Energy Consumption, Emissions and Modal Substitution in U.S. Freight Transportation

James Bushnell[1] Jonathan Hughes[2]

[1]University of California, Davis and NBER [2]University of Colorado, Boulder

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Freight transportation, energy consumption and emissions

- Transportation has surpassed U.S. electricity sector emissions to become largest emitting sector
- Within transportation, freight represents over 31% of U.S. transportation energy consumption
- Unlike passenger cars where fuel economy improvements have largely offset increases in driving, freight emissions have increased substantially in recent years
- Relatively little is known about factors affecting energy consumption and emissions from freight

Freight transportation, energy consumption and emissions

Importance of freight mode choices

- Large differences in energy intensities across modes
  - Air ~30 Btu/ton-mile
  - Truck ~4 Btu/ton-mile
  - Barge and rail ~0.5 Btu/ton-mile
- Differences in rates, travel times, accessibility
- Large literature on freight mode choice doesn't capture recent changes in freight operations
  - Deregulation
  - Rail investments
  - Containerization and information technology

This paper - modeling mode choices

- Exploit newly available shipment-level data to model shippers' mode choice decisions
- Estimate parameters defining shippers' mode choices
- Simulate mode choices under different fuel price scenarios
  - Predict substantial shifts from less-efficient to more efficient modes
  - Estimate fuel use and carbon emissions reductions
- Explore importance of mode choice for transportation policies
  - Model heavy-duty truck fuel economy standards
  - Find emissions increase by "cross-rebound" effect

Data

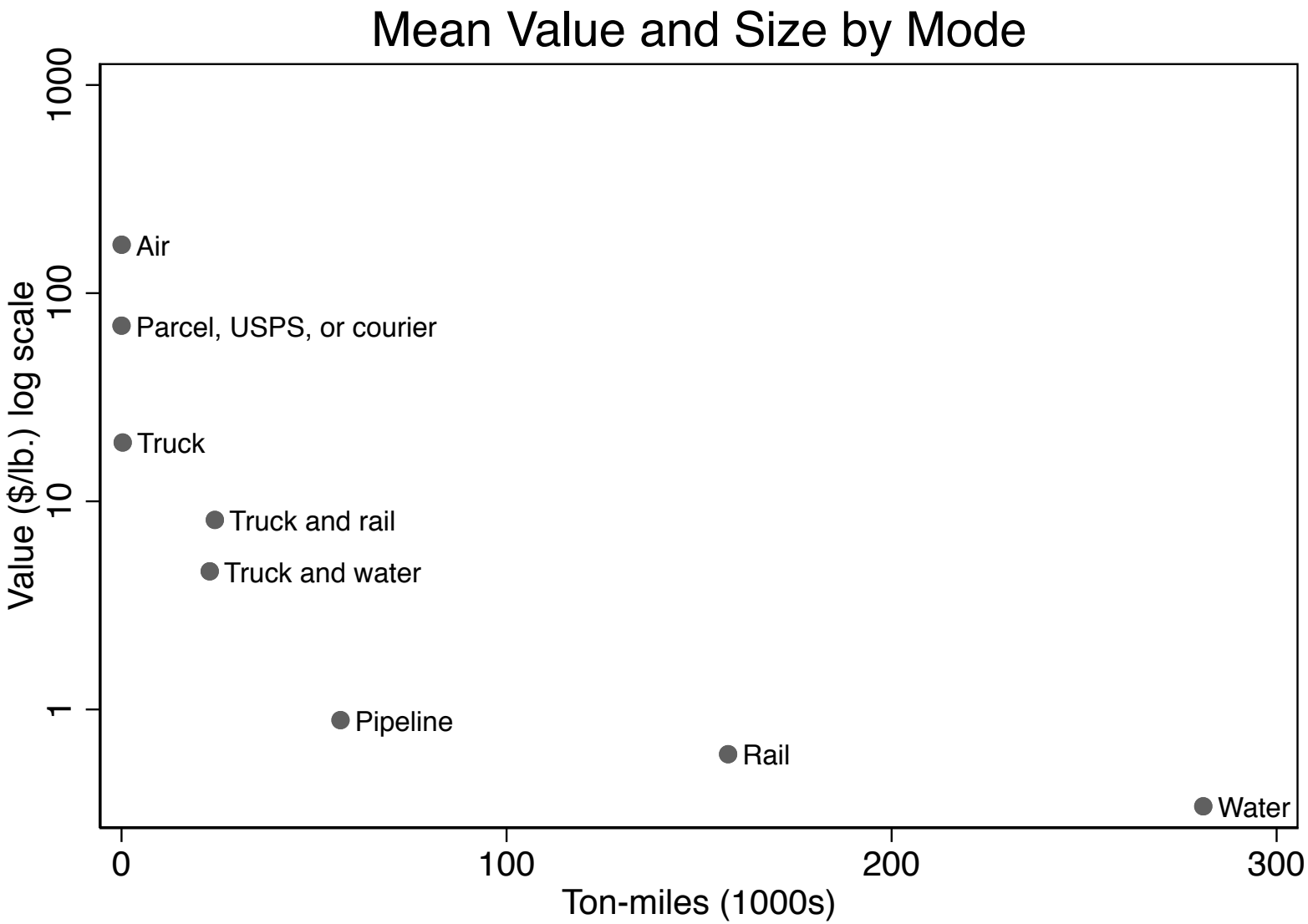
- 2012 Commodity Flow Survey (CFS) Public-Use Microdata (PUM) file
  - Bureau of Transportation Statistics and US Census
  - 4.5 million shipments from 2012
  - Origin and destination state (or metropolitan areas)
  - Transportation mode
  - Good type at STCG level (34 types)
  - Shipment value, weight and distance
  - Sampling weights to reconstruct population
- National average diesel prices from EIA

Modal shares and characteristics of goods shipped

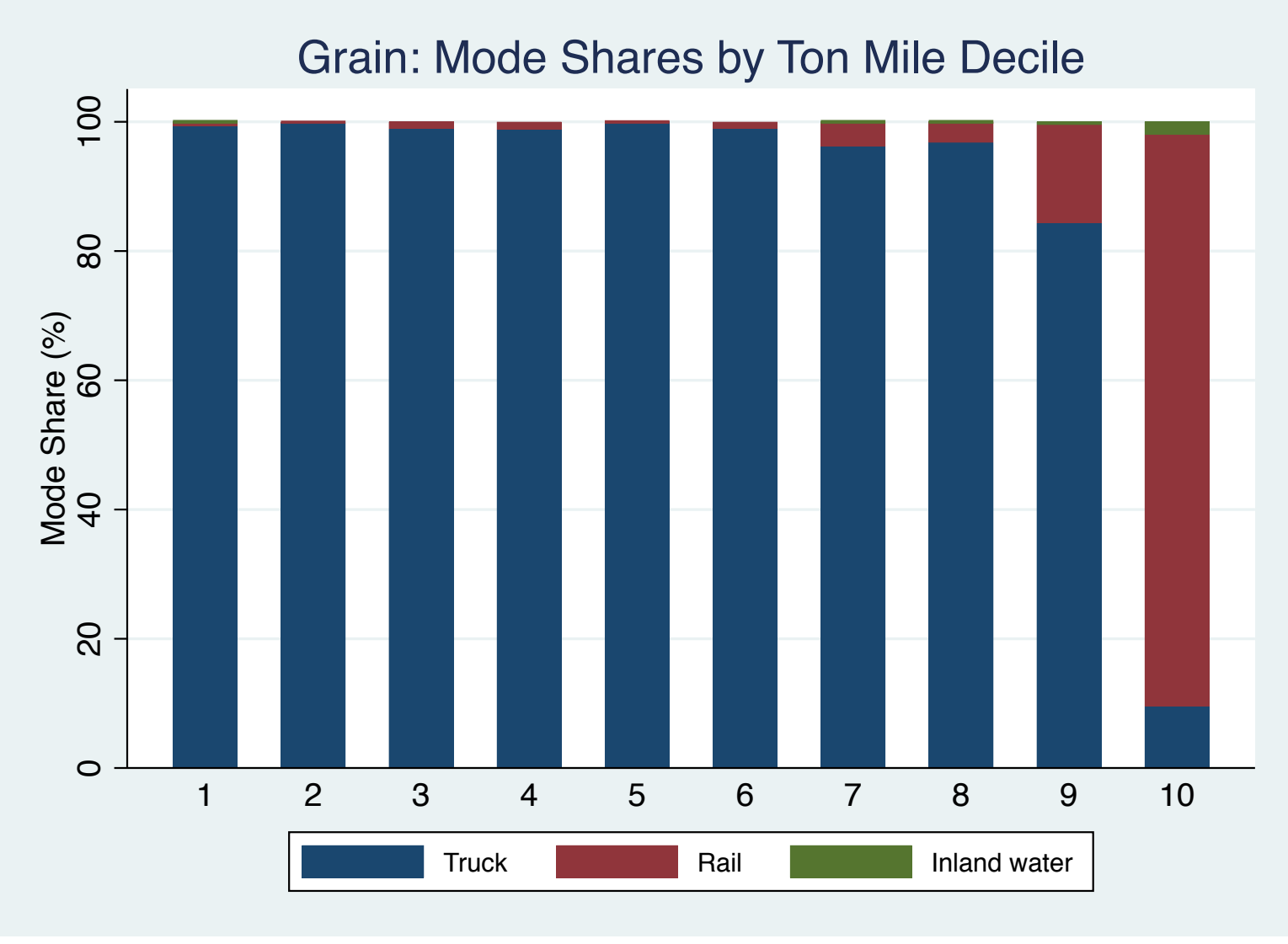
	Ton Mile Wgt. Avg			Mode Share					
Commodity Group	Value	Miles	Tons	Air	Pipeline	Rail	Truck	Water	Parcel/Courier
Basic Chemicals	0.6	1,148	420	0.00	0.01	0.55	0.34	0.10	0.00
Coal	0.01	1,165	17,160	0.00	0.00	0.95	0.02	0.04	0.00
Fertilizers	0.25	1,088	221	0.00	0.01	0.62	0.34	0.03	0.00
Fuel	0.41	680	4,709	0.00	0.24	0.37	0.38	0.01	0.00
Fuel Oil	0.44	454	3,030	0.00	0.26	0.02	0.59	0.13	0.00
Grain	0.14	1,156	4,703	0.00	0.00	0.81	0.10	0.09	0.00
Machinery	6.44	1,270	17	0.01	0.00	0.03	0.92	0.00	0.03
Metallic Ores	0.27	880	30,078	0.00	0.00	0.62	0.07	0.31	0.00
Mixed Freight	2.31	766	14	0.01	0.00	0.04	0.91	0.02	0.02
Non-Metallic Mineral Products	0.39	683	140	0.00	0.00	0.20	0.79	0.01	0.00
Pharmaceuticals	24.91	1,471	9	0.02	0.00	0.00	0.88	0.00	0.10
Primary Base Metal	0.98	955	52	0.00	0.00	0.29	0.71	0.00	0.00
Sand	0.03	688	173	0.00	0.00	0.46	0.54	0.00	0.00
Vehicles	4.52	1,250	30	0.01	0.00	0.18	0.78	0.00	0.03

- Substantial variation in characteristics by type of good shipped
- Strong relationships with modal shares

Modes and shipment characteristics



Variation in modal shares within goods



Model for mode choice of cost-minimizing shippers

Shippers choose mode j to minimize sum of *rate*, *inventory cost* (time), and *fixed cost* per shipment:

$$cost_{ij} = \underbrace{\gamma_j \eta_j P_t \times tonmiles_i}_{\text{Rate}} + \underbrace{1/\sigma_j \times miles_i \times r \times value_i}_{\text{Inventory Cost}} + \underbrace{\delta_j}_{\text{Fixed Cost}}$$

Freight rate

- Fuel intensity (η_j) times ton-miles yields fuel consumption
- Times fuel price (P_t) yields fuel expenditure
- Markup to freight rate (γ_j)

Inventory cost

- Shipment distance ($miles_i$) divided by mode average speed (σ_j) yields travel time
- Times shipment value and discount rate (r) yields time cost

Model for mode choice of cost-minimizing shippers

Estimate reduced form:

$$cost_{ij} = \alpha_{cj} P_t \times tonmiles_i + \beta_{cj} miles_i \times value_i + \delta_{cj} + \epsilon_{ij}$$

- Estimate separately by commodity group (c)
  - Pass-through, fuel intensity, speed, discount rate and fixed cost parameters may vary by type of good shipped
- Fuel price-tonmile term captures *cross-sectional* differences in shipment sizes and (limited) *time-series* variation in fuel price
- Incremental fixed cost for Mississippi River basin (δ_j^m)
- Incremental inventory cost for temperature controlled shipments (δ_j^{tc})

Marginal effects of fuel price change - grain and coal shipments

Effect of Diesel Price on Mode Choice Probabilities

	Grain Shipments				Coal Shipments		
	Truck	Rail	Inland Water		Truck	Rail	Inland Water
10,000 Ton-Miles	-0.018**	0.017**	0.001**	60,000 Ton-Miles	-0.043	0.03	0.013
	(0.008)	(0.008)	(0.000)		(0.047)	(0.034)	(0.016)
20,000 Ton-Miles	-0.093**	0.090**	0.003**	80,000 Ton-Miles	-0.077	0.053	0.024
	(0.046)	(0.045)	(0.001)		(0.085)	(0.060)	(0.029)
30,000 Ton-Miles	-0.223***	0.218***	0.006**	100,000 Ton-Miles	-0.120	0.082	0.037
	(0.060)	(0.060)	(0.003)		(0.122)	(0.085)	(0.043)
40,000 Ton-Miles	-0.249***	0.244***	0.0050	120,000 Ton-Miles	-0.165	0.113	0.052
	(0.053)	(0.050)	(0.004)		(0.130)	(0.090)	(0.050)
50,000 Ton-Miles	-0.143	0.141	0.0020	140,000 Ton-Miles	-0.199**	0.136**	0.063
	-0.106	-0.103	(0.003)		-0.090	-0.061	-0.046
60,000 Ton-Miles	-0.057	0.056	0.001	160,000 Ton-Miles	-0.213***	0.145***	0.069*
	(0.066)	(0.065)	(0.001)		(0.025)	(0.027)	(0.035)
70,000 Ton-Miles	-0.020	0.020	0.000	180,000 Ton-Miles	-0.205**	0.138*	0.066
	(0.029)	(0.028)	(0.001)		(0.102)	(0.076)	(0.042)
80,000 Ton-Miles	-0.007	0.007	0.000	200,000 Ton-Miles	-0.179	0.121	0.058
	(0.011)	(0.011)	(0.000)		(0.174)	(0.123)	(0.059)
Observations	24817	24817	24817		10602	10602	10602

Notes: Average marginal effects for a change in diesel price on mode choice probability evaluated at different shipments sizes (ton-miles). Marginal effect evalated at the means of shipment value and miles. Stardard errors clustered at the route-level in parentheses. ***, ** and * denote significance at the 1 percent, 5 percent and 10 percent levels.

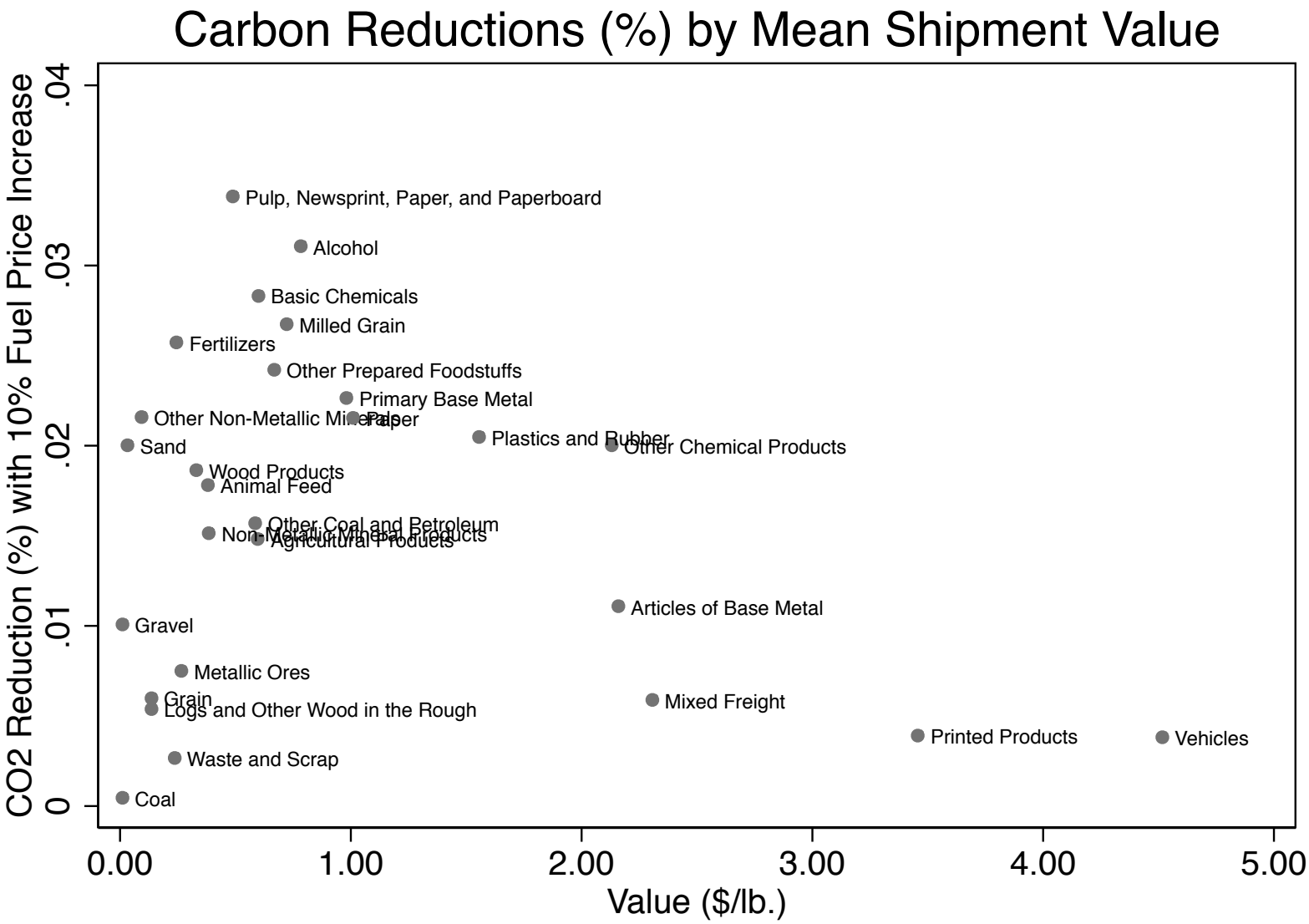
Simulated energy consumption and emissions

Fuel Prices, Fuel Use and Emissions

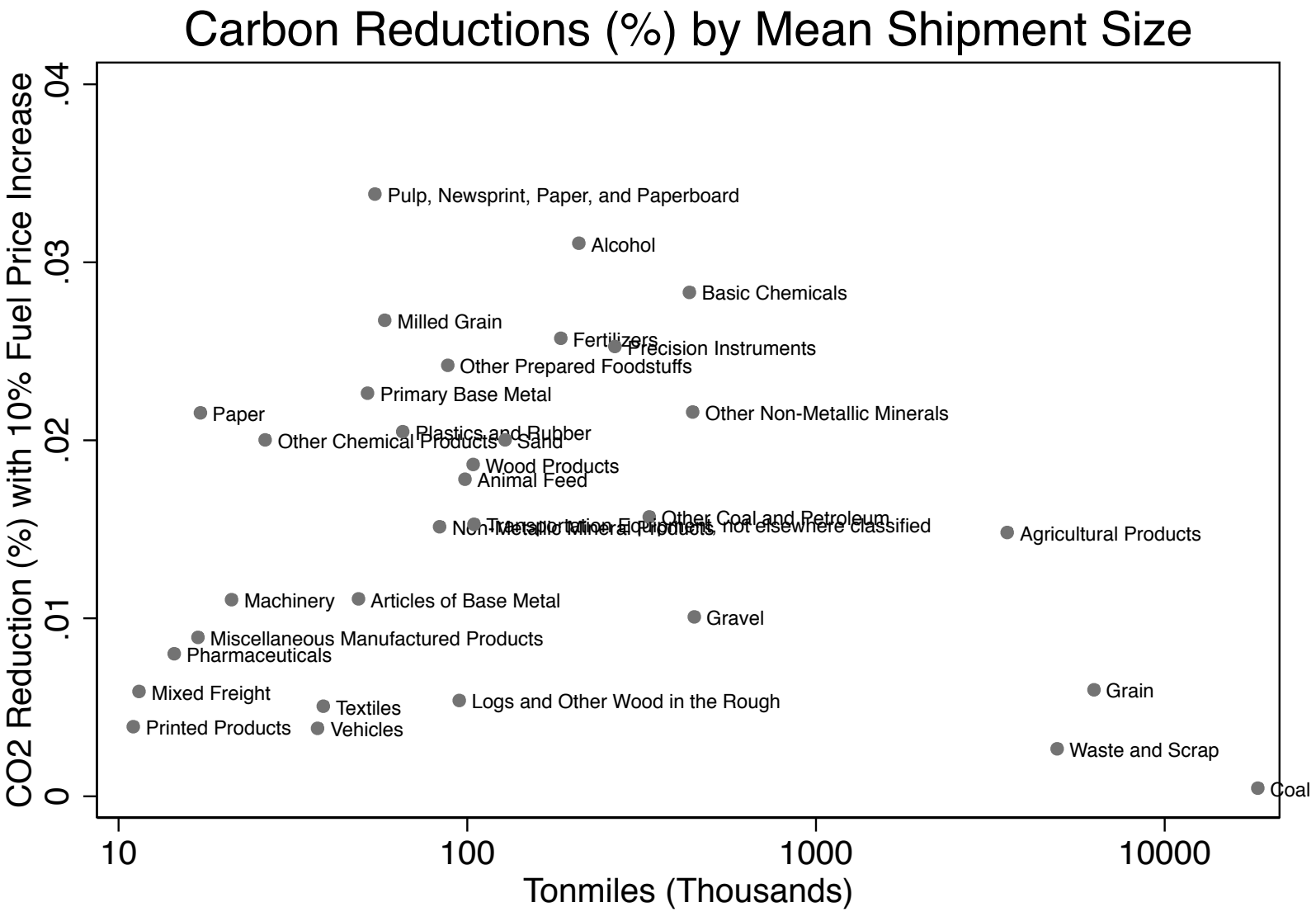
	BAU	10%	25%	50%	100%
Air (billion ton-miles)	2.12	2.02	1.91	1.79	1.62
Inland water (billion ton-miles)	93.64	89.53	82.40	72.78	69.66
Rail (billion ton-miles)	1,275.10	1,304.95	1,348.15	1,410.93	1,501.26
Truck (billion ton-miles)	1,115.45	1,089.80	1,053.84	1,000.81	913.77
Fuel (million gal.)	16,395	16,140	15,786	15,269	14,418
Emissions (MMT)	166.58	163.98	160.38	155.13	146.49
Percent change		-1.6%	-3.7%	-6.9%	-12.1%

- Totals from 500 simulated mode choices for each shipment
  - Predicted mode probabilities are latent variable plus extreme value error draw
  - Assume most probable mode selected
  - Sum up fuel consumption and emissions across shipments by predicted mode
- Essentially all emissions reductions from come truck to rail switching

Emissions reductions by good shipped



Emissions reductions by good shipped



Marginal abatement costs

Main model - 2012 CFS PUM data

- Simulate mode choices and emissions reductions for carbon taxes up to \$100 per MT CO_2
- Assume full pass-through (Marion and Muehlegger, 2011)
- Likely an upper bound because we hold shipments and infrastructure fixed
- A tax of \$50 per MT CO_2 lowers emissions by 3.25 MMT (2%)
  - Electricity generation: \$70/MT CO_2 lowers emissions by 200 MMT (10%) (Cullen and Mansur, 2017)
  - Transportation fuels: \$41/MT CO_2 lower emissions by approximately 165 MMT (10%) (Holland et. al., 2015)

CFS public tabulations for 2002, 2007 and 2012

- Main results rely largely on cross-sectional variation in shipment characteristics
- Check this approach using alternate data and identification
- CFS Public Tabulations for 2002, 2007 and 2012
- Trade-offs
  - Time-series variation in fuel prices ($1.55 to $3.77)
  - Potential to estimate longer run responses
  - Mode shares by average shipment characteristics between origin and destination state
    - Requires somewhat different but analogous modeling approach
  - Redacted observations may create selection problems

CFS public tabulations for 2002, 2007 and 2012

- Observe total tons, tonmiles and value, plus average shipment distances
- If shippers minimize average shipping cost per ton:

$$cpt_{rjt} = \alpha_j' P_t \times \overline{miles}_{rjt} + \beta_j' \overline{miles}_{rjt} \times vpt_{rjt} + \delta_j' + \epsilon_{rjt}$$

- Conceptually, this is equivalent to dividing through by total tons in our main model to get average values
- Fuel prices and shipment characteristics vary by year t
- Shipment characteristics vary by good j across origin-by-destination states r

Energy consumption and emissions - 2002, 2007 and 2012 tabulations

Fuel Prices, Fuel Use and Emissions

	BAU	10%	25%	50%	100%
Air (billion ton-miles)	45.58	45.57	45.56	45.56	45.61
Inland water (billion ton-miles)	626.95	631.31	638.62	649.15	671.29
Rail (billion ton-miles)	3,422.49	3,492.21	3,587.39	3,738.87	3,992.81
Truck (billion ton-miles)	2,320.28	2,246.20	2,143.72	1,981.72	1,705.58
Fuel (million gal.)	42,026	41,314	40,331	38,780	36,139
Emissions (MMT)	426.98	419.75	409.76	394.00	367.17
Percent change		-1.7%	-4.0%	-7.7%	-14.0%

- Estimates using the 2002, 2007 and 2012 CFS tabulations yield slightly larger predicted percentage reductions
- Totals not directly comparable because of pooling and redacted observations

Importance of mode choice in transportation energy policies

Fuel economy standards

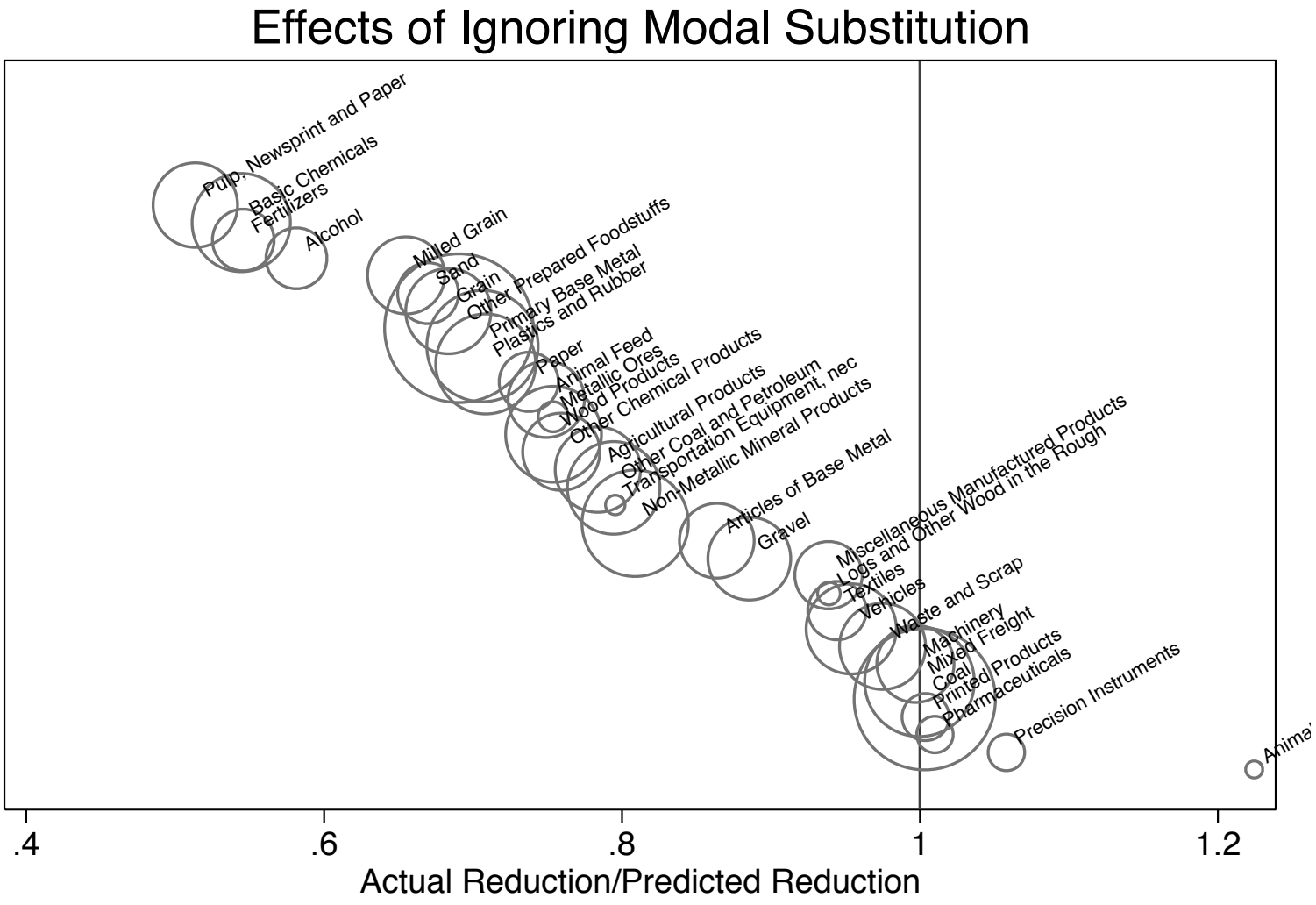
- EPA Phase II heavy-duty fuel economy standards projected to lower fuel intensity 5% by 2025
- Potentially perverse effect where more efficient trucks attract some shipments from rail
- Adapt our model to specify mode-specific energy intensities
  - Assume mean fuel intensities across modes
  - Estimate a mixed logit model
  - Simulate 500 mode choices, fuel consumption and emissions

"Cross-rebound" lowers reductions 22%

Fuel Prices, Fuel Use and Emissions

	BAU	CAFE Pred.	CAFE
Ton-miles			
Air (billion ton-miles)	1.96	1.96	1.95
Inland water (billion ton-miles)	125.97	125.97	125.85
Rail (billion ton-miles)	1,222.08	1,222.08	1,206.39
Truck (billion ton-miles)	1,105.05	1,105.05	1,120.87
Fuel			
Air (million gal.)	261.43	261.43	260.65
Inland water (million gal.)	209.95	209.95	209.75
Rail (million gal.)	2,715.74	2,715.74	2,680.86
Truck (million gal.)	13,000.55	12,350.52	12,527.40
Emissions			
Air (MMT)	2.66	2.66	2.65
Inland water (MMT)	2.13	2.13	2.13
Rail (MMT)	27.59	27.59	27.24
Truck (MMT)	132.09	125.48	127.28
Fuel (million gal.)	16,188	15,538	15,679
Emissions (MMT)	164.47	157.86	159.30
Percent change		4.0%	3.1%

Effects of ignoring modal substitution



Discussion

- Simulations suggest substantial emissions reductions from modal substitution
  - A 10% increase in fuel price leads to a 1.6% decrease in fuel use and emissions
- Main mechanism is shifting from truck to less fuel intensive rail
  - Largest effect for moderately sized shipments of moderately valuable goods
- Abatement from freight mode substitutions comes at relatively high marginal abatement cost
- Ignoring mode choice can lead policy makers to draw the wrong conclusions about transportation polices
  - "Cross-rebound" effect but also policies that change relative speeds of modes or congestion

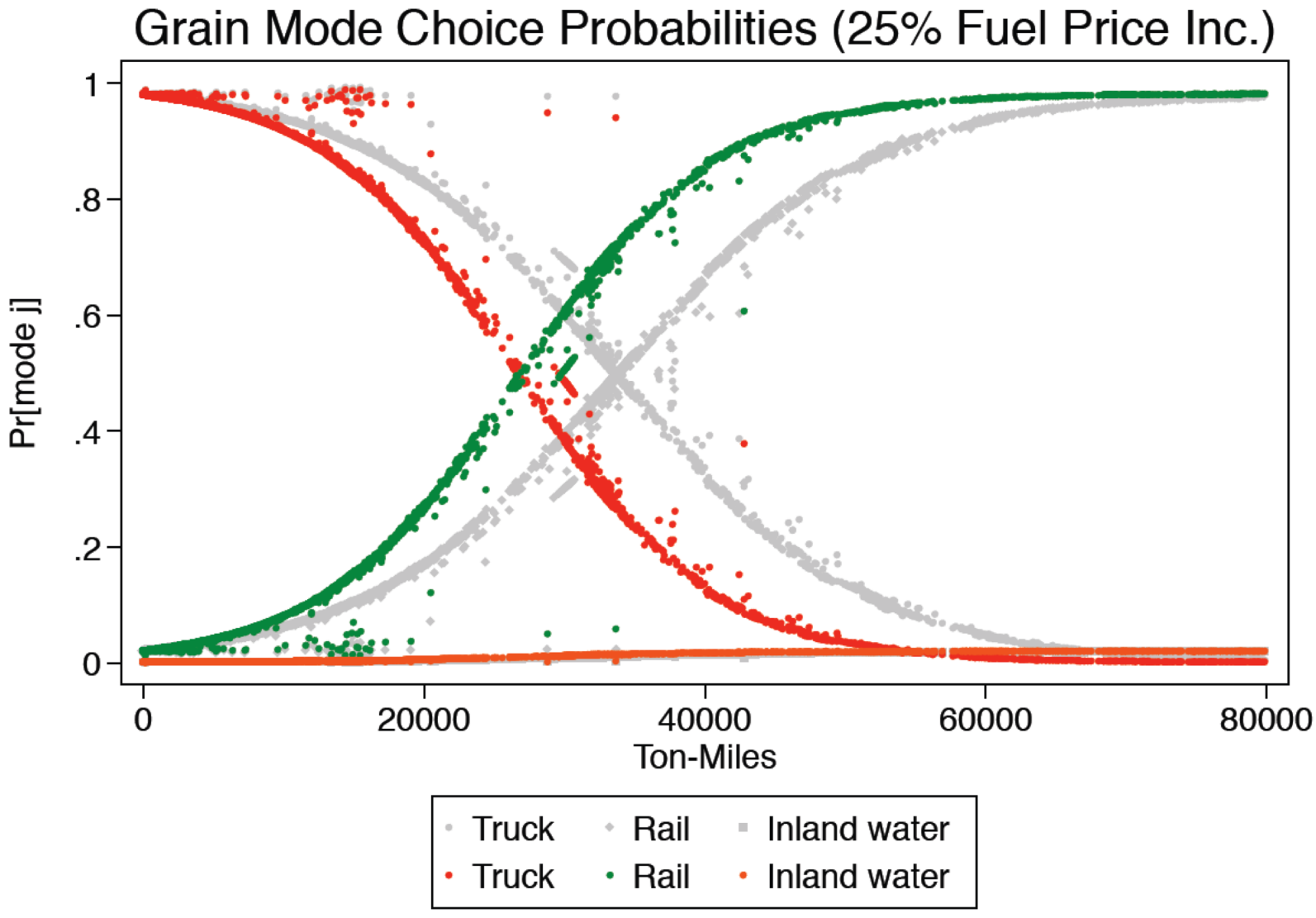
Marginal effects of fuel price change - alcohol and precisions instruments

Effect of Diesel Price on Mode Choice Probabilities

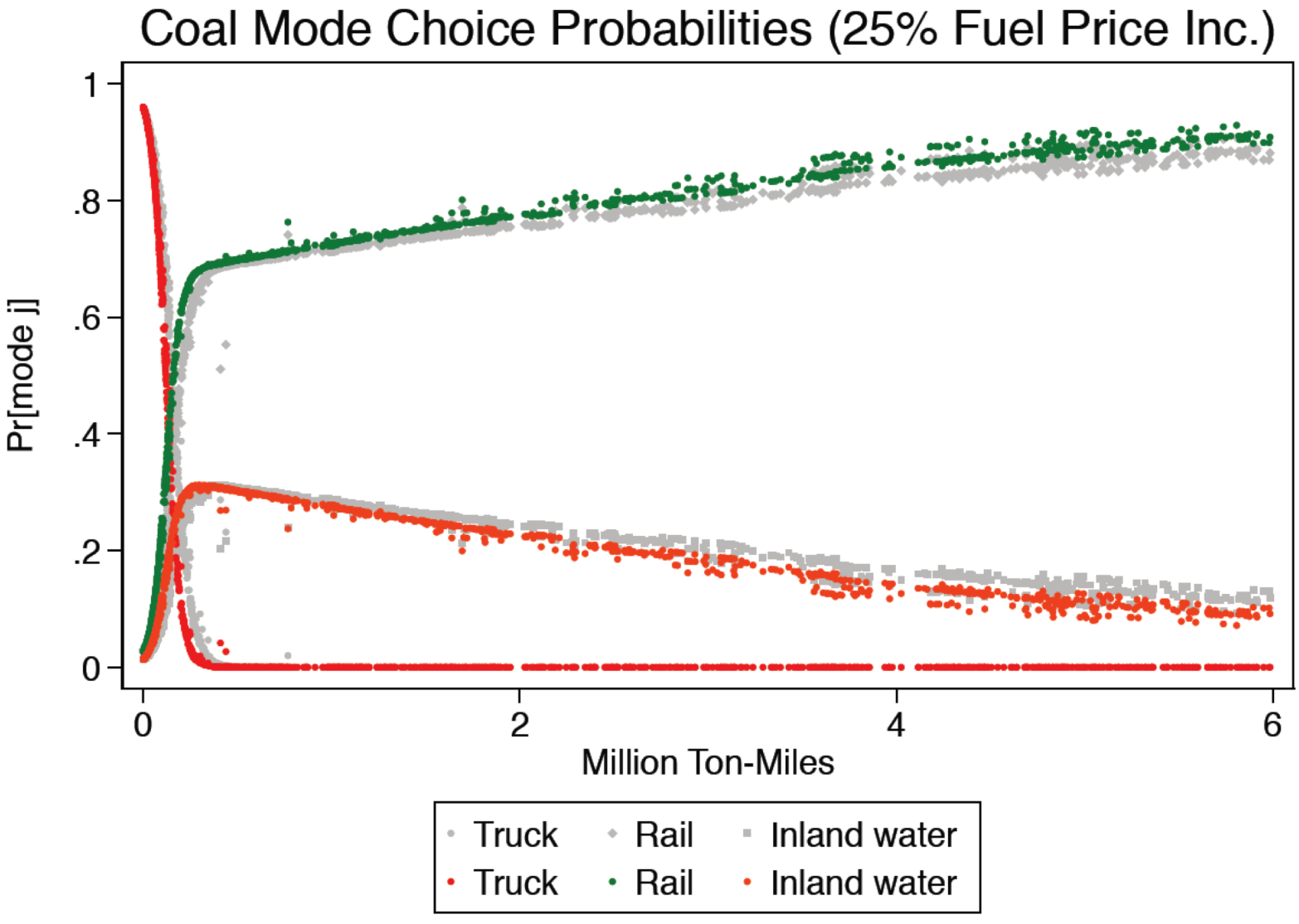
	Alcohol			Precision Instruments	
	Truck	Rail		Truck	Air
30,000 Ton-Miles	-0.009***	0.009***	500 Ton-Miles	0.014***	-0.014***
	(0.003)	(0.003)		(0.004)	(0.004)
40,000 Ton-Miles	-0.035***	0.035***	1,000 Ton-Miles	0.020***	-0.020***
	(0.013)	(0.013)		(0.003)	(0.003)
50,000 Ton-Miles	-0.122**	0.122**	1,500 Ton-Miles	0.022***	-0.022***
	(0.049)	(0.049)		(0.002)	(0.002)
60,000 Ton-Miles	-0.321***	0.321***	2,000 Ton-Miles	0.020***	-0.020***
	(0.105)	(0.105)		(0.003)	(0.003)
70,000 Ton-Miles	-0.506***	0.506***	2,500 Ton-Miles	0.017***	-0.017***
	-0.038	-0.038		-0.005	-0.005
80,000 Ton-Miles	-0.418***	0.418***	3,000 Ton-Miles	0.014**	-0.014**
	(0.113)	(0.113)		(0.006)	(0.006)
90,000 Ton-Miles	-0.213*	0.213*	3,500 Ton-Miles	0.011*	-0.011*
	(0.115)	(0.115)		(0.006)	(0.006)
100,000 Ton-Miles	-0.085	0.085	4,000 Ton-Miles	0.008	-0.008
	(0.061)	(0.061)		(0.006)	(0.006)
	121138	121138	Observations	40807	40807

Notes: Average marginal effects for a change in diesel price on mode choice probability evaluated at different shipments sizes (ton-miles). Marginal effect evalated at the means of shipment value and miles. Standard errors clustered at the route-level in parentheses. ***, ** and * denote significance at the 1 percent, 5 percent and 10 percent levels.

Predicted mode choice probabilities - grain shipments



Predicted mode choice probabilities - coal shipments



Freight output by mode

	Ton-Mile Weighted			
	Mean	**Std. Dev.**	**Min.**	**Max.**
Value	415,000.00	2,750,000	1.00	521,000,000
Miles	1,089.16	731	1.00	6,677
Tons	5,066.56	12,500	0.00	139,000
Air	0.00	0.04	0.00	1.00
Pipeline	0.01	0.10	0.00	1.00
Rail	0.48	0.50	0.00	1.00
Truck	0.46	0.50	0.00	1.00
Water	0.04	0.20	0.00	1.00
Parcel/Courier	0.01	0.09	0.00	1.00

- Truck and rail have approximately equal share of total ton-miles

Multinomial logit observed and predicted output

	Truck		Rail		Water		Air	
Commodity Group	**CFS**	**Pred.**	**CFS**	**Pred.**	**CFS**	**Pred.**	**CFS**	**Pred.**
Agricultural Products	38.5	38.5	28.9	28.8	16.1	16.3	0.0	0.0
Alcohol	20.6	20.6	12.9	12.9	0.0	0.0	0.0	0.0
Animal Feed	33.3	33.3	19.9	19.9	0.0	0.0	0.0	0.0
Animals	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Articles of Base Metal	33.8	33.8	6.1	6.1	0.0	0.0	0.0	0.0
Basic Chemicals	45.8	45.8	72.9	72.9	13.1	13.2	0.0	0.0
Coal	9.8	9.8	603.2	603.2	23.2	23.2	0.0	0.0
Fertilizers	17.8	17.8	32.0	32.0	1.5	1.4	0.0	0.0
Grain	17.5	17.5	136.8	136.9	15.3	15.2	0.0	0.0
Gravel	39.4	39.5	12.6	12.6	7.8	7.8	0.0	0.0
Logs and Other Wood in the Rough	3.2	3.2	0.3	0.3	0.0	0.0	0.0	0.0
Machinery	32.6	32.6	1.1	1.1	0.0	0.0	0.4	0.4
Metallic Ores	2.1	2.1	18.0	18.0	0.0	0.0	0.0	0.0
Milled Grain	34.3	34.3	15.1	15.0	0.0	0.0	0.0	0.0
Miscellaneous Manufactured Products	25.6	25.6	1.2	1.2	0.0	0.0	0.3	0.3
Mixed Freight	66.9	66.9	3.1	3.1	0.0	0.0	0.8	0.8
Non-Metallic Mineral Products	67.8	67.9	17.2	17.2	0.0	0.0	0.0	0.0
Other Chemical Products	36.3	36.3	8.2	8.2	0.0	0.0	0.0	0.0
Other Coal and Petroleum	47.6	47.5	26.8	26.8	9.3	9.3	0.0	0.0
Other Non-Metallic Minerals	15.0	15.0	10.9	10.9	5.4	5.4	0.0	0.0
Other Prepared Foodstuffs	126.9	126.8	68.0	68.1	0.0	0.0	0.0	0.0
Paper	21.1	21.1	3.9	3.9	0.0	0.0	0.0	0.0
Pharmaceuticals	6.6	6.6	0.0	0.0	0.0	0.0	0.1	0.1
Plastics and Rubber	54.4	54.4	43.5	43.5	0.0	0.0	0.0	0.0
Precision Instruments	3.7	3.7	0.0	0.0	0.0	0.0	0.4	0.4
Primary Base Metal	72.1	72.1	29.5	29.5	0.0	0.0	0.0	0.0
Printed Products	12.6	12.6	0.0	0.0	0.0	0.0	0.1	0.1
Pulp, Newsprint, Paper, and Paperboard	40.0	40.0	27.4	27.4	0.0	0.0	0.0	0.0
Sand	20.2	20.2	17.3	17.3	0.0	0.0	0.0	0.0
Textiles	21.3	21.3	0.8	0.7	0.0	0.0	0.0	0.0
Transportation Equipment, not elsewhere (	2.1	2.1	1.5	1.5	0.1	0.1	0.0	0.0
Vehicles	49.1	49.1	11.5	11.5	0.0	0.0	0.0	0.0
Waste and Scrap	43.5	43.6	17.5	17.3	1.7	1.8	0.0	0.0
Wood Products	52.6	52.6	27.3	27.3	0.0	0.0	0.0	0.0

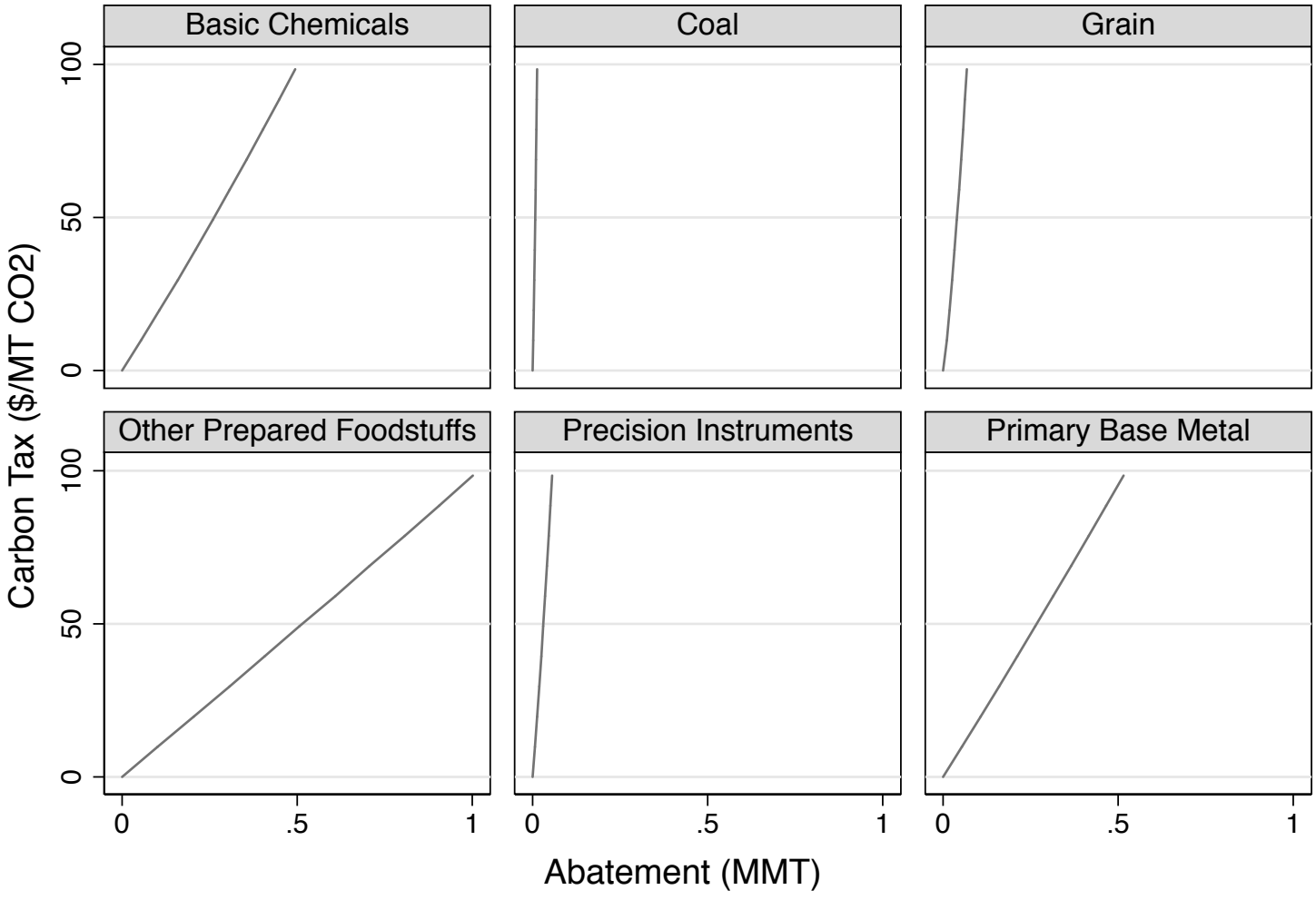
Notes: Commidity Flow Survey (CFS) ton miles by SCTG and mode (in millions of ton miles). Predicted ton-miles by SCTG and mode are average values across our simulated mode choices, Section 4, in millions of ton miles.

Mixed logit observed and predicted output

	Truck		Rail		Water		Air	
Commodity Group	CFS	Pred.	CFS	Pred.	CFS	Pred.	CFS	Pred.
Agricultural Products	38.5	38.7	28.9	26.5	16.1	18.4	0.0	0.0
Alcohol	20.6	20.6	12.9	12.9	0.0	0.0	0.0	0.0
Animal Feed	33.3	33.3	19.9	19.9	0.0	0.0	0.0	0.0
Animals	1.3	1.3	0.0	0.0	0.0	0.0	0.0	0.0
Articles of Base Metal	33.8	33.7	6.1	6.1	0.0	0.0	0.0	0.0
Basic Chemicals	45.8	46.0	72.9	68.7	13.1	17.1	0.0	0.0
Coal	9.8	11.2	603.2	578.3	23.2	46.8	0.0	0.0
Fertilizers	17.8	17.8	32.0	31.8	1.5	1.7	0.0	0.0
Grain	17.5	17.8	136.8	131.7	15.3	20.1	0.0	0.0
Gravel	39.4	39.5	12.6	12.8	7.8	7.6	0.0	0.0
Logs and Other Wood in the Rough	3.2	3.2	0.3	0.3	0.0	0.0	0.0	0.0
Machinery	32.6	32.7	1.1	1.0	0.0	0.0	0.4	0.4
Metallic Ores	2.1	2.1	18.0	18.0	0.0	0.0	0.0	0.0
Milled Grain	34.3	34.3	15.1	15.1	0.0	0.0	0.0	0.0
Miscellaneous Manufactured Products	25.6	25.3	1.2	1.5	0.0	0.0	0.3	0.3
Mixed Freight	66.9	69.4	3.1	0.8	0.0	0.0	0.8	0.6
Non-Metallic Mineral Products	67.8	67.8	17.2	17.2	0.0	0.0	0.0	0.0
Other Chemical Products	36.3	36.3	8.2	8.2	0.0	0.0	0.0	0.0
Other Coal and Petroleum	47.6	47.7	26.8	24.9	9.3	11.0	0.0	0.0
Other Prepared Foodstuffs	126.9	126.9	68.0	68.0	0.0	0.0	0.0	0.0
Paper	21.1	21.1	3.9	3.9	0.0	0.0	0.0	0.0
Pharmaceuticals	6.6	6.6	0.0	0.0	0.0	0.0	0.1	0.1
Plastics and Rubber	54.4	54.4	43.5	43.5	0.0	0.0	0.0	0.0
Precision Instruments	3.7	3.7	0.0	0.0	0.0	0.0	0.4	0.4
Primary Base Metal	72.1	72.1	29.5	29.5	0.0	0.0	0.0	0.0
Printed Products	12.6	12.6	0.0	0.0	0.0	0.0	0.1	0.1
Pulp, Newsprint, Paper, and Paperboard	40.0	40.0	27.4	27.4	0.0	0.0	0.0	0.0
Sand	20.2	20.2	17.3	17.3	0.0	0.0	0.0	0.0
Textiles	21.3	21.3	0.8	0.7	0.0	0.0	0.0	0.0
Transportation Equipment, not elsewhere (	2.1	2.1	1.5	1.4	0.1	0.1	0.0	0.0
Vehicles	49.1	49.1	11.5	11.5	0.0	0.0	0.0	0.0
Waste and Scrap	43.5	43.7	17.5	15.8	1.7	3.1	0.0	0.0
Wood Products	52.6	52.6	27.3	27.3	0.0	0.0	0.0	0.0

Notes: Commidity Flow Survey (CFS) ton miles by SCTG and mode (in millions of ton miles). Predicted ton-miles by SCTG and mode are average values across our simulated mode choices, Section 7, in millions of ton miles.

Marginal abatement costs for representative goods



Aggregate marginal abatement costs - all goods