Trade, CO_2, and the Environment

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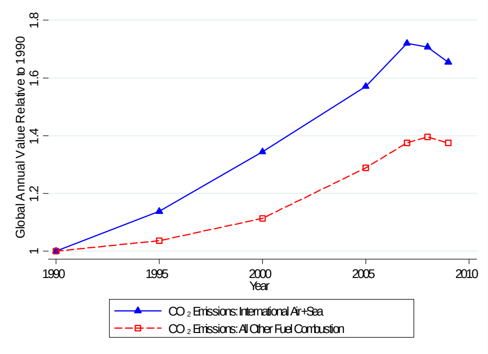
Introduction

- How does international trade affect social welfare?
  - Standard measure: gains from trade
  - This paper adds: environmental costs of trade
- How does regulating the environmental costs of trade affect welfare?
  - Counterfactuals: EU, US, global regulations on CO_2 from shipping
  - EU: "One of the most contested environmental initiatives ever" (NY Times 2011, 2012)

Motivation

- Policymakers: we should restrict free trade because it harms the environment
- Countries are implementing sub-optimal climate policies, we should study them
- CO_2 from international shipping growing quickly
  - 4 percent today but double the growth of other sectors



Graph: GDP v. Trade

Results

- Gains from trade $>>$ Environmental Costs of Trade
- EU, US, Global regulations increase global welfare
  - Regressive
  - Unilateral policy: private welfare gain, even ignoring environment.
- Measurement error important for trade elasticity
  - Conventional estimates overstate gains from trade

Existing Research and Contributions

What is new here?

- Trade and the Environment (Copeland and Taylor 2003)
  - Contributions: framework to evaluate real-world regulations; jointly analyze production and transportation
- Regulation (Greenstone 2002, Goulder et al. 2012)
  - Contributions: hybrid structural+reduced-form
- Gains From Trade (Dekle, Eaton, & Kortum 2007, Caliendo & Parro 2011, Arkolakis, Costinot, Rodríguez-Clare 2012)
  - Contributions: Built environment/energy into gravity models; Inference; Sector-specific trade elasticities

Overview

Model of Trade and the Environment

Data

CO_2 Emissions from Trade

Estimate Trade Elasticities

Welfare Effects of International Trade

Welfare Effects of EU, US, and Global Regulations

Conclusions

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Model of Trade and the Environment: Overview

- Observed data
  - Current bilateral trade (X_{od})
- Data to calculate:
  - $\hat{\tau}_{od}$: carbon tax $\longrightarrow$ trade cost
  - θ: trade cost $\longrightarrow$ trade flow
- How does model calculate effects of untested policies?
  - regression estimates from historic data generate θ

Model of Trade and the Environment: General Setup

- Representative agent
- One factor with inelastic supply: labor
- Armington: each country produces one variety per sector
  - Explanatory device
- Paper has intermediates, trade imblance; ignore in slides
- Environmental harm from CO_2 (no SO_2, other "local pollutants")

Primitive Assumptions

Assumption 1: Preferences

$$U_d = \underbrace{\left[\prod_{j=1}^{J} (Q_d^j)^{\alpha_d^j}\right]}_{\text{Trade}} \underbrace{\left[\frac{1}{1 + (\mu_d^{-1} \sum_o E_o)^2}\right]}_{\text{Environment}}$$

$$Q_d^j = \left(\sum_o (Q_{od}^j)^{\frac{\sigma^j - 1}{\sigma^j}}\right)^{\frac{\sigma^j}{\sigma^j - 1}}$$

- μ_d: Costs of climate change (health damages, etc.)

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- μ_d: Costs of climate change (health damages, etc.)
- Consumer price for sector j: $p_d^j = \left[\sum_o (p_{od}^j)^{1-\sigma^j}\right]^{1/(1-\sigma^j)}$
- Exact price index: $P_d = \prod_j (p_d^j)^{\alpha_d^j}$

Primitive Assumptions

Assumption 2: Production Technology and Market Structure

$$p^j_{od} = w_o \tau^j_{od}$$

Implications:

- Perfect competition, iceberg trade costs

Primitive Assumptions

Assumption 3: Transportation Technology

$$\tau^j_{od} = (1 + t^j_{od})(1 + f^j_{od})exp(\delta^j_{od})$$
$$t^j_{od} = \sum_m D_{odm}\kappa^j_{odm}W^j_{odm}\xi_m\gamma_1 t^j_{odm}$$
$$f^j_{od} = \sum_m D_{odm}\kappa^j_{odm}W^j_{odm}\xi_m\gamma_2 P^{oil}$$

- Interpretation:
  - Fuel costs f = sum over modes: distance * mode share * weight/value * fuel efficiency * fuel price
- f fixed in counterfactuals
- Perfect competition in shipping

Primitive Assumptions

Assumption 4: Environment

$$E_d = \sum_{o,j} \underbrace{\left(\gamma_3 f_{od}^j + \chi_o^j\right)}_{\text{Transport+Production}} \frac{X_{od}^j}{p_{od}^j}$$

- Trade emits CO_2 from production and transportation

Competitive Equilibrium

Assumption 5: Competitive Equilibrium

Utility maximization implies expenditure on sector j:

$$X_d^j = \alpha_d^j I_d$$

Utility maximization also implies "gravity" demand, $\theta^j \equiv 1 - \sigma^j$

$$\lambda_{od}^j = \left(\frac{w_o \tau_{od}^j}{p_d^j} \right)^{\theta^j}$$

Market clearing implies trade balance:

$$\underbrace{\sum_{o,j} \frac{X_{od}^j}{1 + t_{od}^j}}_{\text{d's Imports}} = \underbrace{\sum_{o,j} \frac{X_{do}^j}{1 + t_{do}^j}}_{\text{d's Exports}}$$

▸ Other θ interpretations

Model Robustness

- Full model incorporates trade imbalances, intermediate goods.
- Armington is explanatory device.
- Why similar or identical? Gravity.
  - "[S]ome of the clearest and most robust empirical findings in economics." (Leamer and Levinsohn 1995)

▸ Gravity Models

Counterfactual Methodology

- Measure proportional effects (Dekle, Eaton, & Kortum 2008).
- $\hat{x} \equiv x'/x$.
- Level of indirect utility:

$$V_d = \left[\frac{I_d}{P_d}\right]\left[\frac{1}{1+(\mu_d^{-1}\sum_o E_o)^2}\right]$$

- Equivalent variation:

$$\hat{V}_d = \left[\frac{\hat{I}_d}{\hat{P}_d}\right]\left[\frac{1+(\mu_d^{-1}\sum_o E_o)^2}{1+(\mu_d^{-1}\sum_o E_o')^2}\right]$$

Taking the Model to the Data

- Observe equilibrium in 2007, add shock, calculate counterfactual.
- Observe bilateral trade X^j_{od}
- Calculate effect of carbon tax on trade costs $\hat{\tau}^j_{od}$:

$$\tau^j_{od} = (1 + t^j_{od})(1 + f^j_{od}) exp(\delta^j_{od})$$
$$\hat{\tau}^j_{od} = 1 + \sum_m D_{odm} \kappa^j_{odm} W^j_{odm} \xi_m \gamma_1 t^j_{odm}$$

- Regressions to estimate trade elasticities θ^j:

$$\lambda^j_{od} = \left(\frac{w_o \tau^j_{od}}{p^j_d} \right)^{\theta^j}$$

- Welfare effects $\hat{V}_d$:

$$\hat{V}_d = \left[\frac{\hat{I}_d}{\hat{P}_d} \right] \left[\frac{1 + (\mu_d^{-1} \sum_o E_o)^2}{1 + (\mu_d^{-1} \sum_o E'_o)^2} \right]$$

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Data: Change in Trade Costs

$\hat{\tau}^j_{od} = 1 + \sum_m D_{odm} \kappa^j_{odm} W^j_{odm} \xi_m \gamma_1 t^j_{odm}$

- Distance (D): GIS software for sea distances; other distances from CEPII
- Mode shares (κ: air, sea, rail, truck, other): from statistics/customs offices for 80 percent of international trade
  - Standard: US Imports/Exports of Merchandise, EU Comext (external trade)
  - Non-standard: China (Global Trade Atlas); Trade Statistics of Japan; EU Comext (internal trade); Latin American Integration Association (Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador Paraguay, Peru, Uruguay, Venezuela)
  - Fractional multinomial logit: impute remaining 20%.
- Weight-to-value (W^j_{odm}): like mode shares.

Data: Change in Trade Costs

$\hat{\tau}^j_{od} = 1 + \sum_m D_{odm} \kappa^j_{odm} W^j_{odm} \xi_m \gamma_1 t^j_{odm}$

Fuel efficiency ξ_m: values for each mode:

Mode	Value (gCO2/ton-km)
Air	986
Sea	10
Rail	23
Road	119
Other	0

See Appendix Table 1. ξ_m Details

Data: Estimating Trade Elasticities

US Imports of Merchandise, Australian Bureau of Statistics

- 1991-2010
- Quarterly
- Imports Only
- US: 10-digit Harmonized System codes. Australia: 2-digit Harmonized System codes. Aggregate to 13 sectors.
- Key data fields: trade value, freight + insurance charge
- Quarterly price deflator from CPI

Data: Change in CO2 Emissions

$E_d = \sum_{o,j} \left(\gamma_3 f^j_{od} + \chi^j_o\right) X^j_{od} / p^j_{od}$

- CO_2 from production: χ^j_o
- Trade and production (X^j_{od})
- Source: Global Trade and Analysis Project (GTAP)
  - Input output matrices for each country
  - Bilateral trade from UN-Comtrade
  - IPCC Tier 1 Methodology

Data: Social Cost of Carbon

- μ_d: social cost of carbon=\$19.96/tCO2
  - Source: US government panel (Greenstone, Kopits, and Wolverton 2011)
  - Summarizes integrated assessment models (DICE, PAGE, FUND)
  - Assumed discount rate: 3%
  - Sensitivity analysis of \$4.10, \$1170
  - Bounding analysis
- Region-specific damages from RICE (Nordhaus & Boyer 2000)

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CO2 Emissions from Trade: Results

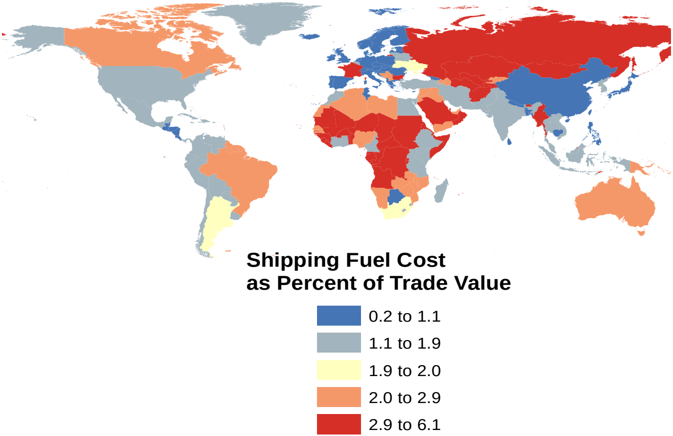
Source	International (1)	Domestic (2)	Total (3)
Shipping	1,368	1,812	3,180
Production	1,192	25,333	26,525
Total	2,560	27,145	29,705

See Table 1. All values in $MtCO_2$.

▸ By Mode ▸ By Sector ▸ By Region ▸ Fuel Costs by Sector

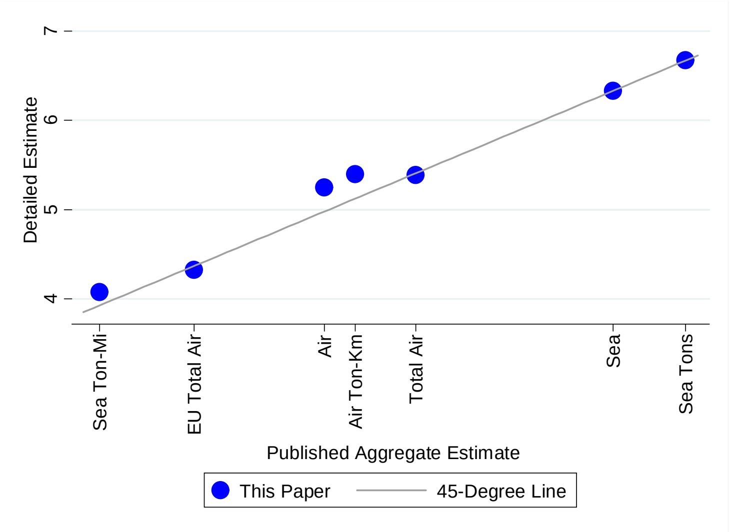
CO2 Emissions from Trade: Fuel Cost Map

$f_{od} = \sum_m D_{odm}\kappa^j_{odm} W^j_{odm}\xi_m\gamma_2 P^{oil}$



See Figure 2. Weight-Value Distance Transport Mode

CO2 Emissions from Trade: Reasonable Estimates?



See Figure 3.

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Estimating Trade Elasticities: Background

- θ^j interpretation: elasticity of bilateral trade with respect to bilateral trade costs
- Arguably most important parameters in trade
  - Design future policies (Doha round)
  - Evaluate past policies (NAFTA)
  - Interpret macro trends (globalization)
  - Measure gains from trade
- Separately by sector but omitting j superscripts

Estimating Trade Elasticities: Parameter Definition

- Gravity demand:

$$\lambda_{ody} = \left(\frac{w_{oy} \tau_{ody}}{p_{dy}} \right)^{\theta}$$

- Transport technology:

$$\tau_{ody} = \underbrace{(1 + s_{ody})}_{\text{Shipping}} \exp \underbrace{(\delta_{od} + \epsilon_{ody})}_{\text{Intangibles}}$$

Estimating Trade Elasticities: Regression Equation

- Combining:

$$\log \lambda_{ody} = \theta \log\left(1 + s_{ody}\right) + \theta \log w_{oy} - \theta \log p_{dy} + \delta_{od} + \epsilon_{ody}$$

- *OLS*

$$\log \lambda_{ody} = \theta \log(1 + s_{ody}) + \epsilon_{ody}$$

- *Fixed Effects Estimator.* Addresses omitted variables, can exacerbate measurement error (Griliches & Hausman 1986):

$$\log \lambda_{ody} = \theta \log(1 + s_{ody}) + \eta_{oy} + \zeta_{dy} + \delta_{od} + \epsilon_{ody}$$

- Measurement error important in trade data (Trefler 1995, Limão and Venables 2001, Hummels and Lugovskyy 2006)

Estimating Trade Elasticities: Regression Equation

- *Instrumental Variables Estimator*.
  - Can solve measurement error problem (Durbin 1954, Ashenfelter & Krueger 1994)
  - If measurement error correlated between endogenous variable & instrument, this lessens attenuation bias.

$$log \lambda^B_{ody} = \theta log(1 + s^B_{ody}) + \eta^B_{oy} + \zeta^B_{dy} + \delta^B_{od} + \epsilon^B_{ody}$$
$$log(1 + s^B_{ody}) = \beta log(1 + s^A_{ody}) + \eta^A_{oy} + \zeta^A_{dy} + \delta^A_{od} + \epsilon^A_{ody}$$

- s^A_{ody}: shipping costs reported in quarters 2, 3
- s^B_{ody}: shipping costs reported in quarters 1, 4
- Standard errors clustered within o-d
- Zeros excluded (Appendix has alternatives)

Estimating Trade Elasticities: Economy-wide Results

$log(\lambda_{ody}) = \theta log(1 + s_{ody}) + \epsilon_{ody}$

	Log Freight Costs (OLS)	Log Trade Costs (FE)	Log Shipping Costs (FS)	Log Import Shares (IV)
	(1)	(2)	(3)	(4)
	-20.95***	-3.71**	0.21***	-7.91**
	(2.61)	(1.82)	(0.05)	(4.23)

See Table 2. ▸ θ for Manufacturing

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Estimating Trade Elasticities: Sector-Specific Results

$log(\lambda^B_{ody}) = \theta log(1 + s^B_{ody}) + \eta^B_{oy} + \zeta^B_{dy} + \delta^B_{od} + \epsilon^B_{ody}$

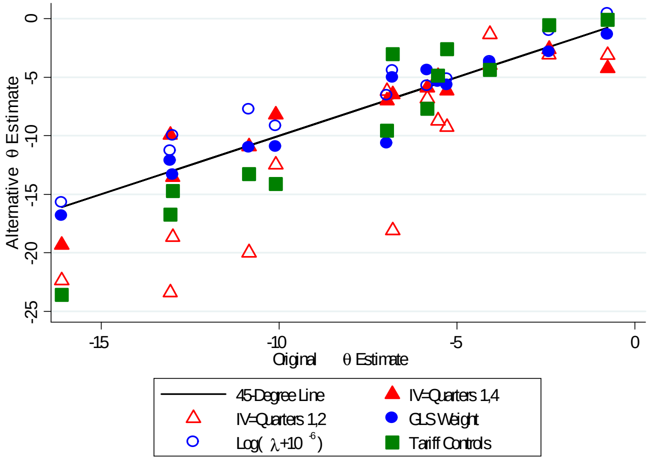
1. Non-Manufactured: Agriculture,	2. Non-Manufactured: Mining	3. Food, Beverages, Tobacco	4. Textiles	5. Apparel, Leather
-3.335	-3.450***	-5.361***	-18.552***	-9.949***
(3.396)	(1.314)	(1.726)	(5.056)	(2.893)

6. Wood	7. Paper, Printing	8. Petroleum, Coal, Minerals	9. Chemicals, Rubber, Plastics
-5.901***	-5.623*	-8.949**	-0.769
(1.818)	(2.936)	(3.766)	(2.557)

10. Metals	11. Machinery, Electrical	12. Transport Equipment	13. Other
-12.926*	-10.908***	-6.868**	-12.768**
(6.737)	(2.795)	(3.448)	(5.374)

See Table 2.

Estimating Trade Elasticities: Other Specifications



See Appendix Table 2c. ▸ Other θ Specifications

Estimating Trade Elasticities: Rauch Test

$$log(\lambda^B_{ody}) = \theta log(1 + s^B_{ody}) + \delta^B_{od} + \eta^B_{oy} + \zeta^B_{dy} + \epsilon^B_{ody}$$

	Log Shipping Costs (FS)	Log Import Shares (IV)
Differentiated	0.26***	-5.75**
	(0.05)	(2.59)
Reference Priced	0.38***	-5.81**
	(0.04)	(2.33)
Homogenous	0.36***	-9.18***
	(0.07)	(2.77)

See Table 3.

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Counterfactual Methodology: Autarky

- Counterfactual: autarky for all countries: $\hat{\tau}^j_{od} = +\infty \ \forall o \neq d$
- Equivalent variation:

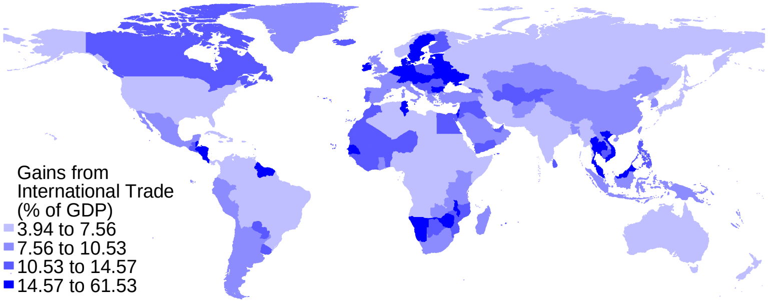
$$A_d = \underbrace{\left[\prod_{j=1}^{J} \left(\lambda^j_{dd}\right)^{-\alpha^j_d/\theta^j}\right]}_{\text{Trade}} \underbrace{\left[\frac{1 + (\mu_d^{-1} \sum_o E_o)^2}{1 + (\mu_d^{-1} \sum_o E'_o)^2}\right]}_{\text{Environment}}$$

- λ^j_{dd} rationale: see Arkolakis, Costinot, and Rodríguez-Clare (2012)
- Inference: resample θ^j_d, bias-corrected bootstrap for 95-percent confidence interval (Efron 1987)

Bootstrap Algorithm CO2 emissions in autarky

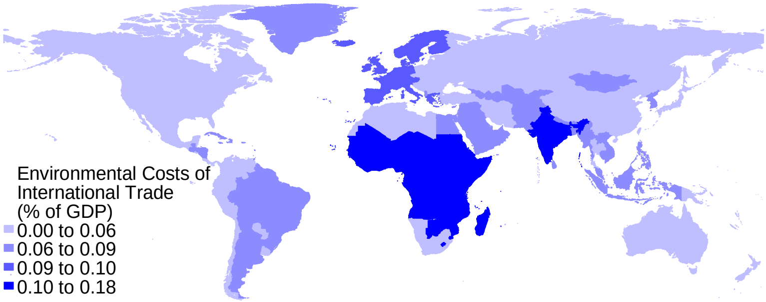
Welfare Effects of International Trade

$$GFT_d = 1 - \prod_{j=1} (\lambda_{dd}^j)^{-\alpha_d^j / \beta_d^j \theta_d^j}$$



Environmental Costs of International Trade

$ECT_d = (\mu_d^2 + \Sigma_o E_o^2)/(\mu_d^2 + \Sigma_o E_o'^2)$



See Figure 4.

Annual Welfare Effects of International Trade

	Gains from Trade	Enviromental Costs of Trade	Social Welfare	Ratio: (1)/(2)
World	5780	-32.0	5809	-180
	[3374 , 17373]	[-41 , -16]	[3515 , 15209]	[-1770 , -87]

See Table 4. Dollar values in 2007 US$ billions. 95% confidence regions in brackets.

Region-by-Region

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Carbon Tax Counterfactuals: Regulation Details

- EU Emissions Trading System (ETS)
  - World's largest climate change regulation
  - New in 2012: air transportation
  - Counterfactual: \$19.96/tCO_2 tax on air shipping
- US Waxman-Markey Bill
  - Passed US House but not Senate in 2009
  - Counterfactual: \$19.96/tCO_2 tax on all CO_2 emissions from shipping
- Kyoto Protocol (1997)
  - Required global cap-and-trade for plane and sea emissions. Never implemented.
  - Counterfactual: \$19.96/tCO_2tax on CO_2 from air & sea shipping

Counterfactual Methodology: Regulation

- Shock:

$$\hat{\tau}^j_{od} = 1 + \sum_m D_{odm} \kappa^j_{odm} W^j_{odm} \xi_m \gamma_1 t^j_{odm}$$

- Model becomes system of N-1 equations in N-1 unknowns $\hat{w}_d$:

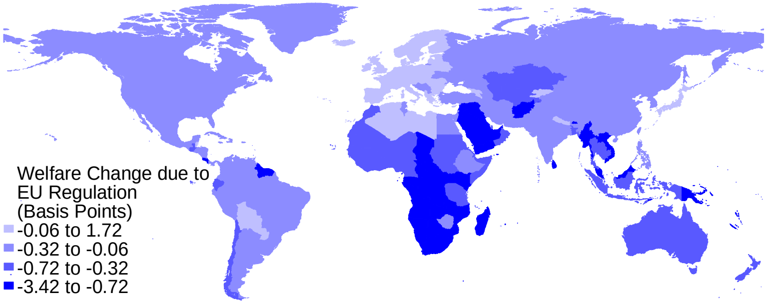
$$\sum_{o,j} \frac{X^{j'}_{od}}{1 + t^j_{od}} = \sum_{d,j} \frac{X^{j'}_{od}}{1 + t^j_{od}}$$

- Then, welfare change:

$$\hat{V}_d = \left[\frac{\hat{I}_d}{\hat{P}_d}\right] \left[\frac{1 + (\mu_d^{-1} \sum_o E_o)^2}{1 + (\mu_d^{-1} \sum_o E'_o)^2}\right]$$

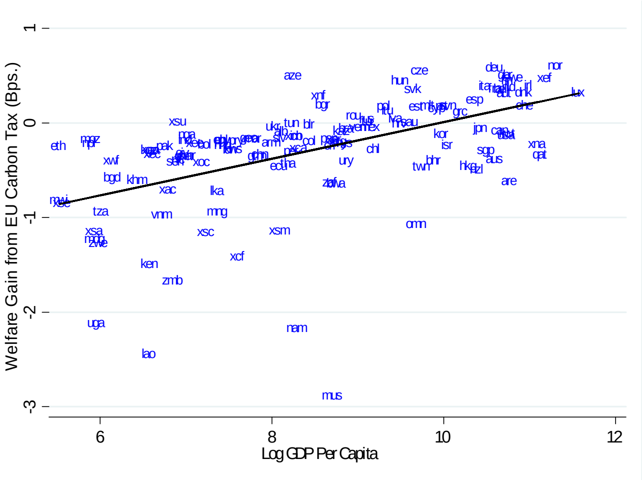
Counterfactuals: Details

Carbon Tax Counterfactuals: EU Carbon Tax Results



See Figure 5. Policy: \$19.96/ton CO_2 tax applied to all air freight CO_2 emissions for EU imports, exports, and domestic trade. Tax revenues rebated lump-sum to EU.

Carbon Tax Counterfactuals: EU Carbon Tax Results



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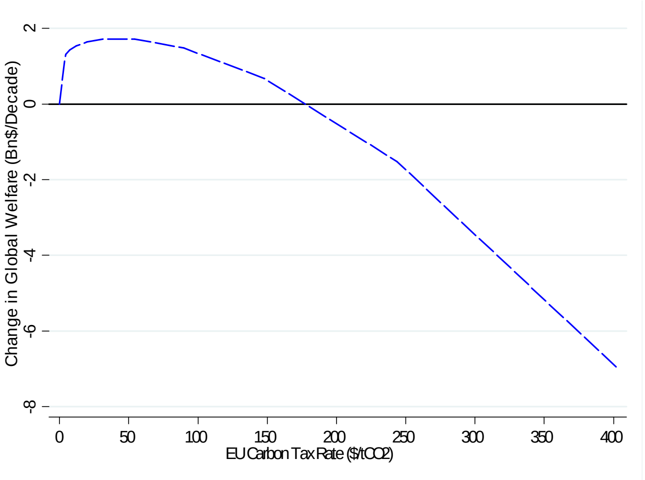

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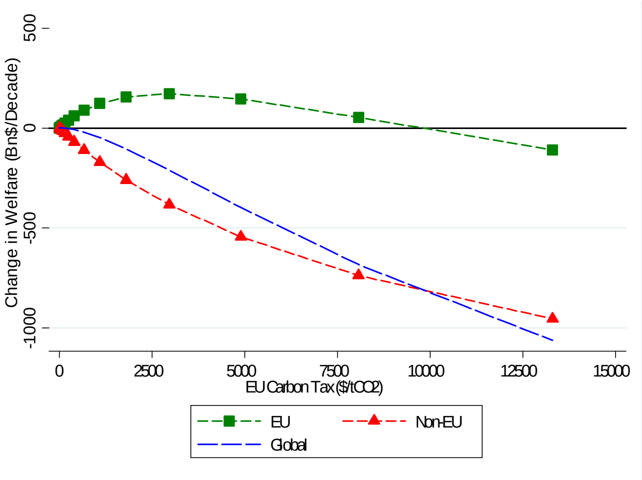

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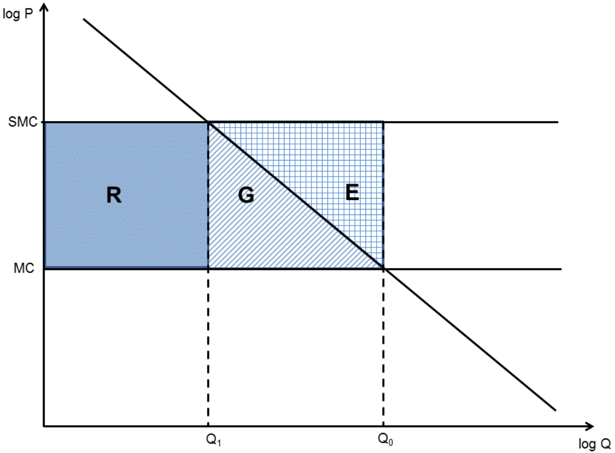
Carbon Tax Counterfactuals: Comparison to Harberger Triangles



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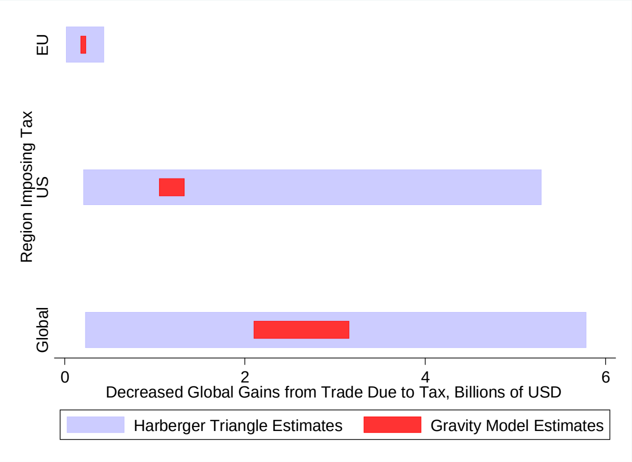

See Appendix Table 4. Harberger: Environmental Costs of Trade

Carbon Tax Counterfactuals: EU Carbon Tax Results

	Gains from Trade	Environmental Costs of Trade	Social Welfare: Total	Social Welfare: Basis Points
		Panel A: Global		
World	-1.6	-6.9	5.2	0.09
	[-1.8 , -1.4]	[-7.1 , -6.6]	[4.8 , 5.6]	[0.08 , 0.10]
		Panel B: By Region		
US	16.9	-0.5	17.4	1.16
	[12.3 , 21.2]	[-0.6 , -0.5]	[12.9 , 21.8]	[0.86 , 1.45]
EU	-6.3	-3.8	-2.5	-0.14
	[-7.2 , -5.2]	[-3.9 , -3.6]	[-3.5 , -1.4]	[-0.20 , -0.08]
		Panel C: By GDP Per Capita		
Richest Third	5.8	-4.9	10.6	0.25
	[3.2 , 8.1]	[-5.1 , -4.7]	[8.5 , 12.8]	[0.20 , 0.31]
Middle Third	-4.5	-1.0	-3.5	-0.31
	[-6.8 , -2.3]	[-1.1 , -1.0]	[-5.9 , -1.3]	[-0.53 , -0.11]
Poorest Third	-2.9	-0.9	-1.9	-0.61
	[-5.8 , -2.1]	[-1.0 , -0.9]	[-4.9 , -1.4]	[-1.56 , -0.43]

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	Gains from Trade	Environmental Costs of Trade	Social Welfare: Total	Social Welfare: Basis Points
		Panel A: Global		
World	-1.6	-6.9	5.2	0.09
	[-1.8 , -1.4]	[-7.1 , -6.6]	[4.8 , 5.6]	[0.08 , 0.10]
		Panel B: By Region		
US	16.9	-0.5	17.4	1.16
	[12.3 , 21.2]	[-0.6 , -0.5]	[12.9 , 21.8]	[0.86 , 1.45]
EU	-6.3	-3.8	-2.5	-0.14
	[-7.2 , -5.2]	[-3.9 , -3.6]	[-3.5 , -1.4]	[-0.20 , -0.08]
		Panel C: By GDP Per Capita		
Richest Third	5.8	-4.9	10.6	0.25
	[3.2 , 8.1]	[-5.1 , -4.7]	[8.5 , 12.8]	[0.20 , 0.31]
Middle Third	-4.5	-1.0	-3.5	-0.31
	[-6.8 , -2.3]	[-1.1 , -1.0]	[-5.9 , -1.3]	[-0.53 , -0.11]
Poorest Third	-2.9	-0.9	-1.9	-0.61
	[-5.8 , -2.1]	[-1.0 , -0.9]	[-4.9 , -1.4]	[-1.56 , -0.43]

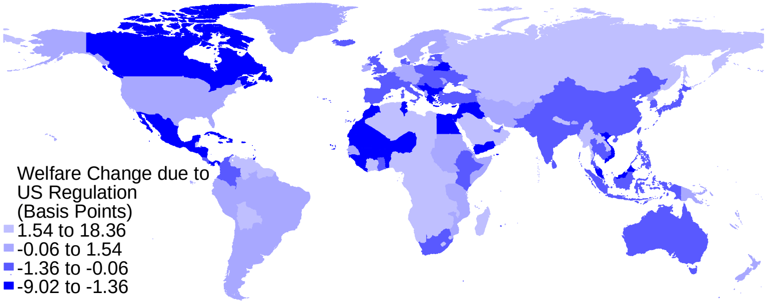
See Table 5. Policy: \$19.96/ton CO_2 tax applied to all air freight CO_2 emissions for EU imports and exports. Tax revenues rebated lump-sum to EU.

Carbon Tax Counterfactuals: EU Carbon Tax Results

	Gains from Trade	Environmental Costs of Trade	Social Welfare: Total	Social Welfare: Basis Points
		Panel A: Global		
World	-1.6	-6.9	5.2	0.09
	[-1.8 , -1.4]	[-7.1 , -6.6]	[4.8 , 5.6]	[0.08 , 0.10]
		Panel B: By Region		
US	16.9	-0.5	17.4	1.16
	[12.3 , 21.2]	[-0.6 , -0.5]	[12.9 , 21.8]	[0.86 , 1.45]
EU	-6.3	-3.8	-2.5	-0.14
	[-7.2 , -5.2]	[-3.9 , -3.6]	[-3.5 , -1.4]	[-0.20 , -0.08]
		Panel C: By GDP Per Capita		
Richest Third	5.8	-4.9	10.6	0.25
	[3.2 , 8.1]	[-5.1 , -4.7]	[8.5 , 12.8]	[0.20 , 0.31]
Middle Third	-4.5	-1.0	-3.5	-0.31
	[-6.8 , -2.3]	[-1.1 , -1.0]	[-5.9 , -1.3]	[-0.53 , -0.11]
Poorest Third	-2.9	-0.9	-1.9	-0.61
	[-5.8 , -2.1]	[-1.0 , -0.9]	[-4.9 , -1.4]	[-1.56 , -0.43]

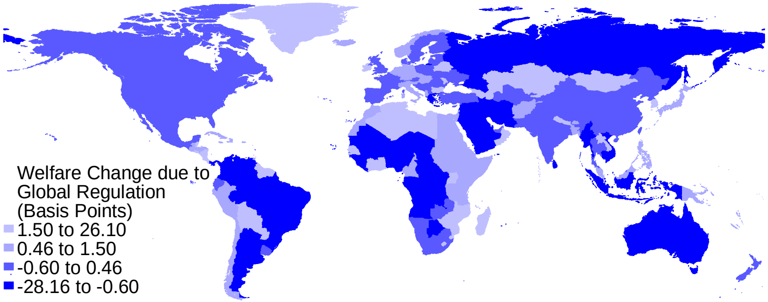
See Table 5. Policy: \$19.96/ton CO_2 tax applied to all air freight CO_2 emissions for EU imports and exports. Tax revenues rebated lump-sum to EU.

Carbon Tax Counterfactuals: US Carbon Tax Results



See Figure 5. Policy: \$19.96/ton CO_2 tax applied to all CO_2 emissions from freight for US imports and exports. Tax revenues rebated lump-sum to US. ▸ Table

Carbon Tax Counterfactuals: Global Carbon Tax Results



See Figure 5. Policy: \$19.96/ton CO_2 tax applied to all air & sea freight CO_2 emissions for global imports and exports. Tax revenues rebated lump-sum to importer.

▸ Table

Overview

Model of Trade and the Environment

Data

Estimate Trade Elasticities

CO_2 Emissions from Trade

Welfare Effects of International Trade

Welfare Effects of EU, US, and Global Regulations

Conclusions

Conclusions

- Model; new CO2 data; estimate trade elasticities
  - Same spirit as "sufficient statistics for welfare analysis" (Chetty 2009)
- Findings:
  - Gains from trade >> Environmental Costs of Trade
  - EU, US, Global regulations increase global welfare
    - Regressive
    - Unilateral policy: privately optimal, even ignoring environment
  - Measurement error important for trade elasticity
    - Gains from trade smaller than conventional estimates imply
- Future work:
  - Environmental implications of heterogeneous firms: Intra-industry reallocation and air pollution
  - Consequences of state-level energy regulations (e.g., California's AB32)

Estimating Trade Elasticities: Other Specifications

	(1)	(2)	(3)	(4)	(5)
Entire Economy	-10.099**	-5.376	-8.472*	-7.534**	-1.544
	(4.662)	(4.278)	(4.332)	(3.298)	(1.181)
Quarters 1,4 Instrument Quarters 2,3	x				
Quarters 1,2 Instrument Quarters 3,4		x			
GLS Weights			x		
Log(x+0.00001)				x	
Include Tariffs in Freight Cost					x

See Appendix Table 2c. Back to Slides

Estimating Trade Elasticities: Other Specifications

	(1)	(2)	(3)	(4)	(5)
Manufacturing Estimates	-6.698***	-6.039	-7.433*	-6.187**	-0.92
	(2.265)	(4.185)	(4.212)	(2.755)	(1.086)
Quarters 1,4 Instrument Quarters 2,3	x				
Quarters 1,2 Instrument Quarters 3,4		x			
GLS Weights			x		
Log(x+0.00001)				x	
Include Tariffs in Freight Cost					x

See Appendix Table 2c. Back to Slides

Estimating Trade Elasticities: Other Specifications

	(1)	(2)	(3)	(4)	(5)
Non-Manufacturing					
Agriculture, Forestry	-2.598	-3.064*	-2.886	-1.074	-0.549
	(1.920)	(1.859)	(4.335)	(2.334)	(3.278)
Mining	-3.949***	-1.33	-3.837***	-3.682***	-4.381***
	(0.935)	(1.021)	(1.458)	(1.231)	(1.464)
Manufacturing					
Food, Beverages, Tobacco	-6.138***	-9.268***	-5.705***	-5.193***	-2.587
	(1.419)	(2.456)	(2.207)	(1.657)	(2.192)
Textiles	-19.326***	-22.376***	-16.874***	-15.731***	-23.596***
	(3.620)	(5.729)	(5.682)	(4.220)	(5.998)
Apparel, Leather	-8.201***	-12.474***	-10.984***	-9.217***	-14.129***
	(1.788)	(2.736)	(3.550)	(2.523)	(4.573)
Wood	-5.891***	-6.828**	-4.438**	-5.769***	-7.679***
	(1.276)	(2.930)	(2.140)	(1.754)	(2.009)
Quarters 1,4 Instrument Quarters 2,3	x				
Quarters 1,2 Instrument Quarters 3,4		x			
GLS Weights			x		
Log(x+0.00001)				x	
Include Tariffs in Freight Cost					x

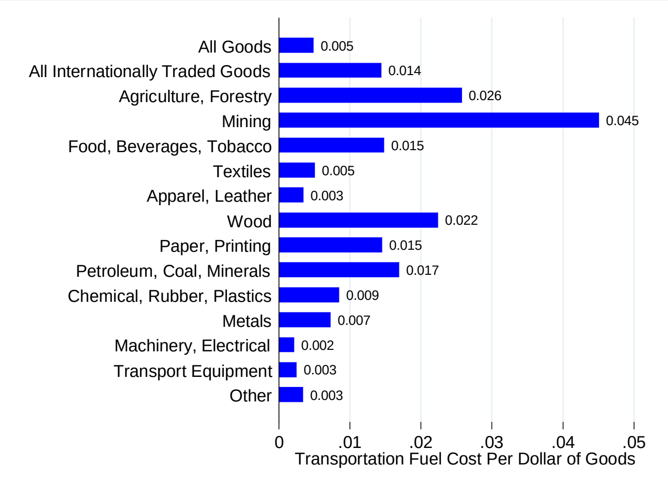
See Appendix Table 2c. Back to Slides

Estimating Trade Elasticities: Other Specifications

	(1)	(2)	(3)	(4)	(5)
Non-Manufacturing					
Paper, Printing	-4.929**	-8.711	-5.348	-5.441**	-4.871*
	(2.039)	(10.231)	(3.634)	(2.702)	(2.755)
Petroleum, Coal, Minerals	-7.008***	-6.170***	-10.684	-6.598*	-9.569**
	(2.370)	(2.196)	(6.790)	(3.650)	(4.224)
Chemicals, Rubber, Plastics	-4.233**	-3.121	-1.419	0.385	-0.088
	(1.828)	(1.919)	(3.064)	(2.006)	(2.946)
Metals	-13.544***	-18.666***	-13.386*	-10.018**	-14.723**
	(4.217)	(6.786)	(7.565)	(5.012)	(6.504)
Machinery, Electrical	-10.924***	-19.976**	-11.051***	-7.789***	-13.273***
	(2.046)	(8.352)	(3.783)	(2.273)	(3.346)
Transport Equipment	-6.473**	-18.075*	-5.079	-4.491	-3.016
	(2.731)	(10.675)	(5.685)	(3.001)	(4.080)
Other	-9.937***	-23.401*	-12.185**	-11.342**	-16.749**
	(3.245)	(13.799)	(5.986)	(4.601)	(6.897)
Quarters 1,4 Instrument Quarters 2,3	x				
Quarters 1,2 Instrument Quarters 3,4		x			
GLS Weights			x		
Log(x+0.00001)				x	
Include Tariffs in Freight Cost					x

See Appendix Table 2c. Back to Slides

Fuel per Dollar of Good



See Appendix Figure 2. Back to Slides

Fuel Efficiency by Mode

Mode	Value (gCO_2/ton-km)	Method	Region	Source
Air	985.97	Fuel consumption divided by ton-km	Global	This paper, IATA (2009)
Air	540	n.a.	Boeing 747	NTM (2012)
Air	912 to 963.45	Calculations from published data	US	Cristea (2011)
Air	595-1916	Engineering estimates	UK	Defra (2009)
Sea	9.53	Global CO2 emissions from IEA (2011) divided by original ton-km freight estimates	Global	This paper
Sea	4.5 to 16.3	Engineering estimates aggregated over ship fleet registeries	Global	Psaraftis and Kontovas (2009)
Sea	15 to 21	n.a.	n.a.	NTM (2012)
Sea	4 to 20	Engineering estimates	UK	Defra (2009)
Rail	23	Summary of studies listed below	Global	This paper
Rail	23	n.a.	Asia	ADB (2010)
Rail	22.7	n.a.	EU15	Giannouli et al. (2006)
Rail	7.3 to 26.3	Literature review	EU	Cefic (2011)
Rail	27.6	Fuel consumption divided by freight transport	UK	ORR (2009)
Rail	10-119	Literature review	Various	IMO (2009)
Road	119	Summary of studies listed below	Global	This paper
Road	119.7	n.a.	EU	Giannouli et al. (2006)
Road	61	n.a.	Asia	ADB (2010)
Road	118.6	Fuel consumption divided by freight transport	UK	Defra (2009)
Road	80-181	Literature review	Various	IMO (2009)
Other	0	Assumption	Global	This paper

See Appendix Table 1. ▸ Back to Slides

CO2 by Mode

	International (1)	Domestic (2)	Total (3)
Air	189	27	216
Sea	653	110	763
Rail	26	36	62
Road	500	1,639	2,139
Shipping Total	1,368	1,812	3,180

See Table 1. All values in $MtCO_2$. Back to Slides

CO2 by Sector

	International (1)	Domestic (2)	Total (3)
Non-Manufacturing			
Agriculture, Forestry	160	757	917
Mining	782	601	1,383
Manufacturing			
Food, Beverages, Tobacco	117	618	735
Textiles	35	71	107
Apparel, Leather	29	26	55
Wood	44	115	159
Paper, Printing	68	297	365
Petroleum, Coal, Minerals	434	1,761	2,195
Chemicals, Rubber, Plastics	353	690	1,043
Metals	333	804	1,137
Machinery, Electrical	133	111	244
Transport Equipment	48	70	118
Other	21	49	70
Non-Tradable Goods	0	21,176	21,176
Total	2,559	27,146	29,704

See Table 1. All values in $MtCO_2$. Back to Slides

CO2 by Region

	International (1)	Domestic (2)	Total (3)
US	355	6,106	6,462
EU	747	4,346	5,093
Brazil, Russia, India, China	360	8,438	8,798
Sub-Saharan Africa	66	528	595
Other	1,031	7,727	8,757
Total	2,559	27,146	29,704

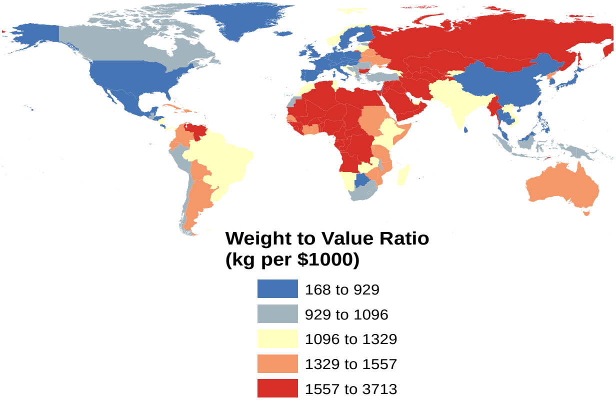
See Table 1. All values in $MtCO_2$. Back to Slides

Textbook Pigouvian Results

	Gains from Trade			Environmental Cost of Trade			Welfare
	Real Labor Income	Tax Revenue	Total	Transport	Production	Total	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Demand Elasticity for Shipping Fuels: -0.02				
EU tax: air	-14.93	14.94	-0.02	-0.04	n.a.	-0.04	0.02
US tax: air, sea, rail, road	-178.89	179.10	-0.21	-0.42	n.a.	-0.42	0.21
Global tax: air, sea	-195.77	196.00	-0.23	-0.46	n.a.	-0.46	0.23
			Demand Elasticity for Shipping Fuels: -0.50				
EU tax: air	-15.35	15.79	-0.44	-0.88	n.a.	-0.88	0.44
US tax: air, sea, rail, road	-183.97	189.26	-5.29	-10.58	n.a.	-10.58	5.29
Global tax: air, sea	-201.33	207.12	-5.79	-11.58	n.a.	-11.58	5.79
			Reprinted from Tables 5-7: General Equilibrium Model Estimates				
EU tax: air	-14.20	13.99	-0.21	-1.80	-0.03	-1.84	1.63
US tax: air, sea, rail, road	-171.22	170.03	-1.18	-3.34	-1.31	-4.65	3.47
Global tax: air, sea	-178.17	175.57	-2.59	-6.84	-1.17	-8.00	5.41

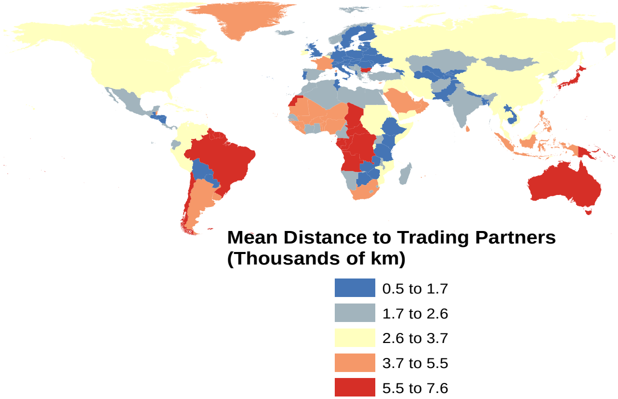
See Appendix Table 4. Back to Slides

CO2 Emissions from Trade: Weight-Value Map



See Figure 2. Back to Slides

CO2 Emissions from Trade: Distance Map



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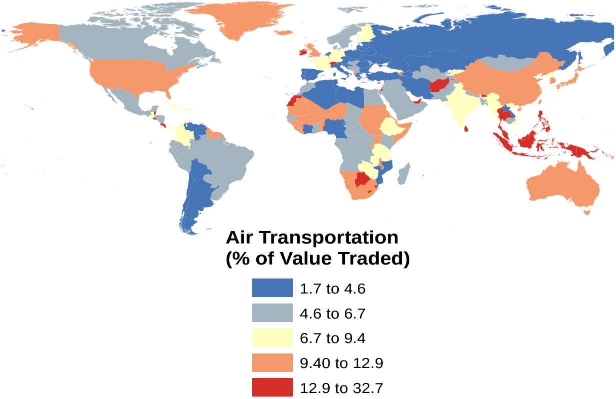
CO2 Emissions from Trade: Air Transport Map



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Counterfactual Methodology: Regulation Detail

$$\hat{I}_d = \frac{\hat{w}_d (w_d L_d) + R'_d - S_d}{w_d L_d - S_d}$$

$$\hat{P}_d = \sum_{j=1}^{j} (\hat{p}_d^j)^{\alpha_d^j}$$

$$E'_d = \sum_{o,j} (\lambda f_{od}^j + \chi_o^j) \frac{X_{od}^j}{p_{od}^j} \frac{\hat{X}_{od}^j}{\hat{p}_{od}^j}$$

$$\hat{p}_d^j = \left[\sum_o \lambda_{od}^j (\hat{c}_o^j \hat{\tau}_{od}^j)^{\theta^j} \right]^{1/\theta^j}$$

$$\hat{c}_o^j = (\hat{w}_o)^{\beta_o^j} (\hat{p}_o^j)^{1-\beta_o^j}$$

$$\hat{\lambda}_{od}^j = \left(\frac{\hat{c}_o^j \hat{\tau}_{od}^j}{\hat{p}_d^j} \right)^{\hat{\theta}^j}$$

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Carbon Tax Counterfactuals: US Carbon Tax Results

	Gains from Trade	Environmental Costs of Trade	Welfare	
			Total	Basis Points
Panel A: Global				
World	-1.18	-4.65	3.47	0.06
	[-1.3 , -1.0]	[-4.9 , -4.4]	[3.1 , 4.0]	[0.06 , 0.07]
Panel B: By Region				
US	19.76	-0.36	20.12	1.34
	[14.1 , 25.0]	[-0.4 , -0.3]	[14.5 , 25.4]	[0.97 , 1.69]
Panel C: By Baseline GDP Per Capita				
Richest Third	8.49	-3.32	11.80	0.28
	[5.4 , 11.8]	[-3.5 , -3.1]	[8.6 , 15.0]	[0.21 , 0.36]
Middle Third	-6.48	-0.70	-5.78	-0.52
	[-9.6 , -3.7]	[-0.7 , -0.7]	[-9.0 , -3.1]	[-0.81 , -0.28]
Poorest Third	-3.19	-0.70	-2.55	-0.80
	[-4.6 , -2.5]	[-0.7 , -0.6]	[-4.0 , -1.8]	[-1.25 , -0.58]

See Table 6. Policy: $19.96/ton CO_2 tax applied to all CO_2 emissions from freight for US imports and exports. Tax revenues rebated lump-sum to US. Back to Slides

Carbon Tax Counterfactuals: Global Carbon Tax Results

	Gains from Trade	Environmental Costs of Trade	Welfare	
			Total	Basis Points
World	-2.59	-8.00	5.41	0.10
	[-3.2 , -2.1]	[-9.6 , -6.9]	[4.6 , 6.6]	[0.08 , 0.12]
Richest Third	8.43	-5.70	14.13	0.34
	[7.2 , 9.6]	[-6.9 , -4.9]	[12.2 , 15.8]	[0.29 , 0.38]
Middle Third	-6.96	-1.20	-5.75	-0.52
	[-8.3 , -5.9]	[-1.4 , -1.0]	[-7.0 , -4.8]	[-0.63 , -0.44]
Poorest Third	-4.07	-1.20	-2.97	-0.93
	[-4.7 , -3.6]	[-1.3 , -0.9]	[-3.6 , -2.5]	[-1.13 , -0.78]

See Table 7. Policy: $19.96/ton CO_2 tax applied to all CO_2 emissions from freight. Tax revenues rebated lump-sum to importer. Back to Slides

Taking the Model to the Data

- Observe π_{od}^{j}: bilateral trade flows
- Estimate θ^{j}: elasticity of bilateral trade costs with respect to bilateral trade

$$\lambda_{od}^{j} = \left(\frac{c_o^j \tau_{od}^j}{p_d^j} \right)^{\theta^j}$$

- Calculate $\tilde{\tau}_{od}^{j}$: Impact of climate policy on bilateral trade costs

$$\hat{\tau}_{od}^{j} = \frac{\left(1 + f_{od}^{j\prime}\right)}{\left(1 + f_{od}^{j}\right)}$$

- Calculate welfare:

$$\hat{V}_d = \left[\frac{\hat{I}_d}{\hat{P}_d} \right] \left[\frac{1}{1 + (\mu_d^{-1} \sum_o E_o)^2} \right]$$

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Counterfactual Methodology: Bootstrap for Inference

- Confidence region: $(\zeta^{(\alpha_1)}, \zeta^{(\alpha_2)})$
  - $\zeta^{(\alpha)}$: 100$\cdot\alpha$th percentile of the B estimates
- Bias-corrected percentiles:

$$\begin{aligned} \alpha_1 &= \Phi(2z_0 + z^{(\alpha)}) \\ \alpha_2 &= \Phi(2z_0 + z^{(1-\alpha)}) \end{aligned}$$

  - $\Phi(\cdot)$: standard normal CDF
  - $z^{(\alpha)}$: 100$\cdot\alpha$th percentile of a standard normal CDF
  - z_0: bias-correction coefficient

$$z_0 \equiv \Phi^{-1}\left(B^{-1}\sum_{b=1}^{B} 1[\zeta(b) < \zeta]\right)$$

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Gravity Models

Others theories in same family:

Model	Type of Competition	Technology	θ Interpretation
Armington (1969)	Perfect	Armington	Elasticity of Substitution
Eaton & Kortum (2002)	Perfect	Ricardian	Productivity Dispersion
BEJK (2003)	Bertrand	Ricardian	Productivity Dispersion
Krguman (1980)	Monopolistic	Homogenous	Elasticity of Substitution
Melitz (2003), Chaney (2008)	Monopolistic	Heterogeneous, Pareto	Pareto Shape Parameter
EKK (2011)	Monopolistic	Heterogeneous, Pareto	Pareto Shape Parameter

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Gravity Models

Others theories in same family:

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Armington (1969)	Perfect	Armington	Elasticity of Substitution
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EKK (2011)	Monopolistic	Heterogeneous, Pareto	Pareto Shape Parameter

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Welfare Effects of International Trade, by Region

	Gains from Trade	Enviromental Costs of Trade		Welfare	Ratio: (1)/(2)
		Total	Transport Share		
	(1)	(2)	(3)	(4)	(5)
US	561	2.6	0.30	558	218
	[315 , 3935]	[2.0 , 4.7]	[0.15 , 0.47]	[313 , 3933]	[150 , 1655]
EU	2,561	19.3	0.70	2,545	133
	[1213 , 9630]	[15.2 , 35.3]	[0.51 , 0.76]	[1198 , 9622]	[81 , 540]
Sub-Saharan Africa	68	1.1	0.63	67	61
	[40 , 294]	[0.9 , 2.1]	[0.47 , 0.71]	[39 , 293]	[44 , 283]

See Table 4. Bracketed numbers represent 95% confidence intervals, estimated with bias-corrected bootstrap.

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Welfare Effects of International Trade, by Income

	Gains from Trade	Enviromental Costs of Trade		Welfare	Ratio: (1)/(2)
		Total	Transport Share		
	(1)	(2)	(3)	(4)	(5)
Richest Third	3,979	25.1	0.64	3,957	158
	[1977 , 16405]	[19.9 , 46.1]	[0.44 , 0.72]	[1907 , 14784]	[98 , 706]
Middle Third	1,062	5.5	0.42	1,057	192
	[575 , 4207]	[4.4 , 10.1]	[0.24 , 0.52]	[556 , 3807]	[133 , 778]
Poorest Third	251	4.8	0.36	247	53
	[142 , 1113]	[3.8 , 8.7]	[0.21 , 0.44]	[138 , 1109]	[39 , 193]

See Table 4. Bracketed numbers represent 95% confidence intervals, estimated with bias-corrected bootstrap.

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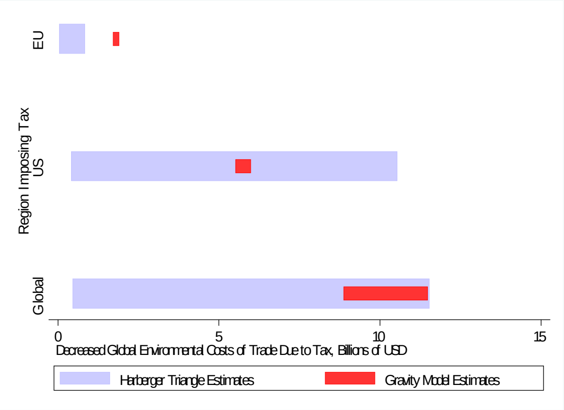
Carbon Tax Counterfactuals: Comparison to Harberger Triangles



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Estimating Trade Elasticities: Manufacturing

$$log(\lambda_{ody}^{B}) = \theta log(1 + s_{ody}^{B}) + \delta_{od}^{B} + \eta_{oy}^{B} + \zeta_{dy}^{B} + \epsilon_{ody}^{B}$$

	Log Freight Costs (OLS) (1)	Log Trade Costs (FE) (2)	Log Shipping Costs (FS) (3)	Log Import Shares (IV) (4)
Overall:	-24.55***	-4.17***	0.22***	-6.68
Manufacturing	(1.84)	(1.07)	(0.04)	(4.21)

See Table 2. Back to Slides

CO2 Emissions in Autarky

$$E_d' = \sum_j (\gamma_3 f_{dd}^j + \chi_d^j)(\lambda_{dd}^j)^{-(1-\beta_d^j)/(\beta_d^j \theta^j)}$$

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Motivation: GDP Versus International Trade

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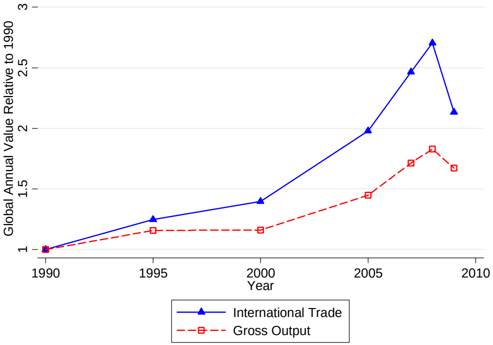
Motivation: Gross Output Versus International Trade



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