Make, Buy, or Share:

Wastewater Management in the Marcellus Shale

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April 7, 2023

Abstract

In many areas of environmental policy, the size of externalities and effectiveness of policy interventions is mediated by the presence of transaction costs. I study how transaction costs affect firms' ability to efficiently coordinate wastewater reuse in the Pennsylvania oil and gas industry. Using detailed geographical data, I decompose producers' wastewater disposal costs into transportation costs, transaction costs, and markups. I find that transaction costs are substantial and lead to excessive wastewater trucking at the margin. Moreover, transaction costs encourage firms to integrate horizontally, potentially resulting in less efficient allocations. Finally, I compare policies aimed at reducing contracting frictions to Pigouvian taxes on trucking. This analysis may inform policy approaches in other shale basins as unconventional drilling becomes more widespread outside the United States.

1 Introduction

Fracking requires large volumes of water, and completed wells generate significant quantities of wastewater in addition to hydrocarbons. This creates an opportunity for reuse – wastewater generated by one well can be used to frack another. In Pennsylvania, the second largest natural gas producing state in the US, about 90% of wastewater from unconventional gas wells is reused in subsequent fracking operations.

From a policy perspective, it is important to understand whether and to what extent wastewater reuse successfully mitigates the environmental impacts associated with wastewater handling and disposal. In general, wastewater disposal entails heavy truck traffic (EPA (2020)) and elevated risks of spills (Maloney et al (2017)), drinking water contamination (EPA (2016)), and even earthquakes (Folger and Tiemann (2016)).

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[†] This draft has benefitted greatly from the support and guidance of Robert Porter, Mar Reguant, and Vivek Bhattacharya. I also thank Bill Rogerson, Tom Hubbard, Mike Powell, Ryan Kellogg, Gaston Illanes, Francisco Pareschi, Gaston Lopez, and the participants in the Northwestern IO Lunch for valuable feedback.

Moreover, most freshwater used in oil and gas production is ultimately removed from the water cycle, raising concerns over resource depletion (Groundwater Protection Council (2019)).

In this paper I examine how transaction costs affect interfirm coordination and thus the environmental impacts of reuse. Most reuse occurs within the boundary of the firm – the firm generating the wastewater is the same firm that reuses it. Less commonly, wastewater is "shared" between firms, in the sense that the firm generating the wastewater is different from the firm that reuses it. Transaction costs may prevent firms from sharing even when doing so would reduce disposal costs for the sender and water acquisition costs for the receiver, leading to a loss of surplus. There are few technological or regulatory barriers preventing greater sharing, which could reduce demand for wastewater trucking, freshwater withdrawals, and disposal.

Coase (1960) famously argues that externalities arise precisely due to the existence of transaction costs. In this setting, externalities exist because Pennsylvania residents and other affected parties are unable to come to an efficient agreement with natural gas producers about appropriate wastewater management and disposal practices. In my analysis I take the existence of externalities as a given, and instead focus on transaction costs that arise *between firms*. Transaction costs between firms influence the pattern of disposal decisions in the short run, and the overall structure of the market in the long run, changing the level and incidence of externalities, as well as the efficacy of regulatory intervention.

In Section 3, I present a simple benchmarking exercise showing that if firm boundaries were irrelevant and trucking distance were the only consideration, industry trucking miles could be reduced by about a third. This suggests that firm boundaries *per se* may play an important role in the efficiency of resource allocation, through well recognized channels such as incomplete contracts, imperfect information, and opportunism. Alternatively, firm boundaries might simply correlate with other factors that make sharing transactions difficult or impossible, such as differences in wastewater composition. To distinguish between these hypotheses, I analyze a merger of two large firms that occurred during the sample period. Prior to the merger, the merging parties never shared wastewater with one another, despite being located in close proximity. Afterwards, significant volumes of wastewater flowed across the what was formerly the firm border. This suggests that sharing between the parties would have been technologically feasible prior to the merger, but did not occur for some other reason, consistent with a transaction costs mechanism.

Transaction costs could arise in this setting from several different sources. For example, some wastewater may be costlier to treat or more likely to impair well productivity, creating information frictions. Moreover, information frictions could be exacerbated by the difficulty of monitoring the productivity impact of particular fracking inputs. In the data, however, I find that observable wastewater characteristics explain relatively little of the variation in the probability of sharing. The timing of firms' drilling decisions potentially plays a more important role: completing a well requires the precise coordination of many different subcontractors on a small parcel of land at once. Keeping a transaction inside the firm ensures that the firm has access both to disposal capacity and a water supply at precisely the moment when these are needed. Transaction costs could therefore arise from temporal specificities (Masten, Meehan, and Snyder (1991), Pirrong (1993)) or supply assurance motives (Carlton (1979), Bolton and Whinston (1993)).

In order to characterize the magnitude of transaction costs and clarify their interaction with market structure I proceed to develop and estimate an empirical model of the wastewater sharing market. Intuitively, firms ship wastewater longer distances to avoid sharing with rivals, revealing the transaction cost associated with sharing. In this way my empirical strategy is closely related to the empirical strategy of Atalay, Hortaçsu, Syverson, and Li (2019), who rely on the same source of identification. However, I adopt a different modeling approach to better capture the two-sidedness of the wastewater sharing market. In particular, I rely on a matching model similar to Choo and Siow (2006) and Galichon and Salanie (2022), which enables me to tractably account for capacity constraints – firms' drilling decisions determine both the volume of wastewater that must be disposed of, and the capacity to reuse it. The estimated loss in joint surplus from transaction costs is large, similar to Atalay, Hortaçsu, Syverson, and Li (2019). For the average sharing transaction, transportation costs only account for around 30% of the observable component of the sender's expected cost.

Transaction costs can affect externalities through direct and indirect channels. On the one hand, transaction costs shift marginal transactions into the firm, increasing trucking distances when shorter sharing transactions are otherwise feasible. On the other hand, transaction costs influence integration decisions and thus the equilibrium size of firms, changing the location of boundaries at which transaction costs are incurred. Intuitively, larger firms drill new wells more often, and therefore have more opportunities to dispose of wastewater internally, foregoing transaction costs and markups borne by smaller firms. Transaction costs can therefore incentivize integration. From an environmental impact perspective, integration can displace socially efficient sharing transactions at the margin, particularly if the merging parties are located far apart. To illustrate this phenomenon I simulate hypothetical mergers between different pairs of firms, finding that foregone transaction costs and markups, rather than reductions in transportation costs, account for most of the reductions in firms' expected disposal costs. Other firms are also affected. Firms that share with the merging parties under the status quo are forced to find alternative (and typically more distant) sharing partners, at increased cost. This occurs without any strategic motivation for foreclosure.

In Pennsylvania, wastewater reuse rates are already very high, so transaction costs mainly affect inframarginal decisions about whether wastewater is shared before reuse, rather than firms' decisions about whether to reuse wastewater at all. I focus on the trucking externality for this reason. In other shale basins with different economics, transaction costs could have pronounced effects on the extensive margin, leading firms to rely more heavily on wastewater disposal methods with greater social costs. A recognition of the significance of transaction costs is therefore important for developing regulatory frameworks that encourage wastewater reuse. Kondash et al (2018) argue that lessons from the shale boom in the United States are likely to shape the future development of shale basins in China, South America, and Europe going forward.

In recent years other gas producing states such as Texas and Oklahoma have taken steps to encourage wastewater reuse. One interesting example is Oklahoma's Oil and Gas Produced Water and Waste Recycling and Reuse Act, which became law in 2020. This law is notable in that it primarily sought to reduce transaction costs – it clarified that wastewater is the property of the operator rather than the landowner, eliminating one source of opportunism and contractual incompleteness, while shielding firms that process and transport wastewater for reuse from liability, eliminating another. This contrasts with Pigouvian approaches to externalities, such as taxing wastewater disposal or transportation.

Motivated by this, I use the estimated model to compare policies that aim to alleviate contracting frictions with conventional Pigouvian taxation. In the model, policies that reduce transaction costs encourage substitution towards sharing at the margin, but also increase the likelihood of matching on unobservables with rivals who are located far away. For sufficiently large reductions in transaction costs, the average shipment distance could increase rather than decrease if the latter effect dominates. This illustrates how transaction cost abatements are only a kind of second best for the specific purpose of mitigating the externalities associated with trucking. In the estimated model, a small per mile tax on trucking would achieve a greater reduction in average shipment distance than the optimal transaction cost abatement. However, these policies have very different welfare implications. The Pigouvian tax simply forces firms to bear high transaction costs, or accept lower quality matches on unobservables within the firm. In contrast, the transaction cost abatement approach directly improves surplus and indirectly facilitates higher quality matches on unobservables.

From a broader perspective, the scope of policy concerns surrounding natural gas production extends far beyond its immediate environmental impacts, given the nuanced role of natural gas production in meeting climate policy objectives. Nevertheless, the linkage between transaction costs, market structure, and externalities has relevance in many other policy areas. Although this market is relatively small, a few features make it particularly well suited to studying these issues. Most importantly, firms' demand for wastewater disposal is in large part exogenous. As soon as a well is drilled, firms incur wastewater disposal costs for as many years as the well continues producing gas. At the same time, once a firm is active in a given area, variation in wastewater disposal costs across well pads and over time is likely to be a second order consideration in drilling decisions relative to factors like the abundance of hydrocarbons or gas prices.

1.1 Related literature

Since Coase (1937), economists have sought to understand the nature of the firm by asking when transactions occur within the firm, and when transactions occur across the firm boundary. The so-called "make-vs-buy" decision has been considered from a variety of theoretical perspectives, most notably transaction cost economics in Williamson (1971), property rights theory in Grossman and Hart (1986), and the incentives-based theory of Holmstrom and Milgrom (1991), among others. I focus on the first of these three literatures, which emphasizes the idea that ownership control is an endogenous response to contracting frictions. Transacting with contracts or markets is inherently costly due to imperfect information, incomplete contracts, and opportunism. Transactions are mediated under ownership control when the costs of coordinating activity within the firm are less than the costs associated with contracts or markets.

One contribution of this paper is to estimate the size of transaction costs relative to other sources of cost heterogeneity. As Demsetz (1988) emphasized, transaction costs affect firm's organizational decisions at the margin, taking into consideration other components of total costs and indeed the heterogeneity of transaction costs across potential counterparties. A firm may incur large transaction costs when the corresponding benefits are large enough. This insight plays a significant role in the recent work of Atalay, Hortaçsu, and Syverson (2014) and Atalay, Hortaçsu, Syverson, and Li (2019). These works examine shipments across a wide range of manufacturing industries using Census data. The former paper finds that trade flows between vertically integrated establishments are surprisingly small, while the latter finds that the net benefits of ownership control in the same industries are substantial. Thus, the benefits of transacting via contracts and markets are sufficiently large offset significant transaction costs. My analysis is much more narrow in scope, but since I focus on a single narrowly defined market, I can more directly measure the relative costs and benefits of transacting inside versus outside the firm.

Relatively few papers in the literature on transaction cost economics have attempted to directly measure the size of transaction costs. One notable exception is Masten, Meehan, and Snyder (1991), who estimate transaction costs using a shipbuilder's component-by-component sourcing decisions. Outside this literature, transaction costs of one form or another are often estimated in trade (Anderson and van Wincoop (2004) or Head and Meyer (2014) provide reviews) and in industrial organization (e.g., Crawford, Lee, Whinston, and Yurukoglu (2018), MacKay (2022), and Hodgson (2022)). Methodologically, my approach is related to Cosar, Greico, and Tintelnot (2015), who estimate a border cost and markups in the absence of price data.

A second contribution of this paper is to extend recent empirical work in environmental economics that highlights the significance of imperfect competition for the level and incidence of externalities (e.g., Mansur (2007), Fowlie (2009), Leslie (2018), Preonas (2023)). In contrast to much of this literature, I address the question of whether wastewater disposal patterns are as efficient as they could be, rather than the question of whether there ought to be more or less wastewater disposal in general. In this way my paper relates to prior work on misallocation in industrial organization, including Borenstein, Bushnell, and Wolak (2002) and Asker, Collard-Wexler, and De Loecker (2019). Less directly, this work relates to a variety of recent papers in empirical industrial organization that study strategic interactions between firms in the oil and gas industry, including Kellogg (2011), Covert and Kellogg (2018), Sweeney and Covert (2022), and Vreugdenhil (2022), among others.

In my empirical analysis I emphasize the connection between transaction costs and market structure, a central theme in the literature on transaction cost economics. In particular, I highlight how transaction costs create incentives for integration, and how integration decisions subsequently affect efficiency. In this way, my work also relates to studies of vertical integration on efficiency, notably Forbes and Lederman (2009) and Forbes and Lederman (2010). This has clear connections to antitrust regulation. Recently, Carlton (2020) discussed the significance of transaction costs in antitrust analysis. More generally, Bresnahan and Levin (2012) discuss the potential benefits of combining perspectives from organizational economics and industrial organization to better understand market structure.

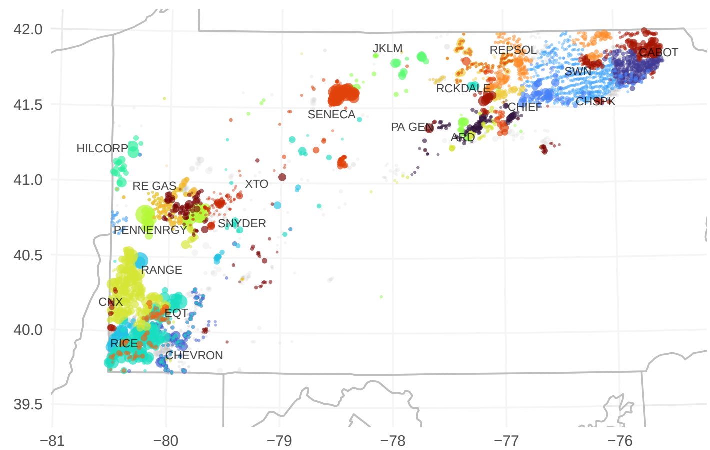
2 Wastewater management in Pennsylvania

Since 2010, natural gas production in the Appalachian region has grown rapidly. Pennsylvania specifically produces more natural gas than any state besides Texas and accounts for about 20% of total US natural gas production. This development can be attributed to improvements in so-called "unconventional" drilling techniques, most notably horizontal drilling and fracking. The industry is relatively unconcentrated, with more than twenty firms producing significant volumes of natural gas. Figure 1 shows the locations of well pads operated by each of the top twenty operators. Notably, firms' operations tend to be tightly clustered geographically, reflecting economies of density in permitting, exploration, drilling, and marketing.

The process of fracking is highly water intensive. A typical fracking event requires over a hundred thousand barrels of water (more than five million gallons), with longer wells requiring more. Much of this water returns to the surface after completion, along with significant quantities of "formation water" (water that was present underground prior to drilling). In the Marcellus shale specifically the total volume of wastewater produced by a new well over ten years is typically 10-30% of the volume of injected water (EPA (2016)).[1] This occurs in two phases: an initial period of rapid *flowback* immediately after a well is completed,

[1] The Marcellus and Utica shales are considered "dry" in the sense that relatively little water returns to the surface. Kondash et al (2018) report that the median wastewater generation is five to ten times greater in the Bakken, Barnett, Eagle Ford, Haynesville, and Niobrara basins. This somewhat limits the generalizability of my analysis.

Figure 1: Locations of Well Pads for Top 20 Firms



and a longer period in which the well produces a steady but declining volume of *produced water* as natural gas is extracted, which occurs over many years.[2]

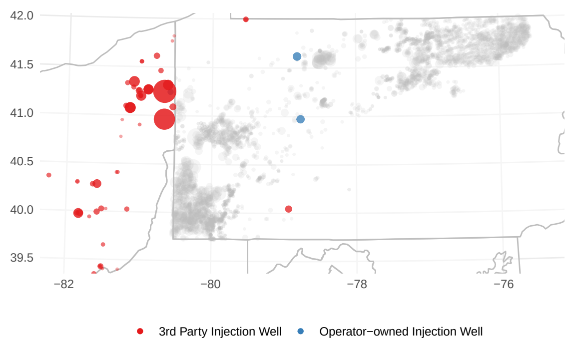
As a result of contact with minerals in the shale, wastewater is highly saline and may contain organic compounds, metals, and naturally occurring radioactive materials, in addition to any chemicals added prior to injection (GWPC (2019)). Outside Appalachia, firms typically dispose of wastewater in deep underground injection wells, which effectively remove water from the hydrologic cycle and have been linked with drinking water contamination and earthquakes in certain instances. In Pennsylvania and West Virginia the underlying geology is not well suited for drilling injection wells (McCurdy (2011)). Injection wells are more easily drilled in nearby Ohio, but the distance between Pennsylvania gas wells and Ohio injection well sites can be significant. This is illustrated in Figure 2, which shows the location of injection wells by market share relative to the location of active gas wells. Consequently, firms that use injection wells can incur significant transportation costs, exacerbated by the fact that most wastewater is transported by truck (EPA (2016)).[3] Menefee and Ellis (2020) report that transportation costs to Ohio disposal wells are about $2-3 per barrel for producing wells in southwestern Pennsylvania and $10-11 per barrel for producing wells in northeastern Pennsylvania, before disposal fees of about $2-4 per barrel.

Alternatively, wastewater can be treated and reused in subsequent fracking operations. In Pennsylvania treatment and reuse accounts for the large majority of wastewater disposal. This can dramatically reduce transportation costs for firms, while also substituting for freshwater, which would otherwise need to be acquired and transported to the well pad. Reuse therefore mitigates all three of the primary sources exter-

[2] I use the term "wastewater" to describe the fluid produced during both of these phases.

[3] In conversation the DEP indicated that some wastewater may be shipped by rail in some cases. In other natural gas producing regions it is common to transport wastewater with pipelines, but this is difficult in Pennsylvania on both on account of topography and the regulatory environment (GWPC (2019)).

Figure 2: Injection Well Locations



nalities due wastewater disposal – excessive trucking, potential freshwater depletion, and the risks associated with injection well disposal – at least in the short run.[4]

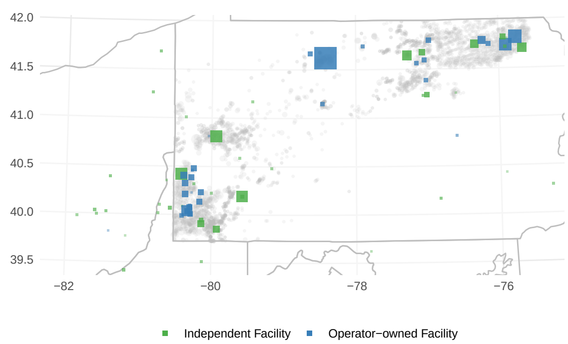
In practice only a limited amount of treatment is needed. Modern fracking fluid formulations are relatively robust to high salinity (Boschee (2014)). The main concern is the presence of solids, greases, bacteria, and trace metals that can lead to corrosion of the well or scaling of underground fractures, lessening well productivity (see, e.g., Conrad et al (2020)). Standard treatment involves simple filtering processes and the introduction of chemical agents such as oxidizers and coagulants to precipitate contaminants. More advanced treatments eliminate ions that contribute to water hardness and scaling. Treated water is then diluted with freshwater before use in the fracking fluid. A mixture of 1:4 mixture of wastewater to freshwater is typical, although this varies depending on the operator and the well.

Standard treatments are not capital intensive and can occur either directly on the wellpad or at a centralized location. Typical procedures cost about \$0.25-0.50 per barrel, which is significantly less than the disposal fees charged by injection well operators. On a well pad, the costs of treatment include the costs of inputs such as filters and chemicals, and the costs associated with spill prevention and regulatory compliance. Furthermore, there may be large shadow costs associated with storing treated and untreated wastewater on the well pad, since space on the well pad can be quite limited while a well is being completed. Some firms instead operate centralized treatment facilities, which are semi-permanent systems of storage tanks or impoundments where similar treatments can be conducted at a larger scale. Using a centralized treatment facility may enable firms to realize some economies of scale, but can increase transportation costs since wastewater must be transported twice – once to the treatment facility, and then again to a well pad

[4] Of course, reuse can only occur while wells are continuing to be drilled. As development slows, the reuse rate necessarily falls. GWPC (2019) and EPA (2020) explore longer term policy solutions to the wastewater disposal problem.

where it can be reused. Some centralized treatment facilities are operated by third party firms. These facilities vary in sophistication and may feature systems capable of treating water to a higher standard in addition to standard treatment and storage. In practice, wastewater intended for reuse rarely needs to be treated beyond the standard of quality that can be obtained in the field, so the choice between centralized and on-pad treatment primarily depends on the tradeoff between economies of scale and overall transportation costs. Figure 3 shows the locations of centralized treatment facilities by market share.

Figure 3: Centralized Treatment Facility Locations



While reuse generally usually occurs within the firm, wastewater can also be shared between firms. That is, wastewater generated at a well pad operated by one firm can be reused at a well pad operated by another firm. Often there is no charge for such transactions, although the wastewater sending firm will sometimes pay the receiving firm a small "tipping fee" on the order of $1-3 per barrel in addition to paying for transportation. Firms may choose to accept wastewater when the marginal cost of acquiring freshwater is high, or when they expect the wastewater sending firm to accept their own wastewater at some other location or sometime in the future. In principle negative prices are possible if the receiving firm has a high enough marginal valuation for wastewater, but this would typically not be the case. In practice, Pennsylvania firms can obtain large quantities of freshwater at relatively low cost, so much of the gain in surplus is due to the reduction disposal costs.

2.1 Description of the sharing market

Wastewater disposal in Pennsylvania is regulated by the Pennsylvania Department of Environmental Protection ("DEP"). The DEP requires oil and gas operators to submit monthly reports indicating the disposal method and disposal location of all quantities of waste materials leaving every well pad, including each barrel of wastewater. These reports constitute the primary data source for this study.[5] Transfers for reuse on another well pad are clearly indicated in the data, as are transfers to centralized treatment facilities. I classify shipments as "internal" or "external" depending on whether the sender was an operator at the destination facility in the month that a shipment occurred. Additional details concerning the data cleaning process are included in Appendix A. The precise format and contents of the waste reporting form has changed over time. It is generally not possible to distinguish internal and rival transactions for the period prior to 2017, so I focus on the period from 2017 to 2020.[6]

Table 1 presents the disposal market shares calculated using this data for each of the options described above. Wastewater shipped to a well pad is always reused.[7] About 46% of wastewater is shipped to an internal well pad, while 8% is shipped to a rival well pad. An important limitation of the data is that it does not indicate the ultimate location of reuse for wastewater that was initially shipped to a centralized treatment facility. These volumes would almost always be reused at some well pad. If we assume most shipments to internal and third party centralized facilities are ultimately reused at a well pad operated by the sender, while those shipped to a rival's centralized facility are ultimately reused at a well pad operated by that rival, then about 10% of all wastewater is shared with a rival. In comparison, less than 10% of wastewater is shipped to injection wells. In the table, the "Other" category encompasses (for example) shipments for reuse in West Virginia and landfill disposal of unusable sludges produced as a byproduct of treatment. Figure 4 shows that these market shares and the overall sharing rate were stable throughout the period that I analyze.

The dataset has a few other limitations worth highlighting. First, only the total volume of water transferred during a month is reported, rather than the dates or volumes of particular shipments. I determine the number of shipments in a month by dividing the total volume by the capacity of a typical water hauling truck.[8] The data also does not indicate the locations where any treatment processes occurred, or if these occurred in different stages at different locations.

When wastewater is transferred to another a well pad for reuse (whether internally or to a rival's),

[5] Typically several wells are located at a single well pad, which encompasses common infrastructure such as access roads and storage tanks. Technically operators are required to report waste information on a well-by-well basis, but since wastewater is often stored in a single location on the pad most simply report well pad-level averages.

[6] It is still possible to calculate aggregate reuse rates for earlier years, although I cannot calculate a sharing rate in this case. Figure 5 presents the full time series of data since 2010.

[7] The DEP precludes firms from accepting water at one well pad and then later transferring it to another. Wastewater that is transferred directly to a well pad must be used on that well pad. This regulation is intended to prevent excessive truck traffic.

[8] I assume that this is 100 barrels, although truck capacities range from around 80 to around 130 barrels. Line items in the data are frequently reported in integer multiples of a truck capacity in this range.

Table 1: Disposal Market Shares, 2017-2020

Destination	Ownership	% Waste
Well pad	Internal	45.6
	Rival	7.8
Centralized facility	Internal	18.1
	3rd party	13.5
	Rival	2.2
Injection well		9.4
Other		3.4

the destination well pad typically accepts a large amount of wastewater from many different sources at once. In contrast, transfers tend to originate at well pads that are currently disposing of smaller amounts of wastewater. A well pad that received internal or rival transfers in a given month received about 30,000 barrels (median 2,250) from 28.5 unique well pads on average, of which 6.0 were operated by rivals. The true volume received would likely be somewhat greater, since this calculation excludes any re-shipments from centralized treatment facilities, which are not observed in the data. In comparison, a well pad that shipped wastewater to an internal or rival well pad sent about 2,000 barrels (median 400) to 1.8 well pads on average, of which 0.4 were operated by rivals. In the average month there were 58.3 well pads accepting wastewater for reuse from 912.2 origin well pads. This "many-to-few" pattern is consistent with the underlying physical processes: on the one hand, wells produce wastewater for as long as they produce gas, in gradually decreasing quantities; at the same time, reuse can only occur as part of a fracking event in which a large quantity of wastewater is used at once. Since storage is costly and re-transfers between well pads are generally prohibited, firms may accept wastewater transfers from rivals only when they have an immediate use for it. In 77% of firm-months in which a firm accepted wastewater from a rival, the same firm fracked a well sometime within the next two months. By comparison, the same figure was only 21% for firm-months in which a firm did not accept wastewater from a rival.

One question raised by Table 1 is whether the observed sharing rate is higher or lower than the efficient level. Given firms' geographic dispersion (illustrated in Figure 1), the efficient allocation could feature a relatively low sharing rate, even if there were few barriers to sharing. I find that most firms participate in the sharing market at least occasionally, suggesting that barriers to sharing are not excessively high. Among the top 20 firms (out of about 80), 17 provided wastewater to another firm and 17 received wastewater from another firm at least once between 2017 and 2020, and 16 were active on both sides of the sharing market. Among the 17 firms that provided wastewater to another firm, firms shared water with 5.9 distinct counterparties on average, and shared water with at least one counterparty in 46% of months. Among the 17 firms that received wastewater, firms received water from 9.2 distinct counterparties on average, and received water from at least one counterparty in 45% of months. Thus, the sharing rate in Table 1 could be close to the efficient level. I explore whether this is the case empirically in the next section.

3 Frictions in the sharing market

This section presents evidence of transaction costs in the sharing market. First, I conduct a stylized benchmarking exercise to gauge the efficiency the sharing market under the status quo. Second, I analyze changes in disposal patterns subsequent to a merger between two leading firms that occurred during the sample period. Finally, I discuss potential sources of transaction costs.

3.1 Optimal transport benchmark

The fact that many firms participate in the sharing market at least some of the time suggests that barriers to sharing are not excessively high, implying that the observed sharing rate could be close to the efficient level. To test for the presence of frictions I attempt to directly construct the efficient allocation, in order to see how this allocation differs from the observed one. Intuitively, I want to perform a test for misallocation, similar in spirit to Borenstein et al (2002) or Asker et al (2019), in which I characterize the optimal reuse plan for the status quo level of reuse.

Consider the flow of wastewater in month t between all well pads K and all disposal facilities D. For each well pad $\kappa \in K$ and disposal facility $\delta \in D$, the data records the actual shipment volume $y_{\kappa\delta}$ in month t (in truckloads). If the distance between κ and δ is $d_{\kappa\delta}$ miles, then a simple measure of industry trucking intensity is the weighted average shipping distance in month t:

$$\frac{\sum_{\kappa \in K} \sum_{\delta \in D} y_{\kappa\delta} d_{\kappa\delta}}{\sum_{\kappa \in K} \sum_{\delta \in D} y_{\kappa\delta}}$$

Loosely, we might think of the efficient allocation as the allocation that minimizes this quantity. Transportation costs are both the primary cost driver for firms, as well as a key source of externalities in the form of emissions, traffic, road damage, and an elevated risk of spills.

Suppose all shipments observed in a month could be costlessly re-allocated, holding fixed the total disposal volume Q_κ at well pad κ and the total quantity of wastewater C_δ received at facility δ. If this were possible, then the efficient allocation would solve the following optimal transport problem:

$$
\begin{aligned}
\min_{\mu} \quad & \sum_{\kappa \in K} \sum_{\delta \in D} \mu_{\kappa\delta} d_{\kappa\delta} \\
\text{s.t.} \quad & \sum_{\delta \in D} \mu_{\kappa\delta} = Q_\kappa \; \forall \, \kappa \in K \\
& \sum_{\kappa \in K} \mu_{\kappa\delta} = C_\delta \; \forall \, \delta \in D \\
& \mu_{\kappa\delta} \in \mathbb{Z}_{\geq 0} \quad \forall \, \kappa, \delta \in K \times D
\end{aligned}
\tag{1}
$$

Since this problem is a linear program, it can be solved easily, delivering a simple benchmark estimate for the socially optimal trucking level at current levels of reuse.

Table 2 compares the solution to (1) with the observed shipment data, averaging across months. I also present a modified version of (1) in which shipments between rivals are highly penalized ("Penalized"), such that the minimum possible sharing rate consistent with the observed marginal shipment volumes is obtained. I find that under the optimal schedule trucking intensity is about a third lower than in the observed allocation. Moreover, the optimal schedule implies a sharing rate of 34%, in contrast to the 12% observed sharing rate.[9] This suggests that there could be significant frictions in the sharing market, and that transportation externalities may be large even at current levels of reuse. In contrast, in the penalized allocation, trucking intensity is about a third greater than in the observed allocation, and the sharing rate is about 8%. This means that the observed allocation is more efficient than the benchmark would imply if barriers to sharing were very large, suggesting that the observed distribution could be well approximated by a model like (1) with modest frictions.

Table 2: Benchmark Results

	Data	Optimal	Penalized
Mean distance	32.2	22.5	41.2
Median distance	21.2	13.2	20.4
Sharing rate	0.12	0.34	0.08

The main limitation of this exercise is that shipments in a given month may not be perfectly "substitutable" in the sense implied by (1). As mentioned previously, a shipment that occurred at the beginning of the month may not have been substitutable for a shipment at the end of the month. This is not reflected in the constraints in (1). Similarly, there could be other unobserved technological or contractual sources of variation in cost. I interpret the fact that the observed allocation lies between the two extremes presented

[9] I exclude the "Other" shipments.

in Table 2 as evidence that (1) is not too poorly specified, but a better strategy would explicitly account for unobserved heterogeneity and other sources of econometric error. The model I develop in Section 4 takes this approach, making it more suitable for estimation and policy analysis. Model (1) can be viewed as the limit case of this richer model as transaction costs and the dispersion of unobserved heterogeneity shrink towards zero.

3.2 Merger analysis

The exercise in the previous section points to the existence of frictions of some kind, but not necessarily to the presence of transaction costs specifically. Mergers provide one valuable source of variation to distinguish between different kinds of frictions.

In June 2017 EQT Production Co ("EQT") and Rice Drilling B ("Rice") announced a merger, which was completed in November 2017. Between July 2016 and June 2017, EQT and Rice were among the top ten natural gas producers in Pennsylvania. Both EQT and Rice operations were primarily concentrated in contiguous areas in Greene and Washington counties in southwestern Pennsylvania. 89% of Rice well pads were located within five miles of an EQT well pad, while 63% of EQT well pads were located within five miles of a Rice well pad. Despite being located in close geographic proximity to one another, EQT and Rice engaged in no sharing prior to the merger. Between July 2016 and June 2017, EQT transferred 83.3% of wastewater internally (i.e., to EQT-operated well pads), 14.1% to third party treatment facilities, and 2.4% to well pads operated by rival firms. In the same period, Rice transferred 63.8% of wastewater internally, 35.9% to third party treatment facilities, and none to rivals. Of the 2.4% that EQT transferred to well pads operated by rivals, none was transferred to well pads operated by Rice. In the same period, EQT received a small amount of wastewater from rivals (about 2.7% of total wastewater received, with the remaining 97.3% received from internal sources), but none from Rice.

After the merger, transfers between formerly-unintegrated EQT and Rice well pads increased to a substantial level. Figure 6a illustrates the trade flows between formerly unintegrated well pads before and after the merger. The change was most significant for well pads that had formerly been operated by Rice. From January 2018 to December 2020, 17.0% percent of wastewater from "old" Rice well pads was transferred to well pads that had been operated by EQT prior to the merger (i.e. "old" EQT well pads). This represents a substantial change, since these locations had not received any wastewater from Rice in the year prior to the merger. Moreover, this figure obscures the true magnitude of the change, since 69.9% of post-merger transfers went to "new" well pads that did not enter operation until after to the merger. Among wastewater transferred from old Rice well pads to old locations (i.e., those that with observed activity prior to the merger), 63.1%

was transferred to old EQT locations. Before the merger, this had been 0%. The corresponding changes for EQT well pads were somewhat smaller in relative magnitude. From January 2018 to December 2020, 1.9% of wastewater from old EQT well pads was transferred to old Rice well pads, representing 5.9% of all transfers to old locations.[10] This information is summarized in Figure 7b.

These patterns suggest that the extent of trade may have been limited by the existence of the firm borders per se, and not only factors such as transportation costs or technological incompatibilities. Interestingly, in the merger prospectus form S-4 filed with the SEC, EQT did indicate to shareholders that one of the potential synergies of the proposed merger was to enable the firms to better coordinate wastewater handling.

3.3 Sources of transaction costs

The literature on transaction costs economics characterizes transaction costs as the costs of contracting in the presence of incomplete contracts, imperfect information, and opportunism. In this context, two potentially important sources of transaction costs relate to the quality of wastewater, and the specificities that arise from the dynamics of wastewater generation and reuse.

Not all wastewater is equally suitable for reuse. Wastewater that is especially high in salts, polymers, or other suspended solids can foul treatment equipment or, if improperly treated, reduce the effectiveness of the fracking operation and ultimately the productivity of a well. In general, the composition of wastewater is highly variable – it depends not only on the composition of the fracking fluid, but also on the underlying geology of the target formation, and the conditions of the fracking event ("soak time," temperature, pressure). Much of the salt and solid content arises from contact with the shale and underground formation waters, rather than from the formulation of the fracking fluid. For this reason, the composition of wastewater produced by a given well also changes over time, becoming more and more saline as a well matures.

These considerations could give rise to transaction costs through a few channels. First, it may be difficult for a firm to comprehensively assess the quality of a given truckload of wastewater before accepting it. Consequently, firms have imperfect information about treatment costs and risks to well productivity when accepting wastewater. Risks to well productivity in particular may be difficult to resolve contractually on account of the difficulty of monitoring production efficiency ex post. Drilling in general is uncertain and complex, making it challenging to measure lost productivity, much less apportion it to specific barrels of wastewater used during the frack. This situation also creates conditions for adverse selection, since firms may prefer to share lower quality wastewater with rivals rather than risk damage to their own wells.

Alternatively, transaction costs could arise from the dynamics of wastewater production and reuse. Mas-

[10] In part the differences in magnitude can be explained by the fact that EQT was the larger firm. Furthermore, new drilling on old EQT well pads was greater than new drilling on old Rice well pads subsequent to the merger.

ten Meehan and Snyder (1991) and Pirrong (1993) discuss temporal specificity as an important source of transaction costs. A firm that has recently drilled a well must dispose of a large volume of wastewater in a short amount of time. A rival firm that is able to accept wastewater in this circumstance has an incentive to attempt to extract quasi-rents that arise from the scarcity of disposal capacity at any particular point in time. A similar dynamic could arise on the other side of the market, since a firm that is about to drill a well must aggregate a large volume of water in a similarly short amount of time. Quasi-rents are magnified by high transportation costs, which reduce the attractiveness of firms' outside options. A firm can avoid costly bargaining over quasi-rents for both types of transactions by simply reusing its own wastewater at some other location. Formal, long-term water sharing agreements or relational contracts between firms might also help to resolve these problems. Anecdotally, arrangements of this kind seem to play some role in this market, although I do not observe them. For example, one large firm reportedly holds formal, long-term bilateral contracts with fourteen rivals specifying terms under which it will accept wastewater, although details of these contracts are not publicly known (Gough 2020). One individual with knowledge of the industry who I communicated with stated that firms might "[switch] off using each other's wastewater" in some circumstances, a form a relational contracting.

To understand the empirical significance of the wastewater quality channel I collect evidence on how sharing patterns vary with observable characteristics that correlate with wastewater quality. I focus on three characteristics in particular – fracking fluid composition, target formation, and well age. The results are summarized in Table 3, which shows the injection well disposal rate, internal reuse rate, and rival reuse rates for each well pad-year in the data. I first consider the chemical composition of the fracking fluid. When firms frack a well in Pennsylvania, they are required to submit a disclosure to the public FracFocus registry indicating the dates and times of the event, the total volume of water used, and the chemical composition of the fracking fluid. Broadly speaking, there are two major categories of fracking fluid – low viscosity "slickwaters" on the one hand, and high viscosity gels on the other, although many formulations are a hybrid of the two. Both types of fluid are used widely throughout the industry, with the determination varying well-to-well depending on the target formation. In comparison to slickwaters, gels are more likely to contain higher concentrations of polymers that result in fouling of treatment equipment. Thus, one might expect transaction costs to be higher when the wastewater originates from a well where a gel based fracking fluid was recently used. The second line and third lines in the table show the reuse rates for well pad years in which there was a FracFocus disclosure that included a keyword associated with gels (e.g., "guar") or slickwaters (e.g., "acrylamide"), respectively.[11] The total share of wastewater reused was almost the same for both types

[11] I obtained specific keywords from the engineering literature. Two particularly valuable sources were Montgomery (2013) and Walsh (2013).

Table 3: Well Pad-Year Disposal Patterns

	% Inj. Well	% Reuse	If Reused: % Internal	If Reused: % Rival	Count
Any FracFocus disclosures	5.6	94.4	91.6	8.4	667
gel keyword	4.0	96.0	94.4	5.6	67
slickwater keyword	4.7	95.3	91.3	8.7	195
Marcellus	4.8	95.2	91.4	8.6	576
non-Marcellus	9.6	90.4	92.6	7.4	91
No FracFocus disclosures	15.0	85.0	88.9	11.1	9385

of well pads. Well pads where gel based fluids were used were less likely to share with rivals conditional on reuse (5.6% vs. 8.7%, $p = 0.014$).

The composition of fracking fluid itself may have only a limited bearing on the quality of wastewater relative to the geology of the target formation and other factors, such as the age of a well. To understand the effect of the target formation, I match the FracFocus records to DEP records which indicate the target formation of each well. About 90% of wells completed during the sample period target the Marcellus shale, which underlies the entire region. The remainder target other formations such as the the older and deeper Utica shale. Wastewater originating from wells that target non-standard formations might have a significantly different profile than wastewater originating from those that target the Marcellus, increasing information frictions. The fourth and fifth lines in of Table 3 show reuse rates for well pad-years in which there was a FracFocus disclosure linked to the Marcellus shale versus those for which all disclosures were linked to other formations. Wastewater from non-Marcellus well pads was more likely to be disposed in an injection well, consistent with elevated costs of reuse, but was only slightly less likely to be shared with a rival conditional on being reused (7.4% vs. 8.6%, $p = 0.31$). I find a similar pattern with respect to well age. The presence of a FracFocus disclosure indicates whether a well was drilled on a given well pad during a given year. Consequently, well pad-years without disclosures are more representative of older well pads than well pad years with disclosures. As mentioned above, older wells tend to produce wastewater that is more saline, and therefore potentially costlier to reuse. Wastewater from well pads with no associated disclosures was far more likely to be shipped to an injection well (15.0% vs. 5.6%), consistent with an elevated cost of reuse. However, conditional on being reused, wastewater from well pads with no associated disclosure was more likely to be reused by a rival (11.1% vs. 8.4%, $p < 0.01$), which is contrary to what one would expect if differences in quality were a significant source of transaction costs. Taking all three exercises together, I find only modest evidence for wastewater characteristics as a source of transaction costs.

4 Disposal market model

In this section I develop an empirical model of the wastewater disposal market in order to disentangle transportation costs, transaction costs, and markups. This enables me to explore how transaction costs interact with market structure and how different policy interventions might affect key outcomes of interest.

Each month, operators report the destination of each barrel of wastewater disposed by well pad. I view this data as the realization of transferrable utility matching market in which firms with wastewater to dispose are matched with firms that have the capacity to accept it for reuse. In particular, individual truckloads of wastewater are matched to individual "delivery slots" at each destination. Firms with disposal needs choose the lowest-cost disposal option for each truckload of wastewater on a truckload-by-truckload basis, while firms with disposal capacity accept truckloads of wastewater on a slot-by-slot basis.

In reality, most reuse occurs within individual firms. Implicitly, I model the firm as a collection of individual decision makers at different locations. When an internal transaction is observed, the decision maker at the sending location is modeled as paying a transfer to the decision maker at the receiving location, even though both locations are under the control of the same firm. These internal "transfer prices" can be interpreted as the shadow costs of using disposal capacity that could otherwise be allocated to internal shipments from other well pads, or sold to rival firms. This structure makes it possible to analyze the wastewater management problem as a discrete choice problem.

4.1 Preferences

Suppose the firm operating well pad $\kappa \in K$ must dispose of Q_κ truckloads of wastewater. The cost associated with disposal of truckload i from well pad κ at facility $\delta \in D$ is represented as:

$$c_{i\delta} = d_{\kappa\delta} + \phi^{\kappa}_{0,\kappa\delta} + p_{\kappa\delta} - \sigma^{\kappa}_{\kappa\delta}\varepsilon_{i\delta} \tag{2}$$

where $d_{\kappa\delta}$ is distance between κ and δ in miles, $\phi^{\kappa}_{\kappa\delta}$ is a transaction cost, and $p_{\kappa\delta}$ is a transfer paid to the firm accepting the water at δ. $\varepsilon_{i\delta}$ is generalized extreme value error that I describe in more detail below, and $\sigma^{\kappa}_{\kappa\delta}$ is the scale of this error. The coefficient on distance $d_{\kappa\delta}$ is normalized to one, so that the remaining parameters are interpretable in terms of the cost of shipping a truckload of wastewater a single mile. The transfer $p_{\kappa\delta}$ can be decomposed into three parts: a marginal cost of disposal mc_δ, a transaction cost $\phi^{\delta}_{0,\kappa\delta}$ incurred by the receiver, and a "markup" $\tau_{\kappa\delta}$ (which may be either positive or negative):

$$p_{\kappa\delta} = \phi^{\delta}_{0,\kappa\delta} + mc_\delta + \tau_{\kappa\delta} \tag{3}$$

Adding and subtracting $\phi^{\delta}_{0,\kappa\delta}$ and mc_{δ} in (2) gives an alternative expression for the disposal cost:

$$c_{i\delta} = d_{\kappa\delta} + \overbrace{\phi^{\kappa}_{0,\kappa\delta}+\phi^{\delta}_{0,\kappa\delta}+mc_{\delta}}^{\phi_{\kappa\delta}} + \overbrace{p_{\kappa\delta}-\phi^{\delta}_{0,\kappa\delta}-mc_{\delta}}^{\tau_{\kappa\delta}} - \sigma^{\kappa}_{\kappa\delta}\varepsilon_{i\delta} \tag{4}$$

In this expression, $\phi_{\kappa\delta}$ is a gross transaction cost which includes the transaction costs incurred on both sides of the market and the marginal cost of disposal, and $\tau_{\kappa\delta}$ is the markup charged by the firm accepting the wastewater. I focus on (4) rather than (2) since (under the assumptions of the model) the shipment data identifies the gross transaction cost $\phi_{\kappa\delta}$ rather than its individual components. Intuitively, shipment patterns are explained by variation in joint surplus, and not simply the sender's surplus.

The preferences of firms that accept wastewater for reuse are similar to preferences of firms seeking disposal. Suppose the firm controlling facility $\delta \in D$ can accept up to C_{δ} truckloads of wastewater – in other words, the firm is endowed with C_{δ} "delivery slots," determined exogenously by the firm's drilling operations. The firm allocates delivery slot j in order to maximize ex post profit. In particular, the ex post profit of allocating slot j at facility δ to a truckload of wastewater originating at well pad κ is given by:

$$\pi_{\kappa j} = p_{k\delta} - \phi^{\delta}_{0,\kappa\delta} - mc_{\delta} + \sigma^{\delta}_{\kappa\delta}\eta_{\kappa j} \tag{5}$$

where $p_{\kappa\delta}$, $\phi^{\delta}_{0,\kappa\delta}$, and mc_{δ} are the same as in (3), and $\eta_{\kappa j}$ is a generalized extreme value error scaled by $\sigma^{\delta}_{\kappa\delta}$. Note that (5) is equivalent to:

$$\pi_{\kappa j} = \tau_{\kappa\delta} + \sigma^{\delta}_{\kappa\delta}\eta_{\kappa j}$$

where $\tau_{\kappa\delta}$ is the markup term discussed previously.

In general, the form of (4) is rich enough to encompass firms' preferences across disposal modes (reuse on a well pad, reuse via centralized treatment facility, injection well disposal), as well as preferences across individual facilities. Likewise, (5) is rich enough to encompass firms' preferences across various sources of wastewater and freshwater. The main focus of my analysis is the reuse market, rather than the injection well disposal market or the freshwater acquisition market. I now describe equilibrium in this market.

4.2 Equilibrium in the reuse market

If firms choose the lowest cost disposal option for each truckload of wastewater on a truckload-by-truckload basis, then the probability that the firm at κ ships a given truckload of wastewater to δ is

$$\rho_{\kappa\delta} = P\left(c^{\kappa}_{i,\delta} = \arg\min_{\delta} c^{\kappa}_{i,\delta}\right) \tag{6}$$

Similarly, the probability $q_{\kappa\delta}$ that a delivery slot at δ is allocated to a truckload of wastewater originating at $\kappa$is

$$q_{\kappa\delta} = P\left(\pi^{\delta}_{j\kappa} = \arg\max_{\kappa} \pi^{\delta}_{j\kappa}\right) \tag{7}$$

In general, (6) and (7) depend on the equilibrium transfers τ as well as the distribution of the unobserved heterogeneity. If ε and η are extreme value type I errors, then $\rho_{\kappa\delta}$ and $q_{\kappa\delta}$ are standard logit choice probabilities, like in Choo and Siow (2006)'s marriage market.

Following Galichon and Salanie (2022), it is straightforward to characterize an equilibrium provided that $\epsilon^{\kappa}_{i\delta}$ and $\eta^{\delta}_{\kappa j}$ are additively separable. In principle this is a restrictive assumption which excludes certain forms of matching on unobservables, but I argue that this assumption is relatively innocuous in this setting. For example, the main sources of unobservable heterogeneity would be compatibilities in timing, wastewater composition, or common subcontractors across well pads. In any particular month, these kinds of factors would be more-or-less constant for a given $\kappa\delta$ pair, and would therefore affect the joint surplus of all $\kappa\delta$ shipments equally. The additive separability assumption rules out matching on unobserved characteristics of specific truckloads from κ and specific delivery slots at δ. In other words, the additive separability assumption implies that the firm sending truckload i has preferences over destinations, and not over delivery slots.

In equilibrium, the total supply of delivery slots at δ to truckloads of wastewater originating at κ is equal to the total demand for delivery slots at δ for truckloads of wastewater originating at κ. Formally, the equilibrium flow of wastewater from κ to δ is given by $\mu_{\kappa\delta}$, where $\mu_{\kappa\delta}$ is:

$$\mu_{\kappa\delta} = Q_{\kappa}\rho_{\kappa\delta} = C_{\delta}q_{\kappa\delta} \tag{8}$$

Equilibrium is characterized by a transfer matrix τ such that (8) is satisfied, when senders and receivers make choices according to (6) and (7). Computation of the equilibrium depends on the parameterization of unobserved heterogeneity, which I discuss in the next section.

In classic matching models with transferrable utility such as the Shapley and Shubik (1971) model, the equilibrium matching does not depend on the transfers in the sense that there are many transfer matrices consistent with the matching that maximizes joint surplus. In contrast, the equilibrium transfer matrix in the Choo and Siow (2006) model and related models is unique when the utility of an outside option is known, as discussed by Graham (2011). When the utility of the outside option is left unspecified, the transfer matrix is still identified up to location. In Section 4.3.2 I describe a set of auxiliary assumptions regarding the utility of the outside option that pins down the transfer matrix (i.e., the markup level), but these assumptions are not necessary for estimating the parameters of the matching market or the relative markups.

4.3 Parameterization

I estimate the model under specific functional form assumptions on the transaction costs $\phi_{\kappa\delta}$ and the distribution of the unobserved heterogeneity, which I describe in this section.

The primary source of variation in joint surplus – aside from distance – is the distinction between "internal" and "rival" shipments. For simplicity I assume that all rival shipments incur a single, constant transaction cost ϕ_{rival}, while all internal shipments incur a single, constant transaction cost $\phi_{internal}$. I normalize $\phi_{internal}$ to zero. Therefore I only estimate a single transaction cost parameter ϕ_{rival} in the main specification.

Of course, many richer parameterizations of the transaction costs are possible. In (4), $\phi_{\kappa\delta}$ is additively separable in $\phi^{\kappa}_{\kappa\delta}$ and $\phi^{\delta}_{\kappa\delta}$, so a natural extension is to estimate sender- and receiver-specific fixed effects at the firm level. I do not pursue this approach. Intuitively, identification of ϕ_{rival} relies on instances in the data in which firms ship wastewater excessively long distances to avoid sharing with rivals. Given the geographic clustering of firms, these events are somewhat infrequent, so it is unlikely that the data would separately identify $\phi^{\kappa}_{\kappa\delta}$ and $\phi^{\delta}_{\kappa\delta}$ for every firm. For robustness one could consider more parsimonious approaches to accommodating transaction cost heterogeneity, such as estimating separate parameters for the southwestern and northeastern parts of the state, or for smaller versus larger firms. I have not done this in the current draft.

As discussed by Galichon and Salanie (2022), the distribution of unobserved heterogeneity plays a central role in empirical models of matching with transferrable utility. Similar to other settings in industrial organization, it is important that the assumed parametric form of the unobserved heterogeneity is rich enough to accurately reflect substitution patterns across potential matches. I consider two different specifications. First, as a benchmark, I consider a heteroskedastic modification of the Choo and Siow (2006) specification, in which ε and η are drawn from type 1 extreme value distributions, but allowing the scale of the errors to differ across the senders and receiver sides of the market. In particular, I assume that $\sigma^{\kappa}_{\kappa\delta} = \sigma_{\kappa}$ for some constant σ_κ which is the same for all κ and, similarly, that $\sigma^{\delta}_{\kappa\delta} = \sigma_\delta$ for some constant σ_δ which is the same for all δ. This specification is straightforward to estimate, but may overstate the gains in expected utility from sharing with rivals due to the independence of irrelevant alternatives assumption – invariably, there are more rival than internal destinations accepting wastewater at any given point in time.

To relax this assumption, I focus on a nested logit specification where internal and rival transactions represent two nests, allowing for correlation in the errors across nests. In this case, the error $e_{i\delta}$ is defined so that the probability that truckload i is shipped to facility δ in nest $N \in \{I, R\}$ is:

$$\rho_{\kappa\delta} = \rho_{\kappa\delta|N}\rho_{\kappa N}$$

where $\rho_{\kappa\delta|N}$ and $\rho_{\kappa N}$ are logit choice probabilities. In particular, $\rho_{\kappa N}$ is the probability that i is shipped to any $\delta \in D_N$, where D_N is the set of all facilities in N, and $\rho_{\kappa\delta|N}$ is the probability that i is shipped to facility δ in particular conditional on being shipped to some facility in D_N. Formally,

$$\rho_{\kappa\delta|N} = \exp\left\{\lambda_N^{-1}\sigma_\kappa^{-1}\left(-d_{\kappa\delta} - \phi_{\kappa\delta} - \tau_{\kappa\delta}\right) - \log F_{\kappa,N}\right\} \tag{9}$$

where $\lambda_{\kappa,N}$ is the nesting parameter and $F_{\kappa,N}$ is denominator of the logit choice probability (i.e., the inclusive value),

$$F_{\kappa,N} = \sum_{\delta\in D_N} \exp\left\{\lambda_{\kappa,N}^{-1}\sigma_\kappa^{-1}\left(-d_{\kappa\delta} - \phi_{\kappa\delta} - \tau_{\kappa\delta}\right)\right\}$$

while $\rho_{\kappa N}$ takes the following form:

$$\rho_{\kappa N} = \frac{F_{\kappa,N}^{\lambda_{k,N}}}{\sum_{n\in\{I,R\}} F_{\kappa,n}^{\lambda_{k,n}}} \tag{10}$$

The errors η on the wastewater-accepting side of the market are defined similarly, with two nests depending on whether a given truckload originates at an internal or rival well pad, with nesting parameters $\lambda_{\delta,I}$ and $\lambda_{\delta,R}$ and inclusive values $H_{I\delta}$ and $H_{\delta N}$.

Galichon and Salanie (2022) discuss the use of nested logit preferences in empirical matching models with transferable utility. The specification I propose retains much of the tractability of the multinomial logit, but partly mitigates the effect of the IIA assumption. In Appendix C I explain how I compute the equilibrium conditional on $\theta_{\epsilon,\eta} = \{\sigma_\kappa, \sigma_\delta, \lambda_{\kappa,I}, \lambda_{\delta,R}, \lambda_{\delta,I}, \lambda_{\delta,R}\}$. This is not overly burdensome; otherwise, estimation would be computationally infeasible. In principle, a richer specification could better capture the true substitution patterns at the cost of tractability. For example, one could define nests at the level of the firm. A more significant limitation of the current model is that I do not account for the fact that a wastewater sending firm's decisions are likely to be correlated across well pads. To address this, one could specify a mixed logit with errors correlated across well pads, although this would be computationally costly.

4.3.1 Centralized treatment facilities

The model is primarily intended to analyze direct transfers between well pads. However, about a third of wastewater is processed at centralized treatment facilities. From a modeling standpoint, the centralized treatment facilities present two difficulties. First, although the large majority of wastewater sent to centralized treatment facilities is ultimately reused, I do not observe where (or when) reuse occurs. As a result, I do not directly observe the transportation costs associated with re-transfer from the centralized facility to the location of reuse. Second, many of the centralized treatment facilities are operated by third parties, and the nature of contracts between firms and third parties may vary from case to case. Often, a third party centralized treatment facility operator would perform treatment on a contract basis for a particular operator, with the sender returning to haul the water to a reuse site after treatment. In this case such shipments might be regarded as "internal," perhaps with some associated transaction costs or markups similar to those charged by other contractors involved in the treatment process (e.g., equipment lenders). In other cases, however, a centralized treatment facility might assume responsibility for finding another operator to accept the treated wastewater, in which case the centralized treatment facility would charge a much higher fee.

Given these challenges, I exclude centralized treatment facilities operated by third parties from the analysis.[12] For centralized treatment facilities operated by oil and gas firms, I assume that the additional marginal cost associated with re-transfer to a subsequent well pad counts towards the joint surplus of the match. I estimate this additional marginal cost using the distance between the centralized treatment facility and the well sites operated by the owner. In other words, for these transactions, the distance term $d_{\kappa\delta}$ represents the sum of the distance between κ and δ and a weighted average distance between δ and well pads where the owner of δ drilled new wells. For robustness I also estimate the model only using data from transfers between well pads, since measurement error should be less severe in this case.

[12] This means that I am unable to account for how shipments to and from centralized treatment facilities operated by third parties would change in counterfactuals. There are a few possible ways that these facilities could be incorporated into the model. For example, one could assume that under the status quo all wastewater shipped to an independent facility is reused by the firm that sent it, and that the associated transaction costs are similar to those associated with internal transactions. With any such strategy, it becomes important to specify whether or how transaction costs incurred when a centralized treatment facility "intermediates" a shipment between rivals might differ from those incurred when firms interact directly.

4.3.2 Injection well disposal market

As discussed above, the level of transfers in the reuse market is only identified if the utility of an outside option is known (along with the relevant marginal participation rate). The injection disposal market can be viewed as the outside option for firms sharing wastewater for reuse. Since this is a business-to-business market, I do not observe the prices charged by injection well operators, which makes it difficult to directly estimate the expected utility of injection well disposal. However, it is possible to estimate the transfer level under additional assumptions, which I now describe.

First, I assume that the transaction costs associated with injection well disposal are approximately the same as those associated with internal reuse. In particular, I assume that the gross transaction cost in this case is a constant $\phi_{injection}$ which is the same for all well pads κ and for all injection well facilities (except those owned by rivals), and that $\phi_{injection} \approx \phi_{internal}$. This might be viewed as a reasonable approximation – engineering estimates suggest that the marginal cost of injection well disposal is about \$0.25 per barrel or less (McCurdy (2011)), which is approximately the same as the cost of treatment for reuse on a well pad. At the same time, any transaction costs incurred in this case would likely be similar in magnitude those included in $\phi_{internal}$ if "internal" transactions in the data can involve unobserved interactions with subcontractors. This assumption is necessary since, in general, $\phi_{injection}$ is not separately identified from the transfer level.

In addition to this assumption, I also need to make a conduct assumption in order to determine how prices are set. In particular, I assume that the firm operating disposal facility δ charges a constant markup $\tau_{\kappa\delta}$ to all shipments originating at κ. Firms choose markups $\tau_{\kappa\delta}$ to maximize expected profits net of transaction costs. In the case that a firm operates a single disposal facility, its problem is:

$$\max_{\tau_\delta} \sum_{\kappa \in K} Q_\kappa \rho_{\kappa\delta} \tau_{\kappa\delta}$$

where $\rho_{\kappa\delta}$ is the equilibrium probability that the firm located at κ chooses to ship a given truckload to facility δ, and $\tau_{\kappa\delta}$ is defined similarly as in (3). In particular, I assume that injection well operators charge different prices to loads originating at different locations (excluding all other forms of contracting).[13]

The optimal markup will depend on the distribution of unobserved heterogeneity in the wastewater-sending firm's preferences. Since injection wells are generally located far from active well pads, I allow the scale of the logit shocks in (4) to differ from the reuse market parameter σ_κ. In particular, I assume that $\sigma^\kappa_{\kappa\delta} = \sigma_{\kappa,S}$ for some constant $\sigma^\kappa_{\kappa\delta} = \sigma_{\kappa,S}$. In the case of the nested logit model, I define an additional nest S representing the injection well disposal facilities.

In the heteroskedastic Choo and Siow (2006) specification, it can be shown that the optimal markup is

[13] Lafontaine and Slade (2010) survey many other forms of interfirm contracting.

for a single facility injection well operator is:

$$\tau_{\kappa\delta} = \frac{\sigma_{\kappa,S}}{1-\rho_{\kappa\delta}} \tag{11}$$

while for the nested logit specification, the optimal markup for a single facility firm is:

$$\tau_{\kappa\delta} = \frac{\lambda_{\kappa,S}\sigma_{\kappa,S}}{1-\rho_{\kappa\delta|S}\left(1-\lambda_{\kappa,S}\left(1-\rho_{\kappa S}\right)\right)} \tag{12}$$

In either case, the markup resembles the Lerner pricing rule familiar from consumer demand – firms charge higher markups to firms with less elastic demand. For instance, a disposal facility located closer to a particular well pad can charge that well pad a higher markup. In reality, some firms operate multiple facilities, and can therefore exercise a greater degree of market power. I provide a derivation of (12) in the more general case with joint ownership in Appendix B. A small number of injection well facilities are owned and operated by oil and gas firms. I assume that these firms charge no markups when providing injection services internally, but charge the oligopoly markup (11) when providing final disposal services to rival firms.[14]

One downside of this approach is that injection well operators do not have capacity constraints. In practice, a particular disposal well could be capacity constrained over the short term. The presence of capacity constraints creates considerable complication in the firm's pricing problem, which I do not address. I do not find consistent evidence of binding capacity constraints in the data, but anecdotal evidence suggests that this could be relevant for some facilities in some months.

To see more clearly how the conduct assumption helps to resolve the identification problem, consider the nested logit specification. In this case, matching patterns in the reuse market identify the inclusive value of reuse up to the location. In particular, the match identifies $\tilde{F}_\kappa = \exp\left\{-\sigma_\kappa^{-1}\tau_0\right\}\left(F_{\kappa I}^{\lambda_{\kappa,I}} + F_{\kappa R}^{\lambda_{\kappa,R}}\right)$ up to some unknown parameter τ_0. Moreover, (10) implies that:

$$\rho_{\kappa S} = \frac{F_{\kappa S}^{\lambda_{\kappa,S}}}{F_{\kappa S}^{\lambda_{\kappa,S}} + \exp\left\{\sigma_\kappa^{-1}\tau_0\right\}\tilde{F}_\kappa} \tag{13}$$

The conduct assumption identifies the inclusive value of disposal $F_{\kappa S} = \sum_{\delta\in D_S}\exp\left\{\lambda_{\kappa,S}^{-1}\sigma_{\kappa,Inj}^{-1}\left(-d_{\kappa\delta}-\tau_{\kappa\delta}\right)\right\}$, while the data reveals $\rho_{\kappa S}$, so this relationship can be used to pin down τ_0.

I hold $\rho_{\kappa S}$ fixed when computing the counterfactuals, although in principle $\rho_{\kappa S}$ can be endogenized. This simplification is necessary unless firms' wastewater acceptance decisions are also endogenized, which is

[14] In this case, I assume that the transaction cost is the same as the transaction cost associated with transacting with a rival in the reuse market. These facilities only account for about 6% of shipments to injection wells.

challenging due to limitations of the data. For example, it is natural to view the freshwater acquisition market as the outside option for firms that accept wastewater, but I only observe very coarse data on freshwater usage. Furthermore, unobserved heterogeneity may be more severe in the freshwater market than in the reuse market – for example, the use of pipelines is more common, but would be unobservable. Another challenge is that transfers of wastewater from centralized treatment facilities can substitute for wastewater transferred directly from wellpads, but are also missing from the data. These same limitations also make it impractical to pin down τ_0 using firm's wastewater acceptance decision, although this is a valid approach in principle.

4.4 Estimation

I estimate the model in two steps. In the first step, I estimate the parameters of the reuse market. In the second step, I estimate the reuse market price level using data from the injection well disposal market.

For the reuse market, I adopt a minimum distance approach to estimation. In the true population matching market, wastewater flows are exactly characterized by (6), (7), and (8). Conditional on the parameter vector $\theta = \{\phi_{rival}, \theta_{\epsilon,\eta}\}$, I compute the equlibrium matching $\mu(\theta)$ by solving for a set of transfers τ that satisfy the equilibrium conditions. To estimate θ I search for a parameter vector θ such that realized flows of wastewater $y_{\kappa\delta}$ are "close" to those predicted by the model. The realized wastewater shipment data is more similar to a standard trade dataset than the marriage datasets typically analyzed in the literature on matching models with transferrable utility, with a large proportion of zeros and, presumably, significant heteroskedasticity in the prediction errors $y_{\kappa\delta} - \mu_{\kappa\delta}$. I borrow standard techniques from the trade literature to help mitigate these issues.

For both the multinomial logit and nested logit specifications, the wastewater flows implied by $\mu(\theta)$ take the following form:

$$\mu_{\kappa\delta}(\theta) = \exp\{f_{\kappa\delta}(\theta; x)\}$$

where $f_{\kappa\delta}$ is a known function that depends on the equilibrium transfers and the data x. Now suppose a multiplicative error term $\omega_{\kappa\delta}$ links the wastewater flows implied by $\mu(\theta)$ to those observed in the data:

$$y_{\kappa\delta} = \omega_{\kappa\delta} \exp\{f_{\kappa\delta}(\theta; x)\}$$

I assume that $E[\omega_{\kappa\delta}|x] = 1$, which implies that:

$$E\left[y_{\kappa\delta} - \omega_{\kappa\delta}\exp\left\{f_{\kappa\delta}\left(\theta;x\right)\right\}|x\right] = 0$$

In other words, the assumption that $E[\omega_{\kappa\delta}|x_{\kappa\delta}] = 1$ implies that $\mu(\theta)$ correctly predicts the reuse flows in expectation. This suggests a non-linear least squares (NLLS) estimator:

$$\arg\min_{\theta_r \in \Theta_r} \sum_{\kappa\delta} \left(y_{\kappa\delta} - \exp\left\{f_{\kappa\delta}\left(\theta;x\right)\right\}\right)^2$$

Santos Silva and Tenroyo (2006) argue that NLLS estimators of this type are inefficient for typical trade data sets, since most of the weight is placed on a small number of observations for which $y_{\kappa\delta}$ is predicted to be large. A more efficient estimator can be obtained under the assumption that $y_{\kappa\delta}$ is heteroskedastic in proportion to its expected value. Here, I assume that:

$$Var\left(y_{\kappa\delta}|x\right) \propto \exp\left\{f_{\kappa\delta}\left(\theta;x\right)\right\}$$

In this case, the weighted NLLS estimator coincides with the Poisson pseudomaximum likelihood estimator:

$$\arg\max_{\theta_r \in \Theta_r} \sum_{\kappa\delta} \left(y_{\kappa\delta} f_{\kappa\delta}\left(\theta;x\right) - \exp\left\{f_{\kappa\delta}\left(\theta;x\right)\right\}\right)$$

I use this estimator to obtain my main results, after extending it to accommodate multiple months of matching data. In the current draft, I obtain estimates using a random subset of months from the data, since evaluating the objective function is expensive for the nested logit specification. I omit standard errors for now, but these could be obtained with a block bootstrapping scheme over months of the sample data.

In the second step I estimate the transfer level under the auxiliary assumptions outlined in Section 4.3.2. First, I estimate $\theta_S = \{\lambda_{\kappa,S}, \sigma_{\kappa,S}\}$ from firm's conditional injection well shipment decisions using maximum likelihood estimation, taking the marginal probabilities $\rho_{\kappa S}$ directly from the data. Similar to Cosar, Greico, and Tintelnot (2015), I solve for a fixed point in the markups for each guess of θ_S. After obtaining an estimate of θ_S, I use the equilibrium markups at the estimated parameter vector to construct $F_{\kappa,S}$. Finally I estimate τ_0 in each month with a logistic regression based on (13).

Table 4: Main Parameter Estimates

	Direct Only		Incl. CTF	
	CS	*Nested*	*CS*	*Nested*
ϕ_{Rival}	-165.7	-225.5	-152.4	-170.6
σ_d	8.0	7.1	22.5	8.8
σ_k	14.2	25.8	2.3	18.1
$\lambda_{k,Int}$	-	0.012	-	0.826
$\lambda_{k,Riv}$	-	0.983	-	0.999
$\lambda_{d,Int}$	-	0.809	-	0.884
$\lambda_{d,Riv}$	-	0.784	-	0.991
$\sigma_{k,S}$	40.6	44.3	40.5	41.8
$\lambda_{k,S}$	-	0.904	-	0.955

5 Results

Table 4 presents the main parameter estimates, both for the heteroskedastic Choo and Siow (2006) specification ("CS") and for the nested logit ("Nested"), with and without the operator-owned centralized treatment facilities. The parameter ϕ_{rival} captures the loss in joint surplus when a transaction occurs between rival firms rather than within a single firm. The estimated value of -170.6 for the nested logit specification implies that this loss in surplus is equivalent to the costs a firm would incur to transport a truckload of wastewater a distance of 170.6 miles. Trucking costs are around \$5 per mile, so his implies a cost estimate of about \$8.50 per barrel, which is roughly the same in magnitude as reported transportation costs to Ohio injection wells for well pads in northeastern Pennsylvania. Since the differences in marginal treatment cost when using one's own wastewater and using a rival's are presumably small, this parameter can be interpreted as a transaction cost.

The point estimate for ϕ_{rival} is similar in magnitude across specifications. The dispersion parameters appear to be less well identified. The total dispersion represented by the sum of σ_κ and σ_δ is similar across specifications, but the relative weights of σ_κ and σ_δ differ. Ex ante, it is not obvious whether there should be a greater degree of unobserved heterogeneity on one side of the market or the other. The nesting parameters have the interpretation that $1 - \lambda_n$ represents the correlation of logit draws within nest n. In the nested logit specification that includes the centralized treatment facilities, the nesting parameters are all close to one, implying that these correlations are small.

Next I explore the estimated markups. Figure 7 shows a binscatter of $\phi_{\kappa\delta} + \tau_{\kappa\delta}$ versus distance at the estimated price level, in one particular month. Recall from (4) that this term, which is the sum of the gross transaction costs and the markups, is equal to the sum of the sender's share of the transaction costs and the transaction price, $\phi^{\kappa}_{\kappa\delta} + p_{\kappa\delta}$. Therefore this quantity represents the systematic component of disposal cost

Table 5: Mean Systematic Disposal Costs

		Tx. Cost + Markups			
Disposal Mode	Transport.	ϕ	τ	$\phi + \tau$	Total
Internal Pads	1.52	0.00	-1.93	-1.93	-0.41
Rival Pads	2.93	13.62	-7.06	6.57	9.50
Injection Well	7.52	0.00	2.02	2.02	9.54

in excess of transportation costs. The figure illustrates that variation in the non-transportation components of cost is largely explained by variation in distance. Markups are higher at shorter distances, implying that wastewater receiving firms extract a greater share of the surplus when transportation costs are lower. This is similar to what would occur in an oligopoly market with price discrimination (like the injection well market in my model), with firms charging higher prices to less elastic consumers in equilibrium.

As explained previously, the relative markups do not depend on the price level, so the distribution of markups in Figure 7 does not depend on the estimated price level. Nevertheless, the estimated price level is helpful for contextualizing the relative magnitudes of each component of cost. Table 5 presents a decomposition of the systematic component of expected disposal costs (i.e., excluding ε and η), averaged across all well pads and months. The mean expected markup for injection well disposal is about \$2 per barrel, which is on the low end of the range reported in prior literature. In total, transportation costs only account for about 30% of expected costs for the mean shipment to a rival. The remaining 70% represents the sum of gross transaction costs and the markup term, $\phi_{\kappa\delta} + \tau_{\kappa\delta}$, or equivalently $\phi^{\kappa}_{\kappa\delta} + p_{\kappa\delta}$. Anecdotally, transaction prices are often exactly zero or small and positive. If $p_{\kappa\delta}$ were always equal to zero, then the estimates imply that senders incur transaction costs of \$6.57 per barrel for the average sharing transaction. Interestingly, this represents the majority of the gross transaction cost ϕ_{rival}, implying that most of the gross transaction cost is borne by the firm that sends the wastewater. This is somewhat surprising given the discussion in Section 3.3, but is consistent with the intuition that more surplus is generated from disposal cost savings than from reductions in water acquisition costs.

6 Transaction costs and market structure

In this section I use the estimated model to consider how transaction costs affect market structure, and how market structure in turn affects the size of the trucking externality. I focus on the nested logit specification including the centralized treatment facilities.

Table 6 presents a similar cost decomposition to the one in Table 5, but aggregated by firm size. In this case, I report the total costs net of markup receipts, to better reflect the fact that internal reuse is ultimately

Table 6: Mean Systematic Disposal Costs by Firm Size Rank

		Tx. Cost + Markups				
Firm Size	Transport.	ϕ	τ^{κ}	τ^{δ}	$\phi + \tau^{net}$	Total
1-10	1.54	0.14	-0.89	-1.08	0.34	1.88
11-20	2.11	5.07	-3.19	1.09	0.79	2.90
21-30	1.98	4.69	-2.94	-1.25	3.00	4.98
31+	2.76	7.83	-8.13	-5.55	5.25	8.01

revenue neutral for firms. Expected costs net of markup receipts are about 75% lower for the ten largest firms than for the smallest firms. This difference is primarily driven by differences in transaction costs and markups, while the transportation cost component is relatively similar regardless of firm size. One possible explanation for this pattern is that larger firms enjoy a form of returns to scale on account of drilling more frequently than smaller firms. Since larger firms drill more often, they are more likely to have opportunities for internal reuse, and are therefore better positioned to avoid transaction costs and markups. This creates a natural incentive for integration.

Intuitively, one would expect greater integration to create private efficiency gains, at least partly in the form of reduced shipment distances. In the absence of unobserved heterogeneity, a monopolist would implement the socially efficient outcome from (1). At the margin, however, incremental mergers do not necessarily result in reduced shipment distances. Shipment distances within a merged entity can increase as relatively distant transactions within the merged firm substitute for costly but nearer sharing transactions under the status quo. To illustrate the significance of this mechanism, I simulate hypothetical mergers between each of the ten largest firms. Table 7 shows the mean change in the systematic component of expected disposal costs for the merging parties, in comparison with all unmerged firms. The merging parties realize a cost savings of about \$0.05 per barrel on average, net of markup receipts. This reduction is driven by the non-transportation components of cost – the merged entity substitutes away from short but costly shipments to rivals towards longer shipments that are now internal to the firm. Thus, although there is a private efficiency gain, this gain actually coincides with an increase in transportation costs. At the same time, transportation costs for unmerged rival firms can also increase as firms that previously shared with the merging parties are now diverted towards more distant counterparties in the sharing market. Moreover, firms that previously accepted shipments from the merging parties now earn lower markups in equilibrium. In total the unmerged parties realize an increase in mean expected costs of about \$0.02 per barrel. This in itself masks significant heterogeneity, since some rival firms would be more affected by a given merger than others. Individual firms could benefit from a merger of rivals, even if firms are harmed on average.

7 Policy response to trucking externalities

The large estimated transaction costs in Section 5 raise the possibility that a regulator could reduce industry trucking intensity by intervening to alleviate any contracting frictions that make sharing difficult.

As discussed in the introduction, recent legislation in major gas producing states can be interpreted as an effort to reduce ϕ_{rival}. In the case of the Oklahoma Oil and Gas Produced Water and Waste Recycling and Reuse Act, two specific areas for intervention relate to the definition of property rights and the assignment of liability. Pennsylvania's requirement that firms submit chemical disclosures to the FracFocus database, mentioned previously, could also have had the effect of reducing ϕ_{rival}, in this case by limiting information asymmetries and the scope for trade secrecy. I do not propose any specific policy changes for Pennsylvania in particular, but note that it is common practice for agencies such as the EPA to solicit input from industry participants regarding specific market frictions.[15]

If (1) included a transaction cost ϕ_{rival}, then reducing this parameter would monotonically decrease shipment distance. However, in a matching model with disaggregated agents and unobserved heterogeneity, the equilibrium match maximizes an implicit social gain function that weights both observable and unobservable sources of match surplus, as discussed in Galichon and Salanie (2022). As ϕ_{rival} falls, the effective "consideration set" for the firm at κ becomes larger and larger, making it more likely that wastewater is shipped to a more distant rival for which the firm receives with a better ε draw. Expected costs fall and the equilibrium sharing rate increases, but the shipment distance can increase or decrease depending on the distribution of firms and the distribution of the unobserved heterogeneity. Figure 8 shows how the mean expected shipment distance changes as ϕ_{rival} shrinks towards zero. This quantity is minimized when ϕ_{rival} is around 110, or about 65% of the estimated level. At the extreme, when ϕ_{rival} is equal to zero, the sharing rate is around 60% (nearly twice the benchmark level), while the expected shipment distance is increased by around 20%. Thus, policies that target ϕ_{rival} can backfire with respect to the trucking externality in particular, even if firm surplus is increased overall.

A per mile tax on trucking distance would be a more effective intervention to eliminate the trucking externality. A tax of around \$0.20 per mile would achieve a greater reduction in average trucking miles than setting ϕ_{rival} to its optimal level. Any further increase in the tax would achieve greater reductions. In this case, there is relatively little change in the sharing rate, even as the tax becomes large. Instead, the tax effectively reduces the probability of matching on unobservables within the firm, resulting in an overall reduction in surplus in excess of the direct effect of the tax.

Table 8 summarizes the differences between the optimal ϕ_{rival} abatement policy and the equivalent tax

[15] See, e.g., EPA (2020) concerning other aspects of the wastewater management problem.

rate. As indicated above, both policies achieve the same (minor) reduction in average trucking distance. From a welfare perspective, however, the optimal ϕ_{rival} abatement policy attains this reduction while increasing welfare in the reuse market by about 25%, whereas the tax would decrease welfare by about 4.4%. The improvement in welfare occurs through both the observable and unobservable channels – the optimal ϕ_{rival} abatement policy increases observable surplus and facilitates better matches on unobservables, while the tax directly reduces observable surplus and leads to to worse matches on unobservables.

8 Conclusion

Wastewater management in unconventional oil and gas development presents a complicated set of policy questions. I study how natural gas producers in Pennsylvania coordinate wastewater reuse in order to better understand how transaction costs affect the size of externalities associated with wastewater disposal, and how different forms of regulation compare in the presence of transaction costs.

Since rates of reuse in Pennsylvania are already high, I focus on externalities associated with trucking intensity, and how these are affected by transaction costs that impair "sharing" transactions. I first show that observed shipment paterns appear to be inefficient, at least by the standards of a simple benchmarking exercise. I use evidence from a merger to conclude that this apparent difference appears to be driven by transaction costs. Some potential sources of transaction costs in this setting include the difficulty of contracting with imperfect information regarding wastewater quality, and frictions arising from the temporal specificity induced by the timing of firms' drilling decisions.

I proceed to develop an empirical matching model that enables me to characterize the magnitude of transaction costs, and to explore how these costs interact with market structure. I find that transaction costs are substantial. I show that disposal costs are lower for larger firms due to the presence of transaction costs, creating an incentive for integration. Mergers reduce expected disposal costs for merging parties, but potentially increase the size of the externality as firms substitute towards longer distance shipments within the firm.

Finally, I show that in the context of the model, policies that intend to alleviate transaction costs may be a poor instrument for the purpose of alleviating externalities. However, policies of this kind can achieve some reductions in the externality while also improve welfare for firms, whereas an equivalent Pigouvian tax would harm welfare. Harms to welfare from Pigouvian taxation occur both directly through the incidence of the tax, and indirectly by reducing the quality of matches.

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Appendix

A Data Preparation

The main dataset consists of Oil and Gas Well Waste Reports collected from the Pennsylvania Department of Environmental Protection web site. For the main analysis, I consider waste reports for all unconventional wells and for all production periods between January 2017 and December 2020. This choice of analysis period reflects the fact waste reports were standardized in 2017 to consistently indicate the location of reuse. Operators are required to report disposal method for various waste products, including solids such as drill cuttings and shredded containment liners. I rely on the classifications from Wunz (2015) as well as knowledge of the functions performed at different waste facilities to identify presumably reusable wastewater.

As described in the main text, the waste reports do not report the dates or quantities associated with specific transfer events, but rather the aggregate quantities of different types of waste transferred from a given well to a given disposal location during a specified month. Wastewater intended for reuse can be transferred either to a centralized treatment and storage facility prior to reuse or directly to another well pad for reuse. These cases appear differently in the data. In the former case, it is not possible to identify the ultimate location of reuse. However, whether the treatment facility is operated by the reporting firm or by a third party can be inferred from the reported permit information and facility names (although in some cases this requires consulting separate DEP resources). In the latter case, if the destination well pad is located in Pennsylvania, a numeric identifier associated with the destination well pad is also provided. I use this numeric identifier to determine whether a given amount of wastewater was transferred for internal or external reuse. In particular, I classify reuse location as internal or external depending on whether the reporting firm is currently listed as an operator for any well at the destination well pad (in a separate DEP data source). If the destination well pad is located outside of Pennsylvania (primarily in West Virginia), no such identifier is provided, and I do not attempt to infer the ownership of the destination well pad.

I identify firms by their DEP OGO Number. I rely on press releases and changes in the data over time to account for changes in ownership over time (the Rice-EQT merger was not the sole merger during the sample period). It is rare for multiple operators to be associated with the same well pad, but when this is the case I treat the well pad as "internal" for both parties

B Proofs

B.1 Injection Disposal Well Pricing

Suppose that a firm owns disposal facilities $D_i \subseteq D_N$. Then the optimal pricing plan $\{\tau_\delta\}_{\delta \in D_i}$ is the solution to:

$$\max_{\{\tau_\delta\}} \sum_{\delta \in D_i} \sum_{\kappa \in K} Q_\kappa \rho_{\kappa\delta} \tau_{\kappa\delta}$$

Equivalently, we can write:

$$\max_{\{\tau_\delta\}} \sum_{\kappa \in K} Q_\kappa \left(\sum_{\delta \in D_i} \rho_{\kappa\delta|N} \rho_{\kappa N} \tau_{\kappa\delta} \right)$$

Consider the first order condition with respect to $\tau_{\kappa\delta'}$:

$$\sum_{\delta \in D_i} \left[\left(\rho_{\kappa\delta|N} \frac{\partial \rho_{\kappa N}}{\partial \tau_{\kappa\delta'}} + \frac{\partial \rho_{\kappa\delta|N}}{\tau_{\kappa\delta'}} \rho_{\kappa N} \right) \tau_{\kappa\delta} \right] + \rho_{\kappa\delta'|N} \rho_{\kappa N} = 0$$

Note that:

$$\rho_{\kappa N} = \frac{\exp\left\{ \lambda_{N,\kappa} \log \left(\sum_{\delta \in D_N} \exp\left\{ \lambda_{N,\kappa}^{-1} \sigma_\kappa^{-1} \left(-d_{\kappa\delta} - \phi_{\kappa\delta} - \tau_{\kappa\delta} \right) \right\} \right) \right\}}{\exp\left\{ \lambda_{N,\kappa} \log \left(\sum_{\delta \in D_F} \exp\left\{ \lambda_{F,\kappa}^{-1} \sigma_\kappa^{-1} \left(-d_{\kappa\delta} - \phi_{\kappa\delta} - \tau_{\kappa\delta} \right) \right\} \right) \right\} + \sum_{n \in \mathcal{N} \setminus \{N\}} F_{\kappa n}^{\lambda n}}$$

$$\rho_{\kappa\delta|N} = \frac{\exp\left\{ \lambda_{N,\kappa}^{-1} \sigma_\kappa^{-1} \left(-d_{\kappa\delta} - \phi_{\kappa\delta} - \tau_{\kappa\delta} \right) \right\}}{\sum_{\delta \in D_N} \exp\left\{ \lambda_{N,\kappa}^{-1} \sigma_\kappa^{-1} \left(-d_{\kappa\delta} - \phi_{\kappa\delta} - \tau_{\kappa\delta} \right) \right\}}$$

therefore, the derivatives appearing in (x) are, respectively:

$$\frac{\partial \rho_{\kappa N}}{\partial \tau_{\kappa\delta'}} = -\sigma_\kappa^{-1} \rho_{\kappa\delta'|N} \left(1 - \rho_{\kappa N}\right) \rho_{\kappa N}$$

and:

$$\frac{\partial \rho_{\kappa\delta|N}}{\partial \tau_{\kappa\delta'}} = \begin{cases} -\lambda_{N,\kappa}^{-1} \sigma_\kappa^{-1} \rho_{\kappa\delta|N} \left(1 - \rho_{\kappa\delta|N}\right) & \text{if } \delta = \delta' \\ \lambda_{N,\kappa}^{-1} \sigma_\kappa^{-1} \rho_{\kappa\delta|N} \rho_{\kappa\delta'|N} & \text{if } \delta \neq \delta' \end{cases}$$

So the first order condition becomes:

$$-\lambda_{N,\kappa}^{-1}\sigma_\kappa^{-1}\rho_{\kappa\delta'|N}\rho_{\kappa N}\tau_{\kappa\delta'}+\sum_{\delta\in D_i}\left[\left(\rho_{\kappa\delta|N}\left(-\sigma_\kappa^{-1}\rho_{\kappa\delta'|N}\left(1-\rho_{\kappa N}\right)\rho_{\kappa N}\right)+\left(\lambda_{R,\kappa}^{-1}\sigma_\kappa^{-1}\rho_{\kappa\delta|N}\rho_{\kappa\delta'|N}\right)\rho_{\kappa N}\right)\tau_{\kappa\delta}\right]+\rho_{\kappa\delta'|N}\rho_{\kappa N}=0$$

or more concisely:

$$-\tau_{\kappa\delta'}+\left(1-\lambda_{N,\kappa}\left(1-\rho_{\kappa N}\right)\right)\rho'_{\kappa\cdot|N}\tau_{\kappa\cdot}+\lambda_{N,\kappa}\sigma_\kappa=0$$

which, in matrix form, becomes:

$$-\tau_{\kappa\cdot}+\left(1-\lambda_{N,\kappa}\left(1-\rho_{\kappa N}\right)\right)\iota\rho'_{\kappa\cdot|N}\tau_{\kappa\cdot}+\lambda_{N,\kappa}\sigma_\kappa\iota=0$$

Implying:

$$\left\{I-\left(1-\lambda_{N,\kappa}\left(1-\rho_{\kappa N}\right)\right)\iota\rho'_{\kappa\cdot|N}\right\}\tau_{\kappa\cdot}=\lambda_{N,\kappa}\sigma_\kappa\iota$$

and:

$$\tau_{\kappa\cdot}=\lambda_{N,\kappa}\sigma_\kappa\left\{I-\left(1-\lambda_{N,\kappa}\left(1-\rho_{\kappa N}\right)\right)\iota\rho'_{\kappa\cdot|N}\right\}^{-1}\iota$$

By the Woodbury matrix identity, this is equivalent to:

$$\tau_{\kappa\cdot}=\left\{\frac{\lambda_{N,\kappa}\sigma_\kappa}{1-\rho'_{\kappa\cdot|N}\iota\left\{1-\lambda_{N,\kappa}\left(1-\rho_{\kappa N}\right)\right\}}\right\}\iota$$

In the special case that $|D_i|=1$, this reduces to:

$$\tau_{\kappa\delta}=\frac{\lambda_{N,\kappa}\sigma_\kappa}{1-\rho_{\kappa\delta|N}\left(1-\lambda_{N,\kappa}\left(1-\rho_{\kappa N}\right)\right)}$$

as shown in (12) in the main text.

C Computational Details

C.1 Computation of the equilibrium

In this section I explain how I compute the equilibrium conditional on $\theta_{\epsilon,\eta} = \{\sigma_\kappa, \sigma_\delta\}$ in the Choo and Siow specification, and $\theta_{\epsilon,\eta} = \{\sigma_\kappa, \sigma_\delta, \lambda_{\kappa,I}, \lambda_{\delta,R}, \lambda_{\delta,R}\}$ in the nested logit specification. I slightly extend Galichon and Salanie (2022)'s simplified computational procedure for the Choo and Siow (2006) model to accommodate the particular assumptions I make regarding the distribution of unobserved heterogeneity as well as the absence of an outside option. In particular, my strategy is to write down a convex function $\mathcal{F}$ with first order conditions corresponding to the market clearing conditions of the equilibrium matching. This can be viewed as a simplification of Galichon and Salanie (2022)'s Min-Emax method.

In the heteroskedastic Choo and Siow (2006) model, I minimize the following function over u and v:

$$\mathcal{F} \equiv \sum_{\kappa \in K} Q_\kappa u_{\kappa Z} + \left(\frac{\sigma_\delta}{\sigma_\kappa}\right) \sum_{\delta \in D} C_\delta v_{Z\delta} + \left(1 + \frac{\sigma_\delta}{\sigma_\kappa}\right) \sum_{\kappa \in K} \sum_{\delta \in D} \mu_{\kappa\delta} \left(u_{\kappa Z}, v_{Z\delta}\right)$$

where $u_\kappa = \log F_\kappa$ is inclusive value for κ, $v_\delta = \log H_\delta$ is the inclusive value for δ, and $\mu_{\kappa\delta}$ depends on u and v through (8). Note that the dimension of this problem is $|K| \times |D|$, with each u_κ and each v_δ corresponding to the expected utility of each sender and receiver, respectively.

In the nested logit case, we can obtain a similar problem, but with dimension $2 \times (|K| \times |D|)$ or less, depending on whether firms have access to internal counterparties. Intuitively, we now need to keep track of each agent's expected utility from each of the rival and internal submarkets. Let K_0 denote the set of well pads without an internal destination, and K_1 the set of well pads with at least one internal destination. Similarly, let D_0 denote the set of delivery points with no internal point of origin, and D_1 the set of delivery points with an internal point of origin. Finally, let $\mathcal{R}$ denote the subset of $K \times D$ pairs corresponding to rival transactions, and $\mathcal{I}$ the subset corresponding to internal transactions.

For $\kappa \in K_1$, the inclusive value is $u_{\kappa Z} = \log \left\{ F_{\kappa R}^{\lambda_{\kappa,R}} + F_{\kappa I}^{\lambda_{\kappa,I}} \right\}$, and the utility differential across markets is $u_{\kappa W}$ such that $\exp\{(\lambda_{\kappa,R} - 1)\log F_{\kappa,R} - u_{\kappa Z}\} = \left\{\frac{\lambda_{\kappa,R}-1}{\lambda_{\kappa,R}}\right\} u_{\kappa W} - \left\{\frac{1}{\lambda_{\kappa,R}}\right\} u_{\kappa Z}$. For $\delta \in D_1$, $v_{Z\delta}$ and $v_{W\delta}$ are defined similarly. For $\kappa \in K_0$, the inclusive value is $u_{\kappa 0} = \log F_\kappa$, while for $\delta \in D_0$, it is is $v_{0\delta} = \log H_\delta$.

Under this parameterization, I minimize the following function over u and v:

$$\begin{aligned}\mathcal{F} \equiv & \sum_{\kappa\in K_0} Q_\kappa u_{\kappa 0} + \lambda_{\kappa,R}^{-1} \sum_{\kappa\in K_1} Q_\kappa u_{\kappa Z} + \left(\frac{\sigma_\delta}{\sigma_\kappa}\right) \sum_{\delta\in D_0} C_\delta v_{0\delta} + \lambda_{\delta,R}^{-1} \left(\frac{\sigma_\delta}{\sigma_\kappa}\right) \sum_{\delta\in D_1} C_\delta v_{Z\delta} \\ & + \beta_1^{-1} \sum_{\kappa\in K_0}\sum_{\delta\in D_0} \mu_{\kappa\delta}\left(u_{\kappa 0}, v_{0\delta}\right) + \beta_2^{-1} \sum_{\kappa\in K_1}\sum_{\delta\in D_0} \mu_{\kappa\delta}\left(u_{\kappa Z}, u_{\kappa W}, v_{0\delta}\right) + \beta_3^{-1} \sum_{\kappa\in K_0}\sum_{\delta\in D_1} \mu_{\kappa\delta}\left(u_{\kappa 0}, v_{Z\delta}, v_{W\delta}\right) \\ & + \beta_4^{-1} \sum_{\kappa,\delta\in\mathcal{R}} \mu_{\kappa\delta}\left(u_{\kappa Z}, u_{\kappa W}, v_{Z\delta}, v_{W\delta}\right) + \beta_5^{-1} \sum_{\kappa,\delta\in\mathcal{I}} \mu_{\kappa\delta}\left(u_{\kappa Z}, u_{\kappa W}, v_{Z\delta}, v_{W\delta}\right)\end{aligned}$$

where $\beta_1, \ldots, \beta_5$ are normalizing constants that depend on $\theta_{\epsilon,\eta}$. The solution to the problem delivers the equilibrium utilities, which can then be used to construct the equilibrium transfers τ.

I solve both problems using the KNITRO optimizer with analytical gradients.

D Additional Figures

Figure 4: Disposal Market Shares by Month, with Sharing Rate (red)

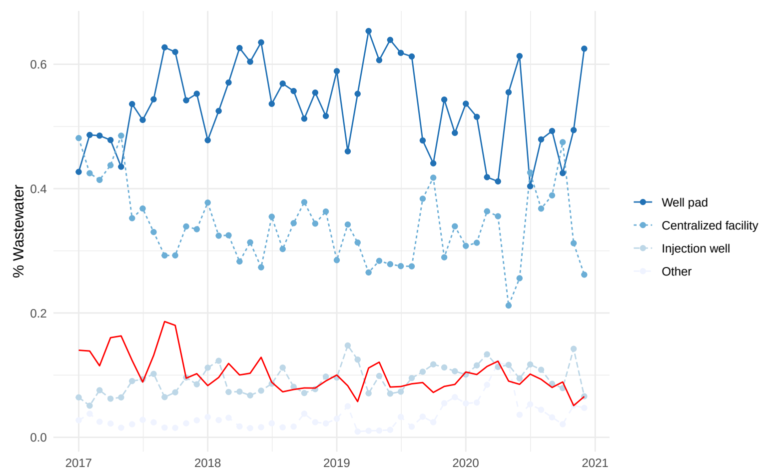
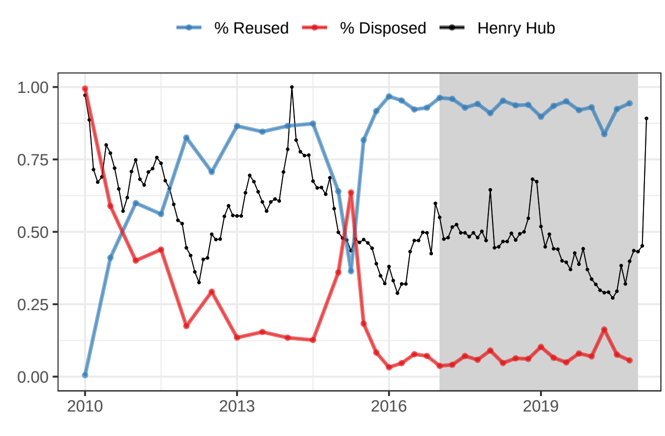


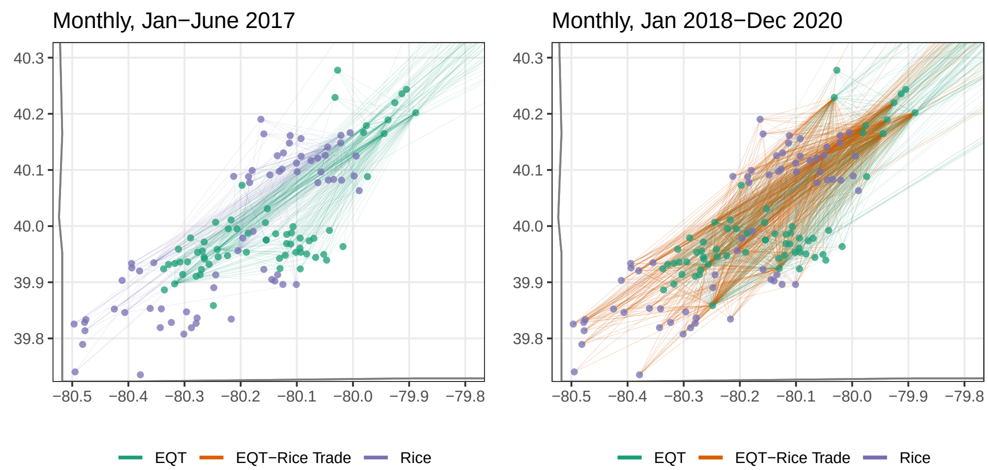
Figure 5: Wastewater Reuse Over Time in PA



Notes: The red and blue lines indicate the share of wastewater shipments in the data for which the reported destination was a site at which only disposal could have occurred (primarily injection wells), or a site at which reuse could have occurred. The black line indicates the spot price of natural gas. The sample period for this analysis is highlighted in gray.

Figure 6: Rice-EQT Merger

(a) Illustration of Wastewater Flows Before and After Merger



	Pre-Merger				Post-Merger			
Source Well Pad	Former EQT	Former Rice	Other Rival	Other External	Former EQT	Former Rice	Other Rival	Other External
Former EQT	-	0.00	0.15	0.85	-	0.16	0.04	0.80
Former Rice	0.00	-	0.00	1.00	0.76	-	0.01	0.23

(b) Change in Wastewater Flows to Formerly-External Destinations

Notes: The left panel of the top figure shows the location of EQT and Rice well pads in southwestern PA prior to the merger (the x- and y-axes are longitude and latitude). The lines indicate wastewater transfers, with the color of the line corresponding to the kind of transfer. The right panel shows flows for the same set of well pads after the merger. The absence of orange lines in the left panel indicates that there were no sharing transfers between EQT and Rice in the indicated time period. The bottom figure shows the relative proportion of non-internal wastewater flows towards different kinds of destinations pre- and post-merger for well pads that had been in operation prior to the merger. The post-merger calculation excludies post-merger flows to destinations that did not exist prior to the merger (such as new well pads).

Figure 7: Binscatter of τ vs. Distance

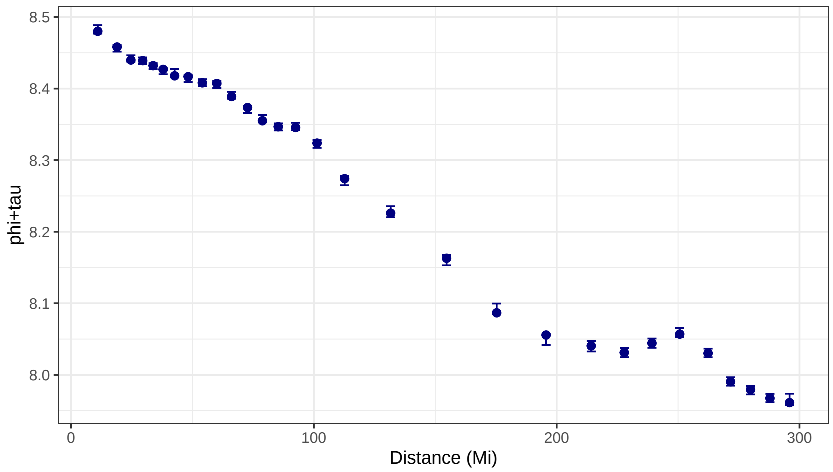


Table 7: Mean Change in Expected Costs per Barrel for Hypothetical Mergers

	Merged Parties	Other Parties
Transport.	0.031	0.006
	(0.012)	(0.001)
ϕ	-0.051	0.008
	(0.009)	(0.001)
$\phi + \tau^{\kappa}$	-0.108	-0.001
	(0.033)	(0.009)
$\phi + \tau^{\kappa} - \tau^{\delta}$	-0.079	0.013
	(0.016)	(0.002)
Transport. $+ \phi + \tau^{\kappa}$	-0.076	0.005
	(0.031)	(0.010)
Transport. $+ \phi + \tau^{\kappa} - \tau^{\delta}$	-0.048	0.019
	(0.019)	(0.002)

Figure 8: Mean Expected Distance vs. ϕ_{rival}

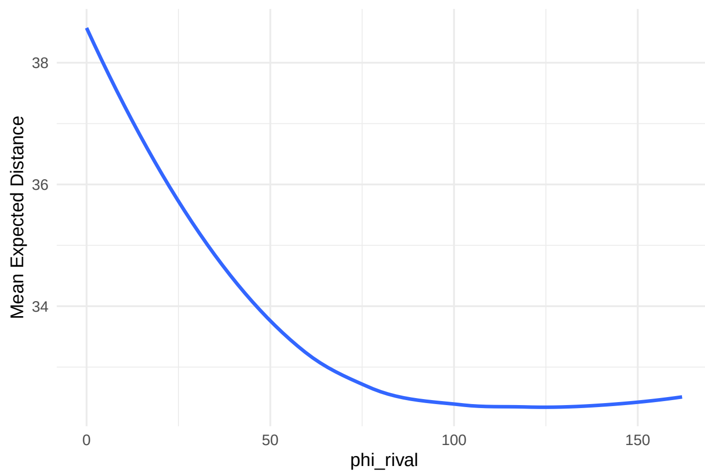


Table 8: Policy Comparison

Firm Size	Mean Dist	Shr %	Match Surplus		
			Obs. Φ	Unobs. $\mathcal{E}$	Total
Status quo	32.62	0.102	-50.02	73.84	23.81
Optimal ϕ_{rival}	32.46	0.131	-47.87	77.67	29.80
Equivalent tax	32.48	0.102	-50.94	73.70	22.76