Global Trade and the Dollar

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Currency Wars and Monetary Policy

Currency wars and expenditure switching

- Currency war: Weaker currency $\rightarrow$ higher exports.
- Works through expenditure switching channel.
- Key assumption (Mundell-Fleming): Depreciation of bilateral exchange rate causes depreciation of bilateral terms of trade.

Pricing paradigms in international macro

- Traditional paradigms in sticky-price int'l macro models:
  - Producer currency pricing (PCP). Friedman ('53); Fleming ('62); Mundell ('63); Obstfeld & Rogoff ('95)
  - Local currency pricing (LCP).
    Betts & Devereux ('00); Devereux & Engel ('03)
- Emphasis on bilateral ER. No single currency central.

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    Betts & Devereux ('00); Devereux & Engel ('03)
- Emphasis on bilateral ER. No single currency central.
- For many countries, majority of imports/exports invoiced in USD.
- Dominant currency paradigm: Gopinath ('15); Casas et al. ('16)
  - Prices sticky in USD.
  - TOT stable in face of bilateral ER movements.
  - USD central to global trade and currency wars.

Our contributions and findings

- Results from new global data set on bilateral trade prices+volumes.
  1. Bilateral non-commodities TOT uncorrelated with bilateral ER.
  2. USD dominates bilateral ER in ERPT and trade elasticity regressions.
  3. Large effects of USD ER on ROW trade and PPI/CPI inflation.
  4. Trade flows involving the U.S. are special.
  5. USD invoicing share important for explaining cross-sec'l heterogeneity.

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  4. Trade flows involving the U.S. are special.
  5. USD invoicing share important for explaining cross-sec'l heterogeneity.

Conclusion: Dominant currency paradigm more relevant benchmark than PCP/LCP.

- Model: Asymmetric monetary policy spillovers due to DCP.

Closely related literature

- Pass-through, trade elasticity: Leigh et al. (‘15); Bussière et al. (‘16)
- PCP vs. LCP: Betts & Devereux (‘00); Obstfeld & Rogoff (‘00); Devereux & Engel (‘03); Gopinath & Rigobon (‘08); Gopinath et al. (‘10); Engel (‘11)
- USD invoicing: Corsetti & Pesenti (’05); Cook & Devereux (’06); Devereux et al. (‘07); Goldberg & Tille (‘08, ‘09); Canzoneri et al. (‘13); Gopinath (‘15); Casas et al. (‘16); Cravino (‘17); Mukhin (‘17)
- USD standard: Triffin (‘61); McKinnon (‘69, ‘14); Gourinchas & Rey (‘07); Maggiori (‘17); Farhi & Maggiori (‘18)
- U.S. financial spillovers: Rey (‘13); Bruno & Shin (‘15)

Outline

1. Conceptual framework
2. Data
3. Bilateral terms of trade and pass-through
4. Determinants of pass-through heterogeneity
5. Model
6. Conclusions

Implications of currency of invoicing under sticky prices

$$p_{ij} = p^{i}_{ij} + e_{ij} = p^{\$}_{ij} + e_{\$j}$$

$$tot_{ij} = p_{ij} - (p_{ji} + e_{ij}) = p^{\$}_{ij} - p^{\$}_{ji}$$

Implications of currency of invoicing under sticky prices

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$$tot_{ij} = p_{ij} - (p_{ji} + e_{ij}) = p_{ij}^{\$} - p_{ji}^{\$}$$

	$\Delta e_{ij} = 1$		$\Delta e_{\$j} = 1$	
	Δp_{ij}	Δtot_{ij}	Δp_{ij}	Δtot_{ij}
PCP	1	1	0	0
LCP	0	-1	0	0
DCP	0	0	1	0

Implications of currency of invoicing under sticky prices

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	$\Delta e_{ij} = 1$		$\Delta e_{\$j} = 1$	
	Δp_{ij}	Δtot_{ij}	Δp_{ij}	Δtot_{ij}
PCP	1	1	0	0
LCP	0	-1	0	0
DCP	0	0	1	0

- Long-run price depends on desired pass-through. Casas et al. ('16)
- Endogenous currency choice reinforces predictions. Gopinath et al. ('10)

Outline

Components of data set

1. Newly constructed Comtrade bilateral trade indices. Unit value and volume, non-commodities. Boz & Cerutti ('17)
2. Country-level import invoicing currency shares.
   Kamps ('06); Goldberg & Tille ('08); Chinn & Ito ('14); Gopinath ('15)
3. Country-level/global macro data: WDI, FRED.

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3. Country-level/global macro data: WDI, FRED.

- Annual, 1989–2015.
- 55 countries (31 advanced). Account for 91% of world's goods imports and exports in 2015. List
- 2,807 dyads (country pairs) in largest specification.
- USD import invoicing share for 38 countries.

New bilateral price/volume indices

- UN Comtrade customs data: Boz & Cerutti ('17)
  - Value, quantity, weight. HS 6-digit level.
  - Remove outliers in cross section and time dimensions.
  - Infer unit values, then aggregate to dyad-level Fisher index.
- We focus on non-commodities data.
  - Remove animal, vegetable, food, mineral, metal products.
- Use importer-reported data.
- Broadly consistent with BLS IPIs for U.S. by origin.

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Terms of trade and bilateral exchange rates

Result 1: Bilateral TOT essentially uncorrelated with bilateral ER.

- Regress change in log TOT (unitless) on lags of bilateral log ER changes.
- Controls: lags of change in log relative PPI (unitless), dyad fixed effects, time fixed effects.
- S.e. clustered by dyad.

Terms of trade and bilateral exchange rates

	unweighted		trade-weighted	
	(1)	(2)	(3)	(4)
VARIABLES	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$
$\Delta e_{ij,t}$	0.0369***	-0.00938	0.0813***	0.0218
	(0.00863)	(0.0130)	(0.0235)	(0.0317)
ΔER lags	2	2	2	2
PPI	no	yes	no	yes
R-squared	0.008	0.011	0.028	0.042
Observations	24,270	19,847	24,270	19,847
Dyads	1,347	1,200	1,347	1,200

- Conclusion true across emerging/advanced country flows.

Exchange rate pass-through into prices

Result 2: USD dominates bilateral ER in ERPT regressions.

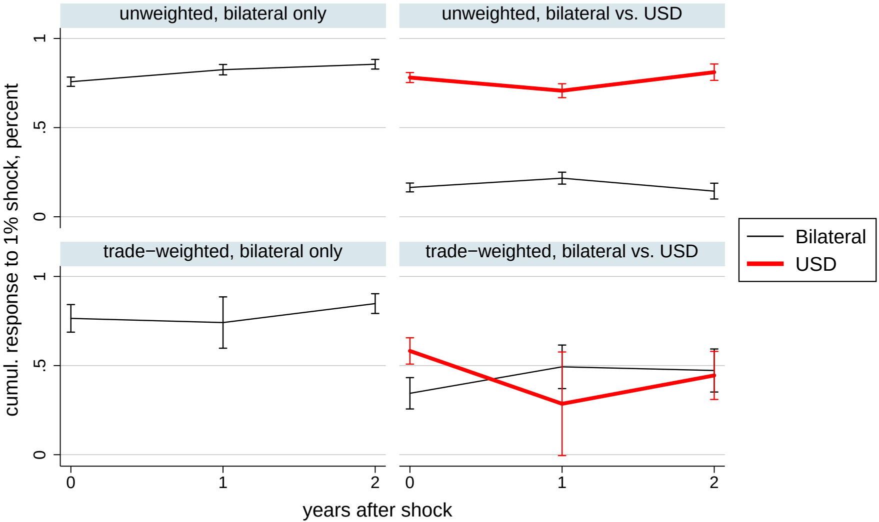
- Standard reduced-form ERPT regressions, except we include importer-USD ER. Burstein & Gopinath ('14); Casas et al. ('16)
- Regress $\Delta p_{ij,t}$ (importer currency) on lags of ER changes.
- ER changes are not collinear (small s.e.).
- Also consider specifications which interact ERs with the importer's USD invoicing share.
- Controls: lags of exporter PPI, dyad fixed effects, time fixed effects.

Exchange rate pass-through into prices

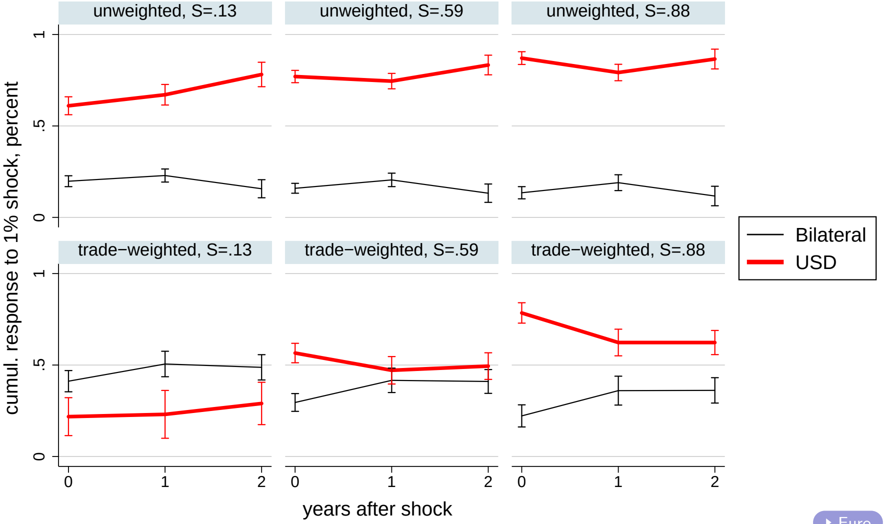
VARIABLES	unweighted (1) $\Delta p_{ij,t}$	(2) $\Delta p_{ij,t}$	(3) $\Delta p_{ij,t}$	trade-weighted (4) $\Delta p_{ij,t}$	(5) $\Delta p_{ij,t}$	(6) $\Delta p_{ij,t}$
$\Delta e_{ij,t}$	0.757***	0.164***	0.209***	0.765***	0.345***	0.445***
	(0.0132)	(0.0126)	(0.0169)	(0.0395)	(0.0449)	(0.0336)
$\Delta e_{ij,t} \times S_j$			-0.0841***			-0.253***
			(0.0240)			(0.0482)
$\Delta e_{\$j,t}$		0.781***	0.565***		0.582***	0.120*
		(0.0143)	(0.0283)		(0.0377)	(0.0622)
$\Delta e_{\$j,t} \times S_j$			0.348***			0.756***
			(0.0326)			(0.0796)
ΔER lags	2	2	2	2	2	2
R-squared	0.356	0.398	0.515	0.339	0.371	0.644
Observations	46,820	46,820	34,513	46,820	46,820	34,513
Dyads	2,647	2,647	1,900	2,647	2,647	1,900

- USD PT strongest for EM→EM flows, but high everywhere.

Exchange rate pass-through into prices



Exchange rate pass-through into prices



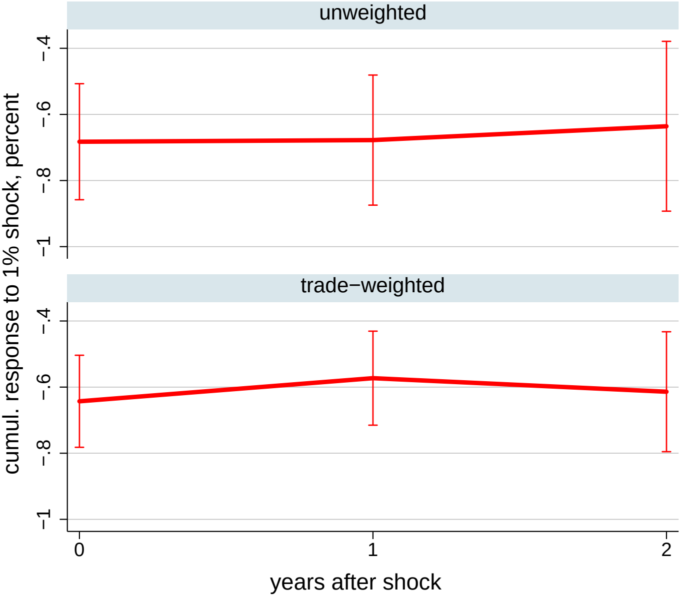
Euro

Trade volume elasticity

Result 3: USD dominates bilateral ER in forecasting trade volumes. Large implied effect of USD appreciation on rest-of-world trade.

- Regress $\Delta y_{ij,t}$ on lags of log ER changes and controls. Fig
- Aggregate up from bilateral regressions to compute effect of USD appreciation on rest-of-world non-commodity trade volume.
  - Hold constant other ERs and global business cycle.

Effect of dollar appreciation on rest-of-world trade



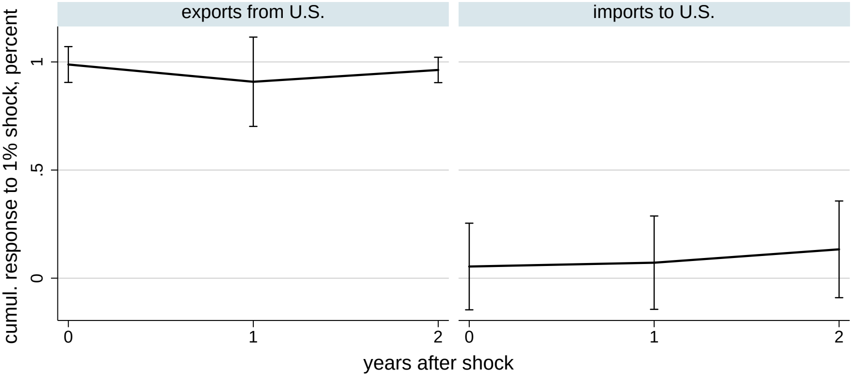
▸ Infl

Trade flows to/from the U.S.

Result 4: Trade flows involving the U.S. are special.

- USD invoicing share for U.S.: exports 97%, imports 93%.
- Run ERPT regressions where importer/exporter = U.S.
- Run trade elasticity regressions with dummy for importer = U.S.

Trade flows to/from U.S.: bilateral pass-through



S.e. corrected for small no. of clusters (countries). Imbens & Kolesár ('16)

U.S. imports: trade elasticity

VARIABLES	unweighted (1) $\Delta y_{ij,t}$	trade-weighted (2) $\Delta y_{ij,t}$
$\Delta e_{ij,t}$	-0.121***	-0.107***
	(0.0141)	(0.0194)
$\Delta e_{ij,t} \times$ ImpUS	0.124***	0.117***
	(0.0329)	(0.0318)
ΔER lags	2	2
Imp. GDP x ImpUS	yes	yes
Time x ImpUS FE	yes	yes
R-squared	0.069	0.180
Observations	52,272	52,272
Dyads	2,807	2,807

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What determines pass-through heterogeneity?

- Previous slides: USD invoicing *a* determinant of cross-dyad heterogeneity. More important than other determinants?
  - Difficult to address with standard constant-coefficients panel regressions.
- Our approach:
  - Bayesian model of cross-sectional pass-through heterogeneity.
  - Novelty: Flexible (semiparametric) specification of dependence on USD invoicing share and other unobserved determinants.

Result 5: Importer's country-level USD invoicing share explains about 15% of cross-dyad variance in dollar pass-through.

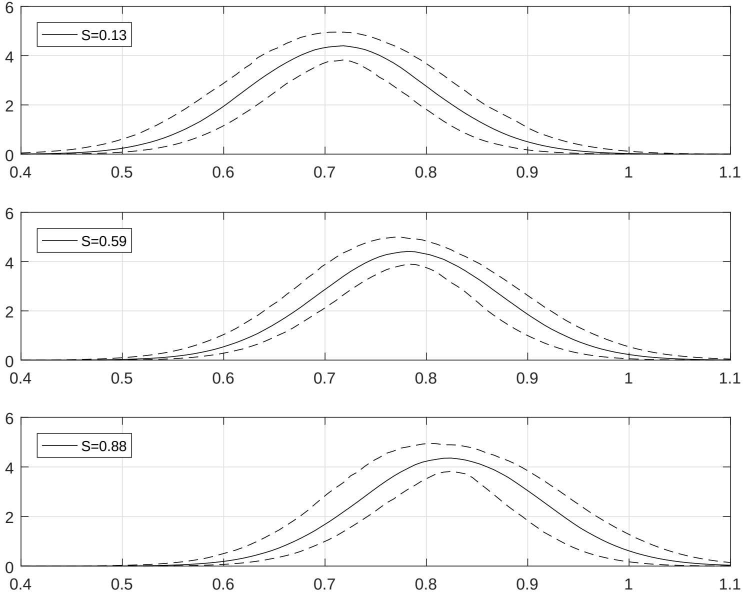
Random coefficients panel data model

- Allow dollar pass-through to vary cross-sectionally:

$$\Delta p_{ij,t} = \lambda_{ij} + \delta_t + \gamma_{ij} \Delta e_{\$j,t} + (\bar{\gamma} - \gamma_{ij}) \Delta e_{ij,t} + \tilde{\theta}' \tilde{X}_{ij,t} + \varepsilon_{ij,t}.$$

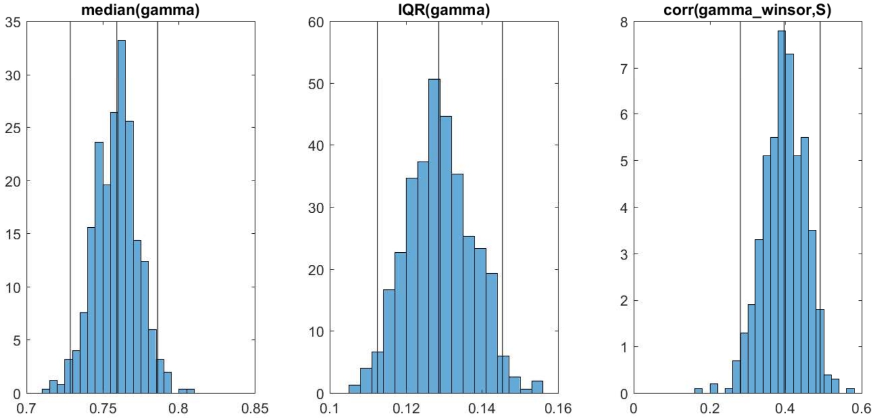
- Flexible, nonparametric specification of cross-sec'l USD pass-through distribution $(\gamma_{ij} \mid S_j)$ as fct of importer's USD invoicing share S_j.
- Data decides trade-off btw two extremes:
  1. Constant coefficients panel regression (constrained, low variance).
  2. Dyad-by-dyad time series regressions (flexible, noisy).

Results: cond'l distr. of dollar pass-through



Mean/std

Results: sample distr. of dollar pass-through



- 95% interval for R^2 in regr. of $\gamma_{ij}^{\text{winsor}}$ on S_j: $[0.08, 0.24]$.
- Could not have obtained results w/o hierarchical model.

▸ θ ▸ TE

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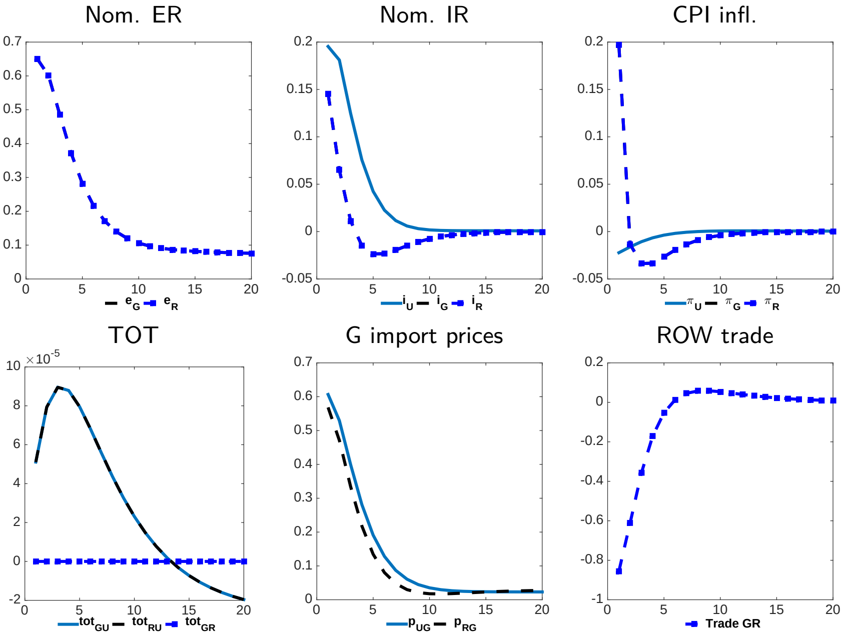
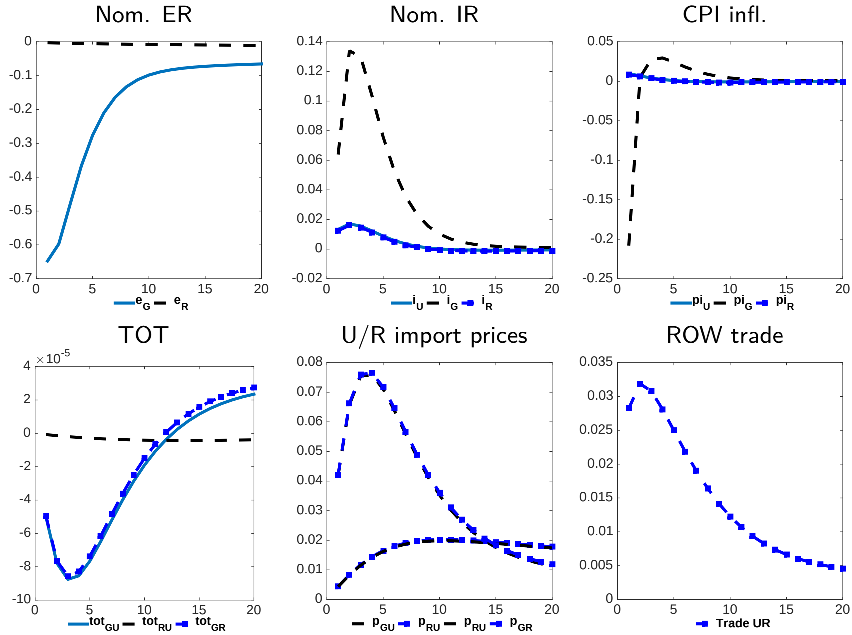
Asymmetry of monetary policy spillovers under DCP

- NK model with three symmetric, large countries U, G & R:
  - International trade denominated in U currency. Domestic prices set in domestic currency. Casas et al. ('16)
  - Imported intermediate good.
  - Sticky prices+wages (Calvo). Strategic complementarity in pricing.
  - Incomplete markets. Internationally traded bond in U currency.
  - MP set according to inertial Taylor rule.
- Unlike SOE set-up, we can shock MP in different countries. With three countries, we can consider asymmetries.

MP tightening in *U*: strong spillovers + affects ROW trade



MP tightening in G: weak spillovers



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Conclusions

- First evidence on DCP using global, bilateral data set.
  1. Non-commodities TOT uncorrelated with bilateral ER.
  2. USD ER movements quantitatively more important for predicting bilateral prices+volumes than bilateral ER.
  3. Large effect of USD on ROW trade and CPI/PPI inflation (in paper).
  4. Trade flows involving the U.S. are special.
  5. USD invoicing important for explaining cross-dyad ERPT heterog'y.
- Model: Asymmetric monetary policy spillovers due to DCP. Dominant currency country MP affects ROW trade.
- Currency wars: TB adjustment through imports (except for U.S.).

Thank you

Country	As exporter #dyads	As exporter avg T	As importer #dyads	As importer avg T	InvS
Africa					
Algeria	20	14.2	49	21.1	
Egypt	54	20.4	52	21.6	
South Africa	54	15.0	53	14.7	
Americas					
Argentina	54	21.8	52	21.8	0.88
Brazil	54	24.2	53	23.1	0.84
Canada	54	24.4	54	24.1	0.75
Chile	52	20.9	50	22.0	
Colombia	53	19.5	52	21.4	0.99
Mexico	54	23.4	52	23.3	
United States	54	24.0	54	23.5	0.93
Venezuela	21	10.9	48	19.9	
Asia					
China	54	23.7	54	22.6	
Hong Kong	54	23.2	52	22.5	
India	54	25.3	53	24.4	0.86
Indonesia	54	23.9	52	23.0	0.81
Israel	53	21.5	51	21.3	0.73
Japan	54	25.6	52	25.5	0.71
Kazakhstan	39	14.6	52	18.2	
Malaysia	54	24.1	53	23.4	
Philippines	54	22.1	50	21.5	
Saudi Arabia	50	20.1	53	21.2	
Singapore	54	24.7	51	24.0	
South Korea	54	25.0	52	24.6	0.81
Thailand	54	24.5	53	24.5	0.79
Turkey	54	24.4	54	23.9	0.59
Vietnam	54	19.3	49	19.0	

Country	As exporter #dyads	As exporter avg T	As importer #dyads	As importer avg T	InvS
Europe					
Austria	54	23.1	52	23.0	0.06
Belgium	54	15.9	53	15.9	0.14
Czech Republic	54	20.6	53	21.3	0.19
Denmark	54	22.3	52	24.4	0.25
Estonia	47	17.9	52	19.3	0.34
Finland	54	25.6	52	25.0	0.42
France	54	23.1	54	22.7	0.21
Germany	54	23.3	54	23.0	0.23
Greece	54	23.0	51	23.6	0.40
Hungary	54	23.6	52	22.6	0.27
Ireland	54	23.4	53	22.5	0.23
Italy	54	23.1	54	22.5	0.29
Lithuania	53	17.3	50	18.9	0.51
Luxembourg	54	15.8	51	14.0	0.16
Netherlands	54	23.7	54	23.2	0.37
Norway	54	23.1	52	23.0	0.21
Poland	54	22.9	52	22.3	0.30
Portugal	54	24.9	53	24.8	0.22
Romania	54	22.6	52	21.4	0.31
Russia	54	21.4	52	21.0	
Slovak Republic	54	20.7	51	20.4	0.12
Slovenia	54	21.1	52	20.7	0.20
Spain	54	24.8	54	24.9	0.35
Sweden	54	23.7	54	23.1	0.25
Switzerland	54	25.6	54	25.1	0.13
Ukraine	53	19.3	52	19.8	0.75
United Kingdom	54	23.4	54	23.3	0.47
Oceania					
Australia	54	25.1	52	25.2	0.53
New Zealand	54	22.7	50	24.0	

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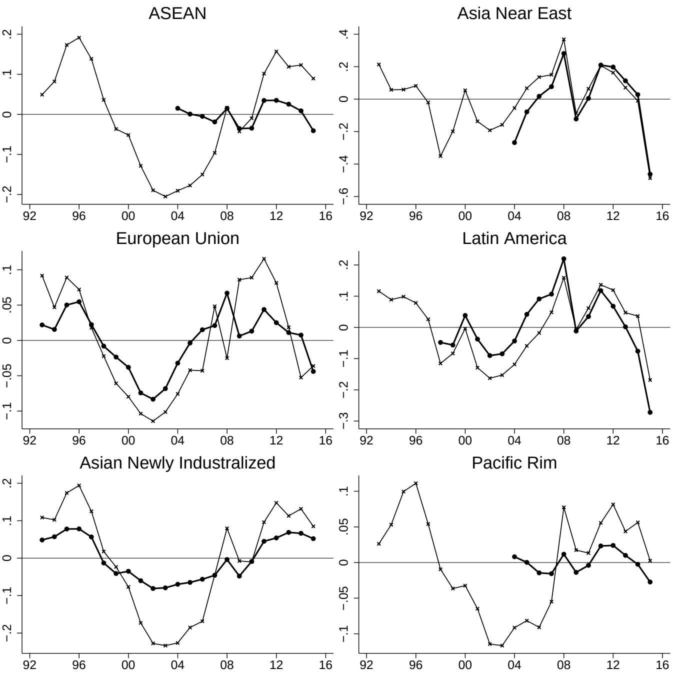

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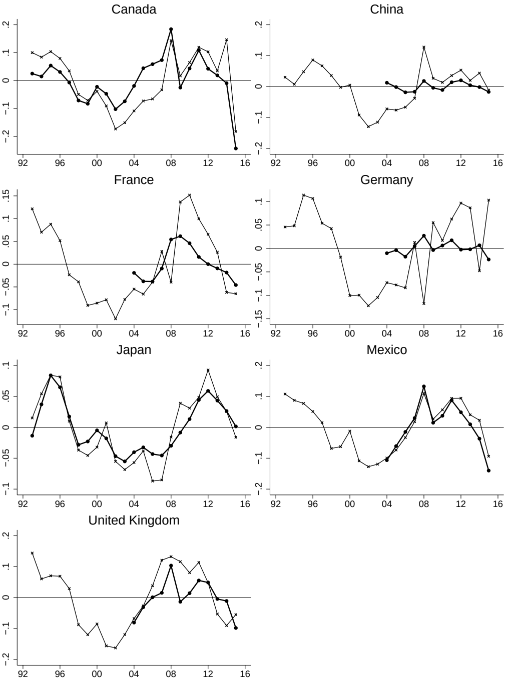
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Terms of trade: country group heterogeneity

	unweighted			trade-weighted		
	(1)	(2)	(3)	(4)	(5)	(6)
	E↔E	E↔A	A↔A	E↔E	E↔A	A↔A
VARIABLES	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$	$\Delta tot_{ij,t}$
$\Delta e_{ij,t}$	0.0189	0.0480***	0.0182	0.0508***	0.111***	0.0220
	(0.0173)	(0.0110)	(0.0256)	(0.0176)	(0.0310)	(0.0473)
ΔER lags	2	2	2	2	2	2
PPI	no	no	no	no	no	no
Time FE	yes	yes	yes	yes	yes	yes
R-squared	0.028	0.011	0.008	0.051	0.078	0.025
Observations	3,527	11,857	8,886	3,527	11,857	8,886
Dyads	217	670	460	217	670	460

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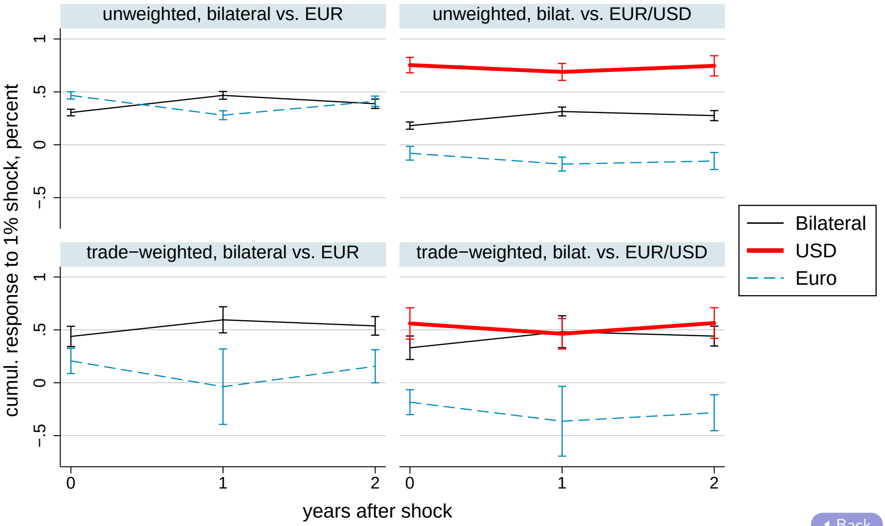
Price pass-through: country group heterogeneity

	unweighted				trade-weighted			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	E→E	E→A	A→E	A→A	E→E	E→A	A→E	A→A
VARIABLES	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$	$\Delta p_{ij,t}$
$\Delta e_{ij,t}$	0.0980***	0.0514**	0.265***	0.332***	0.150***	0.150***	0.433***	0.373***
	(0.0329)	(0.0225)	(0.0379)	(0.0195)	(0.0391)	(0.0269)	(0.132)	(0.0504)
$\Delta e_{\$j,t}$	0.858***	0.766***	0.710***	0.409***	0.820***	0.498***	0.608***	0.287***
	(0.0353)	(0.0364)	(0.0382)	(0.0284)	(0.0487)	(0.0533)	(0.122)	(0.0487)
ΔER lags	2	2	2	2	2	2	2	2
Exp. PPI	yes	yes	yes	yes	yes	yes	yes	yes
Time FE	yes	yes	yes	yes	yes	yes	yes	yes
R-squared	0.470	0.152	0.530	0.142	0.572	0.252	0.467	0.264
Observations	6,763	10,589	12,318	17,150	6,763	10,589	12,318	17,150
Dyads	435	618	700	894	435	618	700	894

◂ Back

Exchange rate pass-through: euro comparison



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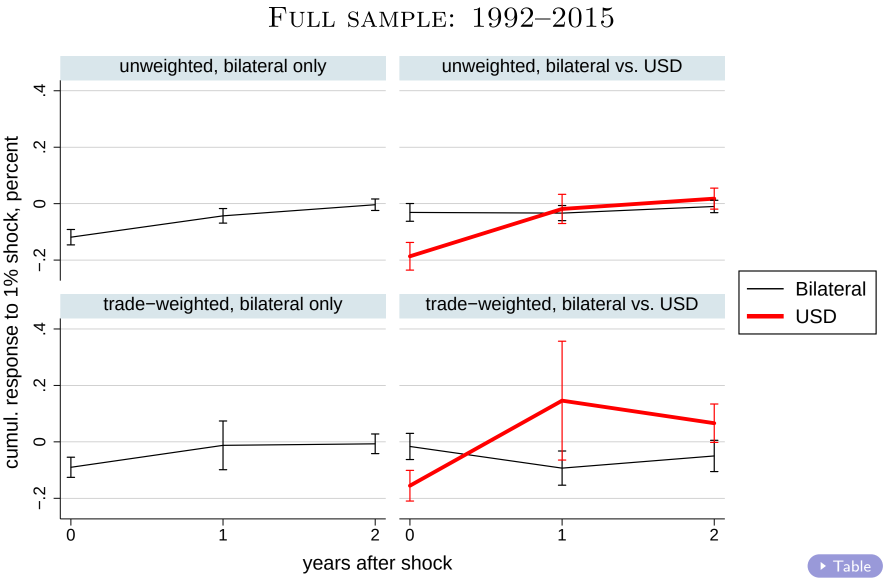
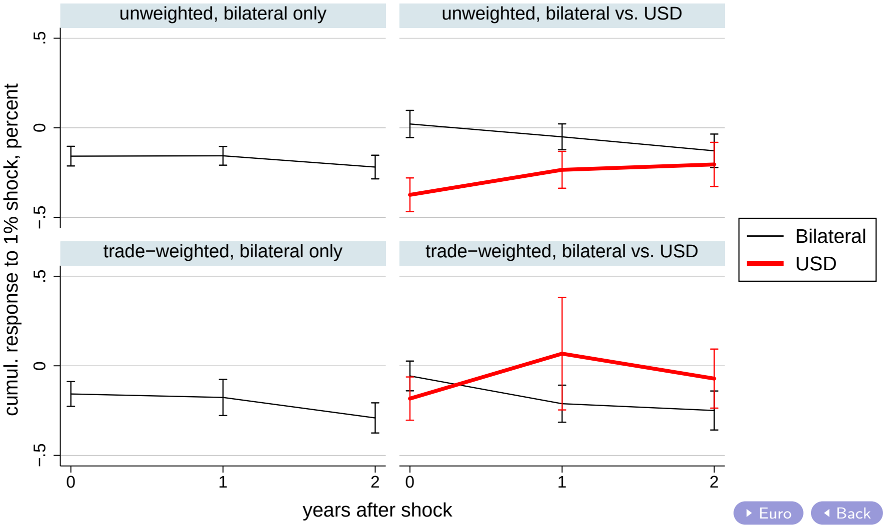
Trade volume elasticity



▸ Table

Trade volume elasticity

Latter half of sample: 2002–2015



▸ Euro ◂ Back

Effect of dollar appreciation on rest-of-world trade

$$\Delta y_{ij,t} = \sum_{k=0}^{2} \left(\alpha_k + \eta_k(1 - S_j - S_j^{€})\right) \Delta e_{ij,t-k}$$
$$+ \sum_{k=0}^{2} \left(\beta_k + \psi_k S_j\right) \Delta e_{\$j,t-k}$$
$$+ \sum_{k=0}^{2} \left(\xi_k + \vartheta_k S_j^{€}\right) \Delta e_{€j,t-k}$$
$$+ \lambda_{ij} + \theta' X_{ij,t} + \varepsilon_{ij,t}$$

- Controls: importer RGDP, global RGDP, global GDP defl., real oil price, VIX. Omit time fixed effects.
- Sample: 2002–2015.
- *Ceteris paribus* effect of 1% USD appreciation on ROW trade:

$$\sum_{j \neq \text{USA}} w_j(\beta_k + S_j \psi_k) = \beta_k + \psi_k \sum_{j \neq \text{USA}} w_j S_j.$$

- w_j: share of j imports in non-US non-com'y imports (avg '02–15).

▸ w_j ◂ Back

Trade volume elasticity

VARIABLES	unweighted (1) $\Delta y_{ij,t}$	(2) $\Delta y_{ij,t}$	trade-weighted (3) $\Delta y_{ij,t}$	(4) $\Delta y_{ij,t}$
$\Delta e_{ij,t}$	-0.119***	-0.0310*	-0.0901***	-0.0163
	(0.0139)	(0.0160)	(0.0182)	(0.0236)
$\Delta e_{\$j,t}$		-0.186***		-0.155***
		(0.0250)		(0.0277)
ΔER lags	2	2	2	2
Imp. GDP	yes	yes	yes	yes
Time FE	yes	yes	yes	yes
R-squared	0.069	0.071	0.172	0.179
Observations	52,272	52,272	52,272	52,272
Dyads	2,807	2,807	2,807	2,807

Het Back

Trade elasticity: country group heterogeneity

	unweighted				trade-weighted			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
	E→E	E→A	A→E	A→A	E→E	E→A	A→E	A→A
VARIABLES	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$	$\Delta y_{ij,t}$
$\Delta e_{ij,t}$	-0.0488	-0.0145	-0.182***	-0.0737	-0.0471	-0.0441**	-0.0377	0.0228
	(0.0333)	(0.0212)	(0.0700)	(0.0481)	(0.0357)	(0.0225)	(0.117)	(0.0518)
$\Delta e_{\$j,t}$	-0.163***	-0.435***	0.00868	-0.340***	-0.208***	-0.251***	-0.0995	-0.302***
	(0.0588)	(0.0749)	(0.0704)	(0.0607)	(0.0641)	(0.0622)	(0.118)	(0.0548)
ΔER lags	2	2	2	2	2	2	2	2
Imp. GDP	yes	yes	yes	yes	yes	yes	yes	yes
Time FE	yes	yes	yes	yes	yes	yes	yes	yes
R-squared	0.093	0.049	0.100	0.082	0.237	0.301	0.218	0.214
Observations	8,239	12,967	12,932	18,134	8,239	12,967	12,932	18,134
Dyads	485	679	719	924	485	679	719	924

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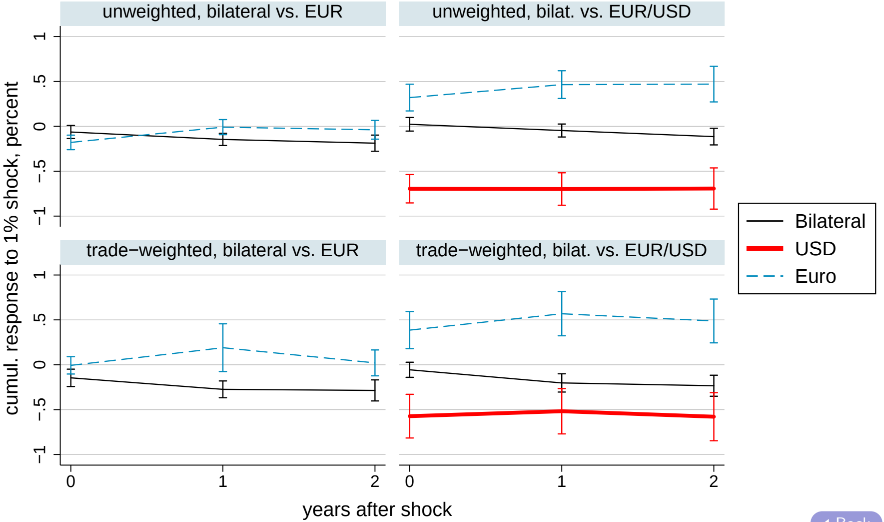
Trade volume elasticity: euro comparison



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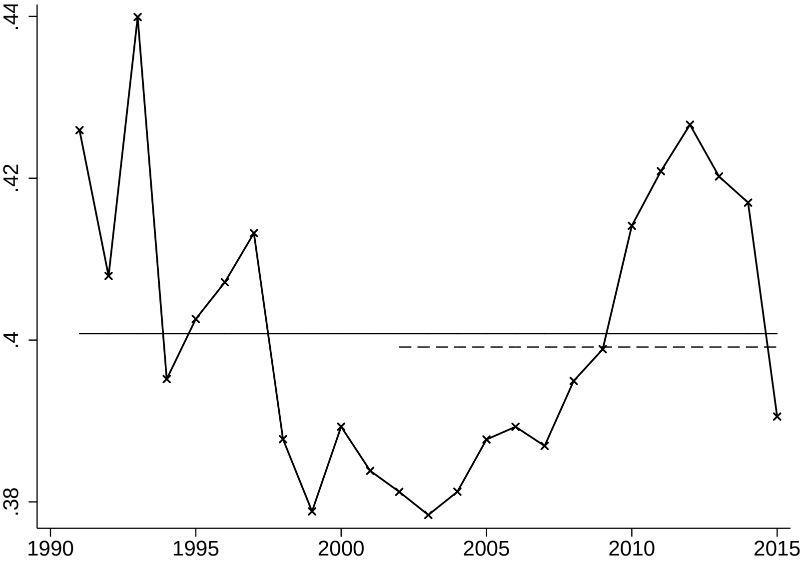
Import-weighted average USD invoicing share



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Effect of dollar appreciation on CPI/PPI

Result: USD ER strongly correlates with country-level CPI/PPI.

- *Country-level* regr's of CPI/PPI log inflation on lags of USD ER.
- Also consider specifications with USD invoicing share interactions.
- Focus on 2002–2015 sample due to high-inflation episodes in 90s.
- Controls: country fixed effects, time fixed effects.

Effect of dollar appreciation on CPI/PPI, 2002–2015

VARIABLES	(1) $\Delta cpi_{j,t}$	(2) $\Delta cpi_{j,t}$	(3) $\Delta ppi_{j,t}$	(4) $\Delta ppi_{j,t}$
$\Delta e_{\$j,t}$	0.106***	0.0221	0.284***	0.182***
	[0.04, 0.18]	[-0.05, 0.09]	[0.14, 0.43]	[0.05, 0.32]
$\Delta e_{\$j,t} \times S_j$		0.181**		0.237*
		[0.04, 0.33]		[-0.03, 0.51]
ΔER lags	2	2	2	2
Time FE	yes	yes	yes	yes
R-squared	0.283	0.453	0.532	0.675
Observations	766	544	697	525
Countries	55	39	52	38

S.e. corrected for small no. of clusters (countries). Imbens & Kolesár ('16)

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Cross-sectional distribution of dollar pass-through γ_{ij}

- Mixture of Gaussian Linear Regressions: Pati et al. ('13); Liu ('17)

$$(\gamma_{ij} \mid S_j) \sim \begin{cases} N(\mu_{0,1} + \mu_{1,1} S_j, \omega_1^2) & \text{with prob. } \pi_1(S_j), \\ \vdots & \\ N(\mu_{0,K} + \mu_{1,K} S_j, \omega_K^2) & \text{with prob. } \pi_K(S_j). \end{cases}$$

- Flexible "stick-breaking" specification for mixture probabilities:

$$\pi_k(s) = \begin{cases} \Phi(\zeta_k(s)) \prod_{j=1}^{k-1} (1 - \Phi(\zeta_j(s))), & k \leq K-1, \\ 1 - \sum_{j=1}^{K-1} \pi_j(s), & k = K, \end{cases}, \quad s \in [0,1],$$

- Allows heavy tails, skew, many modes, nonlinear dependence on S_j.
- Pick no. K of mixture components using a Bayesian version of leave-one-out cross-validation. Gelfand et al. ('12); Vehtari et al. ('16)

▸ Prior ▸ Stan ◂ Back

Prior specification

$$\alpha \sim \text{Cauchy}(0,5), \quad \theta_j \sim \text{Cauchy}(0,5),$$

$$\sigma \sim \text{HalfCauchy}(0,1), \quad \tau \sim \text{HalfCauchy}(0,1)$$

$$\omega_k \sim \text{HalfCauchy}(0,2), \quad \begin{pmatrix} \mu_{0,k} \\ \mu_{1,k} \end{pmatrix} \mid \omega_k \sim N\left(0, \begin{pmatrix} \omega_k^2 & 0 \\ 0 & \omega_k^2 \end{pmatrix}\right)$$

$$\zeta_k(\cdot) \sim GP(0, C(\cdot; A_k)), \quad A_k \sim \text{Exponential}(1)$$

- $GP(0, C(\cdot; A))$: Gaussian process with Gaussian radial cov kernel

  $$C(s_1, s_2; A) = \exp\{-A(s_1 - s_2)^2\} + 0.0001 \times \mathbb{1}(s_1 = s_2), \;\; s_1, s_2 \in [0,1].$$

- Normalize $\mu_{0,1} \leq \cdots \leq \mu_{0,K}$.

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User-friendly posterior simulation using Stan

- How to simulate from posterior distr. of model parameters?
- We use the user-friendly open source Bayesian software Stan.
  - Model is written in natural mathematical language.
  - Stan figures out how to implement MCMC procedure.
  - Tinker with model assumptions without re-programming everything.
- Fast and reliable in our experience.
- Easily adapted to other hierarchical random coefficient models.

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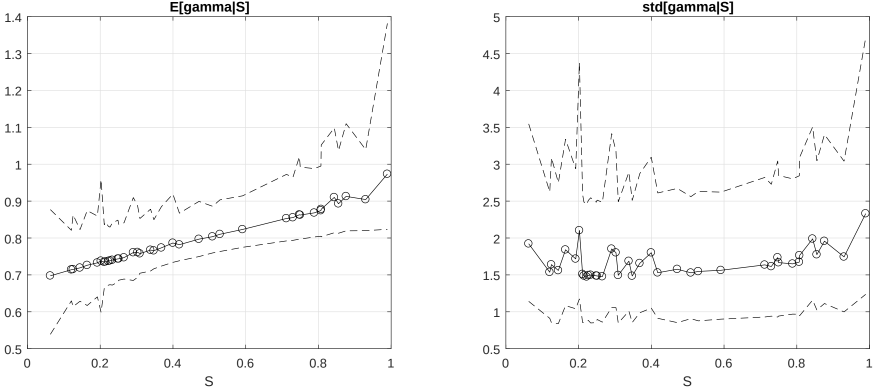
Results: cond'l distr. of dollar pass-through ($K = 2$)



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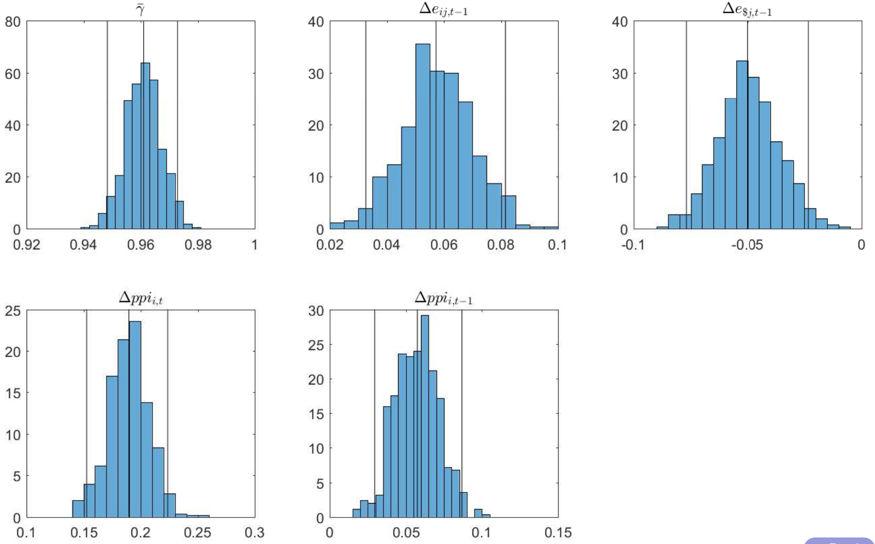
Results: other coefficients in price model ($K = 2$)



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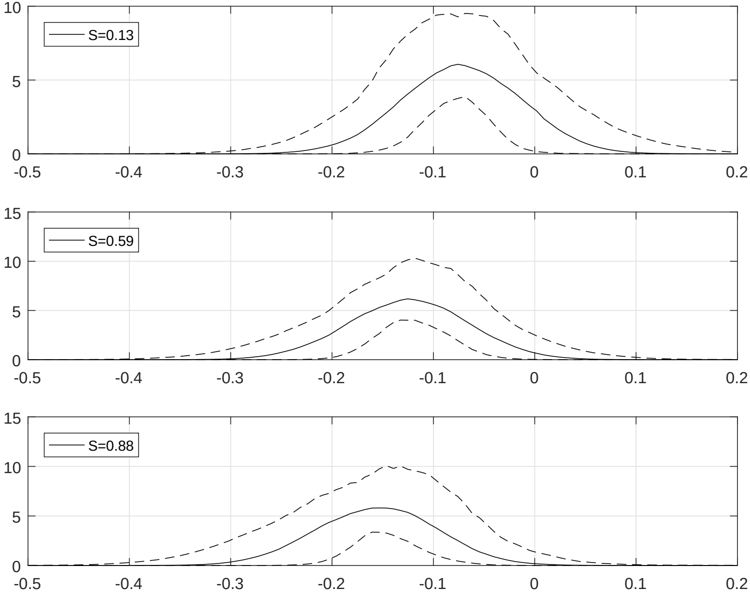
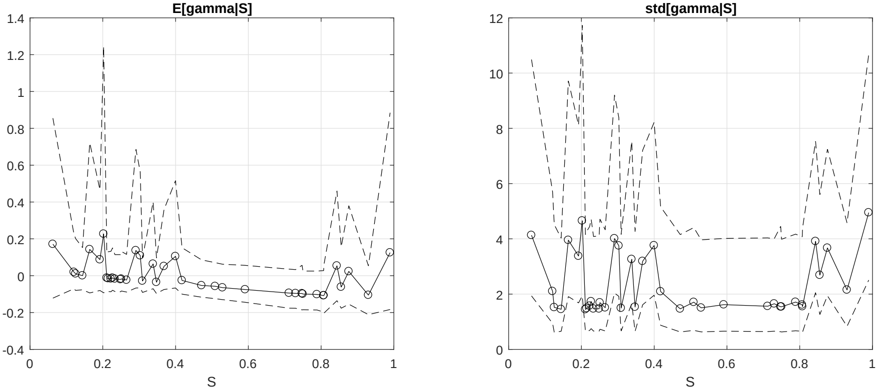
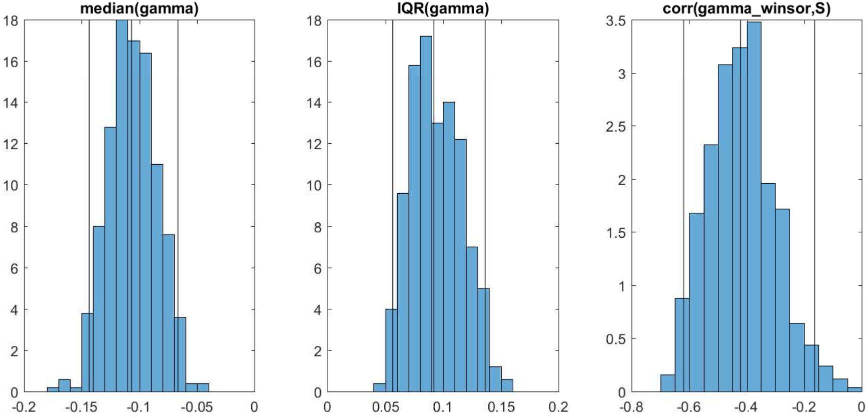
Results: cond'l distr. of dollar elasticity ($K = 4$)



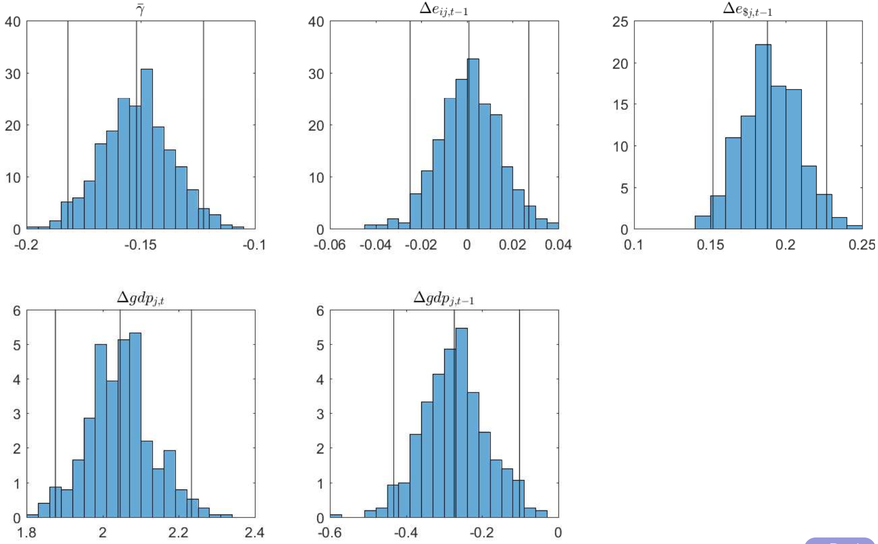
Results: cond'l distr. of dollar elasticity ($K = 4$)



Results: sample distr. of dollar elasticity ($K = 4$)



Results: other coefficients in volume model ($K = 4$)



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