Energy Consumption, Emissions and Modal Substitution in U.S. Freight Transportation
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Freight transportation represents over 31% of transportation energy consumption and over 90% of U.S. diesel fuel consumption. Fuel expenditures make up as much as 30-40% of freight costs. Further, the energy intensity of freight transportation varies dramatically across modes. Air freight can consume 30 BTU per ton-mile, trucks 4 BTU per ton-mile, and 0.5 BTU per ton-mile for barge and rail transportation. However, despite the size of this sector and heterogeneity in energy consumption patterns, we know very little about the role of fuel prices in freight mode choice today.[1] Importantly, recent changes to freight operations, in particular rail, have likely affected how shippers choose modes. Understanding the relationship between fuel prices and mode choice is increasingly important in light of carbon policy or other factors leading to future fuel price changes.

This project seeks to answer the following questions:

1. How do characteristics of goods and shipments, for instance value, distance and size, affect shippers' mode choices?
2. Given large differences in travel speeds, freight rates and fuel efficiencies, which modes see increases (decreases) in freight shipments when fuel prices increase (decrease)?
3. Which types of goods or shipments are affected most by fuel price changes?
4. What are the direct effects of modal substitution on energy consumption and emissions?
5. Are there important secondary effects on, for instance, shipment travel times, inventories or production decisions?

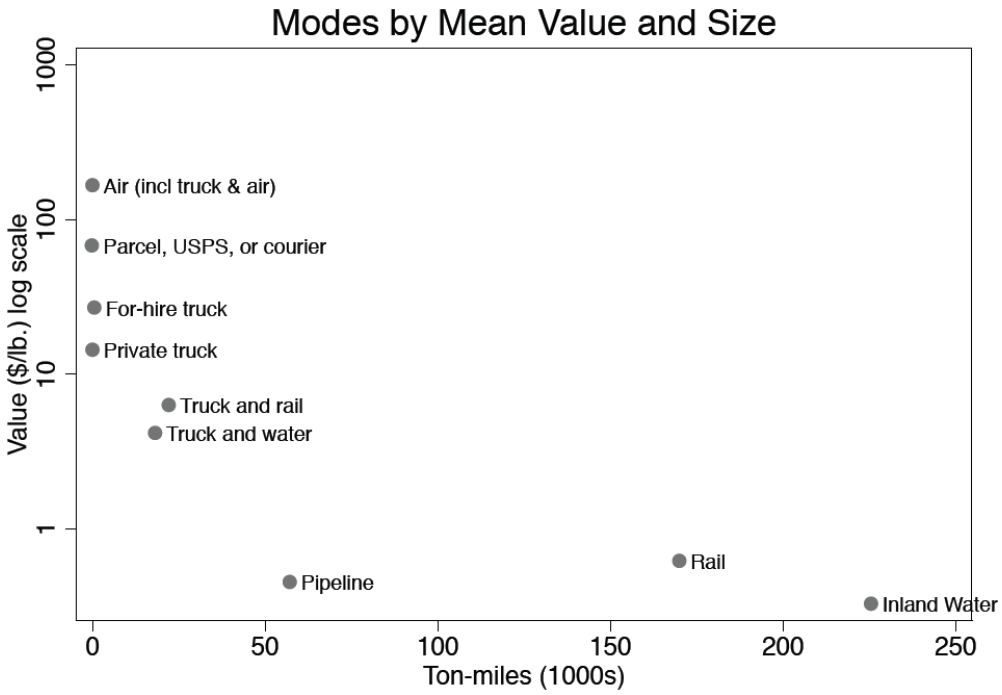
Proposed Research Design

There are few comprehensive data on freight transportation within the US. However, the US Census Bureau has recently released public microdata from the 2012 Commodity Flow Survey (CFS). The CFS contains information on approximately 4.5 million shipments including the type of good being shipped, origin and destination, weight, value, distance and mode. Importantly, it is the only publicly available disaggregate data for the truck/highway mode.

Our approach is to use variation in shipment characteristics to estimate a multinomial logit model for mode choice. Because we are currently limited to the 2012 CFS, we rely on cross-sectional variation. Similar, but not yet publicly available, data exist for other CFS years and we hope the Census Bureau will make these data available during this project. That said, our initial analysis of the 2012 data suggests there is sufficient variation in the cross-section to estimate our model, albeit at the cost of requiring stronger assumptions on the mode choice behavior of shippers.

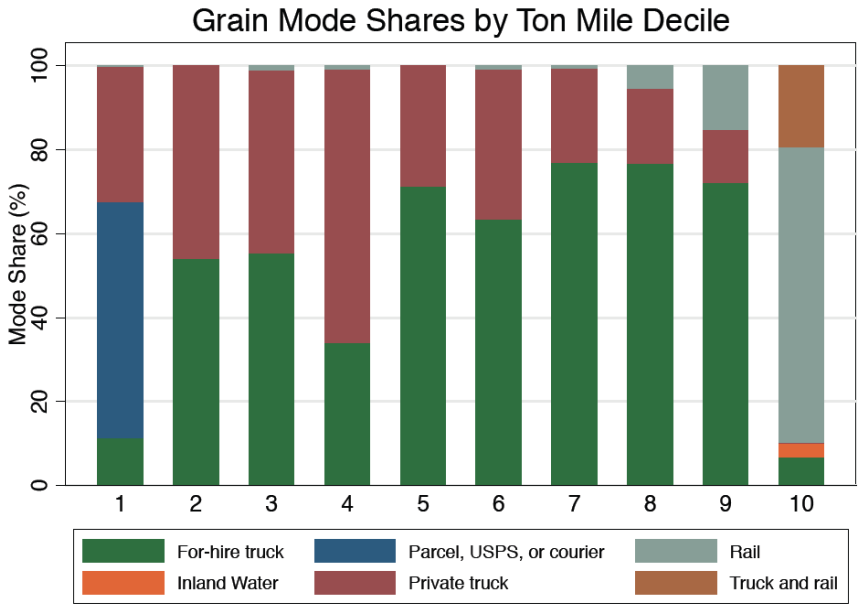
[1] There is a large literature on freight mode choice going back several decades. For instance, see Friedlaender and Spady (1980), Levin (1978), and Winston (1981). However, there is little recent evidence that reflects changes in freight operations over the last several years.

Summary statistics from the 2012 CFS suggest strong relationships between shipment characteristics and freight transportation modes. Below we plot the means of shipment value per pound and shipment size in ton-miles for several common modes. We see smaller, higher value shipments tend to travel by faster less fuel-efficient modes such as air, courier or truck. Larger, lower value shipments move by slower more fuel-efficient modes such as pipeline, rail and water.



There is also substantial variation in mode choice within good type due to differences in shipment size, value and distance. For instance, below we plot mode shares for grain shipments by the deciles of shipment size in ton-miles. We see parcel or courier make up most of the very small shipments in the first decile. Truck, either private or for-hire, dominates over most of the shipment size range. However, rail share grows as shipment size increases, beginning at the eighth decile. For the largest shipments, rail share exceeds 70% and a small number of shipments are made by inland water (barge). Many other goods exhibit similar modal patterns.

With these trends in mind, our empirical model builds on the classical model for freight mode choice (Friedlaender and Spady, 1980). We assume cost-minimizing shippers trade-off rates with inventory costs. Rates depend on mode and shipment characteristics such as fuel efficiency, fuel prices, shipment weight, distance and carrier market power. Inventory costs depend on transit times, that vary by mode, and good characteristics such as perishability and value. There can also be fixed setup costs that vary across modes, such as dryage or transshipment costs.



More formally, we assume shippers chose mode *j* to minimize the sum of freight rate, inventory and setup costs. Rates are set are set as a proportion (γ_φ) of fuel costs, where fuel costs depend on the size of shipment *i* in ton-miles times the fuel efficiency of mode *j* (η_j) and fuel price Pd_t. We model inventory costs as the product of transit time, calculated as shipment distance ($miles_i$) divided by the mean speed of mode *j* (θ_j), times shipment value (v_i) and discount rate (r). Mode-specific fixed costs are denoted by (δ_j).

$$Cost_{ij} = \gamma_j \eta_j Pd_t \times Tonmiles_i + \frac{1}{\theta_j} miles_i \times r \times value_i + \delta_j$$

In practice, we estimate mode choice based on a reduced form of the above, namely:

$$Cost_{ij} = \alpha_j Pd_t \times Tonmiles_i + \beta_j miles_i \times value_i + \delta_j + \epsilon_{ij}$$

Because cost pass-though, inventory and fixed costs likely vary across the type of good shipped, we estimate mode choice separately for each commodity group.

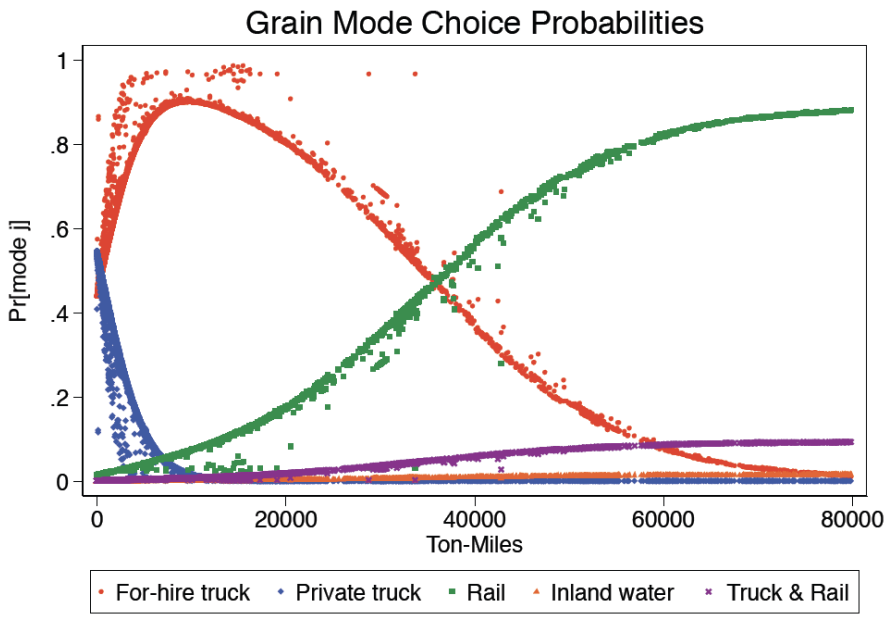
The table below shows the average marginal effect of a change in fuel price on the probability a shipment travels by for-hire truck, rail, inland water or a combination of truck and rail service. We calculate the marginal effect for different shipment sizes, in ton-miles, at the means of value and distance. The largest effects occur for the truck and rail modes and shipments in the 30,000 to 50,000 ton-mile range. In this range, truck and rail are good substitutes. An increase in fuel price is associated with a large decrease in the probability truck is selected, about -0.18 to -0.23, and a large increase in the probability the shipment moves by rail, about 0.16 to 0.21. We see similar marginal effects and substitution patterns for other goods and freight modes.

Effect of Diesel Price on Freight Mode Choice Probabilities

	For-Hire Truck	Rail	Inland Water	Truck and Rail
10,000 Ton-Miles	-0.003***	0.018***	0.000***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
20,000 Ton-Miles	-0.079***	0.072***	0.001***	0.008***
	(0.000)	(0.000)	(0.000)	(0.000)
30,000 Ton-Miles	-0.180***	0.161***	0.003***	0.017***
	(0.000)	(0.000)	(0.000)	(0.000)
40,000 Ton-Miles	-0.228***	0.203***	0.003***	0.022***
	(0.000)	(0.000)	(0.000)	(0.000)
50,000 Ton-Miles	-0.175***	0.208***	0.004***	0.017***
	(0.001)	(0.000)	(0.000)	(0.000)
60,000 Ton-Miles	-0.097***	0.092***	0.001***	0.010***
	(0.001)	(0.001)	(0.000)	(0.000)
70,000 Ton-Miles	-0.046***	0.041***	0.001***	0.005***
	(0.000)	(0.000)	(0.000)	(0.000)
80,000 Ton-Miles	-0.021***	0.018***	0.000***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Observations	24807	24807	24807	24807

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. ***, ** and * denote significance at the 1 percent, 5 percent and 10 percent levels.

Using our parameter estimates, we predict the probability a shipment travels by a given mode. Below we plot the predicted mode probabilities for grain shipments over the range of shipment size in ton-miles. The curves depict the strong relationship between ton-miles and the probabilities of choosing particular modes. Variation around the curves comes from differences in shipment values. Other goods in the CFS exhibit similar patterns.



Finally, we use our model to estimate the short-run effects of hypothetical fuel price changes. For exposition, we again focus on grain shipments. The business as usual scenario (BAU) represents the baseline predictions of our model at 2012 fuel prices. The next four columns model fuel prices that are 10% - 100% higher than 2012. We calculate mode choice probabilities for each shipment and assume shippers choose the mode with the highest predicted probability. We then add up fuel consumption and greenhouse gas emissions in each scenario, taking into account fuel efficiencies/emissions rates across modes. We see that modest increases in fuel price cause shippers to substitute rail for truck service. A 25% fuel price increase is associated with a 9% decrease in truck ton-miles and over a 3% increase in grain shipments by rail. This leads to approximately 3% less fuel consumption and carbon dioxide emissions. Preliminary estimates for a variety of other goods suggest similar reductions in emissions and fuel consumption from mode shifting.

Fuel Prices, Grain Shipments, Fuel Use and Emissions

	BAU	10%	25%	50%	100%
Truck (billion ton-miles)	18.54	17.67	16.85	16.65	15.96
Rail (billion ton-miles)	147.09	151.18	152.00	152.85	153.54
Inland water (billion ton-miles)	3.91	0.69	0.69	0.04	0.04
Fuel (million gal.)	590.93	582.57	572.99	570.96	562.99
Emissions (MMT)	5.32	5.24	5.16	5.14	5.07
Percent change		-1.4%	-3.0%	-3.4%	-4.7%

Overall, this project should greatly improve our understanding of freight shipping patterns and the relationships between fuel prices, mode switching, fuel consumption and emissions. While we plan on exploiting time-series variation from additional commodity flow surveys, our initial analysis of the 2012 CFS suggests the research design is promising even if limited to a single cross-section.

Conflict of interest statement:

There are no financial conflicts of interest to disclose for either author. A portion of this research, if selected, will be conducted while Hughes is a visiting scholar at the National Renewable Energy Laboratory.