Firm Boundaries and External Costs in Shale Gas Production

Matthew O'Keefe (Northwestern University)

January 2024

When do markets form?

- Coase (1937, 1960): when **transaction costs** are low enough
- Large empirical literature testing theoretical predictions (e.g., asset specificity)
- Limited work on *quantifying* transaction costs
  - Wallis and North (1986), Masten et al (1991), Atalay et al (2019), ...

This paper: new evidence from wastewater sharing in Pennsylvania

- Fracking a shale gas well requires 10-20M gallons of water at once
- Over time, 25% returns as wastewater (along with hydrocarbons)
- Firms often **reuse** wastewater as a substitute for freshwater
  - Typical well: saves \$0.25M in freshwater costs, \$0.75M in final disposal costs

This paper: new evidence from wastewater sharing in Pennsylvania

- Fracking a shale gas well requires 10-20M gallons of water at once
- Over time, 25% returns as wastewater (along with hydrocarbons)
- Firms often **reuse** wastewater as a substitute for freshwater
  - Typical well: saves \$0.25M in freshwater costs, \$0.75M in final disposal costs
- Approx. 10% of reuse occurs via **sharing** – trade between rival firms
  - Reduce cost of reuse via more efficient matching of old wells to new wells

This paper: new evidence from wastewater sharing in Pennsylvania

- Fracking a shale gas well requires 10-20M gallons of water at once
- Over time, 25% returns as wastewater (along with hydrocarbons)
- Firms often **reuse** wastewater as a substitute for freshwater
  - Typical well: saves \$0.25M in freshwater costs, \$0.75M in final disposal costs
- Approx. 10% of reuse occurs via **sharing** – trade between rival firms
  - Reduce cost of reuse via more efficient matching of old wells to new wells
- Like all market transactions, sharing is subject to **transaction costs**

This paper: three questions

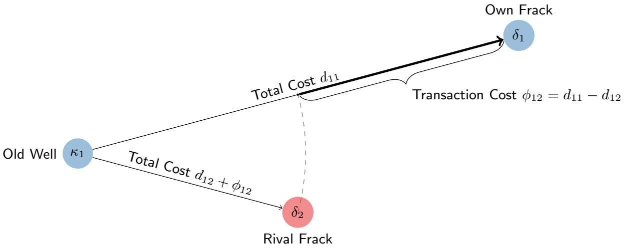
1. How large are the transaction costs of sharing?

2. What are the main sources of transaction costs?

3. What are the environmental impacts of transaction costs?

Quantifying transaction costs

- Data: wastewater shipments *within* and *between* firms, at high spatial resolution
- Water is heavy $\Rightarrow$ transporting wastewater is costly (typically, trucked)
- Idea: transaction costs $\equiv$ "distance premia" firms incur to avoid sharing



Key findings

1. Transaction costs are large, but heterogenous
    - $6/bbl mean across transactions, $2/bbl standard deviation
2. Transaction costs...
    - Are greater for counterparties with poor environmental records
    - Are greater for riskier types of wastewater
    - Vary significantly across firm-pairs
3. In Pennsylvania specifically, environmental impacts are limited
    - Freshwater consumption increased, but transportation impacts mitigated

Related literature

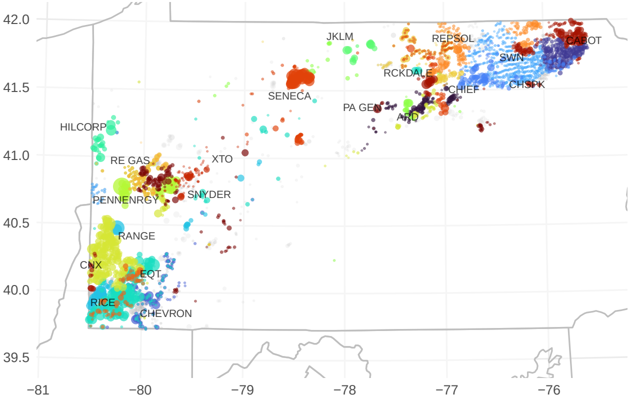
- Quantification of the Coasean transaction costs
  - Masten Meehan Snyder 1991, Atalay Hortacsu Li Syverson 2019, ...
  - Contribution: explores ***distribution*** of transaction costs
- Direct environmental impacts of fracking
  - Hausman and Kellogg 2015, Black et al 2021, ...
  - Contribution: novel framework for studying wastewater policy
- Regulation of environmental externalities in oligopoly
  - Mansur 2007, Fowlie 2009, Ryan 2012, Fowlie et al 2016, Leslie 2018, Preonas 2023, ...
  - Contribution: complementary source of market imperfection

Data: wastewater disposal records

- Monthly disposal records by well pad from Pennsylvania DEP, 2017-20
- What it has:
  - Monthly transfer volumes for **all** well pads / destinations
  - Detailed facility information (precise locations, permit numbers, ...)
- What it doesn't have:
  - Dates, times, or modes of particular shipments
  - Contract terms
  - Prices
- Supplementary data: completion info from FracFocus (incl. fracking inputs)

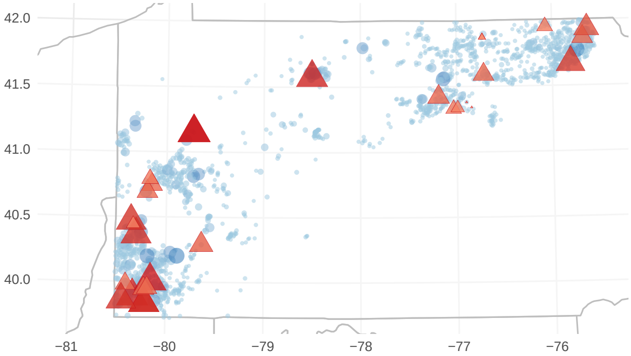
Fact 1: decentralized production

- Wastewater disposal HHI: 1,090
- Locations of twenty largest firms (by disposal volume):



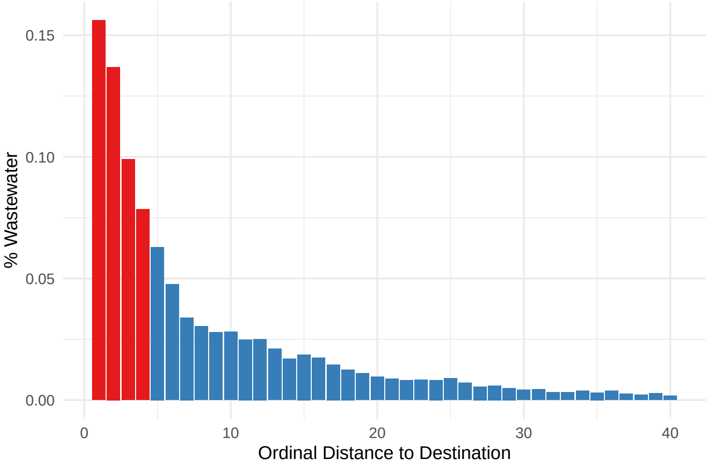
Fact 2: more old wells than new wells

- Average month: 1,721 well pads reporting disposal vs. 55 completions
- June 2018 (well pads reporting disposal in blue, completions in red):



Fact 3: most reuse occurs locally

- 47% of wastewater is shipped to one of the four nearest destinations:



Prevalence of wastewater sharing

- Disposal market shares:

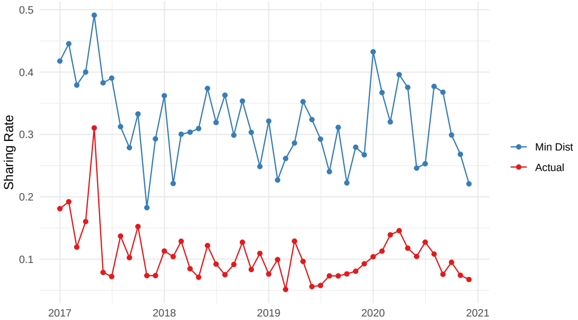
Outcome	Facility	% Vol.
Reuse	Own well/CTF	70.6
	Independent CTF	12.5
	Rival well/CTF	**8.6**
Final Disposal	Injection Well	8.4

- Three reasons for sharing:
  1. Temporal mismatches
  2. Geographic synergies
  3. Non-geographic synergies

Final Disposal

Is there enough sharing?

- Actual sharing rate is lower than distance-minimizing rate:

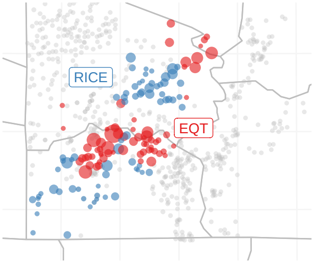


- Why? Either (1) transaction costs; or (2) technological incompatibility

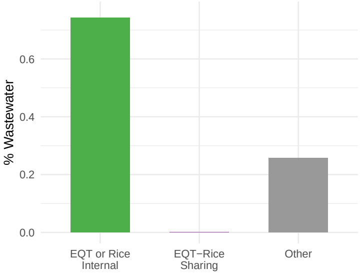
Evidence of transaction costs: 2017 EQT-Rice merger

- EQT and Rice merger created largest gas producer in US

Pre-merger well pads

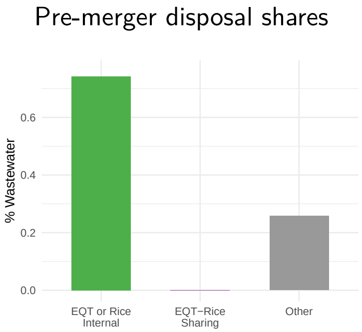


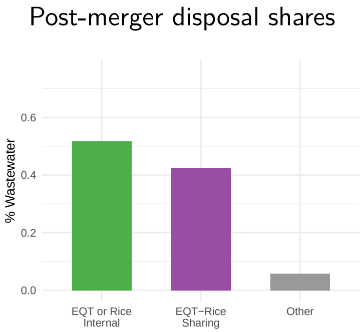
Pre-merger disposal shares



- Large pre-merger transportation synergies, but no pre-merger sharing

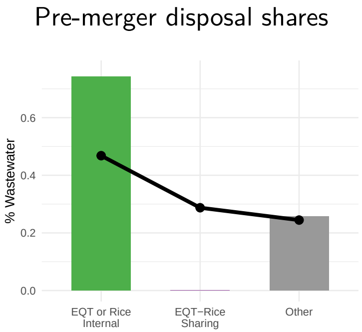
Evidence of transaction costs: 2017 EQT-Rice merger (cont)

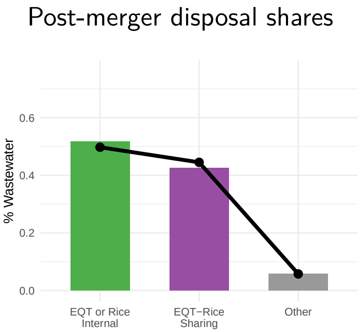




- Post-merger “sharing” rate 43%

Evidence of transaction costs: 2017 EQT-Rice merger (cont)





- Post-merger "sharing" rate 43%, close to **model-implied optimum**
  - Suggests *firm boundaries* matter, not technological incompatibilities

How large are transaction costs?

- K is the set of old well pads in month t
- D is the set of new wells in month t
- A **transaction** is a shipment from an old well pad to a new well
  - One transaction = one *truckload* of wastewater (110 barrels)
- $r^K_{\kappa\delta}$ and $r^D_{\kappa\delta}$ are the costs of reusing wastewater from κ at δ, where:

$$r_{\kappa\delta} = r^K_{\kappa\delta} + r^D_{\kappa\delta} = \begin{cases} \text{Technological Cost} & \kappa \text{ and } \delta \text{ in same firm} \\ \text{Technological Cost} + \text{Transaction Cost} & \kappa \text{ and } \delta \text{ in rival firms} \end{cases}$$

  - Technological costs: transportation, treatment, loading/unloading, ...

Empirical strategy: matching with transferable utility

1. Truckloads of wastewater matched from old well pads K to new wells D

2. Shipment/receipt decisions are made **locally** in response to **prices:**

$$r_{\kappa\delta} = \overbrace{r^{K}_{\kappa\delta} + \tau_{\kappa\delta}}^{\text{Sender's Costs}} + \overbrace{r^{D}_{\kappa\delta} - \tau_{\kappa\delta}}^{\text{Receiver's Costs}}$$

   - τ: intra-firm *transfer prices*, inter-firm *market prices*, determined **in equilibrium**

3. $r_{\kappa\delta}$ identified from observed match (Galichon and Salanie 2022)

   - Within-firm shipments $\Rightarrow$ technological costs
   - Between-firm shipments $\Rightarrow$ transaction costs

Supply: wastewater disposal as a discrete choice problem

- Q_κ truckloads of wastewater are generated at κ
- The operator at κ ships ith truckload to the least cost destination δ:

$$\delta^* = \arg\min_{\delta \in D_0} \quad r^K_{\kappa\delta} + \tau_{\kappa\delta} - \epsilon_{i\delta}$$

  - $D_0 = D \cup \{0\}$ includes all new wells and the outside option (final disposal)
  - $r^K_{\kappa\delta} + \tau_{\kappa\delta}$ is the sender's share of the joint costs of reuse at δ
  - $\epsilon_{i\delta}$ is a truckload-specific, non-systematic latent cost (EV Type 1, dispersion σ_K)

Demand: water acquisition as a discrete choice problem

- C_δ truckloads of water (wastewater or freshwater) are needed at δ
- The operator at δ accepts jth truckload from the least cost source:

$$\kappa^* = \arg\min_{\kappa \in K_0} \quad r^D_{\kappa\delta} - \tau_{\kappa\delta} - \eta_{\kappa j}$$

  - $K_0 = K \cup \{0\}$ includes all producing wells and the outside option (freshwater)
  - $r^D_{\kappa\delta} - \tau_{\kappa\delta}$ is the receiver's share of the joint costs of reusing wastewater from κ
  - $\eta_{\kappa j}$ is a truckload-specific, non-systematic latent cost (EV Type 1, dispersion σ_D)

Equilibrium: local supply = local demand

- Equilibrium is characterized by utility transfers τ and shipments μ
  - $\mu_{\kappa\delta}$ is the number of truckloads expected to be shipped from κ to δ
- Markets clear **in expectation** for each $\kappa \in K$ and $\delta \in D$:

$$\begin{aligned} \mu^*_{\kappa\delta} &= Q_\kappa \times P\left(\delta = \arg\min_{\delta' \in D_0} r^K_{\kappa\delta'} + \tau_{\kappa\delta'} - \epsilon_{i\delta'}\right) && \text{Supply of } \kappa\text{-trucks to } \delta \\ &= C_\delta \times P\left(\kappa = \arg\min_{\kappa' \in K_0} r^D_{\kappa'\delta} - \tau_{\kappa'\delta} - \eta_{\kappa' j}\right) && \text{Demand for } \kappa\text{-trucks at } \delta \end{aligned}$$

Equilibrium as a convex program

- Galichon and Salanie (2022): the unique equilibrium μ^* satisfies:

$$\begin{aligned} \min_{\mu \geq 0} \quad & \sum_{\kappa \in K} \sum_{\delta \in D} \mu_{\kappa\delta} r_{\kappa\delta} + \mathcal{E}\left(\mu, \mathbf{Q}, \mathbf{C}\right) \\ \text{s.t.} \quad & \sum_{\delta \in D} \mu_{\kappa\delta} \leq Q_\delta \quad \forall\, \kappa \in K \\ & \sum_{\kappa \in K} \mu_{\kappa\delta} \leq C_\delta \quad \forall\, \delta \in D \end{aligned}$$

  - $\mathcal{E}$ is a convex ***match entropy*** function that depends on distributions of ϵ and η

- If $\mathcal{E}$ is known, then r is identified by its gradient at the equilibrium match μ^*:

$$r_{\kappa\delta} - \frac{\partial \mathcal{E}\left(\mu^*, \mathbf{Q}, \mathbf{C}\right)}{\partial \mu_{\kappa\delta}} = 0$$

Details

Parameterization

$$r_{\kappa\delta} = \begin{cases} \overbrace{d_{\kappa\delta} + x'_{\kappa\delta}\beta + \xi^{\mathcal{I}}_{\kappa} + \xi^{\mathcal{I}}_{\delta}}^{\text{Technological Cost}} & \kappa \text{ and } \delta \text{ in same firm} \\ d_{\kappa\delta} + x'_{\kappa\delta}\beta + \xi^{\mathcal{I}}_{\kappa} + \xi^{\mathcal{I}}_{\delta} + \underbrace{z'_{\kappa\delta}\alpha + \pi_b}_{\text{Transaction Cost}} & \kappa \text{ and } \delta \text{ in rival firms} \end{cases}$$

- $d_{\kappa\delta}$ represents distance-related costs (over-the-road shipping distance)
- $x_{\kappa\delta}$ is a vector of observable transaction characteristics (e.g., fluid composition)
- $\xi^{\mathcal{I}}_{\kappa}$ and $\xi^{\mathcal{I}}_{\delta}$ are unobserved, additively separable costs of reuse within the firm
- $z_{\kappa\delta}$ is a vector of transaction characteristics (e.g., facility-type interactions)
- π_b is an unobserved friction for firm pair b

Identification

- Data reveals μ^* $\Rightarrow$ system of $|K| \times |D|$ linear equations:

$$d_{\kappa\delta} + x'_{\kappa\delta}\beta + \xi_\kappa^{\mathcal{I}} + \xi_\delta^{\mathcal{I}} + z'_{\kappa\delta}\alpha + \pi_b - \sigma_K \log\left\{\frac{\mu^*_{\kappa 0}}{\mu^*_{\kappa\delta}}\right\} - \sigma_D \log\left\{\frac{\mu^*_{0\delta}}{\mu^*_{\kappa\delta}}\right\} = 0$$

- β, ξ, α, π, σ are identified if system is invertible
- In practice: $\mu_{0\delta}$ is poorly observed $\Rightarrow$ partial identification of ξ and σ

Estimation

- For a given $\theta = (\beta, \xi, \alpha, \pi, \sigma)$, can compute the equilibrium match $\mu(\theta)$
  - $\mu_{\kappa\delta}(\theta) \propto$ equilibrium prob. of observing a shipment from κ to δ
- Maximum likelihood estimator (without outside options):

$$\hat{\theta} = \arg\max_{\theta \in \Theta} \sum_{\kappa \in K} \sum_{\delta \in D} \hat{\mu}_{\kappa\delta} \log \left(\frac{\mu_{\kappa\delta}(\theta)}{\sum_{\kappa\delta} \mu_{\kappa\delta}(\theta)} \right)$$

  - Implemented similarly to BLP (Conlon and Gortmaker 2020)
  - Standard MLE inference (one observation = one truckload)
- In practice: pool data from many markets (one month = one market)
  - Assumption: β, α, π, σ are fixed across months, while ξ adjusts (with facility age)

Estimated transaction costs

- Summary stats (μ-weighted, $N \approx 1.3$M):

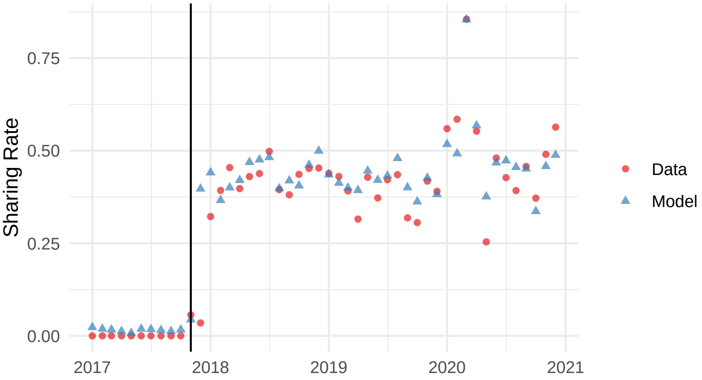
	Est (miles)	SE	\$/bbl
Mean	125.7	0.07	5.71
Std Dev	48.1	0.09	2.18

- The mean transaction cost is equivalent to shipping a truck 125.7 extra miles
- \$5/mile trucking costs $\Rightarrow$ \$5.71/bbl or \$26.3M/year
  - Approx. 67% of typical conventional disposal costs (roughly \$9/bbl)
  - Approx. 5% of "all in" water costs (from sourcing to disposal, roughly \$500M/year)

Dispersion Inverse CDF Full Estimates

Model fit: EQT-Rice merger

- EQT-Rice "sharing" rate pre- and post-merger



More

Sources of transaction costs

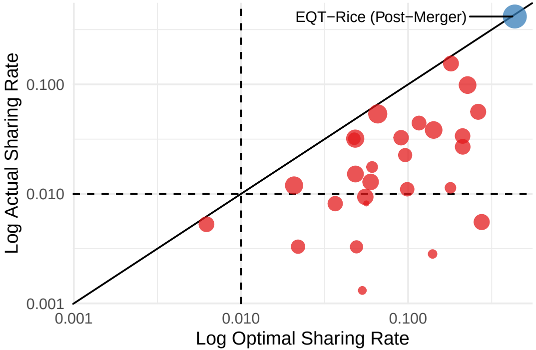
	Est (miles)	SE	\$/bbl
Sharing market cost shifters α			
rival $\times$ poor $\rightarrow$ good env record	-	-	-
rival $\times$ good $\rightarrow$ poor env record	8.5	0.11	0.39
rival $\times$ gel $\rightarrow$ slickwater	-28.6	0.10	-1.30
rival $\times$ slickwater $\rightarrow$ gel	85.3	3.00	3.88
...			
Relationship fixed effects π_b			
mean	117.9	0.07	5.36
std dev	49.2	0.09	2.23

- Interpretation: evidence of *contracting frictions...*
  - Inter-operator environmental liability, information frictions, relationship dynamics

Full Estimates

Limited trade within relationships

- Actual vs. no-friction bilateral sharing rates:



- Evidence of dynamic frictions? Ex ante coordination vs. ex post opportunism
  - Difficult to communicate future fracking plans, commit to delivery schedules

Policy implications

1. To encourage sharing, improve the contracting environment
    - Liability rules / shields (e.g., Oklahoma)
    - Disclosure of wastewater composition
    - Public pre-registration of fracking activity
    - ...
2. Interventions that ignore contracting fundamentals may fail
    - Digital platforms (i.e., Uber for wastewater)

Setting

Model

Estimates

Externalities

Conclusion

Environmental externalities

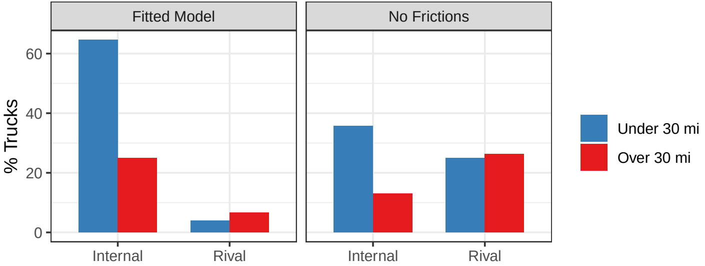
- Potential benefits from improved sharing markets:
    1. Less freshwater usage, less final disposal
    2. Less transportation
- 90% reuse $\Rightarrow$ limited scope for improvement on 1
    - Max reduction in freshwater consumption is approx. 580 acre-feet/year
        - Social value on the order of $1M/year, valued at desalination costs
    - Difficult to quantify social costs of final disposal

External costs of transportation

- In PA: nearly all wastewater transported via heavy water-hauling trucks
  - 500,000 truck trips each year, 30.0 miles per truckload
- Unpriced transportation externalities are roughly $7M per year
  - $3.4M CO2 (EPA Social Cost of Carbon); $3.3M NOx, PM2.5 (EASIUR)
  - Not included: at least 1-2 trucking-related wastewater spills per year

Transaction costs and equilibrium transportation

- Fitted model vs. counterfactual with no transaction costs:



1. Sharing rate increases from approx. 10% to approx. 50%
2. Mean shipment distance increases by 15%
   - $\Rightarrow$ transportation externalities **increase** by roughly \$1M/year

Illustration Details

Implications for optimal regulation

- Net environmental spillovers from transaction costs are likely modest (in PA...)
  - Potentially even positive! If transportation externalities are large
- Nevertheless, Pigouvian intervention could be justified by private cost savings
  - Social costs = external costs + private costs
  - Roughly \$50M/year in excess private costs (direct + indirect)
- In paper: show Pigouvian program can entail large sharing subsidies
  - Depending on interpretation of transaction costs (Pareto relevance?)

Details

Setting

Model

Estimates

Externalities

Conclusion

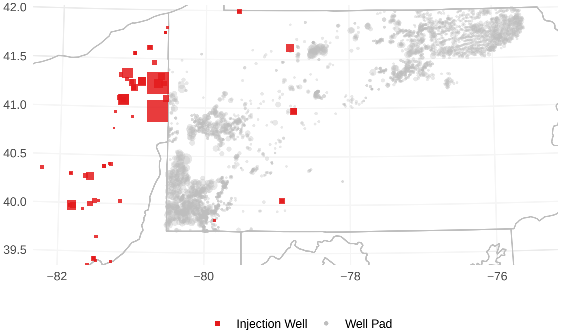
Conclusion

- New evidence on transaction costs from a unique setting
    1. Transaction costs are large, but heterogeneous
    2. Contracting frictions appear to play an outsized role
- Generic empirical framework for wastewater policy evaluation
- Environmental spillovers from are modest in PA, but:
    - Reuse rates significantly lower in Permian, Bakken, ...
    - Large shale plays coming online outside US (Vaca Muerta, Sichuan Basin)

- Thank you!
- Questions/comments: mfokeefe@u.northwestern.edu

Conventional disposal and reuse

- In Pennsylvania, injection well capacity severely limited by geology, regulation



- Due to high transportation costs, 89% of wastewater is **reused** in subsequent fracking
  - Minimal treatment required $\Rightarrow$ cost of reuse $\approx$ cost of transportation

Back

Full estimates

	Est	SE	\$/bbl
Mean $\phi_{\kappa\delta}$			
weighted by data	125.7	0.072	5.71
weighted by benchmark	154.2	0.081	7.01
Sharing market cost shifters α			
rival $\times$ poor $\rightarrow$ good env record	-	-	-
rival $\times$ good $\rightarrow$ poor env record	8.5	0.110	0.39
rival $\times$ gel $\rightarrow$ slickwater	-28.6	0.103	-1.30
rival $\times$ slickwater $\rightarrow$ gel	85.3	2.996	3.88
rival $\times$ large κ $\rightarrow$ well pad	-	-	-
rival $\times$ large κ $\rightarrow$ CTF	25.2	0.044	1.15
rival $\times$ small κ $\rightarrow$ well pad	4.4	0.151	0.20
rival $\times$ small κ $\rightarrow$ CTF	29.6	0.261	1.35
Within-firm cost shifters β			
gel $\rightarrow$ slickwater	6.7	0.092	0.31
slickwater $\rightarrow$ gel	-8.7	0.046	-0.39
small κ $\rightarrow$ CTF	-5.7	0.129	-0.26
$\sigma_\kappa + \sigma_\delta$	22.5	0.006	1.02

Sources Mean

Match entropy function

$$\mathcal{E}\left(\mu, \mathbf{Q}, \mathbf{C}\right) = -G^*\left(\mu, \mathbf{Q}\right) - H^*\left(\mu, \mathbf{C}\right)$$

- $G^*\left(\mu, n\right)$ is the generalized entropy of choice for disposal

$$G^*\left(\mu, \mathbf{Q}\right) = \sup_{U \in \mathbb{R}^{K \times D}} \left(\sum_{\kappa \in K} \sum_{\delta \in D} \mu_{\kappa\delta} U_{\kappa\delta} - \sum_{\kappa \in K} Q_\kappa E\left[\max_{\delta \in D_0} U_{\kappa\delta} + \epsilon_{i\delta}\right]\right)$$

- $H^*\left(\mu, m\right)$ is the generalized entropy of choice for reuse

$$H^*\left(\mu, \mathbf{C}\right) = \sup_{V \in \mathbb{R}^{K \times D}} \left(\sum_{\kappa \in K} \sum_{\delta \in D} \mu_{\kappa\delta} V_{\kappa\delta} - \sum_{\delta \in D} C_\delta E\left[\max_{\kappa \in K_0} V_{\kappa\delta} + \eta_{\kappa j}\right]\right)$$

Logit Back

Match entropy function (cont)

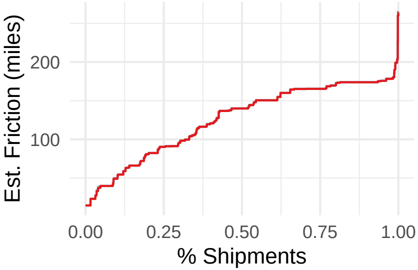
- For ϵ and η EV type 1,

$$\mathcal{E}\left(\mu, \mathbf{Q}, \mathbf{C}\right) = -\sum_{\kappa,\delta} \mu_{\kappa\delta} \left\{ \sigma_K \log\left(\frac{\mu_{\kappa\delta}}{Q_\kappa}\right) + \sigma_D \log\left(\frac{\mu_{\kappa\delta}}{C_\delta}\right) \right\}$$
$$- \sigma_K \sum_{k} \mu_{\kappa 0} \log\left(\frac{\mu_{\kappa 0}}{Q_\kappa}\right) - \sigma_D \sum_{\delta} \mu_{0\delta} \log\left(\frac{\mu_{0\delta}}{C_\delta}\right)$$

Back

Estimated transaction cost distribution

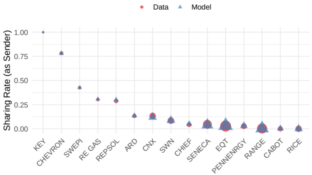
- Inverse CDF (μ-weighted):



Back

Model fit

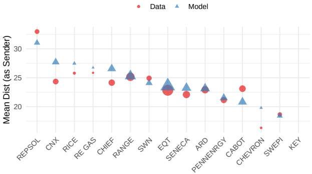
Sharing Rate (as sender, by firm)



Sharing Rate (as receiver, by firm)

Mean Dist (as sender, by firm)

Mean Dist (as receiver, by firm)



Back

Dispersion estimates

- Point estimate for dispersion:

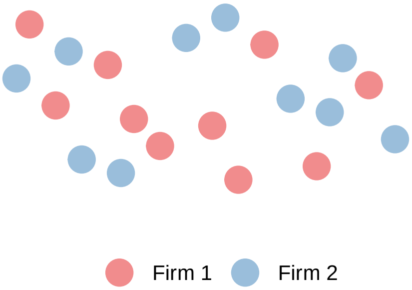
	Est (miles)	SE	\$/bbl
$\sigma_K + \sigma_D$	22.5	0.01	1.02

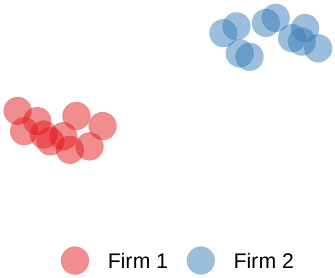
- Counterfactuals:

	Mean Dist (mi)	Share %
Data	24.86	10.60
Fitted model	24.86	10.58
$\sigma_K + \sigma_D \to 0$	21.61	9.72
$\sigma_K + \sigma_D \to \infty$	146.99	84.37

Back

Ambiguous effects of reducing transaction costs

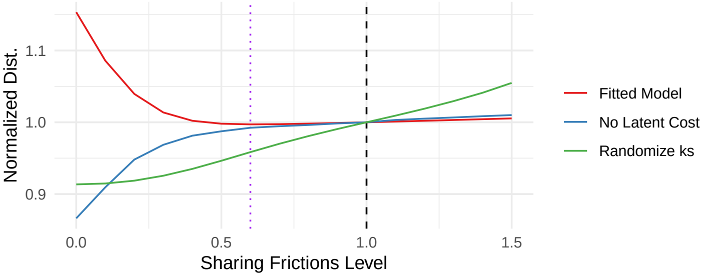




Back

Transaction costs and transportation

- Proportional re-scaling of transaction costs:



- In fitted model, removing transaction costs *increases* shipment distance by 15%
- Why? Non-random distribution of firms + matching on non-transport costs
  - As ϕ shrinks, marginal matches tend to be further away

Back

Pigouvian regulation

- Socially optimal (Pigouvian) shipment plan μ^* solves:

$$\min_{\mu \in \mathcal{M}(Q,C)} \Gamma(\mu) + C(\mu)$$

  - $\Gamma(\mu)$ represents external costs under shipment plan μ
  - $C(\mu)$ represents private costs under μ

- **Question:** should sharing frictions ϕ count towards $C(\mu)$?

Are sharing frictions welfare-relevant?

- Familiar distinction from consumer markets (e.g., switching costs)
  - Some "costs" may be relevant to decisionmakers, but not the social planner
- Examples of welfare-relevant sharing frictions:
  - Wages expended in finding out about sharing opportunities
  - Wages expended in haggling / bargaining / price discovery
  - Quantifiable risks to future profits (e.g., risk of lawsuits)
  - ...
- Examples of welfare-irrelevant sharing frictions:
  - Managerial inattention / status quo bias, loss aversion, excessive secrecy, ...

Pigouvian regulation (cont)

- Let $s \in [0,1]$ index the welfare-relevance of sharing frictions:
- $s\phi$ is welfare-relevant and $(1-s)\,\phi$ is not
  - $s = 0$ if sharing frictions are entirely welfare-irrelevant
  - $s = 1$ if sharing frictions are entirely welfare-relevant
- Socially optimal (Pigouvian) shipment plan μ_s^* solves:

$$\min_{\mu \in \mathcal{M}(Q,C)} \Gamma(\mu) + C_s(\mu)$$

  - $\Gamma(\mu)$ represents external costs under shipment plan μ
  - $C_s(\mu)$ represents welfare-relevant component of private costs under μ

Pigouvian tax rates

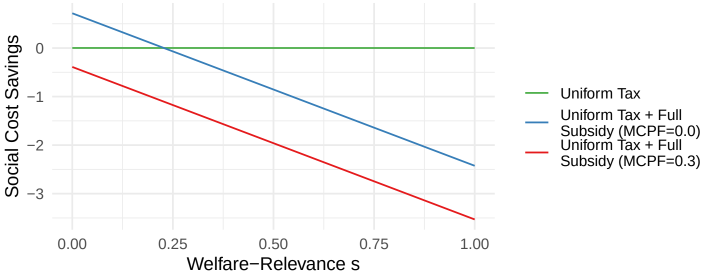
- Hypothetical policy response: Pigouvian tax on truck-miles
- Holding volume fixed, μ^* can be implemented with a tax on truck-miles:

$$tax_{\kappa\delta}^{(s)} = \gamma - (1-s)\, d_{\kappa\delta}^{-1} \phi_{\kappa\delta}$$

  - γ is the marginal external cost of trucking (calibrate to 7%)
  - If $s < 1$, uniform tax + sharing subsidies is optimal
  - If $s = 1$, uniform tax is optimal
- Two inference problems: for optimal tax, regulator needs to know $\phi_{\kappa\delta}$ **and** s
  - In many settings $\phi_{\kappa\delta}$ (or an equivalent parameter) is identified, but s is not
    - Standard practice: argue $s = 0$ or $s = 1$ is more correct, check robustness
  - Even if firms knew s, would have incentives to shade (for larger subsidies)

Social cost savings and regret

- Change in social costs vs. status quo ($/bbl):



- Sharing subsidies can reduce social costs by $0.72 per barrel vs. uniform tax, **but:**
  1. Unnecessary subsidies can increase social costs by $2.43 per barrel (before MCPF)
  2. Not cost-effective for reasonable MCPF values
  3. External costs are increased by 13.5% (not shown)

Back