Applied Economics and Policy Working Paper Series

AEP WP NO. 2022-05

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Keywords: agricultural trade, bunker levy, carbon tax, environmental policy, maritime economics*,* gravity model

JEL Classifications: D22, F18, H23, Q17, R41

Acknowledgments: This research has been supported by the Social Sciences and Humanities Research Council of Canada (SSHRC) project (N 895- 2017-1003): "Green Shipping: Governance and Innovation for a Sustainable Maritime Supply Chain".

May 2022

1. Introduction

The ITF/OECD (2019) acknowledges that emissions linked to international transport represent one of the most challenging environmental problems. This has been a significant on-going concern by policy makers, economists, and industry stakeholders (van Veen-Groot and Nijkamp 1999; Cadarso et al. 2010; Zhu et al. 2018) and has been driven, in part, by expanding global supply chains (Nabernegg et al. 2019). Recent reports indicate that international movements of products lead to 2,600 million tons (Mt) of carbon emissions (CO_2), and that approximately 53% are due to ground transportation, 7% is attributed to air, 2.5% attributed to inland waterways, and 37.5% is linked to sea transportation (ITF/OECD 2019).

International maritime transport emissions are expected to increase by up to 50% by 2050; this is an increase to approximately 1,500 Mt in 2050 compared to the 2018 level of around 1,000 Mt (ITF/OECD 2018; ITF/OECD 2021). The share of shipping in global anthropogenic emissions is also projected to rise from 3% in 2018 to 5% by 2050 (IMO 2020). Due to the challenge posed by shipping emissions, mitigation measures are therefore needed to achieve the goals agreed upon by the IMO in 2018, which aims to cut greenhouse gas (GHG) emissions from shipping by 50% by 2050 compared to the 2008 level.

An economically efficient mitigation option is to set carbon prices that reflect the social cost of transportation (Dominioni et al. 2018; Heine et al. 2017; Heine and Gäde 2018). A number of global or regional Market Based Mechanisms (MBMs) have been proposed (Psaraftis et al 2019; Faber et al. 2009; Kosmas and Acciaro 2017; Cariou et al. 2021; Mundaca et al. 2021) and are recommending the use of taxes (e.g., bunker levies) or emission trading schemes to incentivize the use of low and zero-carbon fuel alternatives.

However, there continues to be much discussion on the appropriate level for such bunker levies (Psaraftis et al. 2019). MBMs are controversial as they may lead to inequities across shipowners and across countries, and therefore it has proven difficult to reach a multilateral agreement for this measure. Empirical research has established that, in general, perceived fairness is an important factor for public support of carbon pricing (Sommer et al. 2022). While the vast majority of economists support the adoption of a carbon tax as an efficient mechanism to reduce greenhouse gas emissions, such a policy may also excessively burden the poor (Fremstad and Paul 2019). As stressed by Bureau et al. (2017), "International transport plays a major role in trade globalization ... and emerging countries fear an increase in the cost of international transport that may impede their development and advanced countries do not want to make progress alone in the fight against global warming. In this context, incorporating climate challenges into the regulation of international transport need to be accompanied by transparent economic impact assessment".

These impacts of MBMs on trade and economic outcomes for industry stakeholders are a consequence of two main effects (DNV 2021; UNCTAD 2021). First, there is a direct impact due to higher compliance costs. Second, there is an indirect impact as new regulations trigger a reaction from the industry, by shipowners, on the optimal speed of vessels and therefore, on transit times. The report by the UNCTAD (2021) sums up these two effects into a total logistical cost to estimate the impacts of IMO short-term measures for three scenarios (compliance to new technical requirements, combined with a High or Low level of ambition) for 184 countries and 11 product categories.

One of the main findings from the DNV (2021) and UNCTAD (2021) studies concerns the sensitivity of trade to maritime transport cost and transit time, and how such sensitivities will affect trade patterns. For instance, countries that are the most affected could be those which have distant trade partners (with longer transit times) and for commodities with a high share of transport costs relative to the total product value (i.e., high CIF/FOB ratios).

Overall, we recognize that maritime regulations will have consequences for both compliance costs and travel times, and our framework will model these considerations explicitly in discussing the importance of demand elasticity (cost and time) on shipowner behavior and on emissions (Section 2). We then provide an empirical application for two agricultural export products and offer a way to measure these elasticities using an augmented gravity model (Section 3). Here we take advantage of the new maritime transport cost database developed by the World Bank and UNCTAD[1]. Section 4 incorporates our estimates to assess ship-owner profits and their potential reaction to the new market conditions, and finally, the impacts on trade and emissions. Section 5 offers our conclusions and avenues for future research.

2. Impact of a maritime carbon tax on profits, speed, trade and emissions

In a simple setting, carbon emissions are positively related to the speed of a vessel and this relationship is shown in the left panel in Figure 1. Any increase in fuel price due to an environmental tax (e.g., bunker levy) will lead to a reduction in the speed and therefore, to a decrease in emissions.

Insert Figure 1 around here

The extent of the reduction depends on the shape of the speed-profit function (illustrated in the right panel in Figure 1). When assuming that demand is inelastic to transit time (shown by the solid and the dashed dark curves in the right panel of Figure 1), a bunker levy encourages the ship-owner to reduce speed (and associated emissions) from A to B. If we assume that demand is sensitive to transit time then another speed-profit relationship exists (shown by the solid and the dashed red curves in the right panel of Figure 1); here the optimal speed is higher than when demand is inelastic to transit time. In this latter case, the maximum profits correspond to the point where transported quantities reach the full capacity of a vessel (shown as point C in Figure 1, at approximatively 15 knots). Although the consequence of a bunker levy leads to a reduction in emissions (from point C to D), the case outlined in Figure 1 illustrates that the initial level of emissions (A versus C) and the extent of the reduction (from A to B versus from C to D) can be significantly different.

The speed-profit relationship can also differ if transported quantities are sensitive to transport costs, and when shipowners decide to shift the burden of the tax to their customers instead of paying the bunker levy. Under this situation (not reported in Figure 1), this may increase ship-owner profits as they do not pay the bunker levy, but this may reduce the total volume of trade and therefore, their revenue. These examples illustrate how the level of the bunker levy and the sensitivity of trade to transportation cost and time are critical to evaluate the reaction from the industry and the impact on the environment. However, in most settings, the volume of demand transported by a vessel is usually assumed to be constant, or it is inelastic to speed.

The idea that trade may be sensitive to time and cost was discussed in Halim et al. (2019). They showed that a bunker levy in the range of 10 to 50 USD/tonne of CO_2 will affect trade, and that a carbon tax applied to all transport modes might even stimulate a shift toward maritime transport from all other modes. Mundaca and al. (2021) show that a global tax of 40 USD/tonne of carbon will reduce CO_2 emissions by 7.65% for the heaviest traded products (at the 6-digit HS level of aggregation) transported by sea and that the greatest CO_2 emission reductions are for products with relatively low value-to-weight ratios. Beghin and Sweizer (2021) highlight that agricultural products will be largely affected by future maritime regulations as moving these goods between markets is costly relative to the farm gate value (Hummels 2007). If the impact of MBMs will be particularly important in the short term for countries that import a significant proportion of their food supply, long-term improvements in fuel efficiency of ships may reduce this effect and as revenues increase we will see a decrease in transportation costs over time (Stocheniol 2011).

Korinek and Sourdin (2009) confirm the general importance of the cost of shipping goods in overall agricultural trade costs using an augmented gravity model. Doubling the bilateral transport costs is associated with a 42% decline in the average value of bilateral country-pair agricultural imports. A doubling of the transport costs of cereals between two given countries would lead to a 37% decrease in their trade.

However, most studies focus on measuring the macroeconomic impacts of GHG reduction measures on trade volume and GDP, without taking into account the potential responses of the shipowners that, as illustrated in Figure 1, can play an important role on the final outcome. In this research, we aim to address the abovementioned gap and provide three contributions in applied economic research. First, we incorporate the perspective of the carriers or shipowners and assess their likely response to the introduction of a bunker levy. Halim et al. (2019) and Vivid Economics (2010) suggest that the response depends on the ability of shipowners to transfer added costs to consumers, which is related to the elasticity of demand to maritime cost. Rojon et al. (2021) suggest that this response depends on the magnitude of the compliance costs associated with the bunker levies. We focus on how the level of tax and the elasticity of demand to cost and transit time affect ship-owner behavior, profits, trade patterns, and emissions. Second, given the potential importance of trade elasticity to cost and time, we propose a methodology that adopts an augmented gravity model to estimate these elasticities for two specific agricultural exports: grain[2] and soybeans. We complement a former study by Korinek and Sourdin (2009) which is, to our knowledge, the only study with a focus on the impact of maritime trade cost on agricultural trade. Third, we answer the call by Beghin et Sweizer (2021) for more applied research on agricultural trade to better understand the impact of new environmental policies applied to maritime transportation. By incorporating estimates from the gravity model into a framework that focuses on ship-owner gross profits for grain and soybeans, we shed new light on the potential reaction of shipowners to environmental regulations and on their impact on agricultural trade and emissions.

3. Empirical Model

3.1. Ship-owner response to maritime regulations

To understand how a bunker levy affects ship-owner decisions regarding vessel speed, we first present the main determinants of their profits. The ship-owner's daily gross profit or the Time Charter Equivalent (TCE) can be presented, in its simplest form[3], as follows (Evans and Marlow 1990).

$$TCE = \frac{R.W}{\left(\frac{d}{24.s}\right)} - OC - p.FC(s) \qquad (1)$$

With $FC(s) = \alpha.s^{\lambda}$

where TCE is the daily Time Charter Equivalent (in USD/day), R is the freight rate (in USD/tonne of cargo), W the transported quantity (in tonnes of cargo), d the distance travelled (in nautical miles), s the speed (in knots, i.e. nautical miles/hour), *OC* are the operating costs, p the price of fuel (in USD per tonne) and FC the fuel consumption (in tonnes per day). The fuel consumption-speed relationship or *FC(s)* is critical to understand the reaction of shipowners to a change in fuel price (*p*). The traditional assumption (IMO 2020; Adland et al., 2020) is to use a speed-to-fuel consumption elasticity equal to 3, which reflects the engine power-speed relationship, so that $FC(s) = \alpha.s^{\lambda}$, with $\lambda = 3$.

When assuming that the transported quantity (*W*) is not affected by a change in transport cost (*Cost*) or in transit time (*Time*), so that ${}^{dW}/_{dTime} = 0$ and ${}^{dW}/_{dCost} = 0$, and for a given voyage between two countries equal to *d*, the speed is the main factor on which the ship-owner can play to maximize the *TCE*. The optimal speed $s*$ that maximizes *TCE* can be determined from the first-order condition $\left({}^{dTCE}/_{ds} = 0\right)$, so that:

$$s^{*} = \left(\frac{24.R.W}{\lambda.p.\alpha.d}\right)^{\frac{1}{\lambda-1}} \qquad (2)$$

The optimal speed therefore changes with the ratio of freight rate to fuel price ($^{R}/_{p}$) and of the vessel specific characteristics included in parameters α and λ. Corresponding to this optimal speed, the amount of carbon emitted per day or per trip can be estimated and is a function of the fuel consumption-speed relationship and on an emission factor (e_f) specific to each type of fuel (according to the fuel's carbon content):

$$CO_2 = e_f . FC(s) \tag{3}$$

We now consider that *W,* the transported quantity for a given route is sensitive to transit time $\left(Time = \frac{d}{24.s}\right)$ that reflects the quality of service or value of time so that $^{dW}/_{dTime} \neq 0$ with $W_{Time} = a.Time^{\beta_1}$. We also assume that *W* is sensitive to transit cost (C*ost*) so that $^{dW}/_{dCost} \neq 0$ with $W_{Cost} = c.Cost^{\beta_2}$. For the latter case, it means that if shipowners transfer the cost of the bunker levy to final customers, the demand (*W*) is also affected. Then, following the introduction of a bunker levy, the ship-owner has two options. First, the ship-owner can pay for the bunker levy (*t*), whereby the price of fuel increases from *p* to (*p*+*t*) and the optimal speed changes from $s*$ to a new optimal speed with $s^* = \left(\frac{24.R.W_{Time}}{\lambda.(p+t).\alpha.d}\right)^{\frac{1}{\lambda-1}}$. Second, the ship-owner may decide to pass the bunker levy to final customers and therefore shift the burden of the tax through an increase in transportation costs. Under this second configuration, the optimal speed changes from $s*$ to a new optimal speed with $s^* = \left(\frac{24.R.W_{Time,Cost}}{\lambda.p.\alpha.d}\right)^{\frac{1}{\lambda-1}}$. Despite the fact that the ship-owner may not have to pay for the tax, they may experience a larger decrease in profits if demand is highly sensitive to transit cost. It means that the level of the bunker levy, the sensitivity of demand to transit time, and the sensitivity of demand to transit costs are going to influence the ship-owner's choice to pay or pass-through the tax. Consequently, this will also affect the level of trade (*W*) and the effectiveness of the policy on CO_2 emissions.

In the next section we describe the data and model we use to evaluate the effects of a bunker levy applied to maritime shipments of grain and soybeans. We propose to estimate the transit time (β_1) and transit cost (β_2) elasticities with an augmented gravity model that has been widely used to examine international bilateral trade. We will then employ the estimates from the gravity model in the ship-owner's profit function and subsequently assess the potential impact of a bunker levy on the vessel speed, trade and emissions.

3.2. A Description of the Data

Our analysis used data on export quantities (in tonnes) for 36 grain exporting countries and 25 soybean exporting countries to 84 importing countries in 2016 (COMTRADE). We use data from 2016 as this is the year for which information on bilateral maritime costs ($Cost_{ij}$) are available from the World Bank-UNCTAD maritime costs database. The trade data and the cost data were merged using the HS product level code.

In addition, we included traditional covariates in the gravity models such as the bilateral maritime distance (d_{ij}) from the CERDI-SeaDistance (Bertoli et al. 2016), which is based on the shortest sea route between the coastal region of the country pairs, with the relevant port being the coastal port of the country with the highest traffic. A proxy of transit time ($Time_{ij}$ in number of days) was calculated by dividing the maritime distance (CERDI) by the average speed of a Panamax bulk carrier, the most common vessel to transport grain and soybeans, with an average sailing speed of 12 knots in 2016 (IMO 2020). We also consider a suite of covariates that are commonly used in gravity models including the existence of a contiguous border between neighboring countries ($CNTG_{ij}$), common language ($LANG_{ij}$) and the existence of former colonial ties ($CLNY_{ij}$) trade patterns (all from the CEPII database).

Insert Table 1 around here

Table 1 reports some descriptive statistics for the top five grain and for the top five soybean exporting countries in 2016. The United States accounts for 39% of grain exports and the top five countries represent approximatively 80% of world grain exports. Overall, across the two commodities there are large differences in transport costs per kilogram (from 0.01

USD/kg to 0.14 USD/kg) which can be explained by the type of product exported, the distance travelled, and the size of vessel used. The share of maritime transport costs in total FOB value is between 7.9% and 10.3% for grains and the average travel time is approximatively 28 days. Exports are more concentrated for soybean exports, with the United States and Brazil accounting for more than 83% of world export volume, amounting for 44% and 39% respectively. Transport routes for soybean trade are longer as reflected by transit time of 49.5 days compared to 28 days for grain trade routes.

Table 1 shows that average transport costs for soybeans are lower than for grain (0.01 USD/kg compared to 0.06 USD/kg) and the share of FOB export values is also lower (around 3.17% for soybeans compared to 9.7% for grains). These differences could be due to a number of factors including port congestion and global demand for bulk ocean services (USDA 2014; Steadman et al. 2019). Ocean freight rates from South America to Asia are for instance often less expensive than from the U.S. Gulf (O'Neil 2015, Delmy 2015) because of dry-bulk vessel route patterns, lower cost port charges, higher Panama Canal tolls, and less burdensome navigation restrictions.

3.3. A Gravity Model Considering Maritime Transit Costs and Times

In addition to the standard computable general equilibrium models (UNCTAD 2020), many approaches using gravity models have also been considered to assess the impact of MBMs (Mundaca et al, 2021). We begin with a model that only includes distance between partner countries, denoted as d_{ij}, in equation (4a), and then in equation (4b) we replace d_{ij} with maritime transport costs ($Cost_{ij}$) and maritime transit time ($Time_{ij}$) as explanatory variables.

$$lnW_{ij} = \beta_0 + \beta_{12} lnd_{ij} + \beta_3 CNTG_{ij} + \beta_4 LANG_{ij} + \beta_5 CLNY_{ij} + \beta_6 lnY_i + \beta_7 lnE_j + \varepsilon_{ij} \quad (4a)$$

$$lnW_{ij} = \beta_0 + \beta_1 lnTime_{ij} + \beta_2 lnCost_{ij} + \beta_3 CNTG_{ij} + \beta_4 LANG_{ij} + \beta_5 CLNY_{ij} + \beta_6 lnY_i + \beta_7 lnE_j + \varepsilon_{ij} \quad (4b)$$

In equations (4a) and (4b), lnW_{ij} corresponds to the logarithm of nominal bilateral international trade flows (in volume) from exporter i to importer j, β_0 is a constant term, $CNTG_{ij}$

is an indicator variable capturing the presence of contiguous borders between trading partners, $LANG_{ij}$ denotes a dummy variable for the existence of a common official language between trade partners, and $CLNY_{ij}$ is an indicator for the presence of colonial ties between countries. The covariates lnY_i and lnE_j are the logarithms of the values of exporter output and importer expenditure, respectively.

In line with Anderson and van Wincoop (2004) and Yotov and al. (2016), we re-estimate equations (4a) and (4b) and account for multilateral resistance terms by adding a set of exporter fixed effects and importer fixed effects in equations (5a) and (5b) as follows:

$$lnW_{ij} = \pi_i + \chi_j + \beta_{12} lnd_{ij} + \beta_3 CNTG_{ij} + \beta_4 LANG_{ij} + \beta_5 CLNY_{ij} + \varepsilon_{ij} \tag{5a}$$

$$lnW_{ij} = \pi_i + \chi_j + \beta_1 lnTime_{ij} + \beta_2 lnCost_{ij} + \beta_3 CNTG_{ij} + \beta_4 LANG_{ij} + \beta_5 CLNY_{ij} + \varepsilon_{ij} \tag{5b}$$

The term π_i denotes the vector of exporter fixed effects, which account for the outward multilateral resistances. Similarly, the vector χ_j denotes the set of importer fixed effects to capture the inward multilateral resistances. Equations (4a), (4b), (5a) and (5b) are estimated using OLS and OLS_Fixed Effects.

To account for heteroscedasticity in the trade data (Santos Silva and Tenreyro 2006), we re-estimate the gravity model in equations (6a) and (6b) using Poisson pseudo maximum likelihood (PPML) estimators and for bilateral flows expressed in absolute values.

$$W_{ij} = exp[\pi_i + \chi_j + \beta_1 lnd_{ij} + \beta_3 lnCNTG_{ij} + \beta_4 lnLANG_{ij} + \beta_5 CLNY_{ij}] \,.\, \varepsilon_{ij} \tag{6a}$$

$$W_{ij} = exp[\pi_i + \chi_j + \beta_1 lnTime_{ij} + \beta_2 lnCost_{ij} + \beta_3 lnCNTG_{ij} + \beta_4 lnLANG_{ij} + \beta_5 CLNY_{ij}] \,.\, \varepsilon_{ij} \tag{6b}$$

Insert Table 2 around here

Our estimates (shown in Table 2) highlight that the models that account for transit costs and transit time (equations 4b, 5b, and 6b) rather than maritime distances (equations 4a, 5a, and 6a), yield better results across the specifications. Furthermore, the PPML estimators provides better results than OLS and OLS Fixed Effects models for both grain and soybeans. According to our results, the grain and soybean export quantities are similarly sensitive to cost and time; the elasticity to maritime transit time is -0.917 for grain and -0.944 for soybeans. This implies that increasing transit time by 10% induces a decrease in trade of approximately 9%. The sensitivity to maritime costs is slightly lower with an estimated elasticity of -0.785 for grain and -0.876 for soybeans.

Our estimates are in line with results from earlier studies. Disdier and Head (2008) and Head and Mayer (2014) find that that the elasticity to distance (a proxy for transportation attributes) is approximately equal to -1.0 and that this is a significant impediment to bilateral trade. Merkel et al. (2021) provide a review of existing estimates on elasticities of maritime freight transport demand with respect to transport time, and they report an average of -0.49. In cargo markets where there is the possibility of switching to other transportation modes, the elasticity estimates are typically lower. For agricultural trade, Korinek and Sourdin (2010) find an elasticity of agricultural trade (in value) to transport time equal to -0.7 and to transport cost equal to -0.8, which are very similar to our results.

In the next section, we use our estimated elasticities to time and cost to simulate the impacts of bunker levies on the vessel speed and profits for shipowners in grain and soybean markets. In a final step, we then assess the implications in terms of trade volume and carbon emissions for the main exporting countries.

4. Simulating the industry and environmental impacts

4.1 Model setup and assumptions

We use the elasticities of exports to cost (β_1) and time (β_2) from the PPML model specified in equation (6b) to simulate the behavior of shipowners across a range of possible bunker levies. In our simulation model, and in line with the conceptual framework described in Section 2 and outlined in Figure 1, we consider two ways that shipowners can react to such a tax. First, they can decide to pay the tax, which is analytically similar to evaluating the impact of an increase in fuel cost when demand is sensitive to transit time. Under this first case, the main consideration is the change in the optimal speed when the fuel price increases and then how such a change in speed will affect the transported quantities (where $^{dW}/_{dTime} \neq 0$ and β_1 is equal to -0.917 for grain and β_1 is equal to -0.944 for soybeans). Second, the ship-owner can decide to pass through the tax to final consumers. Under this configuration, the transported quantity is affected as demand is sensitive to transport costs (with $^{dW}/_{dCost} \neq 0$ and β_2 is equal to -0.785 for grain and β_2 is equal to -0.876 for soybeans).

The calculation of the optimal speed, from the ship-owner's perspective, cannot be derived from the first derivation of the profit function as W is sensitive to the speed. The optimal solution is calculated through iterations for each market, for incremental changes in speed and for different bunker levies. We consider that speed can vary from 8 to 15 knots; using an incremental increase of 0.05 kts, there would be 141 different speeds to consider for each bunker levy. To assess the impact on profits, some technical and economic assumptions are also needed to develop our simulation. The technical specifications are representative of a Panamax bulk carrier which is the most common vessel used to transport grain and soybeans over long distances (we show the main technical characteristics for this carrier in Table 3).

Insert Table 3 around here

Insert Table 4 around here

A set of economic and policy assumptions are also required for our simulation and a summary of the key parameters required are provided in Table 4. We simulate the effects across six levels of bunker levies (from 0% of fuel price to 50% in 10% incremental changes). The time and cost elasticities shown in Table 4 are from Table 2, and the information on distances are from Table 1 (CERDI database). We use a U.S. representative freight spot rate of 25 USD/tonne for 2016 (Clarkson Research, 2022) and we estimated a weighted-distance spot rate for each export market as shorter trade routes are assumed to generate lower spot rates.

4.2 Results

Table 5 summarizes our simulation results for the optimal speed and the corresponding daily profit for each level of tax. The quantity transported varies with the speed and the simulation results are calculated following equation (1) across a range of speeds from 8 to 15 knots (kts) and using the technical and economic parameters presented in Table 3 and Table 4. The values shown in Table 5 only report the optimal solution (maximizing gross profit) for each of the bunker levies from 0 USD/tonne to 250 USD/tonne (in 50 USD increments). We show the results for grain and soybean trade for the case when shipowners pay the bunker levy and then for the case when they decide to pass the bunker levy along to final consumers.

Insert Table 5 around here

There are several important findings included in Table 5. First, a bunker levy of 50 USD/tonne (and less) is found to not trigger any change in the optimal speed of the vessel (it remains at 12 knots). The shipowner will, however, face a reduction in profits given that they will pay the tax (equivalent to 1500 USD/day for a tax of 50 USD/tonne). Second, when the ship-owner passes the cost of the bunker levy on to final consumers, the transported quantities will fall due to the increase in total transportation costs (equivalent to approximatively 1100 USD per day for a 50 USD/tonne levy). Third, as the rate of the bunker levy increases (to 100 USD/tonne and higher), and when the ship-owner pays the tax, they will adjust their speed. When the ship-owner passes the tax on to final consumers, it is optimal to keep the same speed (and same transit time) as long as the tax is equal to, or less than, 100 USD/tonne. Fourth, for bunker levies at 150 USD/tonne and greater and when the tax is passed through to final consumers, it becomes optimal to decrease the vessel speed in order to reduce fuel costs. Furthermore, shipowners are always better off financially when they are able to pass along the burden of the tax. For the case of very high bunker levies (i.e., 250 USD/tonne), we see a decrease in profits when the tax is paid for by shipowners in the grain market, and when it is paid for or passed along by shipowners in the soybean market.

Insert Table 6 around here

Across the same range of bunker levies considered in Table 5, Table 6 presents the impacts on export volumes and on carbon emissions. The change in export volume is driven by the decision of shipowner to pass the tax to final consumers and/or from their decision on the optimal speed. Table 6 also showcases some important results across the bunker levy rates. When the ship-owner pays for the bunker levy and it is less than 100 USD/tonne, there is no change in speed, exports are not affected, and carbon emissions do not change. Following the results shown in Table 5, once the tax is equal to or higher than 100 USD/tonne, shipowners will reduce the speed of their vessels, and this will begin to affect trade and emissions. A bunker levy set at 100 USD/tonne will lead to reductions in exports of between 6.9% and 7.6% for grains and between 6.3% and 6.7% for soybeans.

We see an even larger effect on carbon emission reductions given the combined reduction in trade and the reduction in speed; this leads to an overall decrease in fuel consumption per tonne travelled. With a bunker levy set at 250 USD/tonne, the decrease in exports would be close to 23% for both grains and soybeans, and the reduction in carbon emissions would be 57%. If shipowners are able to pass along the tax to final consumers, the general effect on exports described above would occur even for relatively low levels of bunker levies. A bunker levy of 50 USD/tonne would lead to a decrease in exports of 3.9% for grain and 4.4% for soybeans, and the decrease in emissions is at a level similar to the decrease in exports as the speed remains approximately the same. However, as the bunker levy increases (say to 100 USD/tonne) the decrease in trade and the decrease in carbon emissions is approximately 9%. Finally, for a substantial bunker levy of 250 USD/tonne, we would see a 28% reduction in exports and a 42% reduction in emissions for maritime transportation of grains; for soybeans the 250 USD/tonne levy would lead to a 31% decrease in exports and a 48% decrease in emissions.

In summary, our simulation results indicate that across a range of potential bunker levies applied to maritime transportation, the decision among shipowners to pay or to pass along the tax burden to final consumers leads to similar effects on exports. However, the decision to pay instead of passing along the tax to final consumers will have a more substantial effect on reducing emissions, especially as the level of the tax increases beyond 100 USD/tonne.

5. Conclusion and Implications

Our research provides new insights for how shipowners will respond to a range of bunker levies by taking into account the sensitivity of cost and time on trade patterns for selected agricultural commodities. We developed a modeling framework to consider the effects of levies on vessel speed, ship-owner profits, trade, and emissions (with or without passing along the burden of the tax to final consumers). Specifically, the model that we developed takes into account transit time and transport costs explicitly using a global transport costs database recently launched by the World Bank-UNCTAD. Our analytical framework allows us to examine the impact of changes in transport costs and transit time with the use of bunker levies, and it also allows us to consider some of the potential unintended consequences of these policies. Our results remind us that we need to be mindful of the effects of maritime policy on both transport time and costs on global trade and shipowner behavior.

Our results have important industry and environmental implications. In the scenario where the increase in transport costs is passed along to the customer, the decline in trade of agricultural products will be higher and reduction in GHG emissions will be lower (relative to scenarios where costs are not passed through to customers). In the scenario where the carbon tax is not passed through to customers, a higher carbon tax will result in lower ship speed and a correspondingly higher reduction in carbon emissions. Trade volume would also be less affected when the taxes are paid for by the shipowners. Nevertheless, it is expected that there would be a lower likelihood of observing the scenarios in which the shipowner would pay for the tax in the marketplace. Insights from the most likely scenarios where costs are passed along to final consumers would lead to a reduction in emissions, but only for bunker levies above USD100/tonne.

Our findings show that bunker levies at moderate levels may not lead to large changes in behavior by shipowners. This result is in line with Psaraftis and Lagouvardou (2019) showing that low bunker levies (less than 15 USD/tonne of fuel) will have a limited impact on carbon emissions. Practically, the limited impact of relatively low bunker levies on emissions could also be attributed to the fact that vessel speed is subject to certain contractual constraints, notably the requirement that a vessel must be docked during a predetermined window of time (Adland and Jia 2018; Adland and Prochazka 2022).

Although our findings shed new light on the impact of fuel taxes on maritime transportation, our results are dependent on a number of assumptions and simplifications that we made to describe the maritime shipping industry. The assumption that changes in trade will lead to corresponding changes in transported quantities by all vessels may not fully reflect market conditions and the level of competition within the industry. Furthermore, we do not explicitly model the potential response to increased transport costs with substitution patterns towards products that are sourced closer to home. As showed by Lagouvardou et al. (2022), "in case of prosperous market period the levy should be higher in order to achieve the same level of emissions reductions". This is not considered in our model as freight rates (R) for each sub-market (each agricultural commodity) are assumed to be constant in 2016.

Similarly, the use of elasticities by commodity across all geographic markets is a simplification that allows us to highlight general insights on the potential impact of bunker levies globally. When possible, time-varying effects should be considered in gravity models as a way to capture these effects (Yotov et al. 2016), but this was not possible in our empirical application given that the World Bank-UNCTAD dataset we used was only available for 2016. Furthermore, the characteristics of vessels deployed to carry grain or soybeans vary across geographic regions and across port-specific considerations. Additional elements such as port time, port cost, demurrage to be paid for late arrival and different ballast versus laden fuel consumption-speed relationships are also important (Lagouvardou et al. 2022), but it is beyond the scope of this research to model many of the industry-specific details in the global shipping sector.[4] These are important details that are expected to influence our results in some capacity, however, extending our framework to consider many of these idiosyncrasies is not expected to change the general thrust of results that we present here.

Our research also presents potential avenues for future research. First, results from our work could be used to highlight the cost effectiveness of bunker levies with ratios that compare total emission abatement to economic outcomes and to changes in traded quantities. Second, our modelling framework could be extended to allow for a more nuanced exploration of the impact of bunker levies for a more diverse set of commodities; it is expected that the sensitivity of trade to changes in maritime costs and transit time is different across a wider range of agricultural commodities, other raw materials, and manufactured products. In addition, the gravity model developed can also be augmented with an additional module which explicitly models the elasticity of substitution for the commodities studied. This extension will allow a more comprehensive and thorough analysis of the overall positive and negative impacts on global trade in a holistic manner. Third, future research could explore how shipowners would react to a combination of maritime policy measures. For instance, if the carbon tax is low (less than USD50/tonne of fuel), a second instrument such as an upper limit for vessel speed might be necessary to reduce emissions. If the carbon tax is set relatively high (e.g., USD 200/tonne), the use of subsidies or tax exemptions might be required to reduce the negative and disruptive impacts on global trade especially for heavily affected countries.

Endnotes

[1] The dataset is available at https ://unctadstat.unctad.org/EN/TransportCost.html.

[2] The "grain" category comprises wheat and various coarse grains including maize (corn), barley, sorghum, oats and rye.

[3] In our setting, we do not consider fuel consumption that occurs when the vessel is in port for the auxiliary engine, time in port and potential payments related to demurrage (late arrival). We also did not consider the difference in fuel consumption between ballast and laden conditions.

[4] Other considerations, such as the relationship of engine load to specific fuel consumption, the draft of the vessel, or some correction factors that are related to weather or anti-fouling conditions are not addressed here (IMO 2020; Adland et al., 2020).

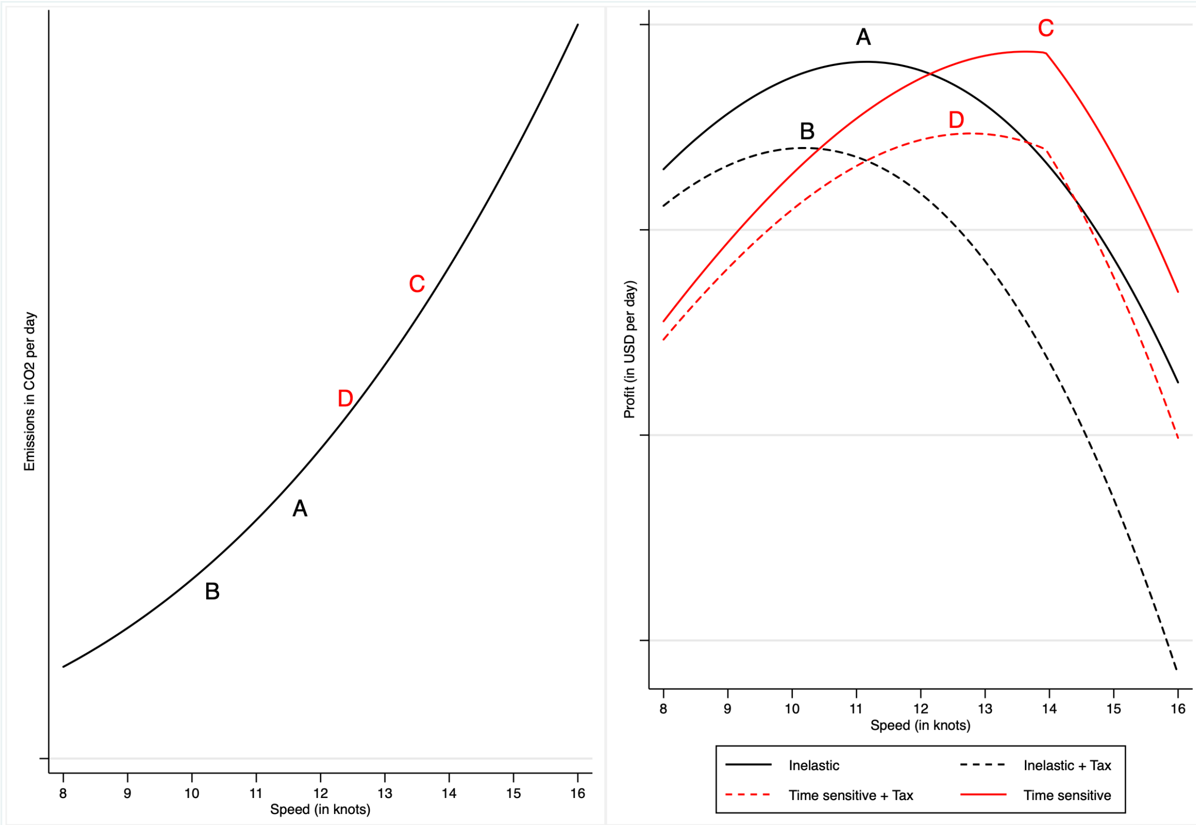

Figure 1. Emission- and profit-speed relationships with time sensitive demand

Table 1. Top grain and soybean exporters, 2016

	Export value (M USD)	Exports volume (M. tonnes/year)	Transit Time (days)	Transport Cost/ FOB Value (%)	Transport Cost (USD/kg)
			Grains[a]		
USA	11 860	60.7	23.7	9.9	0.05
Argentina	4 409	25.1	39.5	9.7	0.03
France	3 000	14.9	11.1	7.9	0.14
Brazil	1 871	10.9	59.1	9.7	0.01
Australia	1 636	10.6	38.1	10.3	0.04
Other	6 876	32.5	20.9	9.8	0.09
Total	29 652	154.8	27.9	9.7	0.06
			Soybeans		
USA	21 360	54.0	34.3	3.12	0.01
Brazil	18 260	48.8	68.3	3.03	0.00
Argentina	2 898	8.1	66.7	3.53	0.03
Paraguay	1 679	5.0	35.1	3.82	0.02
Canada	1 649	3.9	29.9	3.75	0.07
Other	1 098	2.8	20.6	3.75	0.11
Total	46 944	122.5	49.5	3.17	0.01

[a] Grains includes wheat, maize (corn), barley, sorghum, oats and rye.
Source: Authors calculation from COMTRADE, World-Bank UNCTAD transport data (2016) and CERDI (2016)

Table 2. Gravity model estimates for grain and soybean export volume (in tonnes)

	Grain						Soybeans					
	OLS		**OLS_FE**		**PPML_FE**		**OLS**		**OLS_FE**		**PPML_FE**	
Log d_{ij}	-1.066***		-1.629***		-0.872***		-0.374		-1.131***		-1.563***	
	(-8.51)		(-9.03)		(-4.74)		(-1.40)		(-2.93)		(-6.41)	
$CONT_{ij}$	1.535***	1.431***	1.645***	1.506***	1.136***	1.166***	0.923	0.935	2.009	2.425**	0.852*	1.663***
	(4.02)	(3.82)	(2.92)	(2.91)	(2.62)	(2.72)	(1.18)	(1.38)	(1.58)	(2.45)	(1.69)	(3.86)
$LANG_{ij}$	0.077	0.531	0.010	0.481	0.038	0.470	0.468	0.797*	0.321	0.722	0.443	0.422*
	(0.20)	(1.46)	(0.02)	(1.11)	(0.13)	(1.41)	(0.89)	(1.76)	(0.40)	(1.06)	(1.46)	(1.76)
CLY_{ij}	1.424**	1.024*	0.876	0.532	1.472***	1.117**	-1.300	-0.676	-2.580*	-1.534	-3.436**	-1.467*
	(2.40)	(1.92)	(1.03)	(0.60)	(2.87)	(2.31)	(-1.36)	(-0.90)	(-1.67)	(-1.49)	(-2.01)	(-1.73)
Log $Time_{ij}$		-0.980***		-1.393***		-0.917***		-0.925***		-1.220***		-0.944***
		(-8.33)		(-8.09)		(-4.25)		(-3.91)		(-4.01)		(-4.48)
Log $Cost_{ij}$		-1.298***		-1.445***		-0.785***		-1.538***		-1.663***		-0.876***
		(-8.37)		(-8.14)		(-4.78)		(-9.13)		(-7.05)		(-3.50)
Log Yi	0.804***	0.658***					0.682***	0.421***				
	(17.62)	(13.36)					(12.12)	(6.94)				
Log Ej	0.713***	0.641***					0.464***	0.242***				
	(15.29)	(14.37)					(8.88)	(4.43)				
Constant	2.824***	-6.660***	-2.093	-14.035***	-6.817***	-12.777***	-2.239	-7.018***	-6.041	-14.686***	-7.325***	-16.121***
	(2.64)	(-11.90)	(-1.12)	(-9.87)	(-3.72)	(-14.53)	(-0.91)	(-7.73)	(-1.38)	(-6.05)	(-4.28)	(-15.92)
Exporter-FE	NO	NO	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES
Importer-FE	NO	NO	YES	YES	YES	YES	NO	NO	YES	YES	YES	YES
Observations	680	680	680	680	683	683	314	314	314	314	314	314
R-squared	0.435	0.497	0.602	0.650	0.805	0.839	0.487	0.660	0.667	0.775	0.987	0.992

Note: *** p<0.01, ** p<0.05, * p<0.1

Table 3. Technical vessel parameters used in the simulation analysis

Speed	from 8 kt to 15 kt (with +0.05 incremental changes)
Design speed (*ds*)	12 knots
Fuel consumption at design speed (FC_{ds})	30 tonnes/day
Maximum transported quantity per vessel (*W*)	60000 tonnes
Operating Cost (*OC*)	6000 USD/day
Fuel consumption-speed elasticity (λ)	3
Constant ($\propto$)	0.00000126[a]

[a] The constant term is estimated (following Marlow and Evans, 200X.) using fuel consumption (30 tonnes/day) at design speed (ds=12 kts) knowing that $FC_{ds} = \alpha.(24.ds)^{\lambda}$ and for λ = 3 so that $\propto = FC_{ds} / (24.ds)^{\lambda}$.
Source: Clarksons Research (2022) and Aldand et al. (2022).

Table 4. Economic and policy parameters used in the simulation analysis

Fuel price (p)	500 USD/tonne
Environmental tax/bunker levy (t) (shown as both a percent of total fuel price and in USD/tonne)	t0 =0% ; t1 = 10% (50 USD/tonne) ; t2=20% (100 USD/tonne) ; t3=30% (150 USD/tonne) ; t4=40% (200 USD/tonne) ; t5=50% (250 USD/tonne)
Time elasticity β_1	Grains (-0.917)[a]; Soybeans (-0.944)[a]
Cost elasticity β_2	Grains (-0.785)[a] ; Soybeans (-0.876)[a]
Distance (d_{ij})	Derived from table 1 (transit time for a speed of 12 kts with 50% additional distance to account for ballast/repositioning)
Freight spot rate (R)[b]	Weight distance rates using a representative rate of 25 USD/tonne for 10000 nautical miles

[a] Estimates are from the PPML Fixed Effects specification in Table 2.
[b] The representative rate uses the U.S. average export spot rate for 3 routes: Supramax Grain Voyage Rates US Gulf/Japan (HSS) 49,000t; New Orleans – Qingdao 60,000t Grain Panamax Voyage Rates and US Gulf - Egypt 55,000t Grain Panamax Voyage Rates.
Source: Clarksons Research (2022)

Table 5. Impact of an environmental tax on profit (TCE) and optimal speed (s*)

	Profit per vessel (in USD/day)						Optimal speed (kts)					
Tax (in USD)	0	50	100	150	200	250	0	50	100	150	200	250
Grain Exporters - Pay Tax												
USA	4 855	3 355	2 026	979	139	-546	12.0	12.0	11.1	10.3	9.6	9.0
Argentina	4 995	3 495	2 146	1 083	230	-465	12.0	12.0	11.1	10.3	9.6	9.0
France	4 888	3 388	2 053	1 003	160	-527	12.0	12.0	11.1	10.3	9.6	9.0
Brazil	4 871	3 371	2 039	991	150	-536	12.0	12.0	11.1	10.3	9.6	9.0
Ukraine	4 717	3 217	1 908	877	50	-624	12.0	12.0	11.0	10.2	9.5	8.9
Other	4 855	3 355	2 026	979	139	-546	12.0	12.0	11.1	10.3	9.6	9.0
Grain Exporters - Pass Through the Tax												
USA	4 855	3 841	2 826	1 828	904	55	12.0	12.0	12.0	11.7	11.2	10.7
Argentina	4 995	3 975	2 955	1 946	1 007	146	12.0	12.0	12.0	11.8	11.3	10.8
France	4 888	3 872	2 855	1 855	928	76	12.0	12.0	12.0	11.7	11.2	10.7
Brazil	4 871	3 856	2 840	1 841	916	65	12.0	12.0	12.0	11.7	11.2	10.7
Ukraine	4 717	3 708	2 698	1 713	803	-33	12.0	12.0	12.0	11.6	11.1	10.7
Other	4 855	3 841	2 826	1 828	904	55	12.0	12.0	12.0	11.7	11.2	10.7
Soybean Exporters - Pay Tax												
USA	4 741	3 241	1 879	809	-47	-742	12.0	12.0	11.2	10.3	9.6	9.0
Brazil	4 838	3 338	1 963	881	16	-687	12.0	12.0	11.2	10.4	9.7	9.0
Argentina	4 916	3 416	2 031	940	67	-642	12.0	12.0	11.2	10.4	9.7	9.1
Paraguay	4 889	3 389	2 008	920	50	-658	12.0	12.0	11.2	10.4	9.7	9.1
Canada	4 908	3 408	2 024	934	62	-647	12.0	12.0	11.2	10.4	9.7	9.1
Other	4 828	3 328	1 954	874	10	-693	12.0	12.0	11.2	10.4	9.7	9.0
Soybean Exporters - Pass Through the Tax												
USA	4 741	3 614	2 486	1 384	377	-533	12.0	12.0	12.0	11.6	11.1	10.5
Brazil	4 838	3 707	2 575	1 463	446	-475	12.0	12.0	12.0	11.7	11.1	10.5
Argentina	4 916	3 781	2 646	1 527	501	-428	12.0	12.0	12.0	11.7	11.1	10.6
Paraguay	4 889	3 755	2 621	1 505	482	-444	12.0	12.0	12.0	11.7	11.1	10.5
Canada	4 908	3 773	2 638	1 520	495	-433	12.0	12.0	12.0	11.7	11.1	10.6
Other	4 828	3 697	2 566	1 455	438	-481	12.0	12.0	12.0	11.7	11.1	10.5

Table 6. Impact of an environmental tax on exports (W) and on carbon emissions (CO_2)

	Emissions (million tonnes of CO2)						Exports (million tonnes)					
Tax (in USD/t CO2)	**0**	**50**	**100**	**150**	**200**	**250**	**0**	**50**	**100**	**150**	**200**	**250**
Grain Exporters - Pay Tax												
USA	3.73	3.73	2.93	2.36	**1.92**	**1.59**	60.7	60.7	56.3	52.6	49.3	46.6
Argentina	1.54	1.54	1.23	0.99	0.81	0.67	25.1	25.1	23.4	21.8	20.5	19.3
France	0.92	0.92	0.72	0.58	0.47	0.39	14.9	14.9	13.8	12.9	12.1	11.4
Brazil	0.67	0.67	0.53	0.42	0.34	0.29	10.9	10.9	10.1	9.4	8.9	8.4
Ukraine	0.65	0.64	0.51	0.41	0.33	0.27	10.6	10.6	9.8	9.1	8.6	8.1
Other	2.00	2.00	1.57	1.26	1.03	0.85	32.5	32.5	30.1	28.2	26.4	24.9
Grain Exporters - Pass Through the Tax												
USA	3.73	3.58	3.44	3.06	**2.57**	**2.15**	60.7	58.3	55.9	52.3	48.0	43.9
Argentina	1.54	1.48	1.42	1.28	1.08	0.90	25.1	24.1	23.1	21.7	19.9	18.2
France	0.92	0.88	0.84	0.75	0.63	0.53	14.9	14.3	13.7	12.8	11.8	10.8
Brazil	0.67	0.64	0.62	0.55	0.46	0.39	10.9	10.5	10.0	9.4	8.6	7.9
Ukraine	0.65	0.63	0.60	0.52	0.44	0.37	10.6	10.2	9.8	9.1	8.3	7.6
Other	2.00	1.92	1.84	1.64	1.38	1.15	32.5	31.2	29.9	28.0	25.7	23.5
Soybean Exporters - Pay Tax												
USA	4.80	4.80	3.87	3.06	2.49	2.06	54.0	54.0	50.4	46.8	43.8	41.3
Brazil	4.34	4.34	3.54	2.81	2.29	1.86	48.8	48.8	45.7	42.5	39.8	37.3
Argentina	0.72	0.72	0.59	0.47	0.38	0.31	8.1	8.1	7.6	7.1	6.6	6.2
Paraguay	0.44	0.44	0.36	0.29	0.23	0.19	5.0	5.0	4.7	4.4	4.1	3.8
Canada	0.35	0.35	0.28	0.23	0.18	0.15	3.9	3.9	3.7	3.4	3.2	3.0
Other	0.25	0.25	0.20	0.16	0.13	0.11	2.8	2.8	2.6	2.4	2.3	2.1
Soybean Exporters - Pass Through the Tax												
USA	4.80	4.59	4.38	3.77	3.11	2.50	54.0	51.6	49.3	45.4	41.2	37.0
Brazil	4.34	4.15	3.96	3.45	2.81	2.29	48.8	46.7	44.5	41.2	37.2	33.6
Argentina	0.72	0.69	0.66	0.58	0.47	0.39	8.1	7.7	7.4	6.9	6.2	5.6
Paraguay	0.44	0.43	0.41	0.35	0.29	0.23	5.0	4.8	4.6	4.2	3.8	3.4
Canada	0.35	0.33	0.32	0.28	0.23	0.19	3.9	3.7	3.6	3.3	3.0	2.7
Other	0.25	0.24	0.23	0.20	0.16	0.13	2.8	2.7	2.6	2.4	2.1	1.9

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