposals under consideration.

Table 1 - Summary of carbon tax proposals at IMO

Characteristic	Description
Rate	• US$ 56-73/ton CO2 in 2025; • US$ 100/ton CO2eq in 2025, • US$ 250-300/ton CO2eq in 2030; and, • US$ 1285-1683/ton CO2 in 2045
Incidence	• on fuel consumption; • on carbon emission; or • on GHG emissions
Implementation Period	2023 or 2025
Unit of measurement	• tons of CO2, • tons of CO2eq or GHGe emitted; and • intensity ratio or transport-work ratio
Revenues from levy	• Received by the International Maritime Research Fund (IMRF), or IMO Climate Fund; or • Revenue-neutral (rebate mechanism)
Exemptions	• Different phases for SIDS and LDCs; and, • Global implementation.

[5] See ISWG-GHG 12/INF.2 for a summary of previous discussions (between 2006 and 2013, or MEPC 55 to MEPC 65) on proposals for market-based measures (MBMs) at IMO.

In analyzing these options, IMO highlights that several factors must be considered (MEPC 78/WP.6, June 2022). First, the effectiveness of each measure in reducing emissions. Second, the potential impact on trade flows, economic activity, and inflation. Finally, the implementation of revenue recycling, compensatory measures, and exemptions. These factors are crucial to ensure that any MBM adopted by the IMO effectively addresses climate change concerns while minimizing negative economic impacts.

Despite the challenges, the IMO's initial strategy and the consideration of MBMs represent important steps toward reducing GHG emissions from international shipping. Thus, further investigation is necessary in order to make a more informed decision. It can help define the most appropriate instrument and the design that better fits into the decarbonization pathway desired for the sector. In this sense, assessments of the energy-economy-environment-trade linkages of MBM proposals are still lacking.

3. METHOD

3.1 GTAP-E

We employed the global and multi-region GTAP Energy-Environmental augmented version (GTAP-E) to assess the impacts of a carbon tax on shipping. GTAP, as a Computable General Equilibrium (CGE) model, is a powerful tool in providing a range of issues, in particular, to forecast the effects of future policy changes, on which econometric estimation would be less feasible (Pereda and Lucchesi, 2022). While the GTAP-E model yields replicable results for various economic variables and is advantageous in capturing the effects of climate policies on international trade flows and GDP (Rutherford, 2014; Narayan et al., 2017), it was not specifically designed to examine the emissions of the transport sector by mode. However, with adjustments and data inclusion, GTAP-E (or GTAP) can be utilized to assess maritime shipping emissions and policies to achieve emission reductions. Therefore, we utilized the GTAP 10 database, which is the most recent version and contains information on 141 countries and 65 production sectors, providing results for all potential participants under IMO Governance.

The GTAP-E model comprises sets of equations from economic theory and assumes competitive markets and constant returns to scale technology. It describes the domestic economy for each region and the interactions of all agents, including flows of commodities, income, and capital, with the implementation of the market-clearing condition. In CGE models, the Johansen hypothesis is used to simulate the effects of policy changes on economic outcomes (Johansen, 1960). It implies that economic agents adjust their behavior in response to changes in policy variables, such as tax rates or subsidies, leading to long-run effects on macroeconomic variables such as output, consumption, and trade (Francois et al., 2005). In our context, this hypothesis suggests that economic agents would adjust their behavior in response to the carbon tax, leading to long-run changes in output and trade that are different from the short-run effects (Hertel, 1997).

It is important to emphasize that the mathematical relations assumed in the GTAP-E model are generally rather simple, and like most General Equilibrium Models, strong assumptions are considered. The economic behavior parameters determine the direction of results. Some important parameters had been estimated by Hertel and Winters (2005), for international trade elasticities, and by OECD (2001), for agricultural factor supply and demand elasticities. Other economic relations are based on the literature. On the other hand, as stated by Valenzuela et al. (2007) and Liu et al.(2004), GTAP is strongly tested against historical experience presenting robust results.

International trade in GTAP is modeled based on the Armington assumption, widely used in trade modeling literature (Armington, 1969; Broda and Weinstein, 2006). This assumption distinguishes the mix of imported goods by their place of origin and explains the intra-industry trade of similar products. In our modeling framework, trade flows between source and destination regions generate demand for trade and transport services proportional to the quantity of commodities shipped (Devarajan et al., 1996).

Regarding the transport sector, GTAP simplifies by considering that, given the lack of data on the bilateral supply of transport services, each mode of transport is provided at a uniform price worldwide. A global transport sector purchases such services from each region, and the global buyer wants to minimize the cost of acquiring transport services in regions subject to a CES preference function. Optimal demand is given by the regional supply of the service. The global transport price is a composite based on the price of transport exports from each region. For simplicity, therefore, the amount of transport used follows changes in exports. Improvements in transport efficiency are incorporated by considering the per unit efficiency of transportation by mode of freight from origin to destination (Aguiar and Corong, 2020). The transportation sector is disaggregated into three modes: water, air, and road, and importers are assumed to pay for transportation costs. However, the GTAP database does not provide information on carbon emissions from ships, and we explain next how we estimate emissions from international shipping.

3.2 CARBON EMISSIONS FROM SHIPS

We estimate carbon emissions associated with international shipping by using trade data from UN COMTRADE (in US dollars and tons), the database of Cristea et al. (2013), shipping distances per trade flow from Seadistances.org, and ship characteristics per bilateral trade flow and sector. The GTAP database provides information on total international trade, not discriminating by transport mode. Therefore, to estimate emissions from ships, we first need to estimate how much of total international trade, by sector, origin and destination, is transported by ship. Then, we attribute an average ship to each bilateral trade flow (based on the product transported, see Section 3.2.2) and consider the minimum maritime distance between pairs of origin and destination to estimate emissions. The following sections detail the analysis.

3.2.1 Predicting shares of international trade transported by ships

The first step to estimating emissions from international shipping is to understand what proportion of the international trade is transported by ships. We do not observe an official dataset that disaggregates international trade by transport mode. In this context, we based our predictions on Cristea et al. (2013) database, in which there are transport mode shares for each origin, destination and product for year 2004. However, they report shares for 40 regions and 23 industries, which yields a total of 36,800 observations (40 × 40 × 23), we need to predict the shares using the regions and sectors accordingly to GTAP data. Then, we used the below described Lasso (least absolute shrinkage and selection operator) regression, based on a machine learning process, to predict the transport mode shares as a function of each origin-destination pair, considering product characteristics and geographic controls from both origin and destination countries.

It is important to notice that in Lasso regression, an optimal model is selected to focus on predicting the outcome variable. That is, the aim of the machine learning algorithm is to predict an outcome variable, rather than identifying a specific effect on the outcome variable. In this context, we have applied this framework to predict the share of international trade transported by sea by sector and origin and destination countries. By applying these shares to the bilateral trade flows from GTAP, we can estimate the total trade transported by sea in both values and tons. With this information, combined with ship type and distance traveled, we can estimate the total emissions from ships for each bilateral flow by sector/product. This machine learning procedure was employed as it generates better predictions than regular econometric methods[6] (smaller prediction errors, see Appendix Figures 1 and 2 for more details).

The Lasso regression is most useful in contexts of high-dimensional models such as ours, where there is no certainty on which out of the many potential covariates affect the outcome. It estimates model coefficients and then selects which covariates should be included.

The loss function behind the LASSO regression can be written as:

$$L(\beta;\lambda) = \sum_{i=1}^{n} (y_i - x_i\beta)^2 + \lambda \sum_{j=1}^{p} |\beta_j| \qquad (1)$$

In which $\lambda > 0$ is the lasso penalty parameter, y is the outcome variable (trade volume/value share), x contains the p potential covariates/controls (origin, destination or bilateral variables), and β is the vector of parameters that relate our outcome variable, y, to the covariates, x.

The first part of the loss function is the sum of squares (traditionally employed at the least squares estimation) and the second part is a lasso penalty that deals with high degrees of collinearity. As both terms are convex, there exists a solution to the minimization problem (minimization of the loss function). The solution is normally obtained by numerical optimization.

As mentioned, in our case we based our estimates on Cristea et al. (2013) database, in which there are transport mode shares for each origin, destination, and product. Given that there are 40 regions and 23 industries, that yields 36,800 observations (40 × 40 × 23). We created a raw dataset using an analogous process, using all regions and sectors from GTAP and compatibilized regions and sectors.

As Cristea et al. (2013) database had regions more aggregated than ours, we just considered the same shares for each observation. Otherwise, we employed the average of the observations to reach our aggregation. Then, we used the previously described lasso estimator to predict the

[6] On average, the lasso regression presents much smaller errors (total average of 0.19 p.p.) than the linear regression (total average of 3.35 p.p.). Appendix Figure 2 compares the mean prediction error (the predicted share minus the original share) by product category. As we also observe in Appendix Figure 1, the linear model error is, on average, positive. This means the model predicts a higher share of trade transported by sea, on average, than the real variable. On the other side, the lasso regression predicts shares above or below the original but always with a smaller error, as we observe in the former histograms.

shares as a function of those artificially generated shares and each origin-destination pair of geographical controls.

We use the following vector of controls: GDP of both countries (origin and destination); a binary variable that assumes the value 1 if the origin and destination countries are contiguous; a binary variable that assumes the value 1 if origin and destination countries' common official primary language is the same; a binary variable that assumes the value 1 if a pair of countries was ever in a colonial relationship; a binary variable that assumes the value 1 if countries had a common colonizer post-1945; a binary variable that assumes the value 1 for pairs of countries currently in a colonial relationship; a binary variable that assumes the value 1 for pairs of countries in a colonial relationship post-1945; euclidean (or sea) distance between the most populous cities of each country; euclidean distance between the capitals of both countries (population weighted, and CES population weighted with parameter equal to one); a binary variable that identifies the coast extension of the origin and destination countries; and a binary variable that assumes the value 1 if the country (both origin and/or destination) is landlocked; besides fixed effects (non-observable common shocks) by origin, destination and product, respectively.

3.2.2 Ship type by commodity's trade flow

We have reconciled each maritime trade flow with a ship type, depending on the transported commodity (Table 2), based on 6 (six) ship types, following IMO classification[7].

Table 2. Products and its correspondent ship type

Ship type	**Sectors**
Bulk Carrier	Bulk agriculture (low value), chemical, rubber, plastic products, ferrous metals (low value), forestry, metal products (large), metals nec (low value), mineral products nec (low value), minerals (low value), paper products, publishing (low value added), petroleum, coal products (solid).
Chemical Tanker	Chemical, rubber, plastic products (liquids)

[7] This assumption has been done in accordance with IMO GHG inventory studies.

Ship type	Sectors
Container Carrier	Bulk agriculture (high value), chemical, rubber, plastic products (high value or solids), electronic equipments, ferrous metals (semi-finished), fishing, leather products, machinery and equipment nec, manufactures nec, metal products (small), metals nec (high value), mineral products nec (high value), minerals (high value), motor vehicles and parts (parts), paper products, publishing (high value), processed agriculture (high value and live animals), textiles, transport equipment nec, wearing apparel and wood products
LNG Tanker	LNG
LPG Tanker	LPG
Oil Tanker	Oil, petroleum, coal products (liquids)
RoRo	Motor vehicles and parts - Vehicles

We also consider five categories of ship ages following the standard of Clarkson Research Database: (i) 0-4 years; (ii) 5-9 years; (iii) 10-14 years; (iv) 15-19 years; and (v) 20+ years. Additionally, in order to calculate ship emissions, we use data on the IHS Markit Sea-Web service, one of the largest maritime databases available and calculated the maritime traveled distance using seaports from Appendix Table 3 together with sea distances database, which is available online[8]. We select the minimum sea distance for each pair of ports. Then the average of the distance was calculated between the two gathered groups of countries or countries (several important ports in each region, or group of countries).

3.2.3 Emissions by bilateral trade flow

We measured the total carbon dioxide emissions based on the ship type and total transport work (tonnes-miles transported by bilateral trade flow). To do this, we used total fuel consumption (by the main engine of the ship) and CO2 conversions of fuel consumption from IMO (2015), considering the use of Heavy Fuel Oil (HFO).We assume that most ships, but LNG Tankers, use HFO, since it is the common residual fuel used in marine ships and is less expensive than distillate fuels. For LNG Tankers we allocate LNG fuel, based on (IMO, 2020). Our measure of total emissions represents 89.5% of the total CO2 emissions estimated by the 4th IMO GHG Study (IMO, 2020).

[8] https://sea-distances.org/. The database consists of more than 4,000 seaports and 4,000,000 pairwise sea voyage distances. The online system returns the distances in nautical miles for direct routes (eventually passing by Panama Canal, strait of Magellan, Cape Horn, Suez Canal or Cape of Good Hope).

3.3 CARBON TAX SHOCK

As mentioned above, GTAP has data on shipping costs per transport mode in million US$ which serve as the basis for the shock. We follow Lee et al. (2013) to calculate the shock based on the following equation:

$$\Delta s_{mijs} = \frac{\tau \times CO2emissions_{mijs}}{margincost_{mijs}} \quad (2)$$

In which τ is the carbon tax that affects directly costs (in US$/ton), and $CO2emissions$ are the total maritime (m) CO2 emissions from the bilateral trade flow between country i and j for commodity s. $margincost$ is the maritime transport cost computed by the GTAP model. The indexes *m, i, j, s* represent transport mode, country of origin, country of destination and commodity, respectively.

As already mentioned, the carbon tax impacts the model by changing relative transport prices:

$$TransportPrices_{mijs} = margincost_{mijs}(1 + \Delta_m + \Delta_i + \Delta_j + \Delta_s + \Delta s_{mijs}) \quad (3)$$

We consider the carbon tax of US$50/tCO2 ($\tau$), close to the 2020 US$ 51/tCO2 (3% discount rate) reference of global Social Cost of Carbon (SCC) calculated by IWG (Interagency Working Group on Social Cost of Carbon, U.S.G, 2021) and commonly utilized in climate change studies.

4. DATA DESCRIPTION

As the GTAP database's last version refers to 2014, all the data utilized refers to the aforementioned year. Table 3 summarizes the main data we use for comparison reasons. We consider 44 tradable sectors which are subject to carbon taxation (Panel A), representing 81% of the total international trade commercialized in 2014, most of the remaining 19% related to services trade. Our estimate of global emissions from international shipping[9] (863 Mt CO2) corresponds to 89,5% of total shipping emissions calculated in the 4th IMO GHG study.

[9] For more details on how we estimated the maritime emissions based on GTAP emissions data, see Section 3.2.

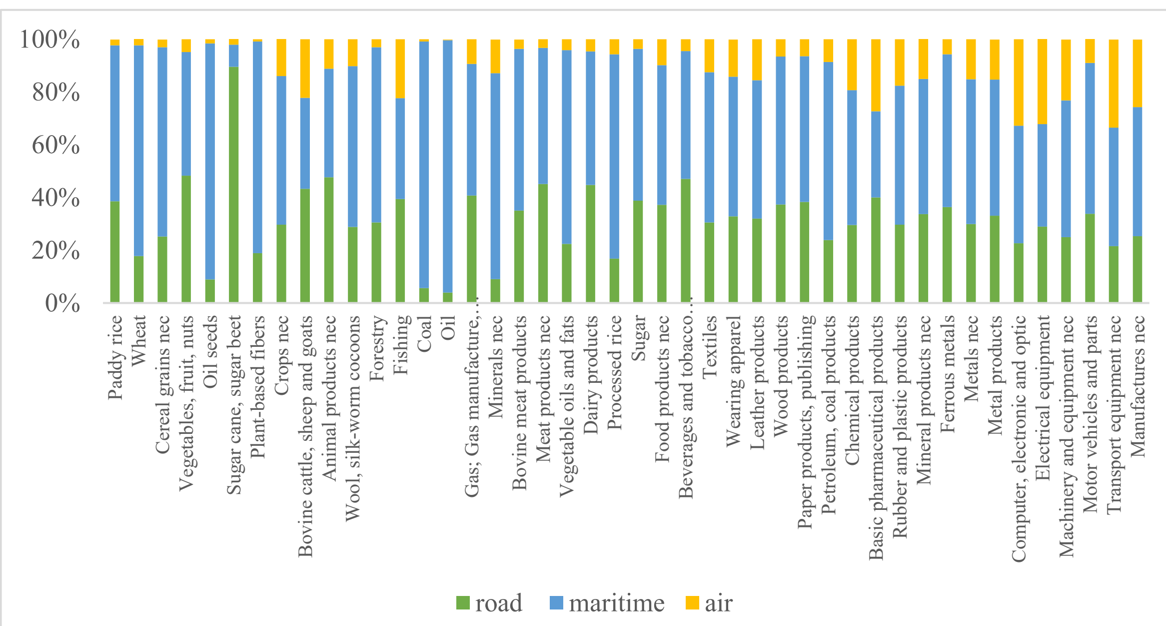
Table 3. Main data description (GTAP and calculated), 2014.

	GTAP-E Model	Description
Panel A. Data relative to the sectors affected by the tax		
Sectors affected by carbon tax	44	Tradeable goods
Total Trade (44 sectors) in 2014	US$ 16.6 trillion	81.2% of total trade[1]
Countries/regions	141	
Total maritime emissions in 2014	863,096,687 tCO2	89.5% of estimates from 4th IMO GHG
Panel B. All GTAP data used for the global analysis		
Total sectors	65	All goods
Total trade (65 sectors) in 2014	US$ 20.4 trillion	

[1] Excluded trade flows are mostly services (90%).

Figure 3 presents the percentage of GTAP's global transportation cost discriminated by mode (road, maritime, or air) for each of the 44 commodities considered. In this sense, 96% of coal, 93% of oil, and 90% of oil seeds' transportation costs refer to shipping; while the commodities with the lowest maritime transportation cost are sugar cane and sugar beet (8%), followed by basic pharmaceutical products (33%) and bovine cattle, sheep, and goats (35%).

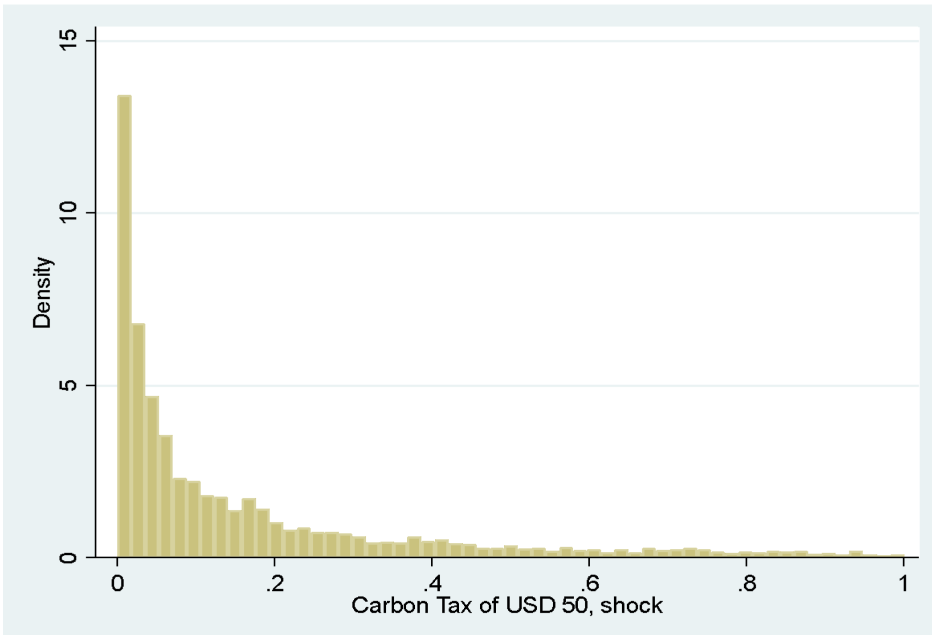
Figure 3. Global transportation cost by sector and mode



Source: GTAP data

Considering all 65 sectors of the GTAP database, Figure 4 indicates that the highest change in maritime transportation cost due to carbon taxation is concentrated in a few pairs of sector-origin-destination.

Figure 4. Distribution of the % change in maritime transport costs due to Carbon tax (Δs_{mijs}):



5. RESULTS

Table 4 summarizes the overall results of the adoption of a carbon tax in the shipping sector. We find that a carbon tax of US$ 50/t CO2 would reduce maritime global emissions by 60 million tCO2e, or 7% (Panel A of Table 4). Our results align with previous studies that estimate changes in global emission reductions considering different global carbon tax rates. According to Keen et al (2012), imposing a US$25 per ton of CO2 price reduces global emissions by up to 5% (raising US$ 26.2 billion in revenues), while Mundaca et al (2021) estimate that a global tax of US$ 40 per ton of CO2 price reduces emissions by 7.65% (with substantial differences across sectors). In turn, considering a unique vessel type, Devanney (2011) estimated a 6% reduction in total very large crude carriers (VLCC) emissions under a US$50 per ton CO2 bunker tax.

We also find that due to the carbon tax, total GDP increases by 0.02% (Table 4, Panel B). However, our analysis shows that results are heterogeneous depending on the region being analyzed. For instance, if we exclude the OECD's member countries, the effect of the proposed carbon tax will be a decrease of 0.13% in GDP.

Table 4. Impacts of a carbon tax in shipping on the global CO_2e shipping emissions and other economic variables (baseline = 2014)

	Carbon Tax of US$ 50/tCO2e
Panel A. Emissions	
Before carbon tax (tCO2e)	863.096.687
After carbon tax (tCO2e)	802.748.261
Change in emissions (tCO2e)	-60.348.426
(% change in emissions using GTAP)	-7,0%
(% change in emissions using 4th IMO GHG)	-6,3%
Panel B. Other economic variables	
% change in total exports	-0,20%
% change in total GDP	0,02%
% change in total GDP, without OECD	-0,13%

As shown in Figure 5, the most penalized regions are located in the African continent, South America, and the former Soviet Union. Oceania (0.16%), North America (0.13%), and Europe (0.12%) registered a positive effect on GDP (Table 5). The positive effect can occur due to price increases, as GDP is measured nominally in the model, or due to trade advantages due to the relative price changes. This is similar to the results of Lee et al. (2013) for international container shipping, in which China, Sub-Saharan Africa, the Rest of Asia, and South America incur the largest GDP losses under a global tax of US$30, US$60 or US$90 per ton of CO2.

Figure 5. Impacts on world GDP in %, by country/region (baseline = 2014)

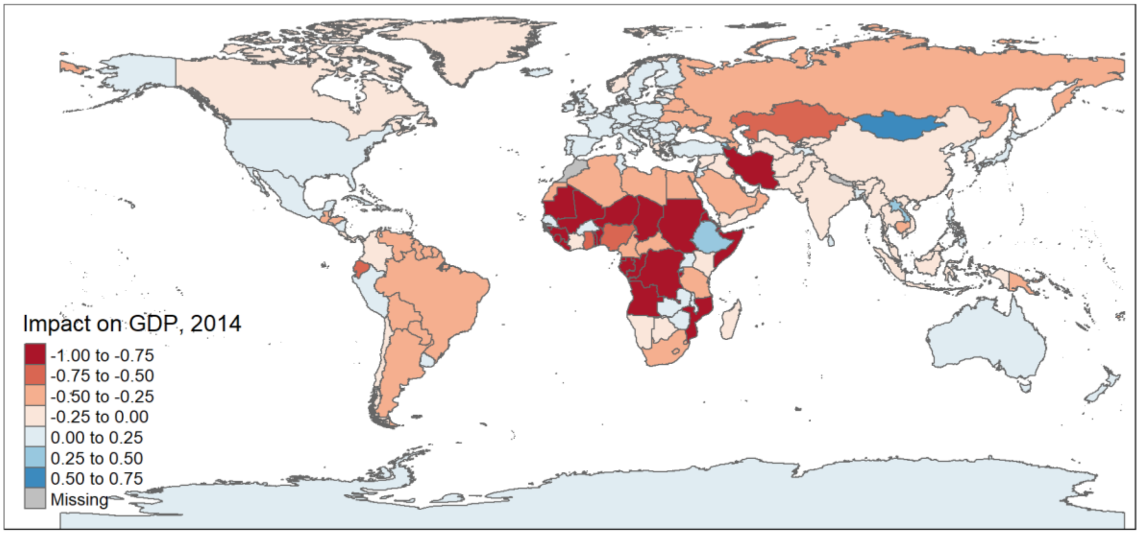


Table 5. Impacts on world GDP in %, by country/region (baseline = 2014)

Region	Change in GDP (%)
Results by region	
Central America	-0.06%
Eastern Africa	-1.10%
Europe	0.12%
North Africa	-0.24%
North America	0.13%
Oceania	0.16%
Other	0.21%
South Africa	-0.41%
South America	-0.25%
South Asia	0.01%
South-Central Africa	-1.00%
Southeast Asia	-0.03%
Western Africa	-0.71%
Western Asia and Former Soviet Union	-0.33%
Total change (all countries)	**0,19**
Change (without OECD countries)	**-1,34**

We also find that due a carbon tax would decrease total exports by 0.20% (Table 4, Panel B). The impact on exports is also negative and very heterogeneous by region, being South Central Asia (-0,70%), Eastern Africa (-0,67%), South America (-0,60%), South Africa (-0,60%), the most negatively affected ones. On the other hand, Central America (-0,05%), Europe (-0,09%) and Southeast Asia (-0,09%) are the least affected regions (Table 6). Differently from CE Delft (2021) report[10], which also utilizes the GTAP model, our results reveal that a carbon tax does not imply positive changes in exports in any of the regions investigated. A key factor affecting this difference is the method utilized to predict maritime emissions, therefore impacting the magnitude of the shock, resulting in different costs across regions and sectors.

Table 6. Impacts on world exports in %, by region (baseline = 2014)

Region	Change in Exports
North America	-0.43%
Central America	-0.05%
South America	-0.60%
Europe	-0.09%
North Africa	-0.25%
Western Africa	-0.40%
South Africa	-0.60%
Eastern Africa	-0.67%
Oceania	-0.17%
Western Asia and the Former Soviet Union	-0.43%
Southeast Asia	-0.09%
South-Central Asia	-0.70%
South Asia	-0.34%
Other	-0.03%

Concerning the impact by sector, Table 7 shows that carbon-intensive commodities such as oil (-1.35%), petroleum (-1.0%) and coal (-4.0%) are the most affected, either in monetary values or in percentage change, in line with Mundaca et al (2021) which products with the largest emission reductions are fossil fuels (11.5%), ores (10.4%), cereals (8.4%), and steel (8.3%).

[10] In our case, the carbon tax is also set at a lower level (US$50 per ton of CO2) in comparison to the CE Delft (2021) carbon tax of US$200 per ton of CO2.

Table 7. Impacts on world exports in %, Top 10 most affected sectors (baseline = 2014)

Top 10 affected in US$ losses		
Rank	Description	Change in X (US$ million)
1	Oil	- $17.488,00
2	Petroleum, coal products	- $7.673,60
3	Coal	- $6.154,40
4	Gas	- $2.272,70
5	Minerals nec	- $2.039,40
6	Chemical products	- $1.748,00
7	Paper products, publishing	- $1.178,60
8	Vegetable oils and fats	- $1.040,20
9	Mineral products nec	- $989,90
10	Ferrous metals	- $864,00

Top 10 affected in %		
Rank	Description	Change in X (%)
1	Coal	-4,05%
2	Forestry	-2,69%
3	Oil	-1,35%
4	Petroleum, coal products	-1,00%
5	Sugar	-0,93%
6	Wheat	-0,83%
7	Vegetable oils and fats	-0,81%
8	Processed rice	-0,80%
9	Gas	-0,68%
10	Minerals nec	-0,66%

6. FINAL REMARKS

This paper analyzes the potential economic and environmental impacts of implementing a carbon tax on maritime shipping. Our findings suggest that a carbon levy of US$50/tCO2e could lead to a reduction in shipping emissions by 7%. However, we show that it is important to consider the negative economic impacts, which are likely to be heterogeneous, and could include a decrease in global exports and GDP in middle- and low-income countries. The main affected sectors - energy, agricultural, and mining products - could also exacerbate regional inequalities across the globe.

At IMO, discussions around carbon pricing policies are ongoing, and technical measures such as the Carbon Intensity Indicator (CII) and GHG Fuel Standard (GFS) are being defined. Future impact assessments need to take into account how these technical measures, either alone or in combination with economic measures, will impact countries and ensure compliance. One possible solution is to use carbon tax as an adjustment mechanism, whereby emissions from older or less efficient ships can be offset by the mitigation efforts of newer and more efficient vessels.

In summary, the economic measures adopted must encourage the transition of the sector to a low-carbon path, while also ensuring that regional inequalities in terms of well-being, GDP, and food security are not exacerbated.

To conduct future analyses, we propose using the GTAP-E model, which is a transparent and widely-used model for evaluating changes in international trade and emissions (Pereda and Lucchesi, 2022). However, there are still limitations to the model that researchers could explore, such as estimating modal substitution elasticities to improve the modal substitution hypothesis. Future simulations could also consider scenarios for assessing the impact of revenue recycling mechanisms, as well as compensation and exemption measures based on the Initial Strategy guidelines to reduce regional inequalities.

Acknowledgement

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APPENDIX TABLES AND FIGURES

Table 1 – Regional aggregation of GTAP

	Code	Description
	aus	Australia
	cxr	- Christmas Island
	cck	- Cocos (Keeling) Islands
1		
	hmd	- Heard Island and McDonald Islands
	nfk	- Norfolk Island
2	nzl	New Zealand
	xoc	Rest of Oceania
	asm	- American Samoa
	cok	- Cook Islands
	fji	- Fiji
	pyf	- French Polynesia
	gum	- Guam
	kir	- Kiribati
	mhl	- Marshall Islands
	fsm	- Micronesia, Federated States of
	nru	- Nauru
	ncl	- New Caledonia
	niu	- Niue
3	mnp	- Northern Mariana Islands
	plw	- Palau
	png	- Papua New Guinea
	pcn	- Pitcairn
	wsm	- Samoa
	slb	- Solomon Islands
	tkl	- Tokelau
	ton	- Tonga
	tuv	- Tuvalu
	umi	- United States Minor Outlying Islands
	vut	- Vanuatu
	wlf	- Wallis and Futuna Islands
4	chn	China
5	hkg	Hong Kong
6	jpn	Japan
7	kor	Korea
8	mng	Mongolia
9	twn	Taiwan
	xea	Rest of East Asia
	prk	- Korea, Democratic People's Republic of
10		
	mac	- Macao, Special Administrative Region of China
11	brn	Brunei Darussalam
12	khm	Cambodia
13	idn	Indonesia
14	lao	Lao People's Democratic Republ
15	mys	Malaysia
16	phl	Philippines
17	sgp	Singapore
18	tha	Thailand
19	vnm	Viet Nam
	xse	Rest of Southeast Asia
20	mmr	- Myanmar
	tls	- Timor-Leste
21	bgd	Bangladesh
22	ind	India
23	npl	Nepal
24	pak	Pakistan
25	lka	Sri Lanka
	xsa	Rest of South Asia
26	afg	- Afghanistan
	btn	- Bhutan
	mdv	- Maldives
27	can	Canada
28	usa	United States of America
29	mex	Mexico
	xna	Rest of North America
	bmu	- Bermuda
30	grl	- Greenland
	spm	- Saint Pierre and Miquelon
31	arg	Argentina
32	bol	Bolivia
33	bra	Brazil
34	chl	Chile
35	col	Colombia
36	ecu	Ecuador
37	pry	Paraguay
38	per	Peru
39	ury	Uruguay
40	ven	Venezuela
	xsm	Rest of South America
	flk	- Falkland Islands (Malvinas)
	guf	- French Guiana
41	guy	- Guyana
	sgs	- South Georgia and the South Sandwich Islands
	sur	- Suriname
42	cri	Costa Rica
43	gtm	Guatemala
44	hnd	Honduras
45	nic	Nicaragua
46	pan	Panama
47	slv	El Salvador
48	xca	Rest of Central America
	blz	- Belize
49	dom	Dominican Republic
50	jam	Jamaica
51	pri	Puerto Rico
52	tto	Trinidad and Tobago
	xcb	Caribbean
	aia	- Anguilla
	atg	- Antigua and Barbuda
	abw	- Aruba
	bhs	- Bahamas
	brb	- Barbados
	vgb	- British Virgin Islands
	cym	- Cayman Islands
	cub	- Cuba
	dma	- Dominica
	grd	- Grenada
53	hti	- Haiti
	msr	- Montserrat
	bes	- Netherlands Antilles
	kna	- Saint Kitts and Nevis
	lca	- Saint Lucia
	vct	- Saint Vincent and Grenadines
	tca	- Turks and Caicos Islands
	vir	- Virgin Islands, US
54	aut	Austria
55	bel	Belgium
56	bgr	Bulgaria
57	hrv	Croatia
58	cyp	Cyprus
59	cze	Czech Republic
60	dnk	Denmark
61	est	Estonia
	fin	Finland
62	ala	- Aland Islands
	fin	- Finland
	fra	France
	fra	- France
63	glp	- Guadeloupe
	mtq	- Martinique
	reu	- Réunion
64	deu	Germany
65	grc	Greece
66	hun	Hungary
67	irl	Ireland
68	ita	Italy
69	lva	Latvia
70	ltu	Lithuania
71	lux	Luxembourg
72	mlt	Malta
73	nld	Netherlands
74	pol	Poland
75	prt	Portugal
76	rou	Romania
77	svk	Slovakia
78	svn	Slovenia
79	esp	Spain
80	swe	Sweden
81	gbr	United Kingdom
82	che	Switzerland
	nor	Norway
	nor	- Norway
83		
	sjm	- Svalbard and Jan Mayen Islands
	xef	Rest of EFTA
84	isl	- Iceland
	lie	- Liechtenstein
85	alb	Albania
86	blr	Belarus
87	rus	Russian Federation
88	ukr	Ukraine
	xee	Rest of Eastern Europe
89		
	mda	- Moldova
	xer	Rest of Europe
	and	- Andorra
	bih	- Bosnia and Herzegovina
	fro	- Faroe Islands
	gib	- Gibraltar
	ggy	- Guernsey
90	vat	- Holy See (Vatican City State)
	imn	- Isle of Man
	jey	- Jersey
	mkd	- Macedonia, Republic of
	mco	- Monaco
	mne	- Montenegro
	smr	- San Marino
	srb	- Serbia
91	kaz	Kazakhstan
92	kgz	Kyrgyzstan
93	tjk	Tajikistan
	xsu	Rest of Former Soviet Union
94		
	tkm	- Turkmenistan
	uzb	- Uzbekistan
95	arm	Armenia
96	aze	Azerbaijan
97	geo	Georgia
98	bhr	Bahrain
99	irn	Iran Islamic Republic of
100	isr	Israel
101	jor	Jordan
102	kwt	Kuwait
103	omn	Oman
104	qat	Qatar
105	sau	Saudi Arabia
106	tur	Turkey
	are	United Arab Emirates
	irq	- Iraq
	lbn	- Lebanon
107	pse	- Palestinian Territory, Occupied
	syr	- Syrian Arab Republic (Syria)
	yem	- Yemen
108	xws	Rest of Western Asia
109	egy	Egypt
110	mar	Morocco
111	tun	Tunisia
	xnf	Rest of North Africa
112		
	dza	- Algeria
	lby	- Libya
	esh	- Western Sahara
113	ben	Benin
114	bfa	Burkina Faso
115	cmr	Cameroon
116	civ	Cote d'Ivoire
117	gha	Ghana
118	gin	Guinea
119	nga	Nigeria
120	sen	Senegal
	tgo	Togo
	cpv	- Cape Verde
	gmb	- Gambia
	gnb	- Guinea-Bissau
	lbr	- Liberia
121	mli	- Mali
	mrt	- Mauritania
	ner	- Niger
	shn	- Saint Helena
	sle	- Sierra Leone
	xwf	Rest of Western Africa
	tcd	- Chad
	cog	- Congo
122	gnq	- Equatorial Guinea
	gab	- Gabon
	stp	- Sao Tome and Principe
123	xcf	Central Africa
	xac	South Central Africa
124	ago	- Angola
	cod	- Congo, Democratic Republic of the
125	eth	Ethiopia
126	ken	Kenya
127	mdg	Madagascar
128	mwi	Malawi
129	mus	Mauritius
130	moz	Mozambique
131	rwa	Rwanda
131	rwa	Rwanda
132	tza	Tanzania
133	uga	Uganda
134	zmb	Zambia
135	zwe	Zimbabwe
	xec	Rest of Eastern Africa
	bdi	- Burundi
	com	- Comoros
136		
	dji	- Djibouti
	eri	- Eritrea
	myt	- Mayotte
	syc	- Seychelles
	som	- Somalia
	sdn	- Sudan
137	bwa	Botswana
138	nam	Namibia
	zaf	South Africa
139	lso	- Lesotho
	swz	- Swaziland
140	xsc	Rest of South African Customs
	xtw	Rest of the World
	ata	- Antarctica
	bvt	- Bouvet Island
141		
	iot	- British Indian Ocean Territory
	atf	- French Southern Territories

Table 2 – Sectoral aggregation of GTAP

Code	Description	Code	Description
pdr	Paddy rice	**chm**	Chemical products
wht	Wheat	**bph**	Basic pharmaceutical products
gro	Cereal grains nec	**rpp**	Rubber and plastic products
v_f	Vegetables, fruit, nuts	**nmm**	Mineral products nec
osd	Oil seeds	**i_s**	Ferrous metals
c_b	Sugar cane, sugar beet	**nfm**	Metals nec
pfb	Plant-based fibers	**fmp**	Metal products
ocr	Crops nec	**ele**	Computer, electronic and optic
ctl	Bovine cattle, sheep and goats	**eeq**	Electrical equipment
oap	Animal products nec	**ome**	Machinery and equipment nec
rmk	Raw milk	**mvh**	Motor vehicles and parts
wol	Wool, silk-worm cocoons	**otn**	Transport equipment nec
frs	Forestry	**omf**	Manufactures nec
fsh	Fishing	**electricity**	Electricity
coa	Coal	**wtr**	Water
oil	Oil	**cns**	Construction
gas	Gas; Gas manufacture, distribution	**trd**	Trade
oxt	Minerals nec	**afs**	Accommodation, Food and servic
cmt	Bovine meat products	**otp**	Transport nec
omt	Meat products nec	**wtp**	Water transport
vol	Vegetable oils and fats	**atp**	Air transport
mil	Dairy products	**whs**	Warehousing and support activities
pcr	Processed rice	**cmn**	Communication
sgr	Sugar	**ofi**	Financial services nec
ofd	Food products nec	**ins**	Insurance
b_t	Beverages and tobacco products	**rsa**	Real estate activities
tex	Textiles	**obs**	Business services nec
wap	Wearing apparel	**ros**	Recreational and other service
lea	Leather products	**osg**	Public Administration and defense
lum	Wood products	**edu**	Education
ppp	Paper products, publishing	**hht**	Human health and social work
oil_pcts	Petroleum, coal products	**dwe**	Dwellings

Figure 1. Histograms of prediction errors – Lasso Regression (top) versus Linear Regression (down)

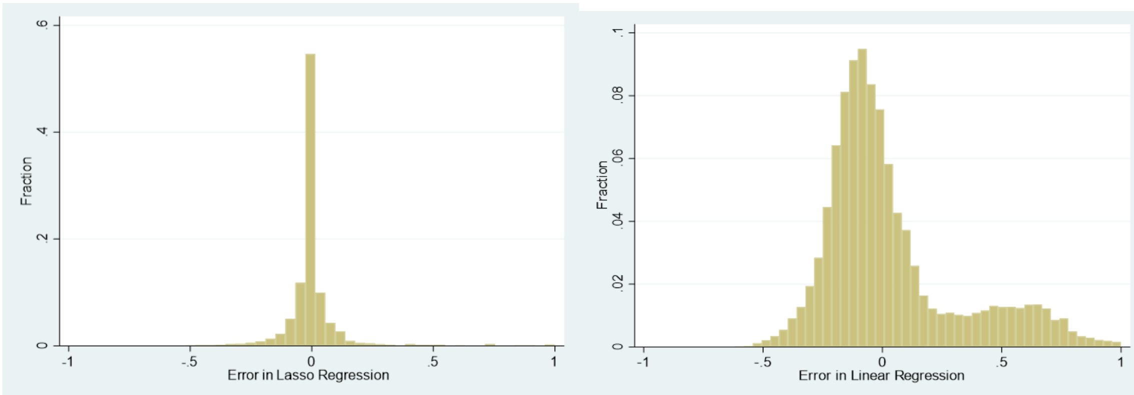

Figure 2. Comparison of prediction error – Lasso Regression versus Linear Regression, by category

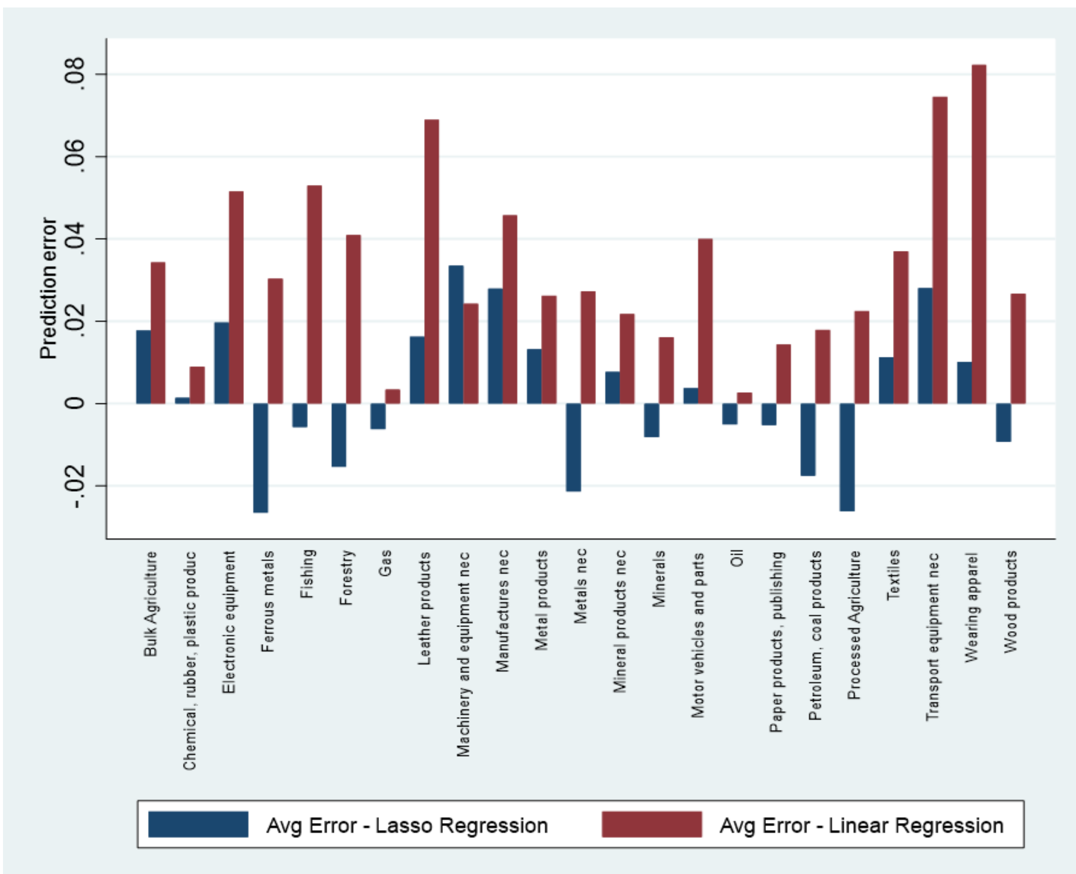

Figure 3. Seaports considered in the study