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THE ENVIRONMENTAL AND SAFETY PERFORMANCE OF GAS UTILITIES IN THE UNITED STATES

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Abstract

The performance of energy service providers has important environmental and safety consequences in local communities. This paper uses a novel dataset compiled from operator reports and infrastructure monitoring data obtained from three different US federal agencies to assess the performance of retail gas utilities nationwide in terms of addressing gas leaks and minimizing leak volumes. Our panel data set includes yearly observations for 727 retail gas utilities from 2009 to 2017. We show that safety hazards and environmental costs of gas leaks are widespread across providers that vary in terms of ownership, size, and region. We then use series of Bayesian hierarchical models to regress four outcome variables--hazardous leaks, end-year unfixed leaks, total gas volume leaked, and significant incidents--on infrastructure conditions, regional service context, and socio-economic service population characteristics. Unlike what is observed in other critical infrastructure cases such as drinking water, socioeconomic conditions are not strongly predictive of service outcomes. Public utilities exhibit better environmental performance on average, and no difference in maintenance backlogs. Because the environmental costs of poor performance--primarily in terms of methane greenhouse gas emissions--are predominantly social, policy tools such as consolidation and privatization are unlikely to improve environmental outcomes.

Keywords

Utilities; gas distribution; leaks; performance; demographics; privatization

1. INTRODUCTION[2]

Gas service problems often gain public attention only when major local catastrophes are publicized in the news media (e.g., Gutman, 2018; Hernandez and Stave, 2018). However,

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[2] EIA: Energy Information Administration
INLA: Integrated Nested Laplace Approximations
PCA: Principal Components Analysis

monitoring and performance records evidence more systemic, widespread problems (Brandt et al., 2014; Jackson et al., 2014; Phillips et al., 2013; Tollefson, 2013). From well to use, estimates indicate 2.5% of all natural gas is leaked (Alvarez et al., 2018). These leaks have serious consequences--leaked methane has an outsized greenhouse effect relative to other emissions (Tollefson, 2013), gas leaks are a major contributor to ozone pollution (Fiore et al., 2002), and on average 13 people are killed each year in pipeline safety incidents (Parfomak, 2015).

This paper addresses one overarching question: How does gas utility performance vary by the infrastructure conditions and socio-economic context of gas service providers? To answer this question, we compile operator reports and infrastructure monitoring data obtained from three different US federal agencies to link gas utility leak and safety outcomes with system characteristics and infrastructure conditions for all US retail gas utilities. Aggregated reporting data describe yearly safety incidents, leaks, and volume losses. Thus, we are able to assess multiple dimensions of performance reflecting safety, public health, and environmental outcomes. Performance is analyzed using a series Bayesian hierarchical models regressing multiple outcome measures--hazardous leaks, end-year unfixed leaks, significant incidents and total gas volume lost--on service system, utility and community characteristics.

This national, comprehensive assessment extends beyond prior work focusing on leaks in particular urban areas (Jackson et al., 2014; McKain et al., 2015) or extrapolating emissions from monitored subsamples (Lamb et al., 2015). By identifying major risk factors and correlates of poor performance in all three areas, these results can guide state regulatory oversight and inform policy interventions targeted to assist managers and regulators. Moreover, evidence from other infrastructure sectors speaks to: (1) how local economic conditions and service population characteristics affect providers' capacity to fund operations and make capital investments (Scott et al., 2018; Teodoro, 2018); and (2) the role of organizational structure (Konisky and Teodoro, 2016) and regional provider landscape (Pierce et al., 2019) in shaping regulatory oversight and service outcomes. Using geographic information systems (GIS) records to link utility service areas to weighted census tract measures, we examine whether gas utility performance similarly varies by socio-economic and organizational context. We proceed by providing a background and rationale for the research, describing the methodology, relaying and discussing results, then finally providing policy implications.

2. BACKGROUND

2.1 Gas service provision in the United States

Retail natural gas services in the United States are provided by an array of organizations that vary widely in terms of ownership, scale, and market orientation. Providers range from small municipally owned and operated systems to major investor-owned firms such as Pacific Gas

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PC: Penalized Complexity
PHMSA: Pipeline and Hazardous Materials Safety Administration
PY: Prior Year

& Electric (PGE), which provides gas service to around 15 million people throughout most of the state of California ("Natural Gas System Overview," 2018). Natural gas infrastructure can be grouped into three main categories: gathering systems, which bring gas from extraction sites to processing and generation facilities, transmission systems, which transport gas from production sites to "city gates", where gas is then received into distribution systems operated by retail providers that bring gas to local homes and businesses. This paper is concerned with distribution systems.

Gas distribution in the United States is regulated within a federalized structure. The US Pipeline and Hazardous Materials and Safety Administration (PHMSA)--a unit of the US Department of Transportation which was created in 2004--enforces a variety of federal statutes related to hazardous materials management and transportation, including the Natural Gas Pipeline Safety Act of 1968, the Hazardous Liquid Pipeline Act of 1979, and the Pipeline Safety Improvement Act of 2002. Following these statutes, PHMSA sets rules concerning a variety of issues such as pipeline placement, build materials, monitoring requirements, and incident reporting. A second federal agency, the Energy Information Administration (a unit of the US Department of Energy), administers a series of surveys required by federal law to collect information about operator finances, resource flows, and pricing. Within this nationwide framework, day-to-day regulation of intrastate pipelines occurs at the state level by public utilities commissions. All states but Alaska and Hawaii have PHMSA-certified safety programs that designate a state agency as bearing primary responsibility for inspections, investigation, and enforcement (PHMSA, 2018a). Up to 80% of each state's program costs are reimbursable by PHMSA, with the exact amount determined by fund availability and past program performance (PHMSA, 2018b) -- in 2017, the proportion of state program spending reimbursed by PHMSA ranged across states from 64% to 70%.[3] Overall, spending on gas pipeline safety is fairly small in scale; in 2017, the state of California reported the highest total spending, around $6M a year, while South Carolina reported $0 in spending and Montana reported around $200k.

The level of spending on pipeline safety is outpaced by the economic damage of major events that occur each year in distribution systems. For reporting purposes, PHMSA distinguishes between "significant" and "serious" incidents based on criteria such as whether loss-of-life occurred and the volume of gas escaped. Figure 1 plots the yearly health and economic damages of all reported incidents from 1998 through 2018: While some years (e.g., 2010) have particularly bad outcomes, in general, around 20 people are killed, and $300 million in economic damages are caused by major gas distribution system incidents each year. Incident reports are only required for "significant events". A significant event is an official designation wherein death or serious injury occurs or where a sufficiently large volume of gas is leaked. To gain a fuller perspective on the environmental consequences of gas distribution system performance beyond significant events, we turn to yearly operator reports filed with the EIA. Figure 2 plots the percentage of lost gas volume over total gas supply by an operator for the year 2017. For most utilities, the utility-estimated lost volume ranges between 0% and 5%--these numbers are nominally small, but represent a

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[3] https://primis.phmsa.dot.gov/comm/publications/CY2017%20StateGrants.xlsx?nocache=9627

considerable amount of emissions. For instance, PGE, the primary provider for much of California, lost 0.36% of its total gas disposition in 2017 (author calculations, based on EIA Form 176), but that percentage represents 3.3 billion cubic feet of natural gas. On average, less than 1% of this leaked gas is lost in significant events (author calculations, based on PHMSA data).

Existing studies of gas utility environmental and safety performance have largely focused on technical fixes, including better leak-detection technology, accounting, and monitoring (Lamb et al., 2016; McKain et al., 2015). However, these studies do not consider organizational and service-oriented performance factors. Many natural gas delivery services carry unfixed leaks at year-end and utilities in the United States must report year-end leak volumes and incidents, thereby providing a systematic, large-scale method of assessing environmental and safety outcomes (Scott and Scott, 2019).

2.2 Gas System Performance

In this analysis, we use four different, but related, measures of gas distribution system performance. First, we consider the **total volume of leaked gas** reported by each operator on a yearly basis. This measure is reported to the Energy Information Administration as a record of yearly gas lost and represents a measure of each utility's environmental performance in terms of wasted emissions.

The second measure is the **number of hazardous leaks** each year. A hazardous leak is defined as "a leak that represents an existing or probable hazard to persons or property and requires immediate repair or continuous action until the conditions are no longer hazardous" (49 CFR Ch. I § 192.949 49). In other words, hazardous leaks pose an imminent safety threat, requiring immediate remedy by the operating firm.

Third, we evaluate the occurrence of **significant events**--events resulting in injury, loss of life, or $120,840[4] in 2018 dollars or more in damage. A hazardous leak is not the same thing as a significant event since a hazardous leak can occur without causing damage to life or property. While volume lost in significant events is included in firms' annual leak volume estimates, we evaluate significant events by count-of-event as some events may have minor gas loss but significant injuries or damages.

The fourth and final outcome measure we use is the **total number of known leaks remaining at the end of each calendar year**. As described by PHMSA in their directions to operators, known leaks are the

> "*the total number pipeline system leaks being monitored and scheduled for repair at the end of the calendar year. Monitored leaks also include those leaks which have been temporarily repaired until a permanent repair can be performed. These leaks are non-hazardous unless reclassified following the operator's operation and maintenance procedures*"
>
> (Department of Transportation, n.d.).

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[4] $50,000 in 1984 dollars, adjusted to 2018 based on CPI.

Since hazardous leaks, by definition, require continuous action until the conditions are no longer hazardous, we expect that unaddressed, but known, leaks are not major safety risks. Instead, these leaks are a measure of maintenance backlog. Small, nonhazardous, methane leaks are not likely to be a major concern for utilities unless the leak jeopardizes system pressurization, or the volume of gas lost exceeds the cost to fix the infrastructure. Concern for small leaks is minimized by the fact that the natural gas delivery is comparatively redundant, with interconnecting pipeline points that provide supply redundancies and physical systems where local disruptions do not lead to cascading failures (AGA, 2014). Utilities can deliver consistent services and maintain a constant balance of leaks by leveraging redundant connections, supplementing escaped gas with increased inputs from storage or the city gate, increasing pressurization at compression stations, and using pressure regulators and emergency vents. Such practices may benefit short-run profits but impose long run environmental and safety costs.

Collectively, these four measures speak to each utility’s ability to operate safely and minimize nonproductive environmental damages. In the next section, we describe the data sources and measures in more detail.

2.2 Service Populations and Service Outcomes

Along with assessing how operator and infrastructure characteristics correspond to performance outcomes, this analysis considers how observed gas utility performance differs by socio-economic context. Although we are unaware of existing studies specifically concerning utility characteristics and local service populations in the case of natural gas services, more broadly the public policy and management literature has long been concerned with the relationship between organizational context and public service outcomes (Burns, 1994; Mullin, 2009; e.g., Ostrom et al., 1961; Parks and Oakerson, 1989). Most relevant are studies of critical infrastructure services--such as water, sewerage, transportation, and electricity--that examine how characteristics of the service provider and the service population affect quality and infrastructure management decisions (Casello, 2007; Mullin and Rubado, 2016; Parinandi and Hitt, 2018; Switzer and Teodoro, 2018; Teodoro et al., 2018b).

A few key takeaways can be drawn from this body of work. First, the relationship between infrastructure development and neighborhood composition is attributable to a complex mix of disproportionalities in siting decisions, market pressures, and enforcement (Banzhaf et al., 2019). As a result of practices such as redlining and segregation, infrastructure decisions made in previous generations have lasting legacies (Grove et al., 2018). Natural gas infrastructure is largely correlated with the wider built environment, and older cast iron pipes are the most leak prone (Jackson et al., 2014). Likewise, disadvantaged communities are less likely to be able to participate in and influence governance (Daley and Reames, 2015).

Second, public service quality also often differs considerably by the economic and ethnic status of local communities (Allaire et al., 2018; Allard, 2017; Teodoro et al., 2018a). One reason is differential patterns of oversight and regulatory enforcement. Evidence from the US Safe Drinking Water Act and the US Clean Air Act demonstrates lessoned oversight and enforcement in disadvantaged communities (Konisky and Reenock, 2018; Teodoro et al., 2018a). Further, these localities face capacity limitations. Critical infrastructure operations rely upon skilled technical labor, a lack of which constrains management success (Teodoro and Switzer, 2016). Service providers also fund capital investments and maintenance through service fees and taxes--where customers are unable to bear higher service fees (Teodoro, 2018) or support major debt obligations (Scott et al., 2018), providers face an uphill battle in maintaining operational quality.

3. DATA AND METHODS

3.1. Data

3.1.1. Data sources—The data used for this analysis come from several different administrative sources. First, the US Department of Energy's Energy Information Administration (EIA) collects an annual form from all gas system operators, Form 176,[5] on which operators report gas volumes, prices, and operational details. While Form 176 data are available from 1997 onwards, our second key data source is only available starting from the year 2010. The US Pipeline and Hazardous Materials and Safety Administration (PHMSA), a unit of the US Department of Transportation, maintains annual data on pipeline infrastructure conditions, leaks and leak volumes, and safety incidents.[6] Operators are required to submit a system report to PHMSA every year and face fines up to $100k per day for a delayed submission (making the response rate quite robust). Third, we draw upon geographic data showing natural gas[7] and electricity[8] service territories from the Department of Homeland Security. Finally, we couple these administrative resources with local demographic and economic data from the US Census Bureau. One barrier to connecting these data is that there are no common keys on which to aggregate the different sources--namely, PHMSA and EIA data, while pertaining to the same utility systems, are not assigned a common identification scheme. Nor are electric and gas utility GIS data linked by a common identifier. Thus, part of aggregating these data involve text-based matchings strategies, which we explain below. In what follows, we establish the unit of analysis and key variables for testing hypotheses.

4.1. Dependent variables

As described above, we use four different measures of yearly system performance: total leak volume, hazardous leak count, significant incident count, and end-of-year known, unfixed leaks. Natural gas leak and incident data are reported at the year-end to both EIA and PHMSA. EIA receives a report of volume of gas lost to natural incidents specifically as part of operator production and distribution reporting. The EIA measure provides an annual quantity of volume lost from leaks, both fixed and unfixed. As such, total leak volume is a measure of environmental performance, reflecting the unproductive greenhouse gas emissions produced by system failures. The EIA instructs operators to "Report known loss volumes as a result of leaks, damage, accidents, migration and blow down…Volume can be

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[5] https://www.eia.gov/survey/form/eia_176/form.pdf, last accessed November 2, 2018.

[6] https://www.phmsa.dot.gov/data-and-statistics/pipeline/source-data, last accessed November 2, 2018.

[7] https://hifld-geoplatform.opendata.arcgis.com/datasets/natural-gas-service-territories, last accessed November 2, 2018.

[8] https://hifld-geoplatform.opendata.arcgis.com/datasets/electric-retail-service-territories, last accessed November 2, 2018.

your best estimate"[9]. Thus, this value is somewhat subjective in that calculation methods between operators (Costello, 2014).[10]

The PHMSA receives an annual report that documents each operators' unfixed leaks and hazardous leak incidents. In addition, significant incidents are always reported to PHMSA. We regard hazardous incident count and significant incident occurrences as measures of safety performance. Leaks are often caused by actions outside the utility such as excavation strikes, land movement, and weather. Significant incidents can arise not only from line strikes or breaks but also from other system failures such as overpressurization. While a utility cannot control for all eventualities, safety programs, stakeholder education, and operations and maintenance efforts do affect safety outcomes (Scott and Scott, 2019).

Finally, remaining known, but unfixed leaks represent maintenance backlog to which a utility has not attended. Importantly, these unfixed leaks are leaks that are scheduled for repair. A pro-active operator might find and schedule more leaks, increasing backlog. Thus, instead of total unfixed leaks, we model annual change in backlog-- a maintenance backlog increase year over year is potentially problematic in terms of service performance whereas a simple volume of unfixed leaks is less problematic and may reflect better leak detection (Barco A. L., 1994; Scott and Scott, 2019). As noted above, these leaks are not immediately hazardous (since hazardous leaks are by law not allowed to remain unfixed).

4.2. Utility, demographic, and contextual variables

For each utility, we incorporate four general attribute categories as explanatory variables for performance: (1) service characteristics; (2) physical infrastructure characteristics; (3) service population demographics; and (4) operating environment. In this section, we briefly explain each set of covariates and how we measure relevant concepts.

First, physical infrastructure characteristics refer to the quantity and material condition of each utility's built capital. For these data, we draw upon yearly operator reports filed with the PHMSA. We then include the prior year's reported leak volume and unfixed known leak balance. PHMSA reports also detail the total number of services and total length of gas mains operated by each utility, as well as itemization of mains and services in terms of the decade in which they were constructed and the materials with which they are made. This is significant because older pipelines were installed using different technologies and subject to older safety regulations. Post-1970 technological improvements in materials construction, welding, and protection make pipelines much more reliable, such that PHMSA pays particular attention to each utility's balance of pre-1970 infrastructure (PHMSA, 2018c). Moreover, cast iron and bare steel pipes are much more prone to corrosion and related safety problems (PHMSA, 2018c). To some extent, these attributes are interconnected--for instance, older pipelines are more likely to be constructed with problematic materials, and older/poorly constructed mains are likely to co-occur with older/poorly constructed services. Thus, we use a principal component analysis (PCA) (Jolliffe, 2011) model to generate a

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[9] https://www.eia.gov/survey/form/eia_176/instructions.pdf, pg. 4, last accessed November 2, 2018.

[10] City-wide comparison of methane emission estimates to air samples demonstrates that distribution systems tend to leak more gas than is reported (Jackson et al., 2014; Lamb et al., 2015; Phillips et al., 2013). Thus, to some extent measurement of performance is confounded by the administration of monitoring and surveillance (Biber, 2013).

"bad infrastructure" factor variable based on the first principal component for the PCA model fit to four variables: % mains pre-1970, % services pre-1970, % bare metal pipes, and % bare metal services. Figure 3 shows the observed relationship between the first principal component and each of the four variables, indicating broad correlation and a strong measurement via one factor.

To control for basic operational characteristics, we also include total gas usage, price per volume delivered to residential customers, and ownership type of utility. These give measures of scale, performance, and ownership structure found to be important in related research (Atkinson and Halvorsen, 1986; Boardman and Vining, 1989; Demsetz and Lehn, 1985; Hiebert and Dean Hiebert, 2002; Parinandi and Hitt, 2018).

To evaluate the variance of performance in relation to socioeconomic drivers, we draw upon US Census American Community Survey data at the tract-level. First, using GIS data for tract boundaries, we compute the overlap between gas service territories and census tracts. Then, we compute weighted measures of demographic indicators--median income, proportion of non-white residents, proportion of owner-occupied households, proportion of population over 25 with a Bachelor's degree of higher, median home price, and median year of built structures--based upon the overlap. For count and ratio variables (e.g., total population and proportion of non-white residents), we compute a weighted sum across all tracts and then compute the ratio statistic; for measures of central tendency (e.g., median home price), we compute a weighted average across all tracts.

Finally, to incorporate regional operational environment, we control for summer and winter temperature at the level of the utility (mean high temperature within service area), state-level gas prices in the current and prior year, and state-level gas receipts and deliveries. Temperature is an important predictor of service context for several reasons. Temperature affects both energy use and operational conditions (e.g., ground upheaval from freezes and thaws). Finally, regional gas prices and import and export behavior reflect how reliant a given state is on natural gas and the extent to which gas is likely to be imported from elsewhere versus sourced locally. All variables are illustrated in table 1.

While there are some missing observations (table 1, column 4), data are largely complete for utilities that are recorded in the Department of Homeland Security utility database as distribution utilities. Where all intersecting census tracts are missing data, the utility is recorded as missing data for that demographic variable. We address missingness within the model by relying on Bayesian inference given observed data (described in the following section).

4.3. Model specification

The basic conceptual model we employ is: *Performance ~ Infrastructure characteristics + service characteristics + service demographics + environmental context*, with yearly system performance measures as units of observation. To account for unobserved between-system heterogeneity, we use a multilevel model that groups system-year observations within modeled system-specific intercepts. Since primary oversight and regulatory responsibilities rest at the state level, we further fit a state-level intercept term that groups observations by state of operation. Finally, we fit a varying intercept term (Gelman, 2005) for each year (2009–2017) in the sample. This means that each regression model is a cross-classified multilevel model because two observations can be from the same operator but different states, or different states but the same year.

In the multilevel model, each group intercept term is modeled using the functional form of an independent and identically distributed (*iid*) random effect. However, in practice, we can only observe one possible outcome for the year 2011 or for Harris County, TX, for instance. Thus, it is more appropriate to think of these varying intercepts to be acting as a shrinkage estimator rather than as a random draw from a possible distribution (Hodges and Clayton 2011). Moreover, evidence shows a high degree of robustness for random effects which violate the normality assumption and does not demonstrate bias in estimates of between- and within-cluster covariates (McCulloch and Neuhaus 2011).

There are several advantages of using varying, instead of fixed, intercepts for this application. First, given the heterogeneous nature of energy service provision nationwide, most data groupings are unbalanced--for instance, some states and counties have many providers, while others just a handful. Modeled intercepts act as a shrinking estimator by accounting for within-group covariance while adjusting for group size and variance (Hodges, 2014). When group size is small or within group variance considerable, the model places more weight on the sample mean, and when group size is large and/or within-group variance is small, more weight is given to the group mean (Gelman and Hill, 2006).

Second, the multilevel structure allows for both time-varying and time-invariant covariates fit at multiple levels. For instance, ownership type is observed at the gas utility level and is non-time varying. Some infrastructure characteristics such as pipeline materials composition change relatively slowly over time such that they are functionally largely time-invariant over the 2012–2017 period.

We fit four separate regression models, each with a different dependent variable. The basic formulation is specified in equation 2, where the dependent variables $Y_{L[i]}$, $Y_{V[i]}$, $Y_{HZ[i]}$, $Y_{S[i]}$, is are observations of known end-year leak counts Y_L, total yearly leak volume Y_V, yearly hazardous leak occurrence Y_{HZ}, and yearly significant incidents Y_S for observation i.

$$Any\ one\ of\ Y_{L[i]}, Y_{V[i]}, Y_{HZ[i]}, Y_{S[i]} = \alpha_u + \rho_s + \tau_t + \beta_m X_{mi} + \in_i \qquad \text{(Equation 1)}$$

where α_u is the modeled intercept for operator u,ρ_S is the modeled intercept for state s, and τ_t the intercept for year t. In equation 1, X is then a matrix of operator-year covariates m (e.g., yearly volume, pipeline material characteristics, etc.), andβ_ma corresponding vector of coefficient estimates. Equation 2 then shows the second level of the model, where each utility-specific interceptα_j is modeled as a function of the whole sample mean α_0 and utility characteristics 1 to n (e.g., sector type), with μ_u representing the utility-level error term.

$$\alpha_u = \alpha_0 + \lambda_n W_{nu} + \mu_u \qquad \text{(Equation 2)}$$

Similarly, equation 3 shows the state-level component of the model:

$$\rho_s = \rho_0 + \theta_p Z_{ps} + \delta_s \quad \text{(Equation 3)}$$

For functional form, we use a zero-inflated negative binomial likelihood to link the observed counts to the linear predictors. We fit models using the *R-INLA* package in R (rinla.org). *R-INLA* estimates hierarchical Bayesian models using Integrated Nested Laplace Approximation (INLA) (Blangiardo and Cameletti, 2015; Rue et al., 2012). In brief, INLA is an alternative to Markov chain Monte Carlo (MCMC) maximum likelihood estimation that uses a Gaussian Markov random field model syntax (Rue and Held, 2005) to estimate the model parameters as a function of a joint hyperparameter distribution (Hodges, 2014).

INLA is a Bayesian modeling technique. This means that model coefficient estimates are in the form of posterior densities--i.e., a probability distribution for a given parameter estimated on the basis of the observed data and the prior, or pre-set distribution. Before discussion posterior densities, we address the issue of priors. Given that many empirical data analyses have limited, if any, preceding analysis, it is common to employ “uninformative priors” (e.g., a flat, uniform prior distribution). However, recent scholarship has demonstrated the superiority of weakly informative penalized complexity (PC) priors for hierarchical models (Fuglstad et al., 2018; Martins et al., 2014). While a full explanation of PC priors is beyond the scope of this paper, in brief PC priors penalize increased model complexity, defined in terms of deviation from a simpler base model. This serves to prevent overfitting to the observed data, which can lead to the estimation of spurious spatial, temporal, or group-level trends in modeled intercepts (Fuglstad et al., 2018).

Interpretation of a posterior density is straightforward -- the posterior density quantifies uncertainty about a parameter value by presenting an estimated probability of the value given the observed data. We then compute a 95% credible interval by identifying the 0.025 and 0.975 quantile values of the posterior density; the credible interval presents a range of values that is predicted to with 95% probability to contain the “true” parameter value. In terms of interpretation, posteriors can be understood as representing the predicted association between a single standard deviation increase in variable α_u, ρ_s, τ_t, or Xm on the difference in the ln counts of volume lost, events, or leaks given the administratively observed data. The standard deviation interpretation results from the independent scaling of all explanatory variables in the model.

5. RESULTS

5.1. Physical Infrastructure Characteristics

In evaluating the results, we first turn to physical infrastructure characteristics (Figure 4). As would be expected, larger systems--those with more miles of mains--are associated with an increased likelihood of all four outcomes. In other words, the more gas mains that a utility operates, the greater the risk of gas leaks and safety hazards. To compute a standardized ratio of gas volume, we divided total volume by the length of mains; here, we see mixed results across the different outcome measures. Volume ratio is a strong predictor of increased leak volume. This makes sense because leak volume should increase with overall gas usage.

For hazardous leaks, we see disparate results. High volume utilities exhibit fewer hazardous leaks on average, holding all else constant. We address this discrepancy in more detail in the discussion section. Finally, high volume usage is not associated with a significant difference in maintenance backlog (known leaks).

Along with volume-to-main-length, we also compute a standardized measure of the services to main length (since total main length and total number of services are strongly correlated). Mains are larger and have better known locations, while services deliver gas from mains to individual users. Thus, this ratio represents a potentially important difference in gas infrastructure: A gas distribution system with a higher services-to-volume ratio is a more complicated and densely concentrated physical system, with more connections and endpoints. This additional complication is reflected in the results--systems which have a higher services-to-volume ratio have significantly more hazardous leaks, greater leak volume, and a larger end-of-year maintenance backlog. Only the rate of significant incidents has no association with services-to-volume ratio.

Figure 4 further shows that prior year outcomes are loosely predictive of current-year results, as both known leaks and leak volume are positively correlated year-to-year. Unsurprisingly, a system with a greater maintenance backlog in one year is likely to have a higher backlog the following year as well, all else equal. Interestingly, carrying a larger maintenance backlog from the prior year does predict an increased rate of hazardous leaks the following year (although there is no corresponding uptick in the rate of significant incidents).

Finally, somewhat unexpectedly the “bad infrastructure” factor variable (representing the extent to which a system relies upon old and/or bare metal gas mains and services) has a mixed association with performance outcomes. Poor infrastructure is positively associated with known leaks--not surprising for a system using older and more corrosive pipes. Likewise, although the credible interval is wide and spans zero (given the relative rarity of significant incidents, results for the model fit to this performance measure tend to be more uncertain in general), poor infrastructure also has a strong positive association with significant incidents. However, there is no significant association between poor infrastructure and leak volume, and the association between poor infrastructure and hazardous leaks is negative. The likely reason for this is twofold: First, most systems have a very low percentage of bare metal pipes remaining in service (1.8% of services and 2.4% of mains, on average), and so even if these pipes leak a lot, the total gas loss attributable to this issue alone must remain small. Second, it stands to reason that utilities prioritize replacing problematic infrastructure in areas where failure is most likely to create a hazardous situation. Thus, even systems carrying a larger inventory of older and/or bare metal pipes are likely to seek to prioritize safety risks, whereas there is less corresponding incentive with respect to lost volume.

5.2. Utility Service Characteristics

Next, figure 5 presents coefficients for three service characteristics--residential gas price, whether a system is public or privately owned, and whether a utility is both a producer and distributor. One might expect that systems with higher prices have greater financial capacity, and thus are better able to conduct operations and maintenance. However, we observe no correspondence between average price and any of the four performance outcomes. Publicly owned and privately owned systems have similar significant incident rates, and likewise differ little with respect to maintenance backlog (known unfixed leaks). Publicly owned utilities do perform significantly better in terms of gas leak volumes and the rate of hazardous leaks. Finally, the coefficient estimates for producer versus non-producer utilities are quite noisy, with wide credible intervals. There are no significant associations observed between vertically integrated systems and performance outcomes.

5.3. Service Population Demographics

Figure 6 presents coefficient estimates for the series of demographic variables used to characterize each service population. Turning first to total leak volume, communities where we observe a higher median home price, a greater proportion of owner-occupied homes, and newer housing stock do have lower gas losses on average. Ethnicity, income, and education are not associated with leak volume.

For maintenance backlog, service population characteristics are not associated with any meaningful differences and all coefficient estimates are closely bounded around zero. As with the prior plots, the relative scarcity of significant incidents results in greater uncertainty and wider credible intervals. All credible intervals for significant incident rate span zero, and the overall pattern is ambiguous (e.g., median income and median home price have a positive association with incident rate). Finally, the results for hazardous leak rate are also mixed--communities with higher median income have fewer hazardous leaks on average, but better educated communities have more hazardous leaks on average. Collectively, these estimates indicate that the attributes of the service community do not correlate with major differences in gas utility performance.

6. DISCUSSION

In evaluating natural gas service performance, this analysis did not observe a consistent divergence in outcomes based on socio-economic strata. To understand why this might be the case, it is helpful to think about how energy services differ from other service sectors, particularly water systems (which, for a variety of reasons, are prominently featured in recent scholarship on environmental service provision). Water services are a useful point of comparison because water and gas systems have many similarities. First, water and gas systems are highly asset specific, with high fixed costs that require significant capital investment, and very technical, requiring trained operators, engineers, and other skilled labor. Second, water provision and hazardous materials transmission are both subject to extensive regulatory oversight at both the state and federal level. Third, water and energy access and affordability are significant social justice issues, with the quality and consistency of service provision having a major impact on livelihoods (McDonald and Jones, 2018; Walker and Day, 2012).

However, in thinking about the population of service providers and the nature of service problems and, the two cases diverge. For water, the costs of poor service-- unsafe water or irregular service for example-- are largely borne by customers, the end users. While there are many social costs attributable to lack of clean water, drinking water service quality is approximately a private good. Although water system leaks can be quite damaging to property, leaky water pipes do not generally pose a public health risk or damage the environment. In contrast, end users of natural gas are not typically concerned with gas condition or quality--during processing, natural gas must be decontaminated, but contaminated gas service is not an issue for customers. Rather, leaky and malfunctioning gas service lines affect users and non-users alike by threatening public safety and harming the environment. Certainly, natural gas consumers are proportionately more at risk since they dwell in piped buildings and use gas systems, but non-users and the public at large also bear the costs of gas service problems.

With respect to our results, this means that the demographics of the user base itself might be less important correlates for gas service problems than has been observed in the case of water. For instance, many leaks and damage incidents are caused by line strikes from excavation and construction (Scott and Scott, 2019). Thus, in a manner of speaking, the construction industry is a major user base for the public goods of gas system safety and environmental performance. Research showing inequality in drinking water services typically points to a user group’s lack of social influence, financial capacity, and political capital as drivers (e.g., Teodoro et al., 2018a). The key “user groups” for gas system performance include not just local residents, but also interest groups such as the local construction industry. Future work to understand utility efforts to inform and educate these stakeholders, and the influence that said stakeholders have on companies, regulators, and local officials, can perhaps better shed light on how community economic and political attributes affect service outcomes.

It is also simply more difficult to assess socio-economic differences in service performance given the large scale at which many gas providers operate. There are vastly more water utilities in the United States than there are gas providers (EPA 2019, DHS 2019). While gas providers such as PGE, Atmos Energy, or Southern Company Gas operate a regional scale (DHS 2019), the very largest water utilities are still municipal systems, and many water systems serve specific neighborhoods or housing developments (EPA 2019). This makes linkages between community attributes and service delivery relatively straightforward. In contrast, demographic estimates for large gas providers’ service territories are less reflective of meaningful differences in socio-economic conditions since values are averaged across many local areas. While our analysis includes both small and large gas providers, for large providers operator-level performance outcomes are likely to be less informative for understanding how socio-economic conditions shape service performance.

Further, after controlling for infrastructure quality we observe better performance on average for public operators versus private firms in terms of total leak volume and hazardous incident occurrence, but no meaningful differences with respect to maintenance backlog or significance incident occurrence. It is not clear what might be driving these observed differences. Research suggests that public infrastructure operators are more difficult to regulate and thus tend to have worse environmental performance relative to private firms (Konisky and Teodoro, 2016). For natural gas systems, however, there is not an active compulsory regulatory program for controlling small methane leaks of a non-hazardous nature such that public operators might be more weakly regulated. The lack of leak regulation coupled with the ability of firms to price losses into rates may mitigate the environmental benefits of privatization (Hausman and Muehlenbachs 2019). Of course, this explanation does not necessarily help to explain the differences in safety outcomes.

Another likely contributing factor to the observed performance differences between public and private gas providers is that a competition-based rationale for privatization is problematic for monopolized gas provision. In their study of benchmark competition in water services, Wallsten and Kosec (2008) conclude that the public-private distinction does not really have an opportunity to matter in the absence of competition. As discussed above, the natural monopoly enjoyed by gas providers, coupled with high concentration in the sector, creates an environment that lags in both standard and benchmark competition. In the electricity sector, which suffers from a similar issue, one policy strategy has been to divorce generation and transmission (Hight, 2018). Under a consumer choice system, such as that in the state of Texas, consumers can purchase electricity from a retail electric provider of their choosing, while the incumbent utility maintains a monopoly on transmission. Under such a model, consumers would be able to choose their retail provider, but not the distribution system operator. While privatization might make sense for other reasons--for instance, lack of technical or financial capacity by the local government--it is unlikely to leverage competitive forces to improve environmental and safety performance.

7. CONCLUSION AND POLICY IMPLICATIONS

Analyses of energy services have often focused on market performance and pricing (Larsen et al., 2012; Marino et al., 2011); however, energy services are subject to the same base considerations-public efficiency, effectiveness, and equity--as other public services. The most enduring finding from existing research asking fundamental questions about what institutional and organizational factors drive effective and equitable service outcomes is that the answers to these questions are highly contextual. For many of the reasons we discuss in this paper, gas services present somewhat of a “hard case” for many theoretical expectations about performance and service outcomes. This speaks to the importance of testing these factors in just such a context, however; what works in water, solid waste, or air quality management might not work in energy, and vice versa. *Our results suggest, for instance, that regulators and policymakers are unlikely to see major gains from privatization alone--at least in terms of environmental damage and public safety based on observations of current outcomes*. However, variation within privatization strategies might obscure critical differences.

Second, there are no clear patterns of differential performance across socio-economic classifications. This provides useful evidence that *despite institutional and infrastructural variation in gas service provision, maintenance of systems and safety performance measured at the operator level is not observably different by race, and class*. Whether this means that gas service performance is more egalitarian than many other public services, or that large scale systems attenuate operator-level comparisons across socio-economic strata, is an important question for future research).

Finally, scholars and practitioners increasingly emphasize governance frameworks for interdependent infrastructure and coupled infrastructure systems (e.g., the “food-water-energy nexus”) (Romero-Lankao et al., 2017; Schlör et al., 2018). While case-based and qualitative work has shed light on the implications posed by coupled systems (e.g., Villamayor-Tomas, 2018), developing a more systematic understanding of coupled infrastructure systems requires building a base of research that helps to frame what performance looks like, and what attributes matter, in component systems. By analyzing the case of gas service delivery, we aim to provide a building block towards achieving a more holistic perspective on metropolitan service delivery that accounts for multiple dimensions of performance.

ACKNOWLEDGEMENTS

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12.: APPENDIX A: Tabular model results

Model 1:

Leak Volume as Dependent Variable

Variable	Mean	0.025 quantile	0.975 quantile	Model
Bad Infrastructure, Eigen	−0.003	−0.088	0.083	Leak Volume
Ed. Bachelor or Higher, %	0.052	−0.054	0.158	Leak Volume
Known Leaks PY, ln	0.036	−0.027	0.099	Leak Volume
Leak Volume PY, ln	0.033	−0.013	0.079	Leak Volume
Mains, ln	1.008	0.867	1.148	Leak Volume
Median Home Price	−0.113	−0.209	−0.016	Leak Volume
Median Income	0.014	−0.052	0.080	Leak Volume
Median Year Structures	−0.123	−0.222	−0.025	Leak Volume
Non White, % ln	0.023	−0.080	0.126	Leak Volume
Owner Occupied Household, %	−0.083	−0.156	−0.009	Leak Volume
Producer	−0.131	−0.657	0.403	Leak Volume
Public Ownership	−0.597	−0.930	−0.265	Leak Volume
Residential Price, avg.	0.003	−0.062	0.067	Leak Volume
Services per mile of mains	0.206	0.090	0.322	Leak Volume
State Avg $	−0.087	−0.196	0.023	Leak Volume
State Avg $, PY	0.155	0.031	0.280	Leak Volume
State Deliveries, ln	0.122	0.034	0.209	Leak Volume
State Receipts, ln	0.021	−0.041	0.085	Leak Volume
Temp Summer	0.002	−0.102	0.106	Leak Volume
Temp Winter	−0.221	−0.355	−0.088	Leak Volume
Total Population, ln + 1	0.859	0.700	1.019	Leak Volume
Volume per miles of mains	0.450	0.338	0.566	Leak Volume

Model 2:

Known Leaks as Dependent Variable

Variable	Mean	0.025 quantile	0.975 quantile	Model
Total Population, ln + 1	−0.039	−0.215	0.134	Known Leaks
Median Income	0.024	−0.062	0.110	Known Leaks
Median Home Price	0.006	−0.062	0.079	Known Leaks
Median Year Structures	0.012	−0.096	0.120	Known Leaks
Non White, % ln	0.017	−0.113	0.146	Known Leaks
Owner Occupied Household, %	0.056	−0.042	0.155	Known Leaks
Ed. Bachelor or Higher, %	0.044	−0.076	0.165	Known Leaks
Volume per miles of mains	0.063	−0.139	0.269	Known Leaks
Residential Price, avg.	−0.014	−0.118	0.090	Known Leaks
Producer	0.308	−0.346	0.977	Known Leaks
Bad Infrastructure, Eigen	0.222	0.119	0.325	Known Leaks
Known Leaks PY, ln	0.654	0.577	0.730	Known Leaks
Leak Volume PY, ln	0.000	−0.060	0.059	Known Leaks
Mains, ln	1.037	0.848	1.227	Known Leaks
Services per mile of mains	0.191	0.067	0.315	Known Leaks
Public Ownership	0.131	−0.184	0.448	Known Leaks
State Deliveries, ln	−0.052	−0.167	0.059	Known Leaks
State Receipts, ln	0.001	−0.105	0.103	Known Leaks
State Avg $	−0.070	−0.227	0.086	Known Leaks
State Avg $, PY	0.005	−0.156	0.162	Known Leaks
Temp Summer	−0.049	−0.172	0.072	Known Leaks
Temp Winter	0.190	0.058	0.325	Known Leaks

Model 3:

Hazardous Leaks as Dependent Variable

Variable	Mean	0.025 quantile	0.975 quantile	Model
Bad Infrastructure, Eigen	−0.098	−0.170	−0.025	Hazardous Leaks
Ed. Bachelor or Higher, %	0.072	0.002	0.141	Hazardous Leaks
Known Leaks PY, ln	0.045	0.009	0.080	Hazardous Leaks
Leak Volume PY, ln	−0.049	−0.080	−0.018	Hazardous Leaks
Mains, ln	1.856	1.748	1.965	Hazardous Leaks
Median Home Price	0.024	−0.043	0.091	Hazardous Leaks
Median Income	−0.053	−0.097	−0.009	Hazardous Leaks
Median Year Structures	0.007	−0.057	0.070	Hazardous Leaks
Non White, % ln	−0.056	−0.139	0.026	Hazardous Leaks
Owner Occupied Household, %	0.011	−0.040	0.062	Hazardous Leaks
Producer	−0.119	−0.410	0.173	Hazardous Leaks
Public Ownership	−0.224	−0.410	−0.039	Hazardous Leaks

Variable	Mean	0.025 quantile	0.975 quantile	Model
Residential Price, avg.	0.018	−0.040	0.076	Hazardous Leaks
Services per mile of mains	0.420	0.341	0.499	Hazardous Leaks
State Avg $	0.056	−0.017	0.130	Hazardous Leaks
State Avg $, PY	0.051	−0.026	0.129	Hazardous Leaks
State Deliveries, ln	−0.026	−0.072	0.019	Hazardous Leaks
State Receipts, ln	0.031	0.000	0.063	Hazardous Leaks
Temp Summer	0.045	−0.012	0.102	Hazardous Leaks
Temp Winter	−0.100	−0.168	−0.037	Hazardous Leaks
Total Population, ln + 1	−0.011	−0.109	0.086	Hazardous Leaks
Volume per miles of mains	−0.104	−0.196	−0.016	Hazardous Leaks

Model 4:

Incident Count as Dependent Variable

Variable	Mean	0.025quant	0.975quant	Model
Bad Infrastructure, Eigen	0.408	−0.037	0.874	Incidents
Ed. Bachelor or Higher, %	0.048	−0.188	0.278	Incidents
Known Leaks PY, ln	0.005	−0.350	0.344	Incidents
Leak Volume PY, ln	0.251	−0.245	0.764	Incidents
Mains, ln	0.710	0.167	1.273	Incidents
Median Home Price	0.079	−0.162	0.325	Incidents
Median Income	0.080	−0.240	0.398	Incidents
Median Year Structures	0.039	−0.046	0.115	Incidents
Non White, % ln	−0.246	−0.740	0.246	Incidents
Owner Occupied Household, %	−0.002	−1.543	1.489	Incidents
Producer	0.110	−0.300	0.502	Incidents
Public Ownership	0.097	−0.124	0.327	Incidents
Residential Price, avg.	0.046	−0.136	0.230	Incidents
Services per mile of mains	−0.034	−0.464	0.399	Incidents
State Avg $	0.159	−0.153	0.474	Incidents
State Avg $, PY	−0.594	−1.483	0.248	Incidents
State Deliveries, ln	0.088	−0.312	0.531	Incidents
State Receipts, ln	0.234	−0.038	0.607	Incidents
Temp Summer	0.566	−0.002	1.158	Incidents
Temp Winter	−0.531	−1.060	−0.026	Incidents
Total Population, ln + 1	−0.317	−0.679	0.036	Incidents
Volume per miles of mains	0.323	−0.062	0.713	Incidents

13.: APPENDIX B: State-level coefficient plots and hyperparameters

This appendix presents the results for state-level coefficients included in the model (figure B1). At the state level, we find that higher state prices the previous year are associated with increased leaks and volume lost the subsequent year, but that the current year's price is negatively associated with reported losses or unfixed leaks--of course current year and previous year price are highly correlated. As we also controlled for single-utility prices, we recognize that increased price per MCF at the utility level was also associated more broadly with increased losses and leaks, but at a non-significant level. Notably, state level competition is not a significant predictor of either known leaks or volume lost.

We also note that states with higher receipts or states that provide gas to the natural gas system have move volume lost, they do not have higher rates of known, unfixed leaks. Meanwhile, as deliveries in state increase, there is an associated increase in volume leaked, but deliveries are inversely associated with the count of known leaks. Overall this suggests increased demand for gas is associated with a decrease in leaks but an increased volume of loss, while increased state level supply is associated with increased leaks while not providing any improvement to the prediction of the number of unfixed leaks at year end.

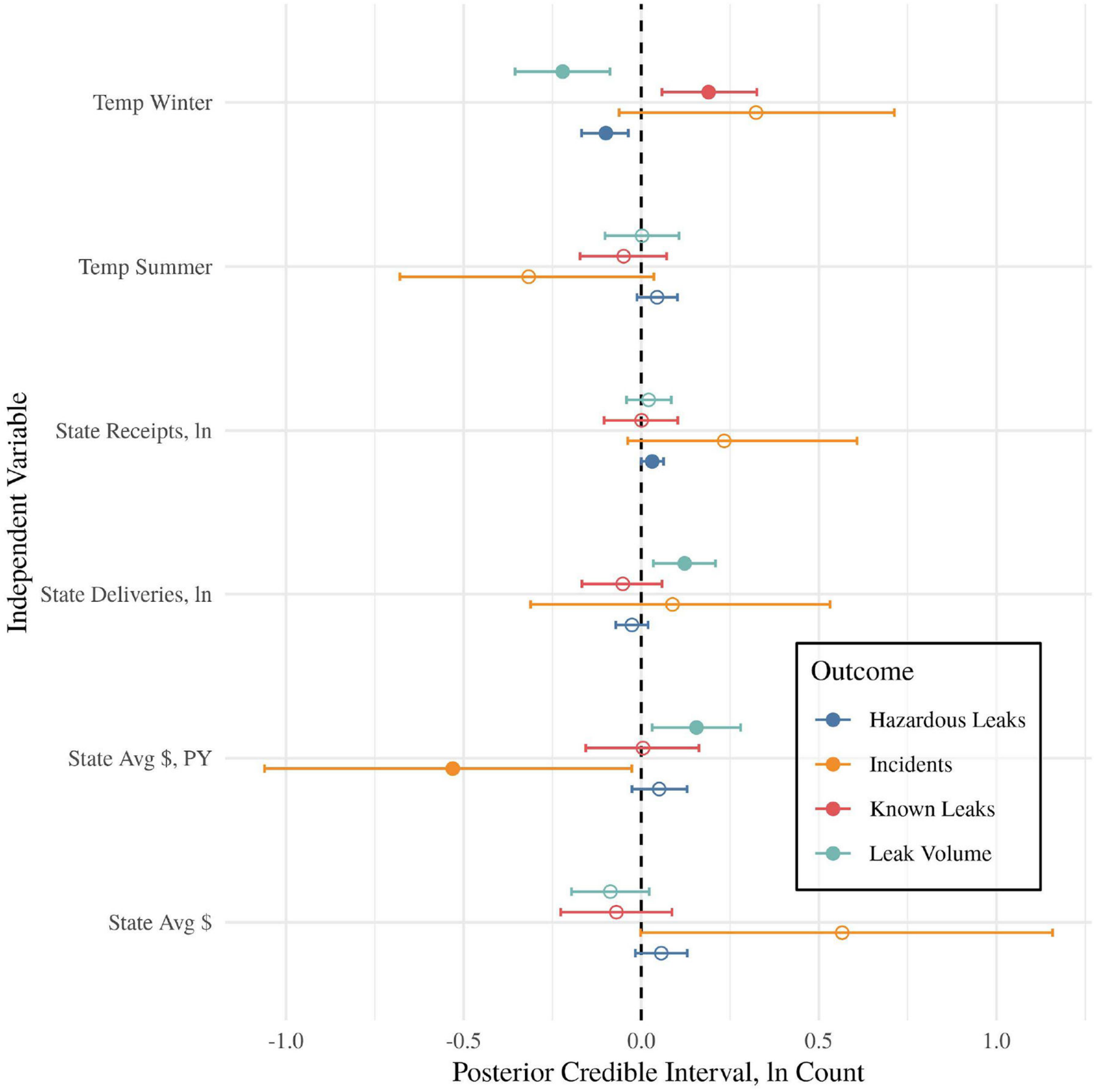

Figure B1:
95% credible intervals for utility and environmental context variables expected to affect gas distribution performance outcomes.

Figure B2 presents model hyperparameter estimates. In a hierarchical Bayesian model, hyperparameters are those pertaining to the estimated distribution of a given varying intercept (e.g., for utility or state).

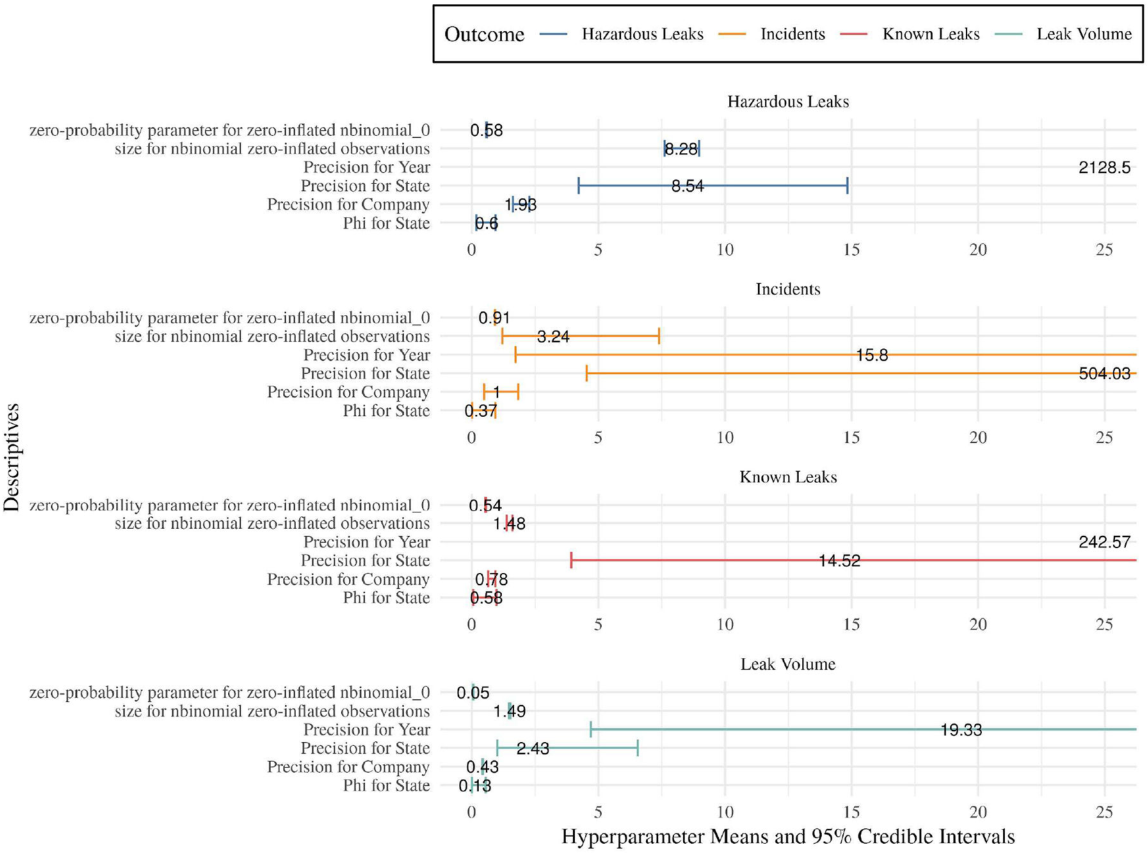

Figure B2:

95% credible intervals for hyperparameters

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Highlights

1. Lost volume, fixed leaks, and maintenance backlogs are common across U.S. gas distribution utilities
2. Service demographics do not explain environmental outcomes but are correlated with safety outcomes
3. Private ownership of gas utilities is not associated with improved environmental or safety outcomes
4. Privatization may not be an effective policy tool for addressing environmental performance shortcomings.

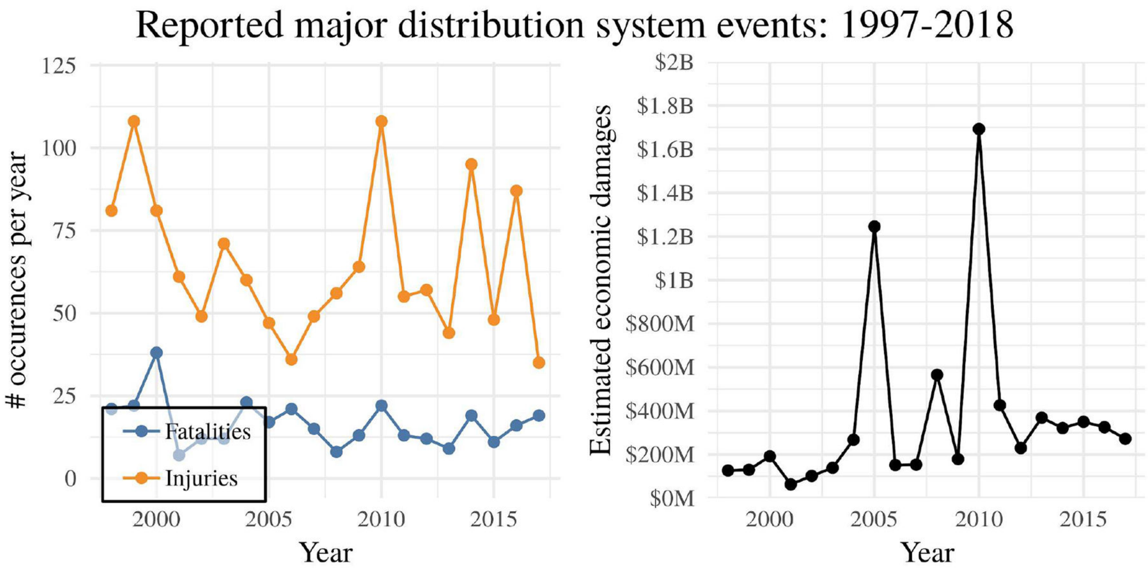

Figure 1:

Health and economic damages from major distribution system events

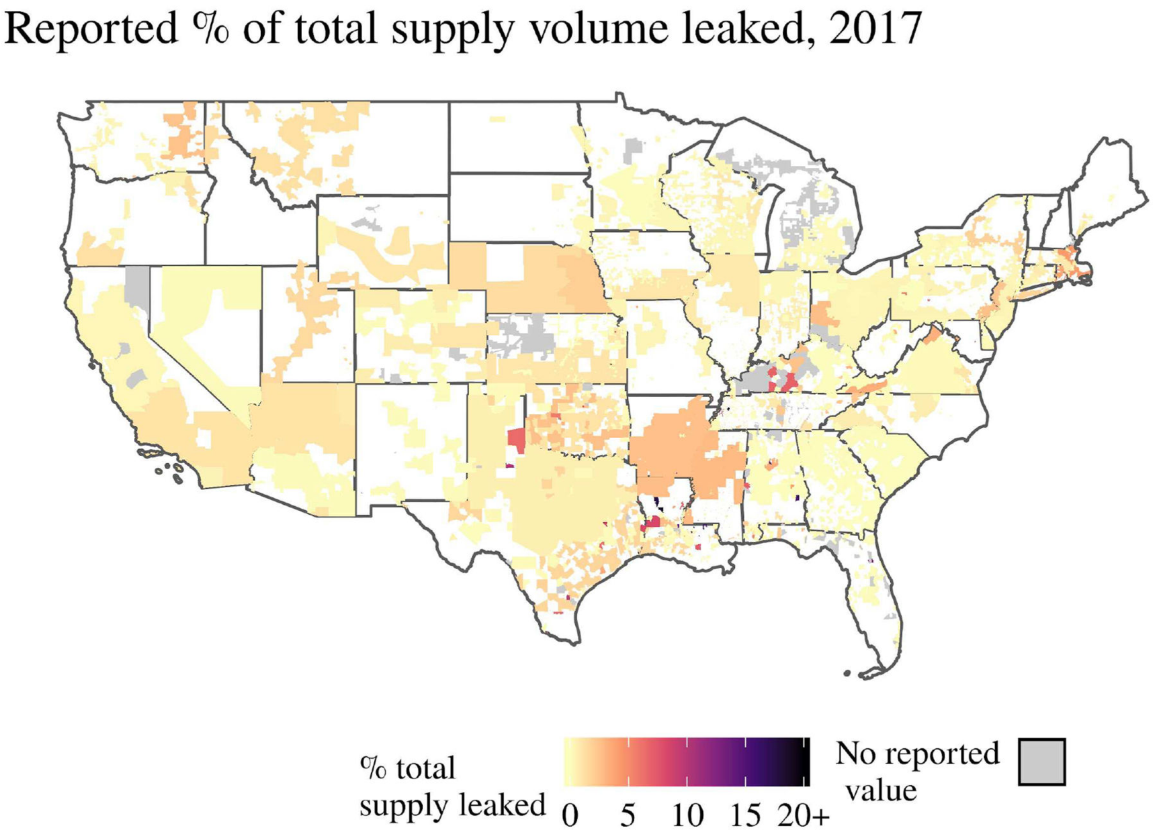

Figure 2:

Map of contiguous United States, showing percentage leaked by service area reported in 2017.

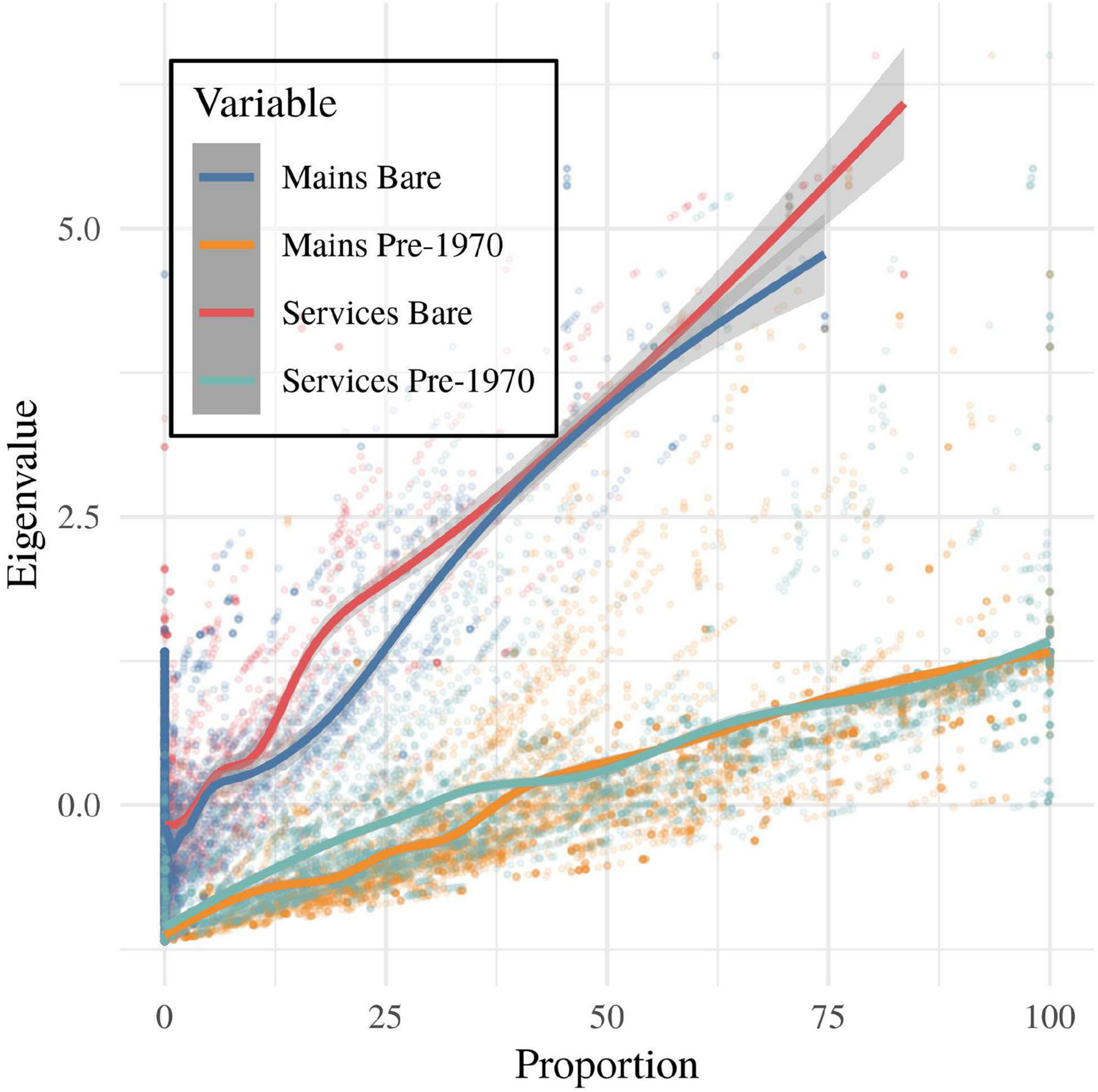

Figure 3:

Observed smoothed relationship between infrastructure characteristics (by proportion of pipes in each category) and the first fit eigenvalue for observations based on a principal components analysis including % mains pre-1970, % services pre-1970, % bare metal pipes, and % bare metal services.

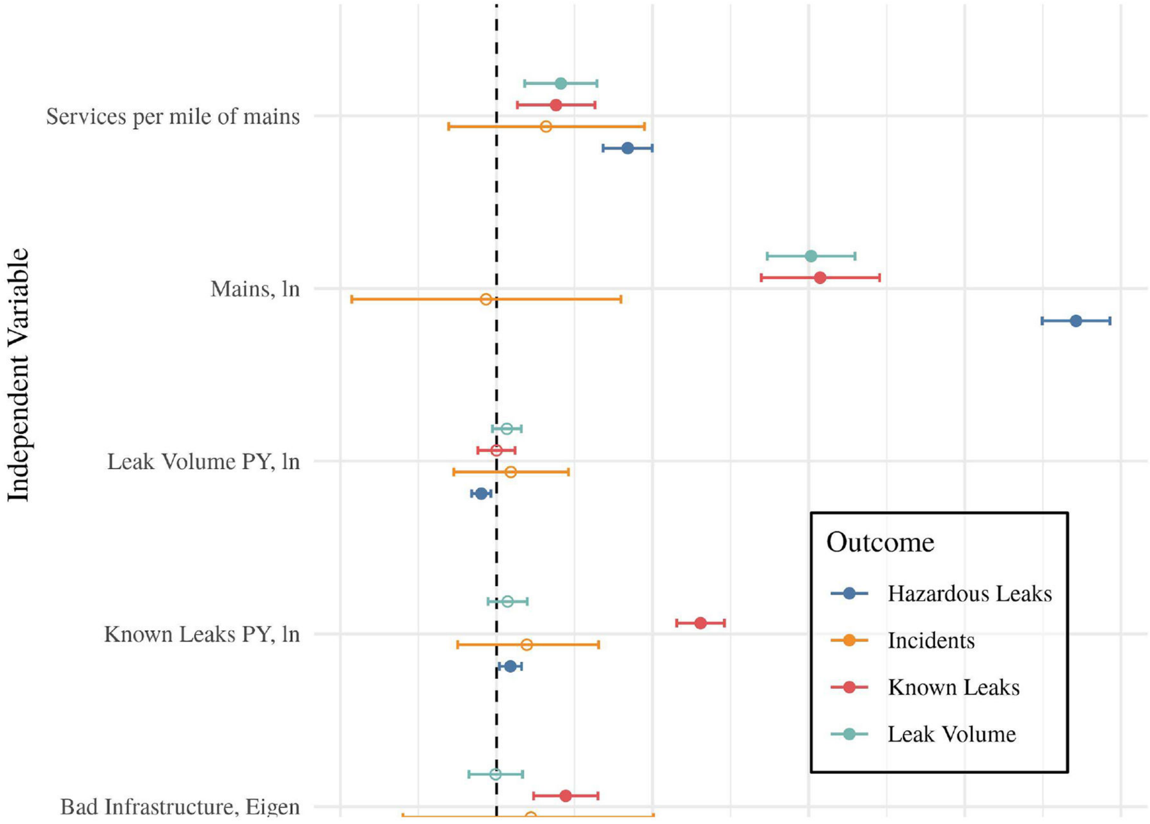

Figure 4:

Infrastructure characteristics and 95% credible intervals for the association of a one standard deviation increase in the observed variable and the ln count of the outcome variable. PY= Prior Year; Eigen = first PCA component fit to observation (see figure 3).

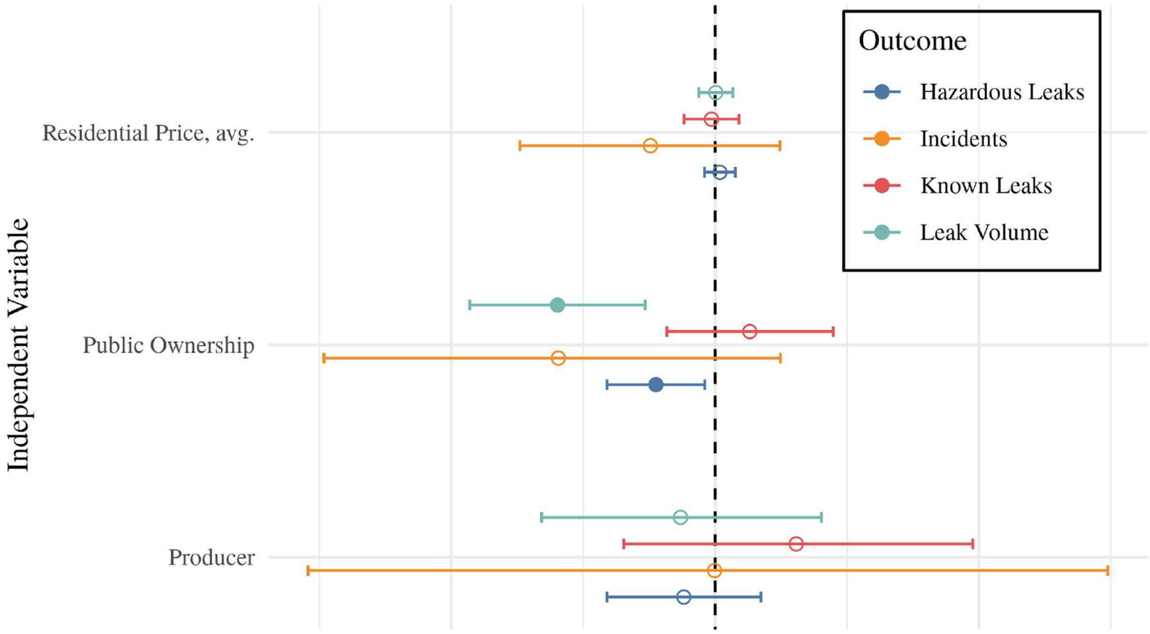

Figure 5:

Utility service characteristics and 95% credible intervals for the association of a one standard deviation increase in the observed variable and the ln count of the outcome variable.

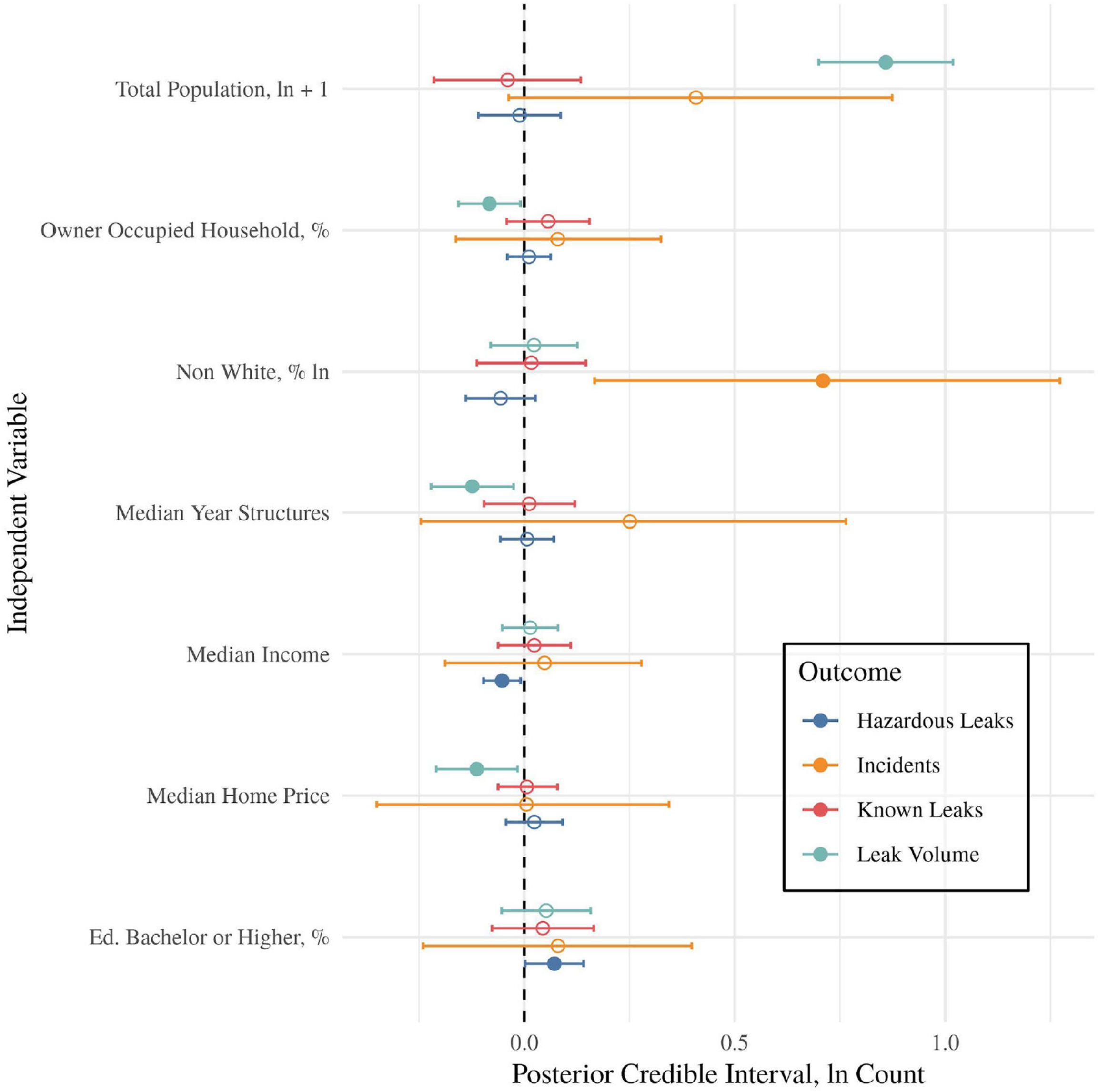

Figure 6:

Service population demographics and 95% credible intervals for the association of a one standard deviation increase in the observed variable and the ln count of the outcome variable. Ed.= Education.

Table 1:

Descriptive Statistics- covariates, varying intercepts, and dependent variables

Variable	Level of observation	Mean (SD) (if numeric)	Missing Values
Explanatory Variables			
Physical infrastructure characteristics			
Total mains (miles)	Utility-year	1380.36 (3928.18)	864 (12.61%)
Bad Infrastructure (factor score)	Utility-year	0 (1)	
% services Pre-1970	Utility-year	37.02 (32.67)	866 (12.64%)
% mains Pre-1970	Utility-year	40.71 (30.54)	866 (12.64%)
% bare services	Utility-year	2.34 (7.91)	864 (12.61%)
% bare metal mains	Utility-year	3.23 (9.16)	864 (12.61%)
# known leaks in prior year	Utility-year	119.9 (670)	892 (13.02%)
Leak volume in prior year (1k ft^3)	Utility-year	102989.3 (518443.11)	852 (12.44%)
Utility service characteristics			
Distributed volume / mile of main (1k ft^3)	Utility-year	10737.02 (73276.55)	224 (3.27%)
# services per mile of main	Utility-year	34.58 (17.748)	864 (12.61%)
Ownership	Utility	4270 public, 2580 private	0 (0%)
Gas producer (generates natural gas)	Utility	6743 = 0, 107 = 1	0 (0%)
Gas Price ($/1k ft^3)	Utility	12.28 (4.41)	605 (10.3%)
Service population demographics			
Median income ($)	Utility-year	22535.01 (5329.72)	1283 (18.73%)
Total population	Utility-year	357726.13 (1245185.24)	0 (0%)
Median home price ($)	Utility-year	113586.69 (54975.3)	1469 (21.45%)
Median year built structure	Utility-year	1973.34 (10.63)	1469 (21.45%)
% non-white population	Utility-year	0.22 (0.19)	1469 (21.45%)
% population with ed. bachelor or higher	Utility-year	0.2 (0.1)	1469 (21.45%)
% owner occupied homes	Utility-year	0.69 (0.1)	1469 (21.45%)
State operational environment			
Total state deliveries (1k ft^3)	State	2090495.19 (1478333.89)	864 (12.61%)
Total state receipts (1k ft^3)	State	1950768.31 (1147692.39)	1072 (9.82%)
State avg. gas price ($ / 1k ft^3)	State	11.95 (2.87)	870 (12.7%)
State avg. gas price, prior year ($ / 1k ft^3)	State	12.22 (2.95)	864 (12.61%)
Winter monthly max temperature, mean (F)	Utility	47.67 (12.99)	238 (3.47%)
Summer … temperature, mean (F)	Utility	71.01 (8.88)	238 (3.47%)
Varying Intercept Terms			
Year		2009–2017	
Utility (by Name)		727 unique utilities	
State		50 States + D.C.	
Dependent Variables			
Incidents	Utility-year	0.141 (0.636)	0%
Known Leaks, Scheduled for repair	Utility-year	120.673 (676.163)	1063 9.73%
Hazardous Leaks	Utility-year	128.090 (500.523)	0%

Variable	**Level of observation**	**Mean (SD) (if numeric)**	**Missing Values**
Leak Volume	Utility-year	105721.3(525000.7)	1389 12.7%