

Firm Boundaries and External Costs in Shale Gas Production

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- ▶ Empirical challenges \Rightarrow few *quantifications* of transaction costs
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 - ▶ Wallis and North (1986), Masten et al (1991), Atalay et al (2019),
- ▶ This paper: new quantification of firm boundaries
 1. **Within-market heterogeneity** in transaction costs (e.g., across counterparties)
 2. **External cost spillovers** from firm boundaries

Wastewater sharing in Pennsylvania

1. Fracking **requires water** and **generates wastewater** as a byproduct
 - ▶ 10-20M gallons for a typical shale gas well
 - ▶ 25% *slowly* returns as wastewater during extraction

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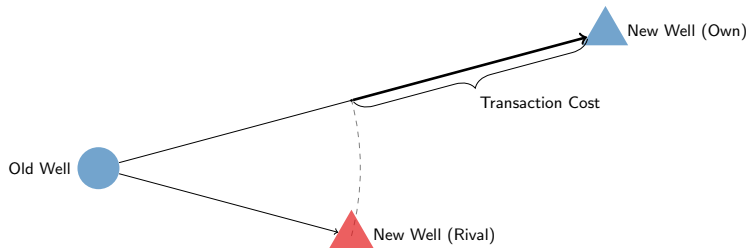
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4. Like all market transactions, sharing is subject to **transaction costs**

Three questions

1. How large are the transaction costs of sharing?
2. What are their main sources?
3. Do transaction costs have significant environmental spillovers?
 - ▶ To what extent do transaction costs result in **less reuse** or **less efficient reuse**?

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

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4. **Limited environmental spillovers**

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
- ▶ Environmental implications of upstream market imperfection
 - ▶ Mansur 2007, Fowlie 2009, Ryan 2012, Fowlie et al 2016, Leslie 2018, Preonas 2023, ...
 - ▶ Contribution: highlight role of interfirm contracting frictions

Setting

Model

Estimates

Spillovers

Conclusion

Data: wastewater disposal records

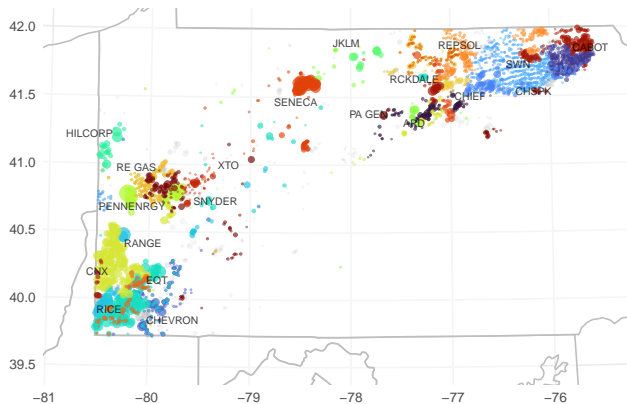
- ▶ Monthly disposal records by well pad from Pennsylvania DEP, 2017-20
 - ▶ Monthly transfer volumes for **all** well pads / destination pairs
 - ▶ Detailed facility info (precise locations, permit numbers, ...) \Rightarrow over-the-road distances

Data: wastewater disposal records

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

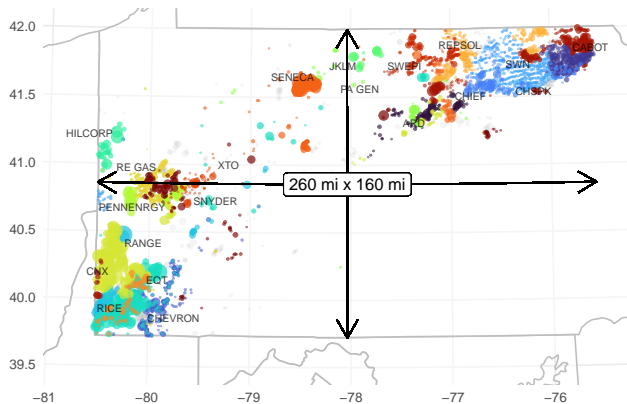
Fact 1: decentralized production

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



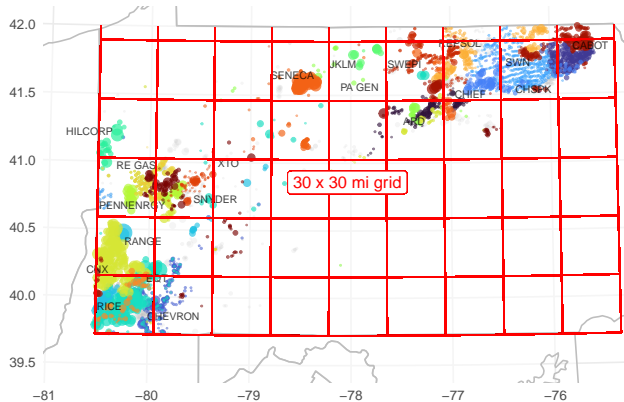
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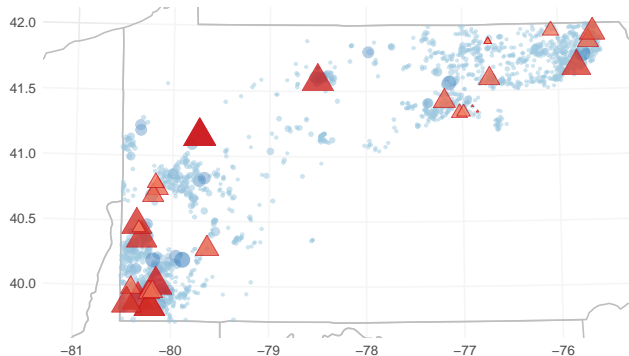
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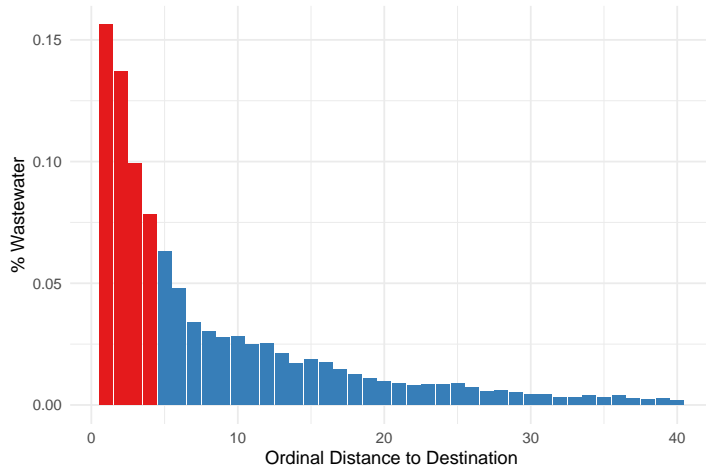
Fact 2: more old wells than new wells

- ▶ 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:



Wastewater sharing

- ▶ 8.6% of wastewater is shipped directly to a rival:

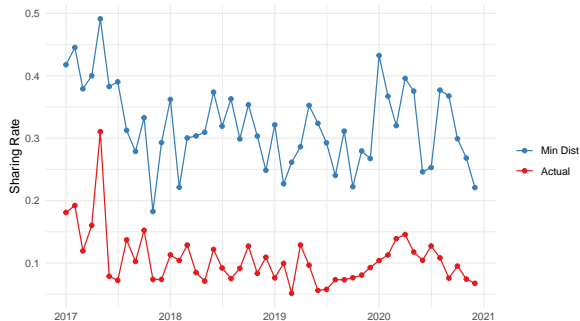
Outcome	Facility	% Vol.
Reuse	Own well/CTF	70.6
	Independent CTF	12.5
	Rival well/CTF	8.6
Final Disposal	Injection Well	8.4

- ▶ Three reasons for sharing:

1. Temporal mismatches
2. Geographic synergies
3. Non-geographic synergies

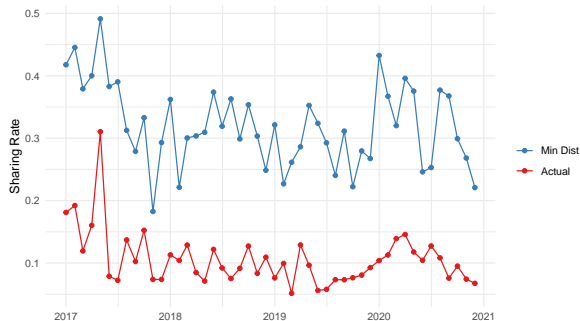
Is there enough sharing?

- ▶ Suppose all truckloads of wastewater are substitutable within a month
- ▶ Exercise: holding local supply/demand fixed, minimize shipping distance
- ▶ Actual sharing rate vs. rate consistent with distance minimization:



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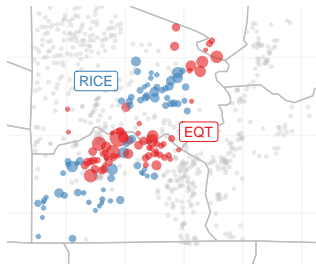
- ▶ Suppose all truckloads of wastewater are substitutable within a month
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- ▶ Why? Either (1) transaction costs; or (2) technological costs

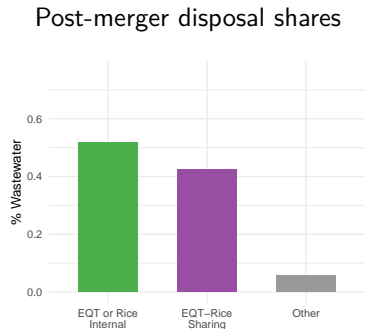
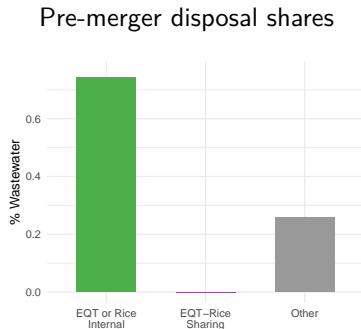
Evidence of transaction costs: 2017 EQT-Rice merger

- ▶ Pre-merger: 2nd and 6th largest firms in Pennsylvania (by wastewater production)
- ▶ Pre-merger well pads:



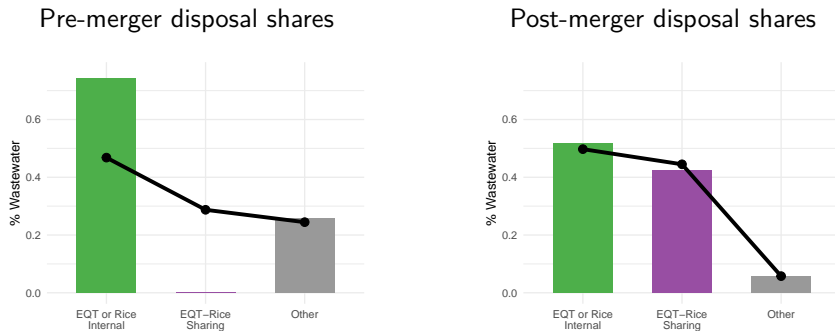
- ▶ Large firms + overlapping acreage \Rightarrow significant geographic synergies

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



► No sharing pre-merger \Rightarrow 43% “sharing” post-merger

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



- ▶ No sharing pre-merger \Rightarrow 43% “sharing” post-merger
 - ▶ Matches **model-implied optimal rate** if merger eliminated transaction costs

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How large are transaction costs?

- ▶ A **transaction** is a shipment from an old well pad κ to a new well δ
 - ▶ One transaction = one *truckload* of wastewater (110 barrels)
- ▶ $r_{\kappa\delta}^K$ and $r_{\kappa\delta}^D$ are sender/receiver costs of reusing a truckload from κ at δ , where:

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

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

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- ▶ Technological costs: transportation, treatment, loading/unloading, ...
- ▶ **Intuition:** if r can be recovered from observed shipments, then:
 1. Within-firm shipments \Rightarrow technological costs
 2. Between-firm shipments \Rightarrow transaction costs

Empirical framework: matching with transferable utility

- ▶ Truckloads of wastewater matched from old well pads K to new wells D
- ▶ Joint costs of reuse divided via **transfers** determined in equilibrium:

$$r_{K\delta} = \overbrace{r_{K\delta}^K + p_{K\delta}}^{\text{Sender's Costs}} + \overbrace{r_{K\delta}^D - p_{K\delta}}^{\text{Receiver's Costs}}$$

- ▶ Between-firm $p_{K\delta}$ is a market price; within-firm $p_{K\delta}$ is a transfer price
- ▶ Key assumption: water management decisions are **decentralized**
 - ▶ Shipment/receipt decisions made facility-by-facility, truckload-by-truckload

Supply: wastewater disposal as a discrete choice problem

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

$$\delta^* = \arg \min_{\delta \in D_0} r_{\kappa\delta}^K + p_{\kappa\delta} - \epsilon_{i\delta}$$

- ▶ $D_0 = D \cup \{0\}$ includes all new wells and the outside option (final disposal)
- ▶ $r_{\kappa\delta}^K + p_{\kappa\delta}$ 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 j th truckload from the least cost source:

$$\kappa^* = \arg \min_{\kappa \in K_0} r_{\kappa\delta}^D - p_{\kappa\delta} - \eta_{\kappa j}$$

- ▶ $K_0 = K \cup \{0\}$ includes all producing wells and the outside option (freshwater)
- ▶ $r_{\kappa\delta}^D - p_{\kappa\delta}$ 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

- $\mathbf{Q} = (Q_1, \dots, Q_K)$ and $\mathbf{C} = (C_1, \dots, C_D)$ are probability masses
- At p^* , markets clear **in expectation**. For all κ, δ :

$$\begin{aligned}\mu_{\kappa\delta}^* &\equiv Q_\kappa \times P\left(\delta = \arg \min_{\delta' \in D_0} r_{\kappa\delta'}^K + p_{\kappa\delta'}^* - \epsilon_{i\delta'}\right) \quad \leftarrow \text{supply of } \kappa\text{-trucks to } \delta \\ &= C_\delta \times P\left(\kappa = \arg \min_{\kappa' \in K_0} r_{\kappa'\delta}^D - p_{\kappa'\delta}^* - \eta_{\kappa'j}\right) \quad \leftarrow \text{demand for } \kappa\text{-trucks at } \delta\end{aligned}$$

- $\mu_{\kappa\delta}^*$ is the expected mass of truckloads shipped from κ to δ in equilibrium

Identification: equilibrium as a convex program

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

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

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

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- \mathcal{E} is a convex *match entropy* function that depends on distributions of ϵ and η
- r is identified by the gradient of \mathcal{E} at the equilibrium match μ^* :

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

Parameterization

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

- ▶ $d_{\kappa\delta}$ represents distance-related costs (over-the-road shipping distance)
- ▶ $x_{\kappa\delta}$ is a vector of observable transaction characteristics (e.g., fluid composition)
- ▶ $\zeta_{\kappa}^{\mathcal{I}}$ and $\zeta_{\delta}^{\mathcal{I}}$ 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 (cont)

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

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

- $\beta, \zeta, \alpha, \pi, \sigma$ are identified if system is invertible

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- $\beta, \xi, \alpha, \pi, \sigma$ are identified if system is invertible
- In practice: freshwater usage $\mu_{0\delta}^*$ is poorly observed
 - Partial identification of ξ and σ is possible with shipments-for-reuse alone

Estimation

- ▶ Maximum likelihood estimator (shipments for reuse only):

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

- ▶ $\mu_{\kappa\delta}(\theta) \propto$ equilibrium prob. of observing a shipment from κ to δ
- ▶ Standard MLE inference: one observation = one truckload

Estimation

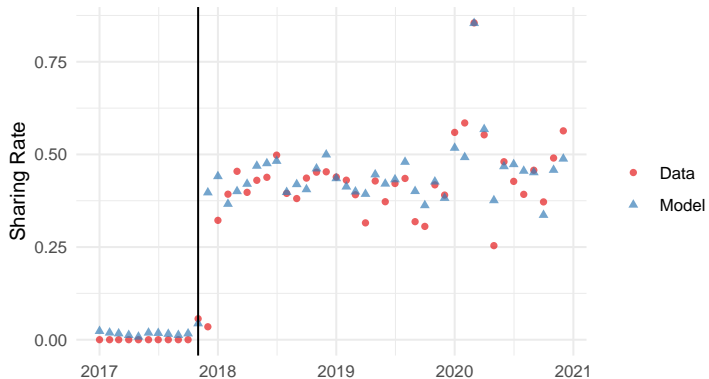
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 - ▶ Standard MLE inference: one observation = one truckload
-
- ▶ In practice: pool data from many markets (one month = one market)
 - ▶ Assumption: β , α , π , σ are fixed across months, while ζ adjusts

Model fit: EQT-Rice merger

- EQT-Rice “sharing” rate pre- and post-merger



More

Setting

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Estimated transaction costs

- Summary stats (μ -weighted):

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

- Mean transaction cost is equivalent to the cost of shipping a truck 125.7 extra miles
- \$5/mile trucking costs \Rightarrow \$5.71 per barrel of wastewater

Dispersion

Inverse CDF

Full Estimates

How large are transaction costs?

- ▶ Transaction costs have **direct** and **indirect** effects on firms' costs:
 1. \$22M/year in **incurred transaction costs**
 2. \$27M/year in **excess technological costs**
- ▶ In comparison, water-related private costs are roughly \$550M/year
 1. \$400M/year in freshwater sourcing costs
 2. \$125M/year in reuse costs (transport + transaction costs only)
 3. \$25M/year in final disposal costs

Sources of transaction costs

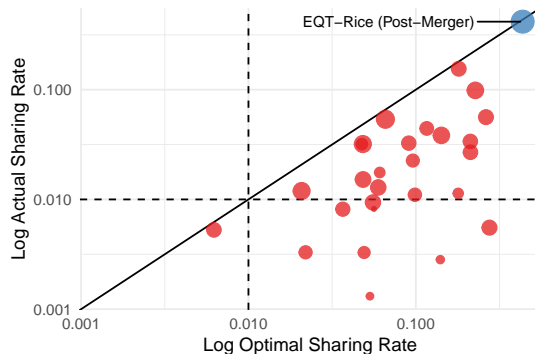
	Est (miles)	SE	\$/bbl
Sharing market cost shifters α			
rival \times poor \rightarrow good env record	-	-	-
rival \times good \rightarrow poor env record	8.5	0.11	0.39
rival \times gel \rightarrow slickwater	-28.6	0.10	-1.30
rival \times slickwater \rightarrow gel	85.3	3.00	3.88
...			
Relationship fixed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

- α estimates provide evidence of **contracting frictions**
 - Inter-operator environmental liability, information frictions

Full Estimates

Limited trade within relationships

- Actual vs. no-friction bilateral sharing rates:



- Evidence of *dynamic* contracting frictions
 - 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)

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Transaction costs and sustainability

- ▶ Do transaction costs substantially worsen environmental impacts?
- ▶ Potential impacts of transaction costs:
 1. **Extensive margin:** more freshwater usage, more final disposal
 2. **Intensive margin:** longer shipments, longer storage durations

Transaction costs and sustainability

- ▶ Do transaction costs substantially worsen environmental impacts?
- ▶ Potential impacts of transaction costs:
 1. **Extensive margin:** more freshwater usage, more final disposal
 2. **Intensive margin:** longer shipments, longer storage durations
- ▶ Today:
 1. **Freshwater consumption**
 2. **Wastewater transportation**

Bounding freshwater consumption impacts

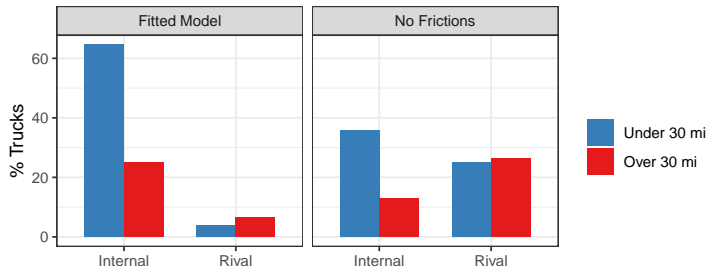
- ▶ Current consumption: 26,000 acre-feet/year
- ▶ Excess consumption due to transaction costs: ≤ 600 acre-feet/year
 - ▶ 90% reuse \rightarrow 100% reuse \Rightarrow 25,400 acre-feet/year
- ▶ External cost of excess consumption: $\leq \$1.2\text{M}/\text{year}$:
 - ▶ Seawater desalination costs (at source): \$500-2000/acre-foot
 - ▶ Not included: transportation to relevant localities

Bounding wastewater transportation impacts

- ▶ Current transport burden: 15M truck-miles/year (0.5M trips x 30 miles)
- ▶ Excess transportation due to transaction costs: $\leq 4\text{M}$ truck-miles/year
 - ▶ Minimum distance benchmark $\Rightarrow 11\text{M}$ truck-miles/year
- ▶ External cost of excess transportation: $\leq \$1.7\text{M}/\text{year}$:
 - ▶ \$0.85M CO₂ (EPA Social Cost of Carbon); \$0.83M NO_x, PM_{2.5} (EASIUR)
 - ▶ Not included: approx 0.5 trucking-related wastewater spills per year

Counterfactual wastewater transportation impacts

- Fitted model vs. counterfactual (holding extensive margin fixed):



- Here: transaction costs **decrease** transportation by 15% (\equiv \$1.1M/year)

Illustration

Details

Optimal regulation

- ▶ Should a regulator intervene to reduce transaction costs?

Optimal regulation

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 - ▶ **Maybe.** Social costs = private costs (\$50M/year) + external costs (\leq \$3M/year)

Optimal regulation

- ▶ Should a regulator intervene to reduce transaction costs?
 - ▶ **Maybe.** Social costs = private costs (\$50M/year) + external costs (\leq \$3M/year)
- ▶ Key questions:
 1. Are one-time interventions possible?
 2. Are transaction costs welfare-relevant?
 3. How significant are strategic incentives?
 4. Can firms conceal relevant information?

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Final thoughts

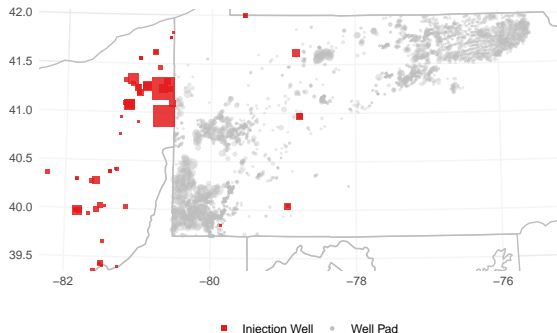
- ▶ New evidence on transaction costs from a unique setting
 1. Transaction costs are large, but heterogeneous
 2. Contracting frictions appear to play an important role
- ▶ Environmental impacts are modest (in Pennsylvania)
- ▶ Generic empirical framework for wastewater policy evaluation
 - ▶ Applicable in other US shale basins with different economics (Permian, Bakken, ...)
 - ▶ Applicable in non-US shale basins (Vaca Muerta, Sichuan, ...)

► 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

Sharing patterns among twenty largest firms

1. Most firms share. In the average month:
 - ▶ 9.5 firms sent wastewater to a rival
 - ▶ 7.0 firms received wastewater from a rival
 - ▶ 3.3 firms did both
2. 58/190 pairs of firms ever shared during sample
 - ▶ 49/99 among those operating wells in the same county (98% of volume)
3. Sharing between counterparties is often infrequent
 - ▶ On average: 3.7 months per year among same-county firms that ever shared

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			
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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 $\kappa \rightarrow$ well pad	-	-	-
rival \times large $\kappa \rightarrow$ CTF	25.2	0.044	1.15
rival \times small $\kappa \rightarrow$ well pad	4.4	0.151	0.20
rival \times small $\kappa \rightarrow$ 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 $\kappa \rightarrow$ CTF	-5.7	0.129	-0.26
$\sigma_{\kappa} + \sigma_{\delta}$	22.5	0.006	1.02

Match entropy function

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

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

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

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

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

Match entropy function (cont)

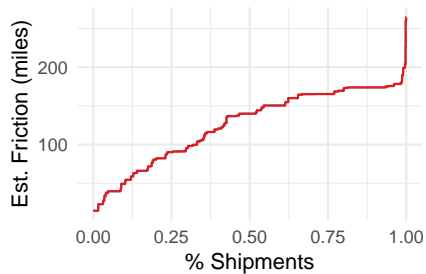
- For ϵ and η EV type 1,

$$\begin{aligned}\mathcal{E}(\mu, \mathbf{Q}, \mathbf{C}) = & - \sum_{\kappa, \delta} \mu_{\kappa\delta} \left\{ \sigma_K \log \left(\frac{\mu_{\kappa\delta}}{Q_\kappa} \right) + \sigma_D \log \left(\frac{\mu_{\kappa\delta}}{C_\delta} \right) \right\} \\ & - \sigma_K \sum_k \mu_{k0} \log \left(\frac{\mu_{k0}}{Q_k} \right) - \sigma_D \sum_\delta \mu_{0\delta} \log \left(\frac{\mu_{0\delta}}{C_\delta} \right)\end{aligned}$$

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Estimated transaction cost distribution

- Inverse CDF (μ -weighted):



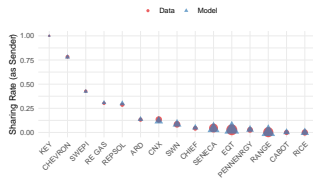
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Private cost assumptions

1. Freshwater costs: \$2.15/bbl
 - ▶ Source: EQT-Rice Investor Presentation
2. Reuse costs: \$5/mile transport costs + estimated transaction costs
 - ▶ For CTFs: use estimated re-shipment distances (described in paper)
3. Final disposal cost: \$5/mile transport costs + \$2/bbl disposal fee
 - ▶ Source: low end of quoted numbers (interview)

Model fit

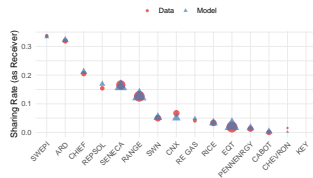
Sharing Rate (as sender, by firm)



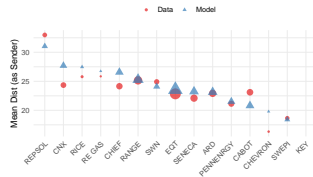
Mean Dist (as sender, by firm)



Sharing Rate (as receiver, by firm)



Mean Dist (as receiver, by firm)



Dispersion estimates

- Point estimate for dispersion:

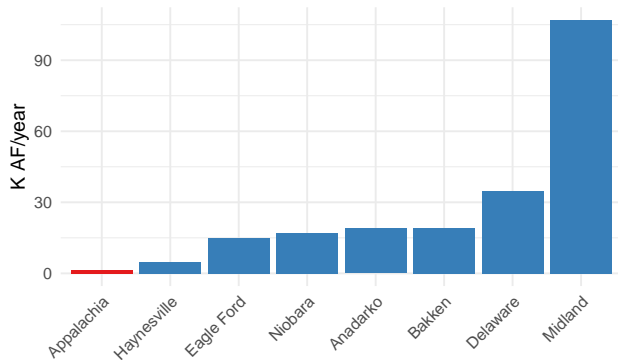
	Est (miles)	SE	\$/bbl
$\sigma_K + \sigma_D$	22.5	0.01	1.02

- Counterfactuals:

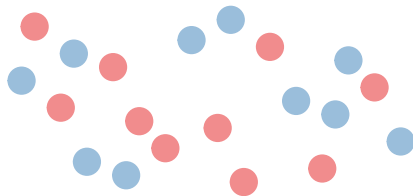
	Mean Dist (mi)	Share %
Data	24.86	10.60
Fitted model	24.86	10.58
$\sigma_K + \sigma_D \rightarrow 0$	21.61	9.72
$\sigma_K + \sigma_D \rightarrow \infty$	146.99	84.37

Bounding freshwater consumption impacts: other basins

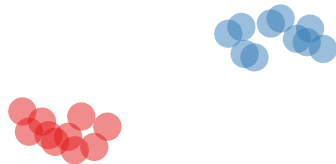
- Across major basins, expanded reuse can save over 218K AF/year:



Ambiguous effects of reducing transaction costs



● Firm 1 ● Firm 2

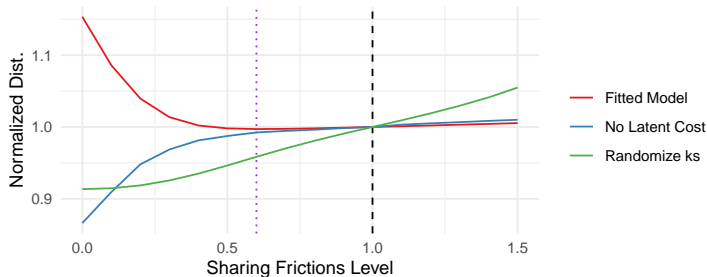


● Firm 1 ● Firm 2

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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

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

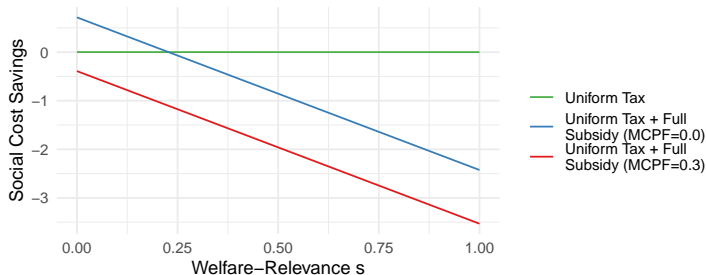
- ▶ Hypothetical policy response: Pigouvian tax on truck-miles
- ▶ Holding volume fixed, μ^* can be implemented with a tax on truck-miles:

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

- ▶ 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)