Journal of Environmental Economics and Management 65 (2013) 153–173

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Economics and Management

journal homepage: www.elsevier.com/locate/jeem

Trade and the greenhouse gas emissions from international freight transport ☆

Anca Cristea [a], David Hummels [b,*], Laura Puzzello [c], Misak Avetisyan [d]

[a] University of Oregon, Eugene, OR, USA
[b] Purdue University and NBER, Department of Economics, 100 S Grant St, 403 W. State Street, West Lafayette, IN 47907, USA
[c] Monash University, Melbourne, VIC, Australia
[d] University of Southern California, Los Angeles, CA, USA

ARTICLE INFO

Article history:
Received 6 June 2011
Available online 1 August 2012

Keywords:
Greenhouse gas emissions
International transport emissions
World trade growth
International trade by transport mode

ABSTRACT

We collect extensive data on worldwide trade by transportation mode and use this to provide detailed comparisons of the greenhouse gas emissions associated with output versus international transportation of traded goods. International transport is responsible for 33 percent of world-wide trade-related emissions, and over 75 percent of emissions for major manufacturing categories. Including transport dramatically changes the ranking of countries by emissions per dollar of trade. We systematically investigate whether trade inclusive of transport can lower emissions. In one quarter of cases, the difference in output emissions is more than enough to compensate for the emissions cost of transport. Finally, we examine how likely patterns of global trade growth will affect modal use and emissions. Full liberalization of tariffs and GDP growth concentrated in China and India lead to transport emissions growing much faster than the value of trade, due to trade shifting toward distant trading partners.

1. Introduction

International trade generates greenhouse gas (GHG) emissions from two sources: the production of traded goods, and their transportation between trading partners. A large literature has focused on the emissions associated with production, examining how trade reallocates production between countries with differing emission intensities, or whether it undermines efforts to control emissions via “carbon leakage”.[1] However, the emissions associated with international transportation are largely overlooked, both in the text of existing agreements such as the Kyoto Protocol regulations, and in data collection efforts.[2]

☆ We thank the OECD for funding, Ron Steenblik for suggesting and encouraging the work. We also thank Bruce Blonigen, Tim Cason, Lata Gangadharan, Tom Hertel, Pete Minor, Paul Raschky, Christis Tombazos, Terrie Walmsley, and seminar participants at the University of New South Wales, University of Melbourne, University of Adelaide, Australian National University, ASSA meetings 2011, International Workshop on Current Issues in CGE Analysis, Midwest International Trade Fall Meeting 2011, Conference on Globalization, Strategies and Effects 2011, Econometric Society Australasian Meeting 2011, European Trade Study Group Conference 2011, and the Empirical Investigations in Trade and Investment 2012 for suggestions and help.

* Corresponding author. Fax: +1 765 496 7434.
E-mail address: hummelsd@purdue.edu (D. Hummels).

[1] Examples include Ederington and Minier [14], Babiker [4], Levinson [29], Levinson and Taylor [30] among others. See also Copeland and Taylor [10] for a comprehensive literature survey.

[2] Van Veen-Groot and Nijkamp [42] argue that the key research focus in advancing the investigation on the environmental effects of international trade should be on “building up a monitoring system and database” to facilitate “measuring the environmental effects of international transport”.

0095-0696/$ - see front matter
http://dx.doi.org/10.1016/j.jeem.2012.06.002

The literature on international transportation emissions consists of Life Cycle Analysis case studies of highly specific products, or of aggregate calculations drawn from world-wide fuel usage. No previous study attributes international transport emissions to origin and destination countries or to individual products on a systematic basis. Yet data of this sort are essential for understanding the magnitude of transportation emissions relative to production, and how these emissions are distributed across trade flows. Without this information we cannot fully measure the total emission intensity of trade, evaluate whether trade on net raises or lowers total emissions, nor can we determine how future trade growth is likely to affect trade-related emissions (i.e., emissions associated with both the production and shipment of traded goods).

The purpose of this paper is to provide two exercises, both of which are novel in the literature. In the first we build an extensive database on output and transport emissions associated with every origin–destination–product trade flow worldwide in a base year 2004. We employ this database to quantify the contribution of international transport to total emissions, and to highlight systematic patterns of transport emission intensities across products and trade pairs. In the second exercise, we calculate the growth in emissions due to a simulated change in global trade arising from tariff liberalization and unevenly distributed GDP growth.

We begin by collecting industry level data for each bilateral country pair on the value and weight of trade and on the transport modes employed in trade (i.e., aviation, maritime, rail and truck). Using these data we calculate the quantity of transportation services, by mode, involved in a particular trade flow. Combining this with information on the GHG emissions produced per kilogram–kilometer (kg–km) by each mode of transport, we provide a "bottom-up" accounting of the emissions associated with international transportation.

The critical step is to re-think trade in terms of transportation services, rather than in value terms as is typical in the trade literature. Emissions depend on the shipping mode employed and on the weight, not value, transported. One million dollars of coal is vastly heavier than a million dollars of microchips, with correspondingly larger transport emissions. Trucks, rail, airplanes and ships have significantly different GHG emissions and modal composition varies widely across trade flows. For example, one kilogram of cargo flown one kilometer on a plane generates between 50 and 200 times the emissions of that same kg–km on a bulk cargo carrier.

Our "bottom-up" accounting of emissions yields worldwide maritime and aviation emissions that are remarkably close to matching emissions estimates from the International Transport Forum [22], which are based on aggregate fuel usage worldwide. Unlike the ITF aggregate data we also measure road and rail emissions, and our emissions numbers are specific to each origin–destination–industrial sector.

Our disaggregated data allow us to describe the importance of transport relative to production emissions for specific trade flows, and show which trade flows are especially emissions intensive once both components are taken into account. World-wide, 33 percent of trade-related emissions come from international transport, though this number is considerably higher in the manufacturing sectors. For example, 80 percent of trade-related emissions in machinery exports come from international transportation. There is also wide variation across countries in the contribution of transport to trade-related emissions. At the low end, only 14 percent of Indian and Chinese export emissions come from transport, while transport is responsible for 66 percent of US export emissions due to substantial use of air cargo.

Rising trade affects emissions through two channels. It increases international transport emissions, and reallocates production emissions from the importer to the exporter. While more transportation always raises emissions, production reallocation could raise or lower emissions depending on the difference in emission intensities of the two countries. By characterizing both production and transport emissions from trade flows we can systematically answer a question previously addressed only by case studies: does consuming foreign goods raise or lower GHG emissions once international transport is accounted for?

We answer this question in two ways. The first is closest in spirit to Life Cycle Analysis case studies. We compare emissions in the base year (with trade) to a partial equilibrium reallocation of production that forces each country into autarky. That is, we hold fixed worldwide consumption, but set trade equal to zero so that each country must produce all consumption locally. Compared to this autarky situation, 31 percent (by value) of trade flows in the base year lower emissions. In these cases the exporter's production is less emission intensive than the importer and international transportation emissions are small relative to the difference in production emissions. In the remaining cases, trade raises emissions, leading to a net increase of 158 g of CO_2 per dollar of trade, or 1274 million tons in aggregate.

These partial equilibrium calculations are very much "back-of-the-envelope" because they do not contemplate whether the reallocation is feasible or likely and the exercise ignores general equilibrium considerations that might exacerbate or attenuate the changes. In a second exercise we examine likely future changes in trade in a full general equilibrium model. We simulate the level and composition of trade growth in four scenarios related to trade liberalization and a fifth scenario examining differential changes in country GDP growth rates through the year 2020. Trade liberalization and output growth are likely to lead not only to growth in the quantity of trade but also to changes in its product and country-pair composition. The question is then whether growth will occur in high or low emissions categories, and whether transport

(*footnote continued*)
For a discussion of the challenges in the measurement and the omission of international transport from policy protocols see Olivier and Peters [35], Miljøstyrelsen Miljøministeriet [32]—the Danish Environmental Protection Agency, Danish Ministry for the Environment, as well as [39].

emissions are likely to grow more rapidly than output emissions. Combining simulated output and trade changes with our emissions data we can then calculate the predicted growth in emissions from trade.

Our findings are as follows. Trade liberalization scenarios currently contemplated under the Doha WTO round generate very small changes in output, exports, and GHG emissions. Full liberalization results in a 6 percent increase in trade, concentrated in those products that are subject to the highest rates of protection. More importantly, liberalization eliminates tariff preferences enjoyed primarily by nearby trading partners (e.g., NAFTA and the EU). Trade shifts away from proximate partners and toward distant partners who cannot be reached by land transport. Use of air cargo rises, and with it, GHG emissions rise 23 to 42 percent faster than trade.

In contrast to the modest effects from tariff liberalization, projected output growth (a 75 percent increase in gross world product by 2020) leads to profound changes in trade and emissions. Exports rise at 3.8 percent per year, 80 percent cumulatively, while transport services (kg–km) rise 173 percent cumulatively as trade shifts to distant but rapidly growing China and India. Transport emissions grow faster than trade by value and faster than output emissions, with especially rapid growth in maritime emissions.

The paper proceeds as follows. Section 2 describes previous attempts to measure the emissions content of international transportation. Section 3 describes our methodology and Section 4 describes the construction of the main data components for our exercises. Section 5 provides evidence on current contribution of international transportation to GHG emissions from international trade. Section 6 provides simulations of trade growth, and calculates how this growth would affect modal use and emissions. Section 7 concludes and highlights the policy implications of our work, including the importance of including transport emissions in GHG mitigation policies and several implications for mechanism design.

2. Related literature and evidence

Efforts to measure the contribution of international freight transport to GHG emissions have been limited in scope. The most careful work is found in the case study based life cycle analyses (LCA) literature. LCA papers typically focus on a particular product and geographic market, and assess the environmental impact of every input in the production and delivery of that product. For example, Sim et al. [38] estimate that the global warming impact of Kenyan and Guatemalan beans shipped to the UK are 20 to26 times larger than UK production. In contrast, Williams [44] finds that cut roses air delivered from Kenya to the UK generate emissions that are significantly lower than roses sourced from the neighboring Netherlands[3]. While LCA studies provide detailed calculations of transport emissions for a particular product and trade flow, they are not informative for the world trading system as a whole.

A few recent papers employ input–output tables to measure international trade emissions, and attempt to incorporate international transport emissions into the calculation [17,36,6]. However, lacking systematic data on trade by transportation mode, these papers either restrict their attention to a single importing country or they base their calculations on entirely imputed transport data.

The only worldwide data on transport emissions comes from the International Transport Forum [22]. They calculate aggregate transport emissions for international aviation and maritime transport by combining worldwide data on fuel consumption from the International Energy Agency [23], along with data on GHG emissions by fuel type.

Table 1 provides the ITF estimates on emissions. From 1990 to 2004, international transport emissions rose slightly faster than total emissions and emissions from all transport. Focusing on 2004, international maritime plus international aviation transportation was responsible for just 3.5 percent of total emissions. This seems small, but total emissions include many activities (e.g., residential energy usage, domestic transportation), which are not directly related to trade or the output of tradable goods. The IEA estimates that industrial production represents only a fifth of worldwide emissions, and most industrial output emissions are unrelated to trade—e .g., if a quarter of steel output is traded then three quarters of the output emissions from steel correspond to domestic consumption. This suggests that international transport measured as a share of trade-related emissions could be significant.

Because the GHG content of specific fuels is well known, the ITF "top-down" approach of measuring actual fuel use is likely the most accurate way to assess worldwide aviation and maritime emissions in a particular year. However, the ITF approach has two key drawbacks. First, road and rail transport represent a significant fraction of international trade for land-adjacent partners but their emissions are omitted from the ITF numbers. This is especially problematic because road and rail transport is a rising share of world trade as decades of regional trade liberalization, especially in North America and Europe, has concentrated trade between partner countries sharing land borders.

The second drawback is that one cannot use the aggregate ITF numbers to assess where or how maritime or aviation fuel was used. Even if one were to track fuel loaded to individual ports this would be of limited use as ships and planes refueling in a particular port could be carrying cargo of any type between any country pair in the world. Without knowing where fuel is used we cannot evaluate the total emissions associated with a particular trade flow (i.e., a specific product traded between a country pair). Further, the product and partner composition of trade has a first-order impact on the types of transportation employed, and on the associated GHG emissions. This means that we learn little from the aggregate

[3] For additional examples of LCA, see Jones [25], Canals et al [8], and Carlsson et al [9].

Table 1
World output and transport emissions, 1990–2004 (selected years).

	1990	1995	2000	2004
CO_2 emissions (mil tons CO_2)				
Fuel combustion, all sources[a]	21,024	21,808	23,487	26,320
Total transport[a]	4,614	5,047	5,678	6,202
International transport (aviation, maritime)[b]	649	710	829	910
International transport emissions				
Share of total emissions (%)	3.1	3.3	3.5	3.5
Share of transport emissions (%)	14.1	14.1	14.6	14.7
CO_2 equivalent grams per dollar of exports	158.8	129.6	104.0	93.3

[a] *Source*: International energy agency.
[b] International transport includes international maritime and aviation transport modes. Data source: International transport forum.

incidence of transport emissions that can be directly applied to particular trade flows, and that emissions may rise faster or slower than overall trade growth as the composition of trade changes. If we want to understand how changes in trade affect emission, or understand which trade flows would be most affected by efforts to mitigate emissions, we need emissions data linked to individual flows rather than worldwide aggregates.

3. Methodology: Base year emissions

In this section we describe the approach we take in constructing the emissions associated with each trade flow. Denote E^T_{odg} as the GHG emissions[4] associated with transporting good g from origin o to destination d. VAL is the value of that flow, and WV is the weight to value ratio so that $VAL_{odg} \times WV_{og}$ is the quantity of the flow in kilograms. A country pair may ship product g using multiple transportation modes. The quantity share of mode m in that flow is QS^m_{odg}, so $VAL_{odg} \times WV_{og} \times QS^m_{odg}$ gives the quantity of the flow for each mode, in kg. Multiplying by $DIST^m_{od}$ the distance traveled from o to d for mode m gives us a measure of transportation services, for each mode, measured in a common unit (one kg of cargo moved one kilometer). Finally, multiplying by e^m, the GHG emissions produced by mode m when providing one kg–km of transportation services, and summing over all modes yields the total emissions associated with that trade flow.

$$E^T_{odg} = \sum_m VAL_{odg} \times WV_{og} \times QS^m_{odg} \times DIST^m_{od} \times e^m \tag{1}$$

This approach has a few limitations owing to data availability. We impose a constraint that emissions for a given mode are common to all products and country pairs and are linear in weight and distance. As such it masks two potentially important sources of heterogeneity. One, some trade flows may employ older, smaller ships and planes with higher emissions per kg–km of transportation services. We partially adjust for this problem in the data by allowing for multiple types of ocean vessels that are specific to certain cargos, and by experimenting with aviation emissions data that reflect the most efficient planes versus those in use in existing fleets. Two, there are emissions associated with "fixed costs" of transport, incurred independent of distance traveled, including port time for ships and higher landing/take off emissions for planes. We provide calculations to suggest that these problems, while significant at very short distances, become insignificant at the international distances seen in the data.

An additional limitation relates to emissions from domestic transport linked to trade. All production requires domestic transport, and we capture this input and its associated emissions as part of output emissions. If production for external trade uses domestic transport to the same extent as production for domestic use, then we capture domestic transport emissions accurately. However, in some instances external trade may require movement of goods over great internal distances, while in others (production near borders, or near air or seaports) external trade may employ very little domestic transport. This may result in under- or over-counting trade-related emissions, but we have no clear indication if there is a bias or which way it runs. Note that this is fundamentally similar to any case in which a heterogeneous production technology is characterized by an aggregate technology.

Starting from Eq. (1), we can provide a number of comparisons and calculations. Trade flows are most commonly reported in value terms. Pulling the value of the trade flow out of this summation we can decompose the quantity of transportation emissions from the flow into a scale measure and an intensity measure

$$E^T_{odg} = VAL_{odg} \times e^T_{odg} \quad \text{where} \quad e^T_{odg} = \sum_m WV_{og} \times QS^m_{odg} \times DIST^m_{od} \times e^m \tag{2}$$

[4] "GHG emissions" refer to both CO_2 and non-CO_2 emissions, represented as CO_2 equivalents.

Using this basic decomposition we can compare the transport emissions from exports across countries. Summing over importers and products, an exporter o's emissions are

$$E_o^T = VAL_o \times e_o^T = VAL_o \times \sum_{dg} (s_{odg} \times e_{odg}^T) \tag{3}$$

where s_{odg} is the share of destination d, good g in total trade for origin o. Transport emissions depend on the scale of trade and the transport emission intensity of a dollar of trade. The latter is a trade-weighted average of emissions from individual flows. If an exporter engages in trade with more distant partners, trades heavier goods, or uses aviation more than maritime transport it will have a higher aggregate transport emission intensity. We can provide similar aggregations by importers (aggregating over exporters and products) or by products (aggregating over country pairs).

We can also use this decomposition to compare the emission intensity of trade arising from two distinct sources: production of traded goods and transport of traded goods. Begin by writing the emissions from output of good (or service) g in country o as the product of output (in dollars) and emissions per dollar of output,

$$E_{og}^Y = Y_{og} \times e_{og}^Y \tag{4}$$

so that aggregate emissions in a country are an output weighted average of emissions for each activity.

$$E_o^Y = Y_o \times \sum_g (s_g \times e_{og}^Y)$$

Aggregating again over all countries yields worldwide emissions, similar to that found in Table 1. If we instead measure both output and transport emissions as an intensity (i.e., CO_2 equivalents per dollar), we can calculate the contribution of each emission component to the total emission associated with a particular trade flow. For any particular o–d–g flow we have:

$$E_{odg} = (e_{odg}^T + e_{og}^Y) \times VAL_{odg} \tag{5}$$

Much of our analysis will consist of a few basic but informative calculations. We compare the magnitudes of e_{odg}^T and e_{og}^Y for particular trade flows, and in the aggregate for different regions. We will also analyze whether moving output from a high emission to a low emission producer induces emission changes that are large or small relative to reallocating trade across partners from high transport emission trade flow to a low transport emission trade flow.

4. Data

In this section we describe the main data components necessary to calculate the GHG emissions from output and international transportation in the base year. These data components are: the weight, value, and modal shares of trade for each bilateral pair and product; the GHG emission intensity for each transportation mode; and GHG emissions associated with output for each producer $\times$ sector pair. Given the improvement in quality and coverage that these new sources of data provide, and their likely use in future research on transport and trade-related emissions, we devote much attention to document the construction of the dataset.

4.1. Aggregation

These disparate data components must fit together precisely, using the same level of regional and product aggregation. In this we are most constrained by the data available for output emissions, which we take from the database underlying version 7 of the Global Trade Analysis Project (GTAP) model. The GTAP database is ideal for our purposes because it contains detailed information on energy usage and GHG emissions by origin country and sector, and because we can use the GTAP computable general equilibrium model in the final section of the paper for performing trade liberalization and output growth simulations.

At its maximum disaggregation, GTAP 7 allows one to model production and trade for 57 traded and non-traded sectors between 113 countries. While it is not computationally feasible to run trade experiments with the full 113 country $\times$ 57 sector version of the model, GTAP allows for flexible aggregation across regions and sectors in order to examine certain especially interesting subsets of the whole dataset. For current purposes, we employ an aggregation of the model with 40 regions (i.e., 1600 bilateral pairs) of which 28 are individual countries and 12 are larger regional groupings, 23 traded merchandise sectors and 6 non-traded service sectors. Detailed listings are reported in Appendix 1.

We followed these principles in aggregating countries into broader regions. We aggregated together countries that were smaller and more similar in their characteristics (geography, endowments, production and trade structure). This minimizes any biases induced by treating individual countries as part of a larger region, and after aggregation the broadest regional groupings (Sub-Saharan Africa, Central America and the Caribbean, Rest of South Asia) still represent less than 1 percent of world trade in the base year. We aggregated less when country level data on weight/value and transportation mode are of high quality, and used broader geographic aggregation for regions where these data are lacking. For example, we represent the Middle East and Africa in only 3 aggregated regions, while Europe is represented with 15 individual countries and 3 aggregated regions. This allows us to minimize the amount of imputation that must be employed to complete the database. Similarly, we aggregated sectors with "similar" transportation characteristics. For example, all sub-categories of bulk agriculture, which primarily uses maritime transport, are aggregated into one category while sub-categories of processed agriculture, which is more likely to employ air transport, are aggregated into a second category.

4.2. Trade and output in the base year: Weight/value, and modal shares

Recalling Eq. (1), we need data on the value of trade, the weight/value ratio, and the quantity shares of each mode. Our base dataset for the value of output and trade comes from the GTAP 7 database, aggregated to 40 regions and 29 sectors (23 merchandise trade sectors) in 2004. By multiplying values in dollars by a weight/value ratio (kg/dollar) that is specific to each origin × sector, we convert these value of trade numbers into kilograms. This physical unit of measurement is consistent across countries and products, is meaningful from a transportation perspective, and can be used directly to calculate GHG emissions from transport.

To construct WV_{og} we draw on three primary data sources that report trade by value and weight at the 6 digit level of the Harmonized system (roughly 5000 products). These are: US Imports and Exports of Merchandise; Eurostats Trade (covering the imports and exports of 27 EU countries), and the ALADI trade database, covering the imports of 11 Latin American countries (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, Mexico, Paraguay, Peru, Uruguay and Venezuela) from all exporters worldwide. The bilateral pair coverage represented by these three datasets is displayed in Appendix SM1 of the online appendix available in the journal's online repository of supplemental material, which can be accessed via 〈http://www.aere.org/journals〉.

It is necessary to concord the HS6 data to the 23 merchandise trade sectors used in our aggregation of the GTAP model. This means that for each importer and exporter there may be several hundred HS codes corresponding to a single GTAP sector such as "electronic equipment". To arrive at a weight/value ratio for each exporter and product, we separately sum the weight of trade and the value of trade and express them as a ratio. This is equivalent to a share-weighted average of the weight/value ratio for each HS6 product traded by that exporter.[5]

For reference we report data by commodity in Appendix Table A1. This includes initial tariff rates and weight/value ratios (each expressed as a trade-weighted average over all country pairs), along with the share of each commodity in world output, world trade by value, and world trade by transportation services units (kg–km). Of interest, some of the goods that represent a larger value share in trade (electronic equipment and machinery) represent a significantly smaller share in transportation services. This reflects large differences in weight/value between these manufactured goods and heavy products such as bulk agriculture, minerals, and oil.

The data for modal shares, QS^m_{odg}, come from the same three sources as the weight/value data described above. Each of those datasets contains information on the weight and value of trade by origin–destination–product and transport mode. The US data split trade into air and ocean modes, but has no modal information on overland transport from Mexico and Canada. To disaggregate these flows into truck and rail we use supplementary data from the Transborder Surface Freight Data.[6] The EU and ALADI datasets report trade by air, ocean, rail, and truck modes. Modal use for the US, ALADI, and EU trade with non-EU partners are measured at the HS6 level. Trade from the EU15 to all other European members but Romania and Bulgaria is measured at the NSTR 3 digit level.[7] To construct modal quantity shares, we first concord the HS6 (or NSTR3) product codes to GTAP sector groupings, and aggregate so that we have the weight of trade for each mode within each o–d–g triplet.

For 35 percent of world trade by value we have no direct data on modal use. In these cases we estimate modal shares as a function of geography, country, and product characteristics basing our estimation sample on those country pairs that do report modal data. These regressions have good explanatory power, especially in the vast majority (all but 2 percent) of the remaining cases where land transport is not an option. Details are provided in Appendix SM1 available in the online appendix.

The results of our data collection generate a full matrix of modal shares for each origin–destination–GTAP sector by value, weight, and transportation service units (kg–km). Table 2 provides modal shares for the imports and exports of each continent, by trade value and kg–km . Table SM1 available in the online appendix reports the numbers by traded sectors.

A few things are notable. There are large differences across regions in the value shares of the transportation modes that largely reflect geography. For example, North America and Europe, with important land-adjacent trade partners, rely much more heavily on road transport.[8] Substitution between air and ocean cargo is especially important as it reflects the largest gap in emission intensities. Worldwide 18 percent of trade by value is air-borne, with much higher ratios in North American and East Asian exports. Excluding land-based modes, air transport represents 48 percent of international (air + ocean) cargo for North American exports and 27 percent for European and Asian exports.

[5] We do not employ weight/value ratios that vary across importers because we do not have weight data for every o–d–g triplet in the data. Apart from the o–d pairs with no data, the weight field is missing from roughly 20 percent of EU observations, though these tends to be relatively small value flows and unrelated to modal use. In general, because aggregating over importers for a given exporter and product reduces measurement error in the more noisy weight data.

[6] The TBSF data have rail v. road splits at the HS2 level. We take each land-based trade flow from the more disaggregated HS6 data and divide it using the splits found in the corresponding HS2 data. We then aggregate to the broader 23 sectors found in the GTAP data.

[7] These intra-EU data were compiled on special request by statisticians at Eurostats.

[8] Most of Asia has very small shares of land transport because the largest trading partners are separated by (short) stretches of ocean. South America, for which land transport is actually an option has rather low land transport shares, probably because economic activity is concentrated on coasts rather than in the interiors close to land borders. When we disaggregate to the country level there are more dramatic differences. Europe as a whole has very high shares of rail and road transport, except for countries like the UK, Ireland, and Finland.

Table 2
Regional modal shares, by trade value and kg–km.

	By value				By kg–km			
	Sea	Air	Rail	Road	Sea	Air	Rail	Road
Panel (A) modal shares by importer								
North America	46.6	21.0	6.7	25.7	91.8	1.4	1.4	5.5
Central America	78.8	16.3	0.3	4.6	97.9	0.6	0.1	1.4
South America	66.4	22.7	0.3	10.6	96.0	1.3	0.2	2.6
Europe	35.5	13.0	4.5	46.9	91.7	1.1	2.0	5.2
South Asia	74.8	21.7	0.6	2.9	99.2	0.5	0.1	0.3
East Asia	72.8	25.8	0.2	1.2	98.8	1.1	0.0	0.1
Middle East/Africa	68.2	19.1	0.0	12.7	88.5	0.9	0.0	10.6
Oceania	78.0	22.0	0.0	0.0	98.1	1.9	0.0	0.0
World	50.2	18.4	3.5	27.8	95.0	1.1	0.8	3.1
Panel (B) modal shares by exporter								
North America	28.3	25.9	9.4	36.4	88.2	4.6	1.4	5.8
Central America	74.0	20.6	0.4	5.0	97.0	0.9	0.2	2.0
South America	85.7	7.3	0.2	6.8	99.1	0.2	0.0	0.6
Europe	35.1	13.0	4.5	47.3	89.3	0.9	2.8	7.1
South Asia	73.9	21.6	0.8	3.7	97.8	1.0	0.2	1.0
East Asia	72.0	26.8	0.2	1.0	98.8	0.9	0.0	0.2
Middle East/Africa	80.6	9.3	0.0	10.1	97.3	0.1	0.0	2.6
Oceania	89.8	10.2	0.0	0.0	99.9	0.1	0.0	0.0
World	50.2	18.4	3.5	27.8	95.0	1.1	0.8	3.1

Note: Calculations refer to the year 2004. The modal shares in panel (A) and (B) refer to international freight transport. Details on the regional aggregation are provided in Appendix 1.

It is also instructive to contrast the value of trade with the transportation services (kg–km) employed by trade. Here, sea transport dominates with 95 percent of transportation services provided. Products that are heavy, and that are transported long distances, are much more likely to be sea-borne. The largest difference relative to value shares comes in the use of road-based transport: while it represents nearly half of European imports by value it is only 5 percent of European imports by kg–km . Road transport constitutes a large share of value and weight moved in European trade; however it is concentrated in the trade of proximate partners. As a result, road transport represents a very small share of kilogram–kilometers shipped.

4.3. Greenhouse gas emissions by transport mode

We draw on data from several studies to calculate emissions per kg–km of cargo moved by each of the four transport modes: ocean, air, rail, and road. These sources, and data on emissions, are reported in Table 3. We briefly remark on the data for maritime and aviation emissions here.

The most recent and comprehensive study for maritime transport comes from "Ship Emissions Study", National Technical University of Athens Laboratory for Maritime Transport [34]. It reports emissions in grams of CO_2 per tonne-km shipped for many distinct ship types, as well as variability across vessels of different sizes within each type.[9] In Table 3, we reproduce the fleet averages for six ship types, and note the ship types employed for each traded goods sector in our model. While other studies lack the detailed data by ship type reported in that study, those studies [27,16] that provide data for containerized cargo arrive at similar emission numbers.

In searching the literature we found few estimates of emissions associated with air cargo. These arrive at widely varying estimates of emissions per tonne-km, and provide little detail on methodology. For example, a Maersk [31] pamphlet cited in the University of Athens [34] study reports that a Boeing 747-400 emits 552 g of CO_2 per tonne-km shipped. A California Climate Change [7] pamphlet for reports emissions per tonne-km shipped ranging from 476 to 1020 g of CO_2.

Given this wide range, we attempted our own calculations based on fuel usage and fleet characteristics. The Air Transport Association of America reports fleet wide fuel usage and ton-miles of cargo shipped for US cargo airlines. Using these totals we calculate that US cargo airlines used 163.6 gallons of jet fuel per thousand ton-miles shipped. Converting gallons of jet fuel into grams of CO_2 and cargos into tonne-km, we calculate CO_2 emissions of 963.5 g of CO_2 per tonne-km.

We also attempted to construct an independent estimate of CO_2 emissions associated with air cargo using data taken from [1], "Freighter Cost Comparisons". This source provides data for 14 major cargo plane types including total fuel use,

[9] In general, CO_2 emissions per tonne-km shipped are much lower for larger vessels within each type. For example, post-Panamax (> 4400 TEU) containerships produce 1/3 the emissions of a less than 500 TEU feeder ship. Because we have no data on the ship size composition of flows, we employ fleet averages for each fleet type. The study also provides data for highly specialized ship types such as Reefers and Ro-Ros. We do not employ this data as our broader trade aggregates contain a mix of goods that would employ these specialized types as a small subset of goods that generally employ container vessels.

Table 3
Emissions per tonne-km of transport services, by mode.

Mode type	CO_2	GTAP sectors	Source
Panel (A) maritime mode			
Bulk	4.5	Bulk agriculture, forestry, minerals, coal products	[34]
Container	12.1	Processed agriculture, fishing, textiles, wearing apparel, leather products, wood products, paper products and publishing, ferrous metals, metals nec, metal products, motor vehicles and parts, transport equipment nec, electronic equipment, machinery and equipment, manufactures nec	[34]
Oil tanker	5	Oil	[34]
LNG	16.3	Gas	[34]
LPG	12.7	Petroleum	[34]
Chemical	10.1	Chemical products	[34]
Panel (B) land mode			
Road	119.7		[16]
Rail	22.7		
Panel (C) air mode			
Boeing 747	552		[31]
Various	476–1020		[7]
US Cargo fleet	963.45		Authors' calculations based on ATA fuel usage data
US Cargo fleet	912		Authors' calculations based on [1] data

Note: Details on the aggregation of GTAP sectors are provided in Appendix 1. In our calculations we employ 552 g per tonne-km as a "LOW" emissions value for aviation. We use 950 g per tonne-km as a "HIGH" emissions scenario for aviation.

revenue ton-miles flown, and share in the fleet. Combining fuel use, emissions per gallon of jet fuel, and tonne-km flown it is possible to construct a measure of average CO_2 emissions per tonne-km flown. The numbers range from 493 to 1834, depending on the plane type and how it was used (i.e., for short v. long haul cargo carriage). For comparison, applying this method to the Boeing 747 yields emissions of 700 g of CO_2 per tonne-km, which is close to the Maersk study. Taking a weighted average of these emission numbers over the fleet shares reported, we arrive at the average emission rate of 972 g. Finally, if we update the fleet composition using 2008 shares (from ATA) we arrive at average emissions of 912.1 g.

In the calculations that follow we employ 552 g/t-km as a "LOW" emissions value for aviation. This corresponds to the use of the most efficient aircraft on the longest flights. We use 950 g/t-km as a "HIGH" emissions scenario, and it corresponds to the use of a mixed fleet of smaller planes on shorter flights.

To amplify this last point, landing/take off (LTO) requires high fuel use relative to cruising, but this effect is most pronounced at short distances. We collected detailed data from [15] on fuel usage on LTO and cruise for a variety of planes and calculated emissions per ton-km for various trip lengths to see how this would affect our calculations. For example, a 747-400 with a 60 percent load factor on a 1852 km flight emits 556 g/t-km (close to our LOW scenario), while that same plane and load factor emits 912 g/t-km on a 463 km flight. This represents an important diseconomy of scale for much shorter flights of the kind one would see with domestic US cargo usage. However, once one gets to flights of international distances, the effects become muted. At 463 km, LTO fuel represents nearly 55 percent of total fuel use, dropping below 5 percent for distances above 6000 km. The median travel distance in our data is 8000 km.

The final component we need to calculate transport emissions is distance traveled. For rail, road, and air transport we rely on the simple distances reported by the CEPII.[10] Bilateral distances between country pairs are calculated following the great circle formula, which uses latitudes and longitudes of the most important city in each country.[11] For ocean transport, direct line distances significantly understate actual distances traveled. Containerships rarely travel point to point between importer and exporter and frequently stop at multiple ports of call en route. We draw on a dataset of actual ship itineraries from Hummels and Schaur [20] that allow us to calculate actual distances traveled due to these indirect routings.

4.4. Greenhouse gas emissions from output

The GTAP 7 database provides data on GHG emissions produced by each sector g in each country o, E^Y_{og} in Eq. (4). We briefly summarize how these data were constructed, and direct readers to more detailed discussions available from Lee [28] and Rose et al. [37]. The database contains information on the quantity of six energy inputs (coal, oil, gas,

[10] The CEPII dataset is available for download at 〈http://www.cepii.fr/anglaisgraph/bdd/distances.htm〉.
[11] For aggregation at the regional level we weighted each constituent country's distance by its GDP share in the region's GDP.

petroleum products, electricity, and gas distribution) used by sector g in country o.[12] Using a standard formulation provided by Intergovernmental Panel on Climate Change [24] guidelines, the quantity of fuel consumed (in units of energy) by each energy input of sector g in country o is converted into CO_2 emissions using information on emissions per unit of energy specific to each energy input. Finally, these data are supplemented by calculating non-CO_2 greenhouse gases emitted as a by-product of production (primarily in agriculture).[13] These are converted into CO_2 equivalents based on their global warming potentials, following the IPCC's methodology also used in US EPA [41].

Combining these data we have total GHG emissions for each country o and sector g. To provide comparisons to our transportation emissions, we describe these as emission intensities per dollar of output e^Y_{og} by dividing total emissions for o–g by the market value of output.

Energy use differs across countries and sectors due to differences in technology, resources, and policy. Technology affects both the energy requirements of production in each sector, and the efficiency with which energy is used. The choice of energy inputs and resulting emissions are affected by the availability of particular energy inputs in each respective country (some have large endowments of natural gas, others of coal), and the prices of those inputs. Finally, taxes, subsidies and other carbon mitigation policies in force during our base year may affect energy usage and the emissions it generates. The GTAP database makes no attempt to ascribe differences in emission intensities to these underlying causes, it simply tracks energy used and emissions produced.

In our Section 5 and 6 we simulate changes in transport and output emissions taking these output emission intensities as given. As a consequence, output emissions change as a result of scale and sector composition of output, but not through changes in emission intensity for a given producer and sector induced by changes in technology, resources, or policy. While a more rigorous modeling of within sector change in output emission intensity is of considerable interest we have not pursued it here because our focus is on international transport emissions. As a result, our exercises should be thought of as first order comparisons of the size and growth of transport and output emissions that ignore possible feedback effects on emission intensities working through technology, resources or policy.

5. Transport and output emissions in the base year

In this section we provide three main exercises. First, we compare our "bottom-up" approach to calculating international transport emissions to the ITF "top-down" approach as a methodological check. Second, we compare transport to output emissions for a given trade flow to gauge the importance of transport emissions in trade. Third, we use the transport and output data in combination to consider whether some partial equilibrium changes in the pattern of specialization and trade will yield rising or falling GHG emissions.

5.1. *Aggregate emissions from international transport: Comparing methodologies*

Our "bottom-up" approach to emissions calculates the quantity of transportation services (kg–km) performed by each mode in each origin–destination–product trade flow, and then multiplies by emissions per kg–km for each mode. This yields transportation emissions that are specific to nearly 36,000 individual trade flows. Summing over all trade flows we have an alternative estimate of total CO_2 emissions from international transport. How does this bottom up approach compare to the top down ITF [22] approach based on worldwide fuel usage? The answer is: surprisingly well. In 2004, the ITF calculates that international aviation and maritime transport together were responsible for 910 million tons of CO_2 production, 520 from maritime and 390 from aviation. We calculate 522 million tons of maritime emissions. When we employ the LOW emissions intensity we calculate aviation emissions of 419 (and a total of 941 million tons) in 2004.[14] Accordingly, we will focus most of our subsequent calculations on the LOW aviation emissions scenario. While there are large methodological differences between our approach and the ITF, we match emission aggregates quite closely. This gives us confidence that our estimates for disaggregated flows will also be informative.

Using our more comprehensive emissions data we calculate that total international transport emissions are 1205 million tons in 2004. Measured relative to the value of world trade, international transport emits 145 g per dollar of trade, while output of traded goods generates 300 g per dollar of trade. That is, total trade-related emissions are 445 g per dollar, of which 33 percent come from international transport.

Our calculation of 1205 million tons of CO_2 equivalent contrasts with the 910 million tons calculated by the ITF. By omitting road and rail, the ITF calculation misses 28 percent of international transport emissions. This may help to explain

[12] The main data source for the GTAP energy volumes is the 2003 International Energy Agency's "Extended Energy Balances". The energy volumes in GTAP are expressed in kilotons of oil equivalent (koe). These can be easily transformed in units of energy applying tera joules to koe conversion factors which vary across energy sources.

[13] The GTAP non-CO_2 greenhouse gases (NCGG) are derived from USEPA country-level data on NCGG emissions classified, following the IPCC, in 29 non-CO_2 and Other CO_2 emissions categories with 153 emissions subcategories. Each of these emission subcategories has been mapped to the GTAP sectors by matching the corresponding IPCC emission source and driver descriptions to the CPC and ISIC classifications underlying the GTAP sectors.

[14] Note that the HIGH aviation intensity, based on the current composition of the US air cargo fleet, yields aviation emissions of 721 million tons, much higher than the ITF values. There are two possible explanations here. One, the ITF separates fuel use into domestic and international usage. If some international fuel use were inaccurately recorded as domestic usage, they would under-estimate emissions. Two, it may be that the composition of the US air cargo fleet, including smaller planes and shorter routes than are typically found in international aviation, may overstate emissions.

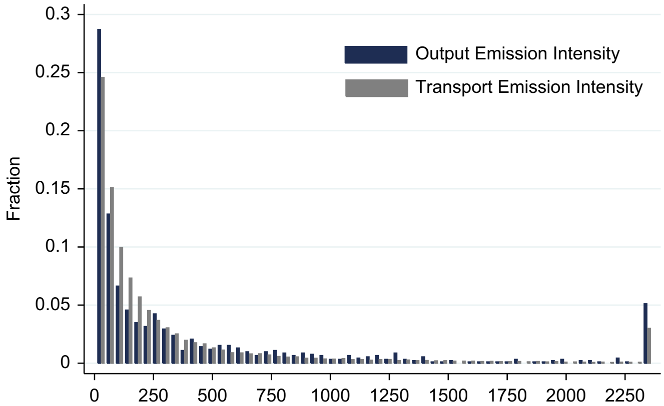

Fig. 1. Distribution of emission intensities.; ***Note***: The plotted CO_2 emission intensities are calculated for each origin–destination–sector (o–d–g) trade flow using data for the base year 2004. Transport emissions intensities (e^T_{odg}) are constructed as described in Eq. (2), while output emissions intensities (e^Y_{og}) are calculated following Eq. (4). In both cases, emission intensities are expressed in grams of CO_2 per dollar.

a curious pattern in Table 1. Using the ITF emission numbers we see that international (maritime plus aviation) transport emissions per dollar of world trade dropped sharply from 159 g per dollar in 1990 to 93 g per dollar in 2004. Why did trade appear to become less emission intensive from 1990 to 2004? The key is that land-based trade, omitted from the ITF emission values, interacts in an interesting way with the structure of protection. In this period trade grew especially fast with land-adjacent partners,[15] promoted by policy measures that offer preferential tariff rates, investment rules, regulatory harmonization and currency union with those close partners. Table 2 shows that international road and rail are responsible for nearly a third of world-trade by value—half of intra-European trade by value is land based.

Note, however, that this pattern need not persist. Were trade liberalization at the multilateral level to erode preferential tariff rates, or were output to grow more rapidly outside of North America and Europe, trade would likely shift towards distant partners. We revisit this point in Section 5.

5.2. Emissions from trade: Comparing output and international transportation

We begin by comparing trade-related emissions from output of traded goods and international transport at the level of 35,880 individual trade flows (that is, 40 exporters × 39 importers × 23 traded goods sectors). We plot the distribution of emission intensities as CO_2 grams per dollar of trade in Fig. 1. Output and transport emissions are similarly distributed because they have similar medians (transport—120 g per dollar, output—137 g per dollar) and are highly correlated at the level of individual trade flows.[16]

There is a wide variance in both transport and output emissions, ranging from close to zero grams of carbon per dollar to well over 2 kg of CO_2. This variance is notable because the average value of 145 g per dollar for transport as a whole is driven by a concentration of trade in o–d–g flows with very low emission intensities. There are many flows with much higher emissions, and carbon taxation would have a pronounced effect on these goods.

It is useful to put these values into perspective by calculating the tariff equivalent of policies designed to reduce total trade-related emissions. Consider the export of a good which, combining output and transport, produces 200 g of CO_2 equivalent emissions per dollar of trade. A carbon tax of \$50 per ton raises the delivered price of that good by one percent, and so is equivalent to a 1 percent tariff.[17] For comparison, actual tariffs in our data average 3.2 percent, which is equivalent to a carbon tax of \$50 applied to a trade flow with trade-related emissions of 650 g per dollar.

Next we examine the contribution of transport emissions to trade-related emissions when calculated on a common per dollar basis. We aggregate transport emissions for each industry by summing over all country pairs. Taking the transport emissions for each industry and dividing by the value of trade yields a (weighted average) transport emission intensity for that industry. A similar procedure yields the average output emissions intensity. Adding these together as in Eq. (5) enables us to calculate the share of transport emissions in total trade-related emissions for each industry. Fig. 2 provides this comparison with industries sorted from smallest to largest transport emissions share (data in grey, scale displayed on

[15] This pattern, in sharp contrast to the conventional wisdom pointing to the "death of distance", has been pointed out by several authors looking at the effect of distance variables in gravity regressions [13,5], and others who have noted the remarkably large effect of NAFTA and EU liberalization policies on trade within those regions.

[16] Trade flows with high output emissions also have high transport emissions, and this is true whether we look at total emissions or emissions intensities. A regression of transport emission intensities on output emission intensities for the exporter yields an elasticity of 0.26 and an R^2 of 0.10. A regression of total emissions from transport on total output emissions yields an elasticity of 0.76 and an R^2 of 0.73.

[17] 200 g equals 0.0002 metric tons. If carbon is taxed at \$50 per metric ton, this is a tax of 1 cent for every dollar of trade, the equivalent of imposing a 1 percent ad-valorem tariff.

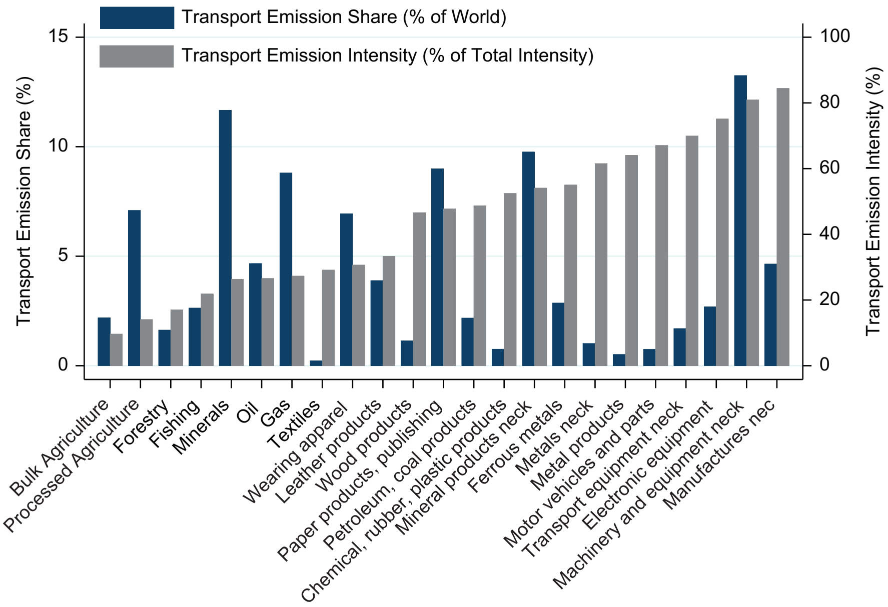

Fig. 2. The contribution of transport to total trade-related emissions. *Note***:** All calculations rely on base year 2004 data. The transport emission share, in percentage, measures the fraction a given sector contributes to the world-wide CO_2 emissions from international transport (i.e., E_g^T/E^T). The transport emission intensity, in percentage, is calculated as the fraction of a sector's transport emission intensity in that sector's total trade-related CO_2 emission intensity (i.e., $e_g^T/(e_g^T+e_g^Y)$). The aggregation of the transport emission intensity shares at the sector level uses trade weights. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the right vertical axis). For perspective we also display transport emissions for that industry as a share of total transport emissions (data in blue, scale displayed on the left vertical axis).

Recall that worldwide transport is responsible for 33 percent of trade related emissions. At the industry level we see wide dispersion in these numbers. At the low end are bulk products (agriculture, mining) with significant output emissions, and which tend to be shipped using the most efficient maritime bulk carriers. At the high end are manufactured goods. Over 75 percent of the trade-related emissions of transport equipment, electronic equipment, machinery, and manufactures not elsewhere classified (nec, henceforth) come from transportation.

We provide similar calculations for international transport and output emissions by regional groupings and for selected countries.[18] In Fig. 3, we show the contribution of selected regions and countries to trade-related emissions worldwide, including emissions from the production and international transport of exports and imports. There are several notable patterns here. First, there is a significant difference between the output share of emissions and the trade share of emissions. North America and Europe are together responsible for just over a third of output emissions but over 60 percent of transport emissions. The US alone is responsible for almost a third of world emissions from transportation of exports. The opposite pattern holds for China, which is responsible for 20.8 percent of output emissions and only 3.5 percent of transport emissions from exports. Second, for many regions there is a large imbalance between international transport emissions in imports and exports. The US export emissions share is much larger than its import emissions share while this imbalance is reversed from the European and East Asian perspective.

To some extent these shares are driven by the size of each region, reliance on trade, and trade imbalances. To eliminate these effects in Fig. 4 and Table 4 we calculate the emission intensities for exports and imports, measured in grams of CO_2 equivalent per dollar of trade. To make the numbers comparable, both output and transport emissions are reported as weighted averages of country $\times$ sector emissions, where the weights in each case reflect trade shares.[19]

In Table 4 we see large differences between regions in the emission intensities of output and transport. There is significant variation in output intensities, driven largely by the commodity composition of trade. South America, Oceania and the Middle East/Africa have very high output emissions per dollar of trade, driven by their reliance on emission intensive commodity production. Manufacturing oriented exporters see much smaller output intensities. Perhaps more surprising there are also very large differences in the transport intensities. The transportation of North American exports is four times more emission intensive than the transportation of both East Asian or European exports (and the transport of US exports is eight times more emission intensive than Chinese exports.) This is a consequence of an unusually large

[18] The calculations for the full sample of regions and countries are available upon request.

[19] By using trade shares, the importance of a particular sector is the same for both output and transport emissions. Were we to use output shares for output, goods with a large share of output but a small share of trade would skew the averages.

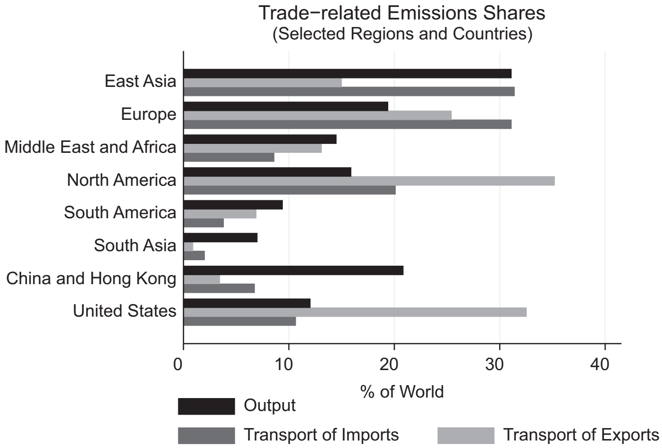

Fig. 3. World shares of trade-related emissions. *Note*: Each horizontal bar measures the fraction of the CO_2 emissions accounted by a country/region in world-wide emissions of CO_2. These shares are measured separately for emissions from output, international transport of exports, and of imports, respectively.

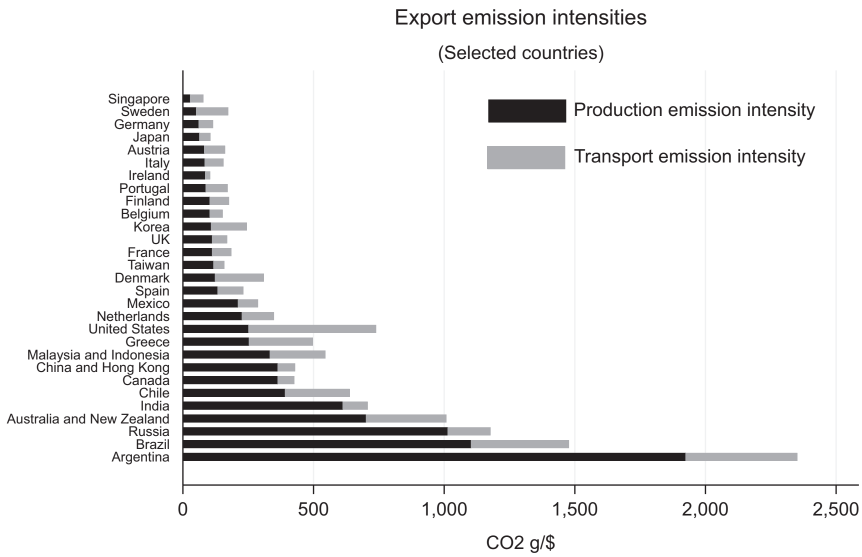

Fig. 4. Output and transport emission intensities of exports, by country. *Note:* Emission intensities are calculated based on Eq. (3) for transport, and Eq. (4) for output. The aggregation to the region level uses trade rather than output weights. The units are grams of CO_2 per dollar of exports. Data is for base year 2004. Countries are ordered by increasing production emission intensity of exports.

Table 4
Output and transport emission intensities, by region.

	Emission Intensities (CO_2 g/$)							
	Exports				Imports			
	Total	Output	Transport	Transport share (%)	Total	Output	Transport	Transport share (%)
North America	606	270	336	55	395	259	136	34
Central America	557	404	153	27	510	376	135	26
South America	1476	1138	337	23	760	474	286	38
Europe	262	179	83	32	355	253	101	29
South Asia	674	581	93	14	731	562	169	23
East Asia	306	224	81	26	562	352	210	37
Middle East/Africa	1176	908	268	23	697	476	221	32
Oceania	1008	701	307	30	440	245	194	44
World	445	300	145	33	445	300	145	33

Note: Emission intensities for each the *o–d–g* trade flow are calculated based on Eq. (2) for transport, respectively Eq. (4) for output, using year 2004 data. They are then aggregated by exporter and by importer, respectively, using trade shares as weights. For comparability with transport emissions, output emissions are constructed as a weighted average of sector level output emissions, using trade rather than output weights.

reliance on air cargo in US exports. We also see a strong imbalance in emission intensities. East Asian imports are much more emission intensive than the exports, while the reverse is true for North America.

These numbers make clear that including transport significantly changes our perspective on which regions have emission intensive trade. Using the emission intensities represented in Fig. 4, India's production of traded goods has 143 percent more emissions per dollar of trade than the US, but after incorporating transportation, its exports are less emission intensive in total. A similar pattern is found when comparing US exports to exports from Greece, Malaysia and Indonesia, China, Canada and Chile.

A key implication derived from Fig. 4 is that both production and transportation emissions should be considered when evaluating policy changes designed to curtail emissions. In some countries the impact of regulation will be felt most acutely on the production side, whereas in countries like the US, the main effect will primarily be on transport. We return to this point in the concluding section.

5.3. Reallocating production: Does more trade mean more emissions?

A central question of the previous literature on trade and carbon emissions is: will rising trade lead to higher or lower emissions? If two countries engaged in trade have similar output emission intensities, then more trade means more international transport and higher emissions. However, if the difference in output emissions is large enough to offset the transport emissions, trade could lower emissions.

This question has been previously addressed with case studies [25,38,44] or with largely imputed data [36]. We can use our data to address it comprehensively. To begin we provide a straightforward partial equilibrium calculation. We compare emissions in the base year, where trade takes place, to a partial equilibrium reallocation of production in which we hold consumption fixed but require each country to produce all consumption locally. Denoting the exporter or origin country as "*o*", the importer or destination country as "*d*", and the good "*g*", we can then calculate the change in emissions associated with the trade of good *g* as follows:

$$\Delta E_{odg} = [(e^{Y}_{og} - e^{Y}_{dg}) + e^{T}_{odg}] VAL_{odg} \tag{6}$$

A negative value means that output emissions in the exporter are lower than output emissions in the importer, and that the difference is more than enough to offset emissions from transport. We will consider all possible reallocations over all country pairs, and weight these reallocations by the value of trade.[20] The question can then be framed as: is the difference in output emissions large or small relative to transport emissions, and what fraction of trade reduces emissions despite incorporating emissions from transport?

In Fig. 5a we provide a histogram of 29,300 production reallocations (weighted by the corresponding export value), with units in grams of CO_2 per dollar traded.[21] In total, 26.5 percent of trade flows equaling 31 percent of world trade by value have negative values for Eq. (6), meaning that trade results in a net decrease in emissions. The median *o*–*d*–*g* trade flow increases emissions by 39 g per dollar traded, while the mean trade flow increases emissions by 158 g. In the aggregate, this corresponds to an increase in emissions equal to 1274 million tons of CO_2, of which 98 million tons is due to output reallocation and 1178 million tons is due to transport emissions.

To understand the mechanics of this reallocation better, we provide a similar distribution for two illustrative sectors: wearing apparel and bulk agriculture.[22] For wearing apparel, cross-country differences in output emissions are quite small. This means that trade acts primarily to increase emissions from transport. By value, 80 percent of trade in wearing apparel raises emissions, though the average increase is quite small (61 g per dollar traded). In contrast, there are large differences across countries in output emissions from bulk agriculture, and as we noted in Fig. 2, transport is a small share of trade-related emissions. In this case, trade reduces emissions in 41.6 percent of trade flows (34.4 percent by value), in many cases substantially. However, the remaining cases represent significant increases in emissions so that the average effect of trade is to increase emissions by 359 per dollar of trade.

Because we sought to duplicate the spirit of Life Cycle Analyses, the calculations in Fig. 5 are mechanically focused only on GHG emissions as part of a reallocation exercise that ignores general equilibrium considerations. We hold fixed consumption and reallocate production, but do not address the feasibility of local production (i.e., given resources and technology, can a country actually produce all consumption locally), how prices might change, and how this would feed back to changes in consumption. As such they are meant to be illustrative of the extent to which the existing trading system increases or decreases emissions, without worrying about the feasibility of the autarkic counterfactual. In the next

[20] There are two observations for the US and China trading electronics, one in which the US is the origin, and another in which China is the origin. This implies that the comparison of production emission intensities (the difference term in the square brackets) is symmetrically distributed around zero. However, these differences are weighted by the value of trade. Depending on whether more trade by value takes place in emission reducing or emission increasing flows, trade on net can reduce or increase emissions.

[21] We drop the top and bottom 5 percent of values to eliminate outliers that distort the histogram.

[22] Table SM2 in the online appendix provides similar calculations for each country and producing sector, reporting the fraction of trade reallocations that are GHG emission reducing. High income countries tend to have low output emissions and intensively use airplanes in trade, and here, few trade exchanges are CO_2 reducing. Low income countries have high output emissions and intensively use maritime transport. Here, more than half of trade reallocations are emission reducing.

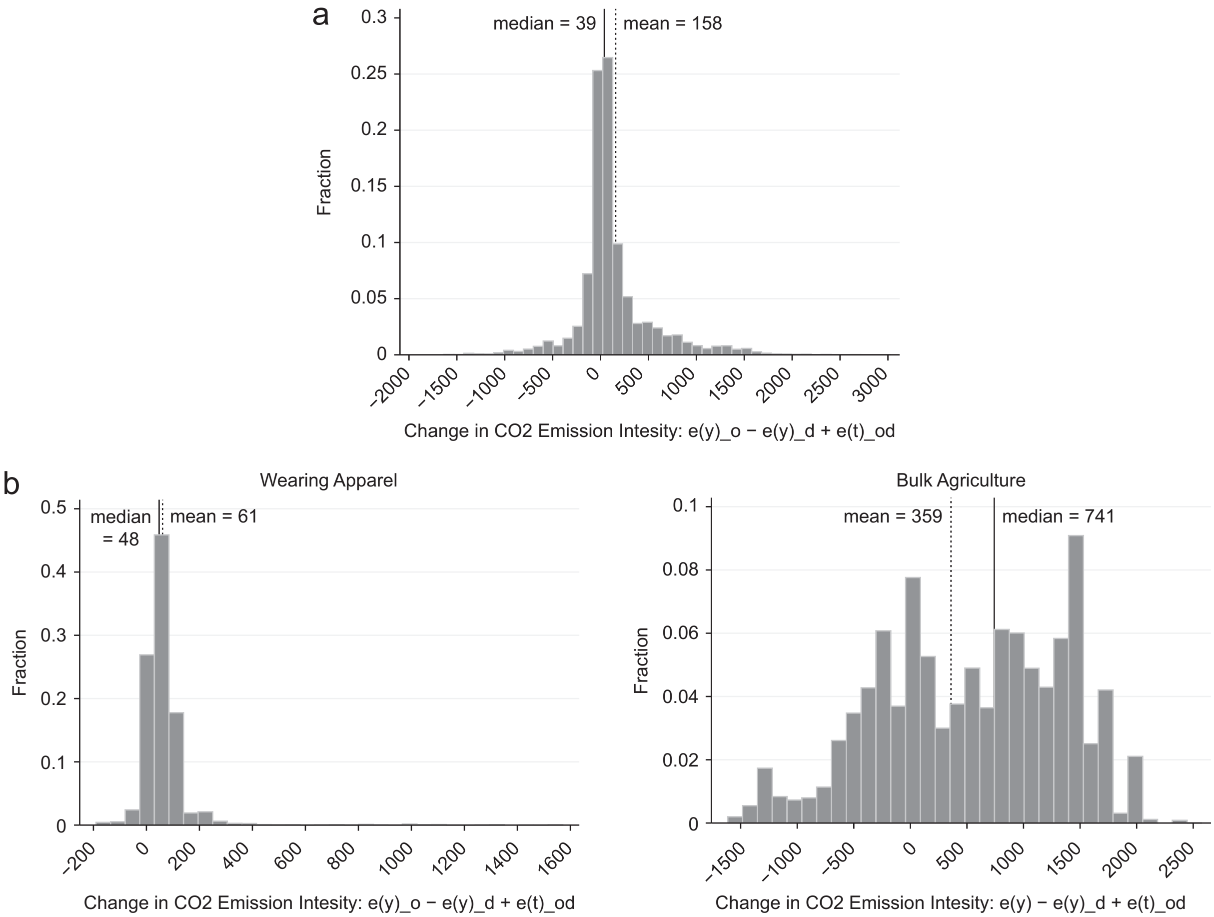

Fig. 5. (a) Net change in CO_2 emissions due to trade. (b) Net change in CO_2 emissions for selected sectors. *Note***:** The changes in emission intensities resulting from all possible *o–d–g* production reallocations correspond to the square brackets term in Eq. (6). The units are in grams of CO_2 per dollar. The histogram weights each change in CO_2 emission intensity by the value of trade corresponding to that origin–destination–sector pair.

section we consider general equilibrium shocks to the trading system in order to analyze how likely future patterns of trade growth will affect emissions.

6. Trade growth and changes in international transport emissions

The emission intensity of individual trade flows varies dramatically depending on what product is being traded, which countries are trading, and how they are transporting it. As a consequence, trade growth that also changes the composition of trade can result in pronounced differences in trade-related emissions.

In this section we will use a CGE simulation to generate changes in the value and composition of trade resulting from tariff liberalization and GDP growth. Combining this with our scale vs. intensity decomposition we can calculate the effect of growing trade on emissions growth. Fixing the emission intensity of a particular output sector *o–g*, the growth in output related emissions is:

$$\Delta E^Y_{og} = \Delta Y_{og} \times e^Y_{og} \tag{7}$$

Fixing the emission intensity of a particular *o–d–g* trade flow, the growth of trade-related emissions is then

$$\Delta E^T_{odg} = \Delta VAL_{odg} \times e^T_{odg} \tag{8}$$

This exercise holds fixed the modal shares for each *o–d–g* flow, and the emission intensity of each mode. Put another way, this exercise takes the transportation system as given and examines how changes in trade affect the greenhouse gas emissions from international output and transport. We do not model how changes in fuel prices, spurred either by rising demand for fuel or changes in carbon/fuel taxes, affect mode-specific prices. Nor do we explicitly examine endogenous technological change in transportation, although we do explore sensitivity of our results to assumptions on the fuel and emission intensity of air transport.

Our approach of fixing modal shares for each *o–d–g* flow yields a reasonable approximation of aggregate changes in modal use and emissions in two cases. One, if tariff liberalization or GDP growth does not generate large changes in relative transportation prices (e.g., the price of air relative to ocean shipping), then we would not expect modal shares within an *o–d–g* flow to change much. This would be the case if there are few aggregate changes in modal use, or if trade growth does not affect input costs differentially across modes. Two, suppose that modal use varies primarily across (rather than within) *o–d–g* flows due to immutable geography, infrastructure, and product characteristics. For example, land-adjacent countries will continue to move goods via road and rail independent of ocean shipping prices while countries separated by an ocean will be unable to use road and rail. Similarly, product weight will force grain onto bulk cargo carriers regardless of the price of air cargo. In these cases, small changes over time in modal use within each *o–d–g* flow will be swamped by changes in the trade shares of flows that use one mode more than another.[23]

6.1. Simulated trade growth

We wish to simulate the changes in worldwide output and trade (ΔY_{og} and ΔVAL_{odg} in Eqs. (7) and (8), respectively) associated with various tariff liberalization and output growth scenarios, which requires the use of a computable general equilibrium (CGE) model of trade. We employ version 7 of the GTAP model, aggregating the model to 40 regions and 23 traded and 6 non-traded goods. A highly detailed description of this widely used model can be found in Hertel and Tsigas [18]. We briefly summarize key characteristics here.

Within each sector firms are constant returns to scale with a production structure that is Leontief in factor inputs (labor, capital, and land) and intermediate inputs including energy commodities. Substitution between factor inputs is governed by a CES structure, as is substitution between intermediate inputs that are Armington differentiated by origin. On the consumption side, households have Cobb–Douglas preferences over consumption, government spending and saving. Demands over consumption goods employ a CDE (constant difference of elasticities) form, and households regard the output of each source country as Armington differentiated.

To capture possible effects of trade liberalization we explore four scenarios. There have been a wide variety of liberalization proposals as part of the Doha round of the WTO talks. We choose a representative three, referred to in Minor [33] as Doha Scenarios 4, 5, and 9, because their design is closest to the proposals currently under consideration. Appendix SM2 available in the online appendix contains detailed notes on these scenarios. In summary, Scenarios 4 and 5 focus on agricultural market access only with tariff cuts for developed countries ranging from 40 to 60 percent, and those for developing countries being one third smaller. Scenario 9 accounts for both agricultural and non-agricultural market access (NAMA), and here non-agricultural tariffs are cut progressively, i.e., peak tariffs are cut more than lower tariffs. In a final "full liberalization" scenario, all import and export tariffs and subsidies are set to zero.

Tariff liberalization may lead to modest increases in trade, but rising output is likely to lead to much more rapid trade growth. Moreover, output growth is likely to be asymmetric with some developing countries such as China and India growing much faster than developed countries. To experiment with output growth we use a specialized version of the GTAP model called GDyn (or Dynamic GTAP). This version of the model contains detailed projections of GDP and factor endowment growth rates from 2004 to 2020 for each country in the database Walmsley [43].[24] This model takes both real GDP growth and factor input growth as exogenous (values shown in Table SM3 of the online appendix), and allows a Hicks neutral technological change variable to reconcile these changes with other model values.

This simulation allows us to examine two key points. First, predicted GDP growth rates vary widely across countries, with especially rapid growth in China and India, and slower growth in developed European economies. Second, this growth occurs through uneven rates of factor accumulation, with some countries rapidly accumulating capital and skilled labor while others see relatively rapid growth in unskilled labor. This allows us to model changes in both the scale of each economy and in comparative advantage arising from changing factor supplies.

6.2. Results

Table 5 summarizes the changes in output, exports, modal use (by value and by kg–km), and CO_2 emissions under each of the five scenarios. Changes in output value, output emissions, and export values come directly from the GTAP model. Combining these with our data on trade weight/value and distance we calculate changes in exports by weight and by transportation services. Combining changes in transportation services with base year data on modal shares and emission factors per tonne-km, we calculate the changes in modal use and in the associated GHG emissions. For robustness we calculate changes in transport intensity assuming both a HIGH emissions scenario (aviation emissions matching the US

[23] We also hold fixed the weight-value ratio of trade for a given flow, assuming that small changes over time in weight–value within an *o–d–g* flow will be swamped by changes in the trade shares of light versus heavy flows.

[24] [43] in turn builds GDP and input growth estimates based on World Bank, Global Economic Prospects 2005 [45], [2], and [11]. GDyn explicitly models the dynamics of capital accumulation, which makes it easier for the modeler to hit a given GDP growth target. It allows for international capital mobility so that closing the model requires us to allow investment to vary endogenously in one country (we chose South Africa, given its relative unimportance for the major issues at hand). The result was an unrealistically high rate of capital accumulation in South Africa. However all results are robust to including/excluding South Africa, except for those in Table 6.

Table 5
Worldwide changes in output, trade and associated emissions by scenario.

	Doha S04	Doha S05	Doha S09	Full Liberalization	GDP growth 2004–2020	
					Per annum	Cumulative
% change						
Output	−0.09	−0.04	−0.22	−1.22	3.57	75.2
Exports:						
Value	0.07	−0.13	1.12	6.09	3.76	80.4
Weight	0.24	−0.08	0.57	5.72	5.83	147.8
kg–km	0.46	−0.06	1.10	6.05	6.48	173.3
Modal use (value)						
Sea	0.54	0.03	2.70	12.25	4.52	102.8
Air	−0.31	−0.34	1.78	7.41	3.82	82.1
Rail	−0.23	−0.23	−1.20	−3.72	2.88	57.6
Road	−0.50	−0.27	−1.85	−4.66	2.21	41.8
Modal use (kg–km)						
Sea	0.51	−0.04	1.16	6.32	6.59	177.5
Air	−0.48	−0.44	3.60	13.14	4.93	116.1
Rail	−0.33	−0.60	−0.63	5.21	4.82	112.5
Road	−0.52	−0.27	−1.33	−4.73	3.69	78.7
CO_2 emissions (% change)						
Output	0.84	0.42	0.92	0.41	4.50	102.2
Transport:						
HIGH Scenario	−0.06	−0.22	2.10	8.63	5.10	121.7
LOW Scenario	0.04	−0.16	1.72	7.51	5.14	123.1

Note: Changes in world-wide output and trade corresponding to each the five scenarios are simulated using the GTAP CGE model. Changes in output and transport emissions are calculated as described in Eqs. (7) and (8), respectively. Doha Scenarios 4 and 5 account for agricultural market access only. Doha Scenario 9 accounts for both agricultural and non-agricultural market access. In the "full liberalization" Scenario, all import and export tariffs and subsidies are set to zero. The "GDP growth" scenario takes as exogenous countries' projected GDP and primary inputs growth for the period 2004–2020.

cargo fleet), and a LOW emissions scenario (aviation emissions corresponding to the most efficient long range planes, and matching 2004 total emission values from the ITF).

The three Doha scenarios are largely uninteresting from a transport and emissions perspective. Simply, these liberalization efforts are so modest that they yield little growth in trade, in transport, or in emissions. The most far-reaching scenario yields a 1.1 percent increase in trade (by value or kg–km), and a slightly higher (1.7–2.1 percent) rise in transport emissions.

The full liberalization scenario eliminates all import and export tariffs. While this is not currently on the negotiating agenda, it is an interesting exercise because it reveals an important intersection between the structure of protection and emissions. Tariff rates are not set uniformly across trading partners and significant preferences are given to partners within trading blocs such as the EU and NAFTA. Because trading blocs tend to be geographically concentrated, tariffs are lower for more proximate partners and especially for land-adjacent partners. In our base year, the trade-weighted average tariff rate for land-adjacent partners is 1 percent, while the average tariff for non-adjacent partners is 5.5 percent. This is an important phenomenon from a transportation perspective because rail and road transport dominate international trade between land-adjacent countries. Tariff liberalization that removes tariff preferences for land-adjacent countries will then shift trade toward distant partners and away from road and rail transport.

These effects show up clearly in our results. In Table 5 we see that full liberalization increases trade by 6 percent, concentrated in those products (agriculture, textiles and wearing apparel) that are subject to the highest rates of protection.[25] International transport emissions rise faster than trade, due in part to a rise in trade at a distance and in part to an expansion of emission intensive air cargo. As we see in Table 5, rail and road usage shrinks substantially while international aviation and maritime transport grow quickly.

In contrast to the tariff liberalization simulations, the GDP growth scenario yields profound changes in output, trade, and greenhouse-gas emissions. Output and trade value rises at similar rates, accumulating to 75–80 percent growth over this period. Trade measured by transport services (kg–km) rises much faster, 6.5 percent per annum, accumulating to 173 percent growth. Not surprisingly then, transport emissions rise faster than output and trade by value, and faster than output emissions.

To understand this, note that tariff liberalization created trade growth biased toward long distance trade because of the erosion of proximity-based tariff preferences. The GDP growth experiment creates trade growth biased toward long distance trade because the fastest growing countries (China, India) are far away from other large markets. As with tariff liberalization there is faster growth in air and sea transport relative to rail and road transport.

[25] The small negative effect on output value is due to terms of trade effects. Real quantities of trade rise.

Table 6
Trade value and output growth by emission intensity: WLS estimates.

Dependent variable	Trade growth		Output growth	
	Full liberalization	**GDP growth**	**Full liberalization**	**GDP growth**
Panel (A) On quartiles of transport emission intensity			On quartiles of output emission intensity	
II quartile	0.036***	0.093***	−0.016	0.085
	[0.013]	[0.025]	[0.015]	[0.062]
III quartile	0.040***	0.229***	0.006	0.094**
	[0.012]	[0.029]	[0.009]	[0.043]
IV quartile	0.049***	0.417***	0.010	0.314***
	[0.012]	[0.032]	[0.012]	[0.049]
Constant	−0.001	0.361***	−0.015***	0.403***
	[0.006]	[0.015]	[0.006]	[0.028]
N	34,162	34,162	879	879
R^2	0.007	0.570	0.012	0.195
Panel (B) On transport emission intensity determinants				
Distance	0.035***	0.055***		
	[0.005]	[0.009]		
Weight/value	0.019***	0.090***		
	[0.004]	[0.008]		
Air use	0.010***	0.008**		
	[0.002]	[0.004]		
Constant	−0.182***	0.149*		
	[0.046]	[0.086]		
N	30,906	30,906		
R^2	0.051	0.602		

Note: Robust standard errors in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.
In panel (A) quartiles are based on the distribution of (log) emission intensity. A trade flow's emission intensity is calculated using the LOW scenario emissions content. All coefficients are estimates by WLS using 2004 export values as weights. All regressions include unreported indicator variables for imports and exports involving South Africa. This is done in order to account for the fact that in the GTAP GDP growth simulation South Africa is used in closing the model. The Gas sector is a huge outlier and so it is removed from the sample.

These aggregated numbers hide a wealth of interesting variation we wish to explore. Recalling Eq. (8), we ask: what is the relationship between transport emission intensity in the base year, and the subsequent growth in trade? In the top left panel of Table 6 we group 34,162 o–d–g trade flows into quartiles using transport emission intensity, and assign each o–d–g observation a quartile dummy variable.[26] We then regress trade growth (by o–d–g) on emissions quartiles with the constant representing growth in the lowest emission quartile. In both the full liberalization and GDP growth scenarios, the higher the transport emission intensity of the trade flow the faster trade grew. This effect was considerably stronger in the GDP growth scenario, both in the size of the coefficients and in the regression R-squared. In the bottom left panel we examine correlates of transport emission intensities. Trade growth in both scenarios is fastest for trade flows that occur over longer distances, and use a higher share of air cargo, and in products with higher weight/value ratios.

The top right panel of Table 6 performs a similar exercise on output emissions. For each of 879 origin–products we group production into quartiles based on output emission intensities, and regress output growth on these quartiles. Full liberalization has very little effect in reorienting output growth toward more or less emission intensive production. However, GDP growth orients output growth toward those countries and products with high output emissions. This is primarily the effect of rapid GDP growth in China and India. Because their output is more emission intensive (in the fourth quartile of intensities), more rapid GDP growth in those countries will push overall emissions higher.

7. Conclusions and policy implications

Most of the work on trade and climate change has ignored international transportation, or considered it in the context of case studies. This neglect is due in part to a lack of data, and in part to the belief that international transportation represents a small portion of overall emissions.

In this paper we combined data on trade, transportation modes, transport emissions, and output emissions to calculate the contribution of transportation to trade-related greenhouse gas emissions in the aggregate and for all trade flows world-wide.

[26] We also omit the GAS sector and incorporate fixed effects for South Africa. GAS is an outlier that skews results badly because its weight/value ratio and transport modal use are poorly measured. For technical reasons noted above South Africa is treated differently in the model closure, which results in unrealistic measures of capital growth.

What are the policy implications of this research? Incorporating international transport emissions in carbon mitigation policies presents significant challenges for negotiation and implementation. Were these emissions trivial in magnitude, they might reasonably be ignored.

While international transportation is a small fraction of overall emissions it is a surprisingly large fraction of trade-related emissions. Two-thirds of trade-related emissions in U.S. exports are due to international transportation, and world-wide over 75 percent of the trade-related emissions of transport equipment, electronic equipment, machinery, and manufactures nec come from transportation. Many exporters and products that look relatively "clean" when we focus only on output emissions are in fact heavy emitters once incorporating transportation.

This is not to say that trade itself necessarily generates higher GHG emissions. If a country has very high output emissions, and transports goods efficiently, importing the good from a low emission producer can reduce emissions. Using a partial equilibrium exercise, we find that 31 percent of trade (by value) in the base year of 2004 results in a net reduction in emissions. Further, we employ a series of general equilibrium trade growth simulations designed to illuminate the role of tariff liberalization and GDP growth on emissions. Our projections for likely patterns of trade growth indicate that transport emissions will become increasingly important, growing twice as fast as the emission from trade-related output. The largest effect is due to GDP growth in India and China, which results in a significant increase in both the scale of trade and the distance over which it takes place.

In addition, our tariff liberalization experiments provide evidence for a novel finding: the current structure of trade protection interacts in an interesting way with modal use and emissions. Current tariff preferences favor proximate and land-adjacent partners who use rail and road transport to move goods short distances. Undoing this preference results in a shift in trade toward distant partners, a more intensive use of air cargo, and transport emissions growth that is more rapid than trade growth. The share of transport in trade-related emissions rises, reversing a downward trend created by preferential trade agreements. Perhaps most important, trade shifts away from transport modes (rail, road) for which it is relatively easy to measure and assign carbon emissions toward transport modes (maritime, aviation) for which it is hard.

All this suggests that both production and transport emissions should be considered when designing policies to curtail GHG emissions world-wide. The UN Framework Convention on Climate Change [40] suggests several options for including international transport in the global framework for emissions. (1) Allocate international transport emissions across trading partners and include them in countries' national caps; (2) treat international transportation as a global entity, capped independently of national representation or country environmental targets, and then link it to existing global emission trading schemes; (3) apply carbon taxation or levies on fuel consumption.[27] In light of these alternatives, our results provide significant implications for mechanism design.

Consider the first option, in which international transport emissions from a trade flow are included as part of the trading countries' carbon allocation. Precisely how this is done has important distributional consequences. We highlight large imbalances in GHG emissions, both in scale and intensity, from the transport of imported goods versus exported goods. Based on our calculations, the US would much prefer an import based allocation rather than an export based allocation, while China and the rest of East Asia would prefer the opposite.

Of course, associating emissions with a particular trade flow is a significant challenge. Ships and planes do not produce their emissions in a way that is easily assigned to a single country. They purchase fuel all over the world, and produce emissions all over the world. Company headquarters do not correspond to where the transport assets are employed and a given ship or plane may carry goods from many countries on a given trip. The only way that this mechanism can be implemented is if emissions are assigned via a "bottom up" approach similar to what we provide in this paper.

For these reasons some have argued that international maritime and aviation sectors should be treated independently of individual country caps, in essence treated as countries unto themselves. Given our projections that transport emissions will grow twice as fast as output, this would imply a progressively sharp increase in costs of trade. Moreover, a cap-and-trade approach would make it difficult to assign "common but differential responsibility" to developing countries, or to allow exemptions to vital shipments such as food security items, without requiring detailed information on the incidence of emissions (i.e., monitoring and control of international shipments at origin–destination–sector level).

A cap-and-trade system would also be difficult to implement without global agreement about how transport sectors should be treated. These are not hypothetical concerns. Beginning January 1, 2012, aviation emissions were incorporated into the EU Emissions Trading Scheme. All flights landing in an EU airport are legally required to offset emissions, which necessarily implies that carriers are charged for carbon emitted during parts of flights outside EU airspace. This has prompted an immediate uproar and threats of trade war from non-EU countries who insist this extra-territorial provision violates trade rules. China has forbid its carriers from complying and another 25 countries including air-dependent countries such as the US, Canada, Japan, and Singapore are threatening to follow suit [3].

Finally, our emissions calculations are well suited to examine the economic costs of mitigation policies that directly tax carbon output. For example, a $50 per ton carbon tax on emission from international transport applied to (world-wide average) international transport emissions of 145 g per dollar corresponds to a tariff of 0.8 percent. There is however

[27] All these options fall under the umbrella of market based measures to curb greenhouse-gas emissions. In addition, governments and industry are encouraged to adopt operational measures towards carbon mitigation, such as efficiency standards (e.g., fleet renewal, use of biofuels, optimized cruise speed, etc.). See Kageson [26], UNFCCC [40], ICTSD [21] among others.

Table A1
Baseline descriptives by commodity.

Commodity	Tariff	Weight/value	Share of		
			World output	Trade value	kg–km
Bulk agriculture	8.98	3.56	2.51	1.40	4.69
Processed agriculture	9.68	1.24	16.39	6.69	5.54
Forestry	1.13	8.87	0.55	0.16	0.74
Fishing	3.37	0.35	0.51	0.17	0.03
Minerals	1.56	16.56	1.63	1.61	26.53
Oil	1.22	5.01	2.86	5.86	23.69
Gas	0.09	6.33	0.61	0.87	3.52
Textiles	6.91	0.38	2.88	3.20	0.72
Wearing apparel	7.69	0.07	2.14	2.36	0.12
Leather products	7.37	0.21	0.82	1.24	0.19
Wood products	1.66	1.21	2.35	2.04	1.21
Paper products, publishing	1.64	1.41	5.05	2.34	1.97
Petroleum, coal products	3.25	5.13	4.72	2.43	8.27
Chemical, rubber, plastic products	2.57	0.90	12.22	14.22	8.15
Mineral products nec	3.71	2.48	2.66	1.28	1.95
Ferrous metals	2.46	2.43	3.69	3.01	4.74
Metals nec	2.11	0.63	2.14	3.00	1.31
Metal products	3.03	0.90	4.20	2.33	1.21
Motor vehicles and parts	3.45	0.19	7.82	10.48	0.98
Transport equipment nec	2.01	0.11	2.18	3.10	0.26
Electronic equipment	1.14	0.08	7.78	13.36	1.01
Machinery and equipment nec	2.58	0.23	11.66	16.66	2.88
Manufactures nec	2.57	0.19	2.64	2.20	0.31
Total	3.21	1.31	100	100	100

Note: Details on the sectoral aggregation are provided in Appendix 1. Tariff rates and weight to value ratios are trade-weighted averages across all country pairs.

significant variation in the associated tariff equivalents of carbon taxes across goods (ranging from 0.19 percent for motor vehicles and parts, to 4.08 percent for minerals), across importing countries (ranging from 0.32 percent for Belgium, to 3.08 percent for South Africa), and across exporting countries (ranging from 0.09 percent for Ireland, to 2.53 percent for the Rest of East Asia).[28]

As a final note, our calculations assume away changes in modal usage within a particular trade flow over time, and do not allow for technological change in emission intensities due either to innovation or to updating the vintage of the transportation fleet capital stock. Including these additional margins of response is beyond the scope of the current study, but in future work this could be useful for understanding interactions between trade, transportation and emissions. In particular, the much higher fuel intensity of air cargo, suggests that climate mitigation policies could have pronounced effects on how goods move and the kinds of goods that nations trade. This is especially important for countries like the US, whose reliance on air cargo results in unusually high transportation emissions.

Appendix 1. Model aggregation

Region aggregation: We begin with 113 constituent countries/regions available in the GTAP database, then aggregate into the 40 "regions" listed in bold. Some regions are single countries and others are aggregations of the 87 constituent countries available in the GTAP database.

North America: (2 regions) Canada, United States.

Central America: (2 *regions*) *Mexico, Other Central America and Caribbean* (Central America, Rest of FTAA, Rest of Caribbean).

South America: (4 *regions*) *Argentina, Brazil, Chile, Rest of South America* (Colombia, Peru, Uruguay, Venezuela, Rest of Andean Pact, Rest of South America).

Europe: (18 regions) Austria, Belgium–Luxemburg , Denmark, Finland, France, Germany, Greece, Ireland, Italy, Netherlands, Portugal, Spain, Sweden, United Kingdom, Russia, Rest of European Union (Cyprus, Czech Republic, Estonia, Hungary, Latvia,

[28] Appendix Table A2 includes the detailed list of the tariff equivalents from imposing a $50 per ton carbon tax on international transport.

Lithuania, Malta, Poland, Slovakia, Slovenia, Bulgaria, Romania), Other Europe—EFTA (Switzerland, Iceland, Liechtenstein, Norway), Other CEE and Other CIS (Albania, Croatia, Turkey, Rest of Former Soviet Union).

South Asia: (2 *regions*) *India, Other South Asia* (Bangladesh, Sri Lanka, Afghanistan, Rest of South Asia).

East Asia (8 regions) Japan, Korea, Singapore, Malaysia–Indonesia , China–Hong Kong, Taiwan, Other East Asia (North Korea, Macau, Mongolia), Other South East Asia (Philippines, Thailand, Vietnam, Rest of Southeast Asia).

Middle East/Africa: (3 *regions*) *South Africa, Middle East and North Africa* (Middle East, Morocco, Tunisia, Rest of North Africa), *Sub-Saharan Africa* (Botswana, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Madagascar, Uganda, Rest of South African Customs Union, Rest of Southern African Development Community, Rest of Sub-Saharan Africa).

Oceania Countries (1 region): (Australia, New Zealand, Rest of Oceania).

Sectoral aggregation: GTAP provides data on 57 sectors. We aggregate these to 27 sectors, and focus on 23 tradable sectors described in Table A1 below. Manufacturing and mining sectors are analyzed using the same level of detail as in the GTAP data. Agricultural sectors are aggregated as follows.

Bulk agriculture: (Paddy rice; Wheat; Cereal grains nec; Oil seeds; Sugar cane, sugar beet; Plant-based fibers; Crops nec);

Processed agriculture: (Vegetables, fruit, nuts; Bovine cattle, sheep and goats, horses; Animal products nec; Raw milk; Wool, silk-worm cocoons; Bovine meat products; Meat products nec; Vegetable oils and fats; Dairy products; Processed rice; Sugar; Food products nec; Beverages and tobacco products).

Table A2
Tariff equivalents of carbon taxation.

	Tariff equivalent of \$50 per ton carbon tax on international transport			
By	**Exporter**	**Importer**		**Sector**
Argentina	2.14	1.70	Minerals	4.08
Austria	0.40	0.43	Gas	3.26
Belgium	0.37	0.32	Forestry	2.40
Brazil	1.87	1.40	Petroleum, coal products	2.08
Canada	0.33	0.82	Mineral products nec	1.49
China and Hong Kong	0.32	0.69	Metal products	1.45
Chile	1.24	2.21	Bulk agriculture	1.13
Central and Caribbean Americas	0.77	0.68	Ferrous metals	1.13
Denmark	0.93	0.60	Oil	1.09
European Union	0.48	0.46	Fishing	0.96
Rest of East Asia	2.53	0.77	Paper products, publishing	0.89
Finland	0.25	0.52	Processed agriculture	0.77
France	0.37	0.41	Wood products	0.61
Germany	0.27	0.55	Chemical, rubber, plastic prod.	0.60
Greece	1.22	0.55	Machinery and equipment nec	0.58
India	0.48	0.91	Electronic equipment	0.53
Ireland	0.09	0.50	Textiles	0.50
Italy	0.36	0.53	Leather products	0.44
Japan	0.21	1.53	Metals nec	0.40
Korea	0.68	1.20	Manufactures nec	0.38
Middle Eastern and North Africa	1.30	0.78	Transport equipment nec	0.24
Mexico	0.38	2.15	Wearing apparel	0.23
Malaysia and Indonesia	1.06	1.02	Motor vehicles and parts	0.19
Netherlands	0.61	0.54		
Oceania countries	1.54	0.97		
Other East Europe	1.04	0.65		
Rest of European Countries	0.28	0.50		
Portugal	0.42	0.44		
Rest of South East Asia	0.42	0.78		
Rest of South Asia	0.44	0.69		
Russia	0.82	0.60		
Singapore	0.25	1.17		
South Africa	1.84	3.08		
Spain	0.49	0.51		
Sweden	0.61	0.78		
Sub Saharan Africa	1.26	1.24		
South and Other Americas	1.44	1.08		
Taiwan	0.21	1.20		
United Kingdom	0.29	0.53		
United States	2.44	0.47		
Average	**0.73**	**0.73**	**Average**	**0.73**

References

[1] Aircraft Economics, Freighter cost comparisons, Aircraft Economics 45 (1999) 50–56.
[2] Ahuja, V. and Filmer, D., 1995. "Educational Attainment in Developing Countries; New Estimates and projections Disaggregated by Gender," World Bank Policy Research Working Paper 1489.
[3] David Badger, "A strange new climate", International Freight Weekly, February (2012) 10.
[4] M. Babiker, Climate change policy, market structure and carbon leakage, Journal of International Economics 65 (2) (2005) 421–445.
[5] M. Berthelon, C. Freund, "On the conservation of distance in international trade", Journal of International Economics 75 (2008) 310–320.
[6] M.-A. Cadarso, L.-A. Lopez, N. Gomez, M.-A. Tobarra, CO_2 emissions of international freight transport and offshoring: measurement and allocation, Ecological Economics 69 (2010) 1682–1694.
[7] California Climate Change 2006. Comparing Energy Options.
[8] L.M. Canals, S.J. Cowell, S. Sims, L. Besson, Comparing domestic versus imported apples: a focus on energy use, Environmental Science and Pollution Research 14 (5) (2007) 338–344.
[9] A. Carlsson-Kanyama, M. Pipping Ekstrom, H. Shanahan, Food and life cycle energy inputs: consequences of diet and ways to increase efficiency, Ecological Economics 44 (2003) 293–307.
[10] B.R. Copeland, M.S. Taylor, Trade, growth, and the environment, Journal of Economic Literature 42 (1) (2004) 7–71.
[11] CPB, 1999. "WorldScan: the Core Version," CPB Netherlands Bureau for Economic Policy Analysis.
[13] A.C. Disdier, K. Head, "The puzzling persistence of the distance effect on bilateral trade", The Review of Economics and Statistics 90 (1) (2008) 37–41.
[14] J. Ederington, J. Minier, Is environmental policy a secondary trade barrier? An empirical analysis, Canadian Journal of Economics 36 (1) (2003) 137–155.
[15] EEA. 2007. "EMEP/CORINAIR Emission Inventory Guidebook", Group 8.
[16] M. Giannouli, G. Mellios, Overall Energy Efficiency and Specific CO_2 Emissions for Passenger and Freight Transport, European Environmental Agency, 2005 TERM 2005 27 EEA 32.
[17] J.-M. Grether, N.A. Mathys, J. de Melo, Global manufacturing SO_2 emissions: does trade matter? Review of World Economics 145 (4) (2010) 713–729.
[18] Hertel, T. and Tsigas, M., 1997. The Structure of GTAP. GTAP Working Paper 413.
[20] Hummels, D.L. and Schaur G., 2012. "Time as a Trade Barrier". NBER Working Paper 17758.
[21] ICTSD, 2010. International Transport, Trade and Climate Change. International Center for Trade and Sustainable Development, Note no. 17.
[22] International Transport Forum, 2010. Transport Greenhouse Gas Emissions 2010. ITF/OECD.
[23] International Energy Agency, 2010. CO_2 Emissions from Fuel Combustion 2010. IEA/OECD.
[24] IPCC/OECD/IEA. 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Paris: Intergovernmental Panel on Climate Change (IPCC), Organization for Economic Co-operation and Development (OECD), International Energy Agency (IEA).
[25] A. Jones, A Life Cycle Analysis of UK Supermarket Imported Green Beans from Kenya. Fresh Insights No. 4, International Institute for Environment and Development, London, United Kingdom, 2006.
[26] Kageson, Per, 2009. Making International Transport Pay its Bill. International Transport Forum's Transport for a Global Economy, OECD/ITF.
[27] H.O. Kristensen, Cargo transport by sea and road—technical and environmental factors, Naval Engineers Journal 118 (2006) 115–129.
[28] Lee, H.-L., 2008. The Combustion-based CO_2 Emissions Data for GTAP version 7 Data Base. GTAP Working Paper 4470.
[29] A. Levinson, Technology, international trade and pollution from US manufacturing, American Economic Review 99 (5) (2009) 2177–2192.
[30] A. Levinson, M. Taylor, Unmasking the pollution haven effect, International Economic Review 49 (1) (2008) 223–253.
[31] Maersk Line, 2007. Constant Care for the Environment.
[32] Miljøstyrelsen Miljøministeriet (Danish Environmental Protection Agency, Danish Ministry for the Environment), 2003. "Greenhouse Gas Emissions from International Aviation and Allocation Options". URL: ⟨http://www2.mst.dk/common/Udgivramme/Frame.asp?http://www2.mst.dk/udgiv/publications/2003/87-7972-489-2/html/helepubl_eng.htm⟩.
[33] Minor, P., 2006. Projected Impacts of the Doha Development Round on Egypt's Trade and Production. GTAP Working Paper 3363.
[34] National Technical University of Athens Laboratory for Maritime Transport, 2008. Ship Emissions Study.
[35] Olivier, J., Peters, J., 1999. International marine and aviation bunker fuel: trends, ranking of countries and comparison with national CO_2 emissions. RIVM Report 773301 002. National Institute of Public Health and the Environment (RIVM), The Netherlands.URL: ⟨http://www.rivm.nl/bibliotheek/rapporten/773301002.pdf⟩.
[36] G.P. Peters, E.G. Hertwich, CO_2 embodied in international trade with implications for global climate policy, Environmental Science and Technology 42 (5) (2008) 1401–1407.
[37] Rose, S., Avetisyan, M. and Hertel, T., 2010. Development of the Preliminary Version 7 Non-CO_2 GHG Emissions Dataset. GTAP Working Paper 4618.
[38] S. Sim, M. Barry, R. Clift, S. Cowell, The relative importance of transport in determining an appropriate sustainability strategy for food sourcing. A case study of fresh produce supply chains, International Journal of Life Cycle Assessment 12 (2007) 422–431.
[39] Transportation Research Board, 2009. "Guidebook on Preparing Airport Greenhouse Gas Emissions Inventories". Research Sponsored by the Federal Aviation Administration.
[40] UNFCCC, 1999. Methods Used to Collect Data, Estimate and Report Emissions from International Bunker Fuels. United Nations Framework Convention on Climate Change, Report Prepared by Det Norske Veritas.
[41] US EPA, 2006. Global Emissions of Non-CO_2 Greenhouse Gases: 1990–2020 . United States Environmental Protection Agency (US-EPA), Washington, D.C., EPA Report 430-R-06-003.
[42] D. Van Veen-Groot, P. Nijkamp, Globalization, transport and the environment: new perspectives for ecological economics, Ecological Economics 31 (1999) 331–346.
[43] Walmsley, T., 2006. A Baseline Scenario for the Dynamic GTAP Model. GTAP Working Paper 2854.
[44] Williams, A., 2007. Comparative study of cut roses for the British market produced in Kenya and the Netherlands. Précis Report for World Flowers, February.
[45] World Bank, 2005. Global Economic Prospects 2005.