Firm Boundaries and External Costs in Shale Gas Production

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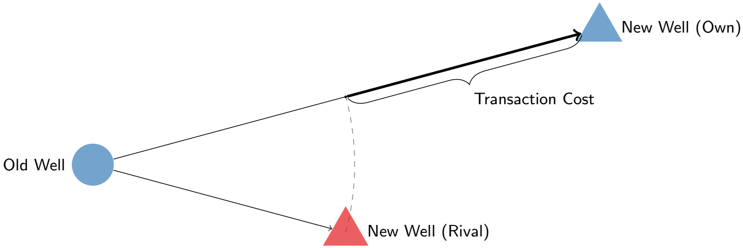
4. Like all market transactions, sharing is subject to **transaction costs**

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

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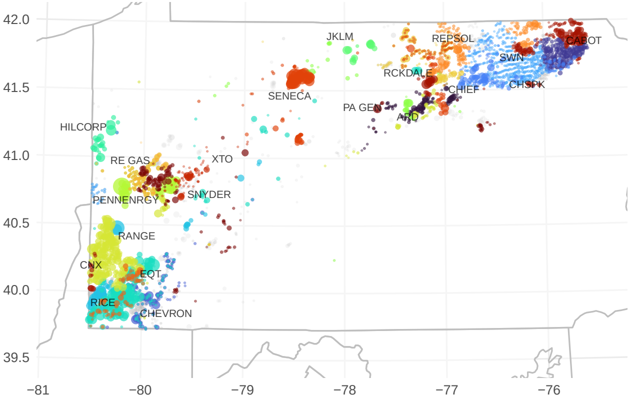
  - Monthly transfer volumes for **all** well pads / destination pairs
  - Detailed facility info (precise locations, permit numbers, ...) $\Rightarrow$ over-the-road distances
- What it doesn't have:
  - Dates, times, or modes of particular shipments
  - Contract terms
  - Prices
- Supplementary data: 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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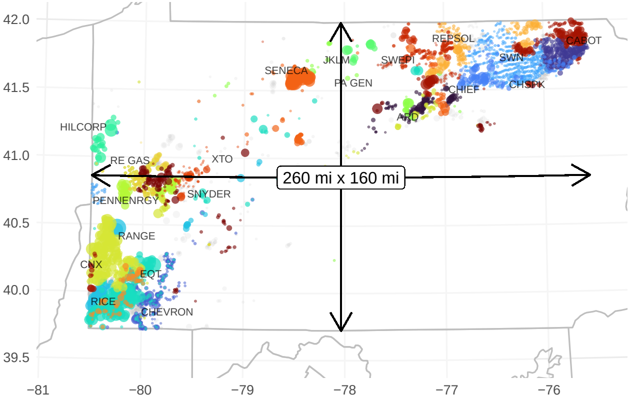

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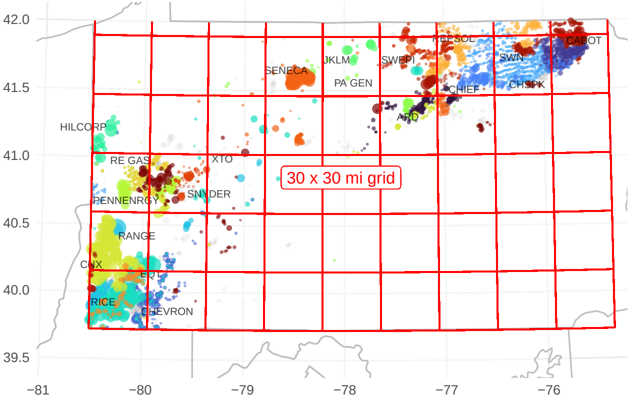
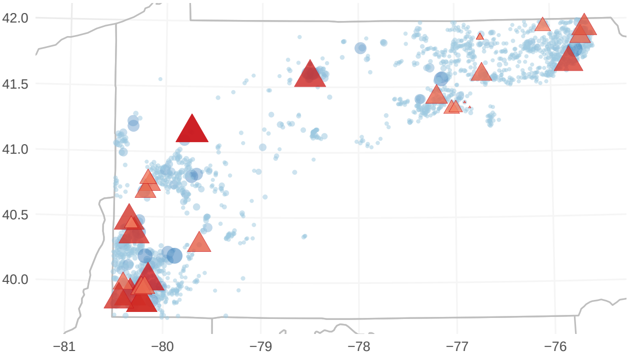


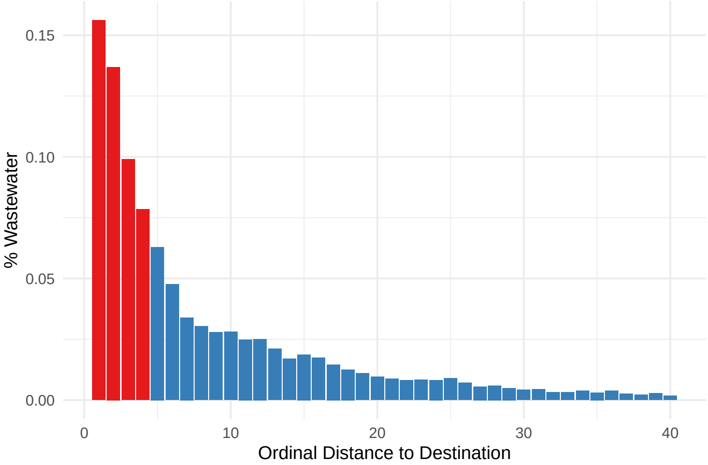
Fact 2: more old wells than new wells

- 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

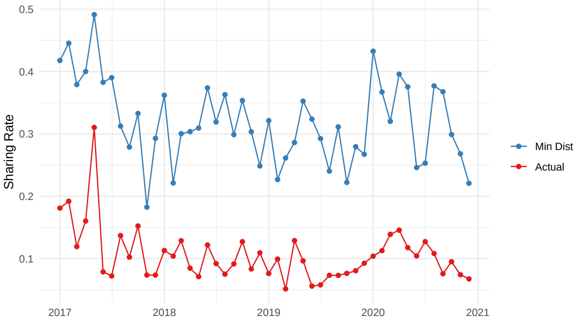
- Three reasons for sharing:

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

Participation Stats Final Disposal

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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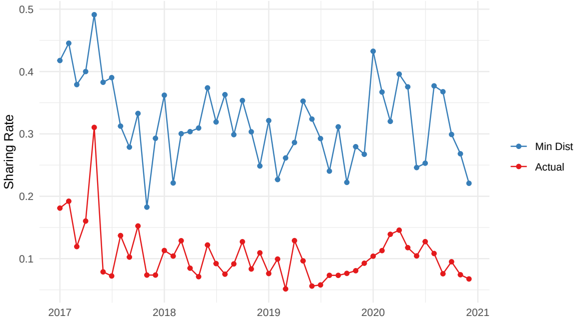
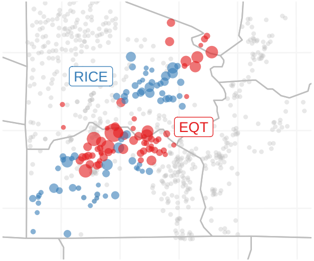


- Why? Either (1) transaction costs; or (2) technological costs

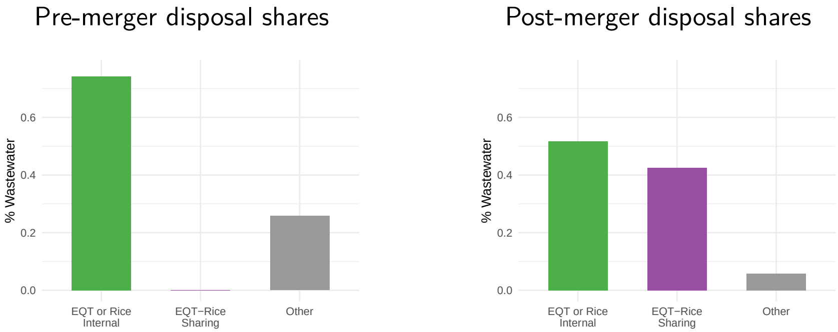
Evidence of transaction costs: 2017 EQT-Rice merger

- 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

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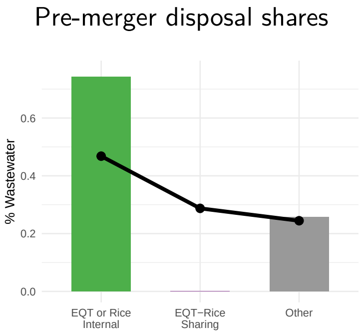

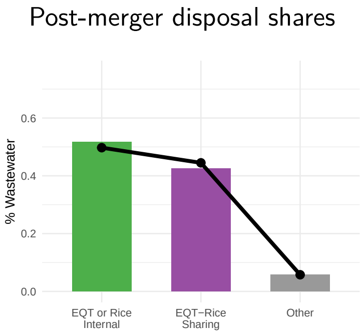

- No sharing pre-merger $\Rightarrow$ 43% "sharing" post-merger
    - Matches **model-implied optimal rate** if merger eliminated transaction costs

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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)
- $r^K_{\kappa\delta}$ and $r^D_{\kappa\delta}$ are sender/receiver costs of reusing a truckload from κ at δ, where:

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

  - 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*:*

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

  - Between-firm $p_{\kappa\delta}$ is a market price; within-firm $p_{\kappa\delta}$ 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 ith truckload to the least cost destination δ:

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

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

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

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

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

$$\mu^*_{\kappa\delta} \equiv Q_\kappa \times P\left(\delta = \arg\min_{\delta' \in D_0} r^K_{\kappa\delta'} + p^*_{\kappa\delta'} - \epsilon_{i\delta'}\right) \quad \leftarrow \text{supply of } \kappa\text{-trucks to } \delta$$

$$= C_\delta \times P\left(\kappa = \arg\min_{\kappa' \in K_0} r^D_{\kappa'\delta} - p^*_{\kappa'\delta} - \eta_{\kappa' j}\right) \quad \leftarrow \text{demand for } \kappa\text{-trucks at } \delta$$

  - $\mu^*_{\kappa\delta}$ 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}\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
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- r is identified by the gradient of $\mathcal{E}$ 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 (cont)

- 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

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- β, ξ, α, π, σ 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):

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

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  - Standard MLE inference: one observation = one truckload

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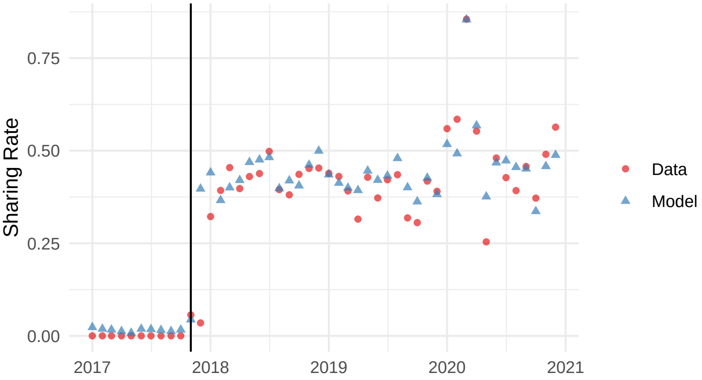
- In practice: pool data from many markets (one month $=$ one market)
  - Assumption: β, α, π, σ are fixed across months, while ξ adjusts

Model fit: EQT-Rice merger

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



More

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

Assumptions

Sources of transaction costs

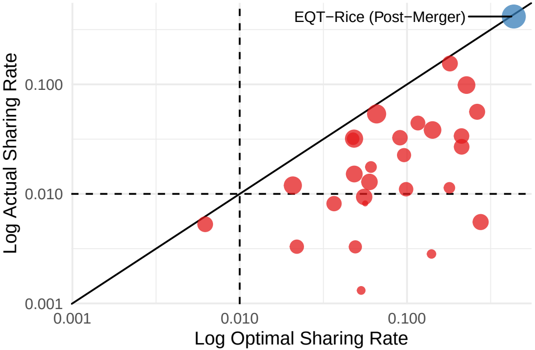
	Est (miles)	SE	$/bbl
Sharing market cost shifters α			
rival $\times$ poor $\rightarrow$ good env record	-	-	-
rival $\times$ good $\rightarrow$ poor env record	8.5	0.11	0.39
rival $\times$ gel $\rightarrow$ slickwater	-28.6	0.10	-1.30
rival $\times$ slickwater $\rightarrow$ gel	85.3	3.00	3.88
...			
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)

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

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- 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: $\leq$ 600 acre-feet/year
  - 90% reuse $\rightarrow$ 100% reuse $\Rightarrow$ 25,400 acre-feet/year
- External cost of excess consumption: $\leq$ \$1.2M/year:
  - Seawater desalination costs (at source): \$500-2000/acre-foot
  - Not included: transportation to relevant localities

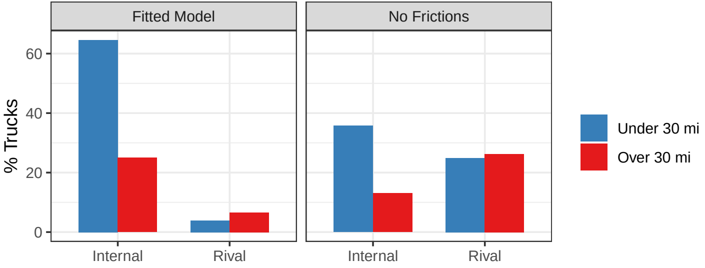
Other Basins

Bounding wastewater transportation impacts

- Current transport burden: 15M truck-miles/year (0.5M trips x 30 miles)
- Excess transportation due to transaction costs: $\leq$ 4M truck-miles/year
  - Minimum distance benchmark $\Rightarrow$ 11M truck-miles/year
- External cost of excess transportation: $\leq$ \$1.7M/year:
  - \$0.85M CO_2 (EPA Social Cost of Carbon); \$0.83M NO_x, PM2.5 (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

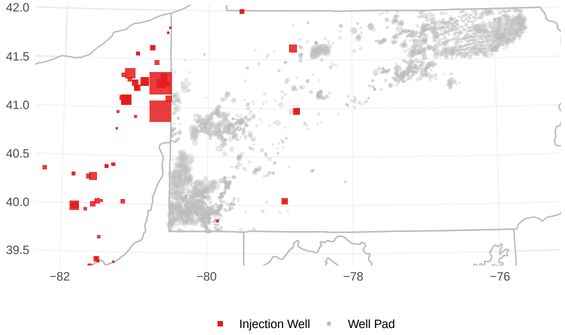
- Environmental impacts are modest (in Pennsylvania)

- 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

Back

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

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

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

- $G^*(\mu, n)$ 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

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

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Match entropy function (cont)

- For ϵ and η EV type 1,

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

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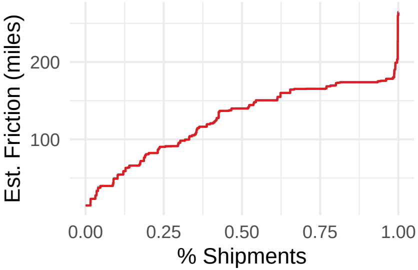
Estimated transaction cost distribution

- 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)

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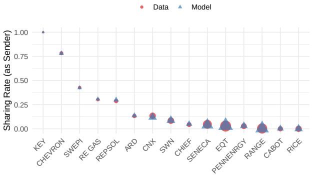
Model fit

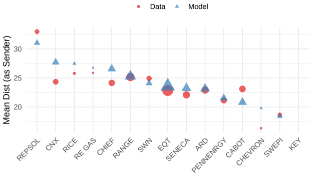
Sharing Rate (as sender, by firm)



Sharing Rate (as receiver, by firm)

Mean Dist (as sender, by firm)

Mean Dist (as receiver, by firm)



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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

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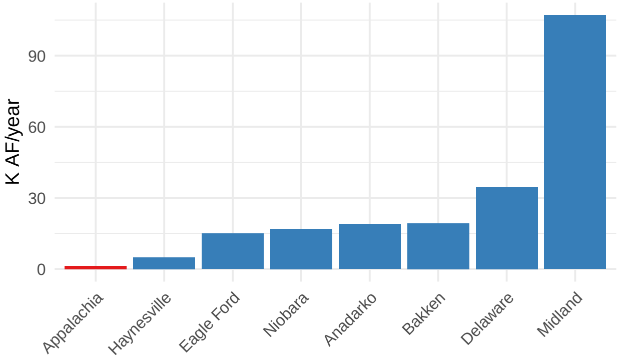
Bounding freshwater consumption impacts: other basins

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



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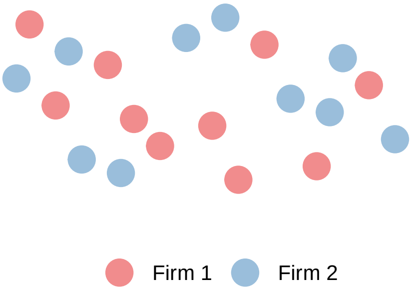
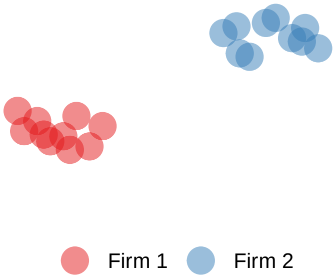
Ambiguous effects of reducing transaction costs





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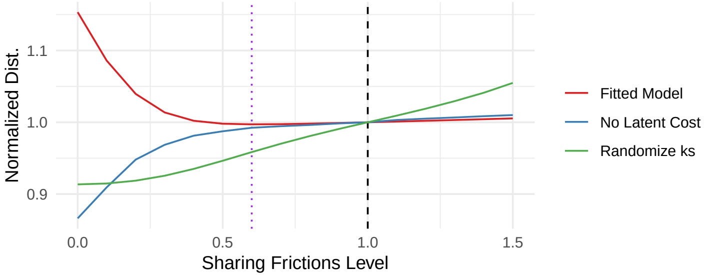
Transaction costs and transportation

- 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

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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

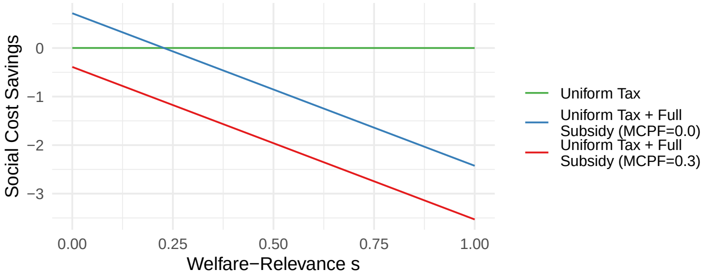
- Hypothetical policy response: Pigouvian tax on truck-miles
- Holding volume fixed, μ^* can be implemented with a tax on truck-miles:

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

  - 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)

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