Burying the Lead: Effects of Public Lead Service Line Replacements on Blood Lead Levels and Property Values

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July 22, 2023

Abstract

Despite the well-known health consequences of lead exposure, an estimated 6 to 10 million lead service lines still deliver drinking water to homes throughout the US. Disadvantaged communities are disproportionately exposed to lead service lines, contributing to health and human capital disparities. This paper studies the effects of public lead service line replacements on targeted households using address-level data on children's blood lead levels, home sales, and public service line installations from Rhode Island. Replacements significantly reduced child blood lead levels by about 0.4 $\mu g/dL$, increased property values by 7-8 percent, and increased the probability of moving among renters.

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The EPA, CDC, and WHO agree that no level of lead exposure in children is considered "safe." Lead is a neurotoxin that causes damage to the brain and nervous system, developmental delays, seizures, and, at high levels, death. Lead exposure impacts fertility and birth outcomes (Clay et al., 2021; Dave and Yang, 2022; Grossman and Slusky, 2019), harms cognitive function, test scores, human capital, and earnings (Clay et al., 2019; Sorensen et al., 2019; Grönqvist et al., 2020; Aizer et al., 2018; Rau et al., 2015), and leads to behavioral problems, (Aizer and Currie, 2019; Feigenbaum and Muller, 2016; Reyes, 2015, 2007).

Despite these well-known health consequences of lead exposure, an estimated 6 to 10 million lead service lines still deliver drinking water to homes throughout the US and about 15 to 22 million individuals are served by water systems with lead lines. Lead crises, such as those in Washington, DC, Flint, MI, and Newark, NJ, have captured the nation's attention and underscored the persistence of this health threat to drinking water supplies. Disadvantaged communities are disproportionately exposed to these lead service lines, which may contribute to existing health and human capital disparities and leaves these households vulnerable to another public health emergency. Although $15 billion was recently dedicated to replacing lead service lines throughout the US as part of the Infrastructure Investment and Jobs Act of 2021, we know very little about the effect of lead service line (LSL) replacements on direct measures of health, such as child blood lead levels (BLLs), and whether targeted households benefit from this place-based policy.

This paper is the first to study the causal effects of public lead service line replacements on child blood lead levels, moving behavior, housing prices, and neighborhood changes. I use confidential data on child blood lead levels with address information, tax assessor data on home sales, and data on the geocoded location and timing of service line installations conducted as part of a Lead Service Line Replacement (LSLR) Program in Providence, Rhode Island.[1] As a consequence of exceeding the EPA's lead action level, the water system spent over $55 million replacing about 10,000 public-side lead service lines between 2007 and 2010.[2]

[1]Providence Water serves 60 percent of the state's residents, about 600,000 people, and had about 25,600 LSLs in 2006.

[2]Service lines deliver water from the water main, which runs under the street, to the customer's home and consist of public and private-owned segments. The "public" service line segment runs from the property line to the water main and is owned by the water system. The "private" service line segment runs from the

The effect of public-side LSL replacements on child blood lead levels is not obvious. Mineral scale buildup over time on the inner surface of older plumbing may prevent lead from leaching into drinking water. When mineral scale is removed, disturbed, or has yet to develop, lead may leach into drinking water.[3] Depending on the presence of mineral scale and disturbance of that scale on remaining lead pipes during partial replacements, child blood lead levels may go up, down, or even stay the same.

I find that lead exposure through drinking water is a significant contributor to children's overall blood lead levels and even partial lead service line replacements can help reduce BLLs in children. Replacement of public-side lead service lines significantly reduced child blood lead levels among non-movers by about 0.4 micrograms per deciliter ($\mu g/dL$), or about 13 percent from the mean. Relative to the gap in average blood lead levels for children in newer versus older homes likely built with lead service lines, public-side replacements close the gap by about 31 percent.

Despite improving health, not all households targeted by the replacement program received these benefits. I find households are about 8-9 percent more likely to move to a new home after replacements and this moving behavior is driven primarily by renters. There is no evidence that homeowners are more likely to sell their homes, but when they do, they receive about 7-8 percent higher sale prices, suggesting new home buyers value the public LSL replacements. Demographic changes at the neighborhood level are mixed, with some evidence that new residents are more white and paying higher rent, but other estimates suggestive of a decline in income. Importantly, these results indicate that place-based policies may not yield benefits for those living in targeted homes. Renters, in particular, are less likely to remain in targeted homes and do not benefit from increased home values.

This paper makes several important contributions to the literature. First, this paper contributes to a relatively small literature on the modern-day effects of water pollution on

property line to the home and is the responsibility of the homeowner. Figure A1 depicts a typical service line and denotes the portion of each line that is owned by the homeowner or the water system.

[3]Besides during partial LSL replacements, another way disturbance of mineral scale may occur is through water main construction. Water mains typically run under the street, whereas service lines deliver water from the water main to the customer's home. Gazze and Heissel (2021) provides evidence that construction from water main replacements in Chicago did not disturb LSLs enough to affect lead levels in water or children's blood lead levels. Whereas most water systems have already replaced lead water mains, millions of lead service lines remain in operation today.

direct measures of health in the US (Marcus, 2021b; Hill, 2018; Currie et al., 2013). Unlike air pollution, water pollution exposure is much more difficult to measure (Keiser and Shapiro, 2019). Testing for contaminants often only happens at drinking water treatment facilities and can be infrequent, making it difficult to know household-level exposure at a given time. Moreover, even when data on household-level exposure to contaminants exists, the variation is typically cross-sectional in nature or changes are endogenously determined by household decision-making and avoidance behavior. This paper exploits a unique setting with plausibly exogenous household-level variation in removal of lead service lines that rolls out over time. Because the water utility, rather than the homeowner, determined the location and timing of LSL replacements, these replacements are unlikely to be correlated with other household-level changes.

Second, this paper provides the first causal estimates of the effect of LSL replacements on child blood lead levels. Lead service lines are an important, yet understudied, source of lead exposure in children. Existing economics research on lead exposure in children has primarily focused on other channels, including leaded fuel (Grönqvist et al., 2020; Hollingsworth and Rudik, 2020; Clay et al., 2019; Aizer and Currie, 2019; Zahran et al., 2017; Reyes, 2015, 2007) and lead-based paint (Aizer et al., 2018; Billings and Schnepel, 2018; Jones, 2012).Efforts to address lead exposure through de-leading gasoline and lead-based paint remediation have been the primary focus of policymakers and have been quite successful.[4] However, exposure to lead through the millions of LSLs that still deliver water to homes has received much less attention.

Most of the research on the negative effects of lead pipes comes from the early 20th century, when water distribution systems were relatively new (Ferrie et al., 2012; Clay et al., 2014; Feigenbaum and Muller, 2016). A smaller literature documents the modern-day impact of exposure during recent lead drinking water crises in Flint and Newark on fertility and health at birth (Dave and Yang, 2022; Grossman and Slusky, 2019). This paper contributes to this literature to show that lead service lines are a significant threat to health, even in a modern non-crisis context when many believed that mineral buildup would protect lead

[4]A number of key regulations helped to dramatically reduce child blood lead levels since the 1970s, including the 1970 Lead Paint Poisoning Prevention Act, the Clean Air Act, and the Environmental Protection Agency's rules on leaded gasoline.

from leaching into drinking water, and provides policy-relevant estimates of the impact of public LSL replacements on child BLLs.

Next, by studying the effect of public-side LSL replacements on the price of homes, this paper contributes to a literature on the valuation of environmental hazards using housing prices. Existing work has shown the effect of various environmental hazards on housing prices, including air pollution improvements from the Clean Air Act (Chay and Greenstone, 2005), toxic plants and hazardous waste sites (Currie et al., 2015; Gamper-Rabindran and Timmins, 2013; Greenstone and Gallagher, 2008), power plants (Davis, 2011), as well as shale gas development (Muehlenbachs et al., 2015; Boslett and Hill, 2019), among others. A much smaller literature focuses on the effect of lead hazards on home prices. For example, lead paint remediation in older homes impacts housing values and the sorting of households across homes (Gazze, 2021; Billings and Schnepel, 2017). Christensen et al. (2022) find that the lead crisis in Flint, Michigan reduced home values by 27-43 percent. This paper contributes by documenting the effect of public-side lead service line replacements on home values.

Finally, this paper contributes to a literature studying the effects of place-based policies (Banzhaf et al., 2019; Banzhaf and Walsh, 2013). Pollution remediation is naturally tied to place, given that the majority of pollution sources are stationary. Yet, human exposure to pollution depends on the mobility of people. Individuals have been shown to respond to information about pollution by moving residential locations or changing location decisions (Marcus, 2021a; Bae, 2012; Currie, 2011). This paper shows that LSL replacements increase the probability of moving for families living in homes targeted by the program, and this moving behavior is driven primarily by renters. Renters tend to be more disadvantaged and are disproportionately exposed to lead service lines. These results provide evidence that place-based remediation of environmental hazards may not necessarily reach those living in the targeted homes due to residential mobility. To the extent that households move to homes with other environmental hazards, remediation efforts may fall short of expectations in closing gaps in exposure between more and less disadvantaged households.

The rest of the paper proceeds as follows. Section 1 provides background on the health effects of lead exposure, the history of lead regulation in the US, and Rhode Island's lead regulation and lead service line replacement program. Sections 2 and 3 describe the data and the empirical strategies, respectively. Section 4 describes the results on child blood lead levels, moving behavior, housing prices, and neighborhood changes. Finally, Section 5 discusses the findings and concludes.

1 Background

1.1 Health effects of lead exposure

Exposure to lead can occur through the skin, inhalation or ingestion. Lead quickly enters the bloodstream and is subsequently deposited in bones, soft tissues, and organs, including the brain. While the half-life of lead in blood is about a month, lead is also stored in the teeth and bones, accumulating over time, and can be re-mobilized into the blood. On average, it takes over a year for children with elevated blood lead levels above 10 $\mu g/dL$ to fall below that threshold (Dignam et al., 2008). Lead serves no purpose in the human body, but rather displaces or mimics necessary metals, such as calcium. Lead can affect any of the body's organs and is known to impair brain development, cognitive function, attention, short-term memory, and impulse control. Lead can also have detrimental effects on the cardiovascular, renal, and reproductive systems.

This paper focuses on lead exposure in children, as they tend to be more susceptible to lead and show signs of severe lead toxicity at lower levels than adults. Conditional on exposure, children absorb more lead than adults, and children's nervous systems are still developing. While nearly all lead in adults is excreted from the body within weeks, only about one-third of the lead in children will leave the body. Undernourished children are even more susceptible to lead, because the body will absorb more lead if other nutrients, such as calcium or iron, are lacking (Goyer, 1995; Hollingsworth et al., 2020). Even developing fetuses are at risk of lead exposure as lead can cross the placental barrier and can cause damage to the nervous system, affect behavior, and increase the risk for miscarriage.

While the range and severity of the effects of lead increase with exposure levels, there is no known "safe" level of blood lead concentration (Lanphear, 2017).[5]

1.2 US History of Lead in Drinking Water

Although the harmful effects of lead exposure are well-known today, millions of lead service lines remain in use due to a variety of historical features. Due to lead's durability and malleability, lead service lines were regularly installed in the US for water distribution on a major scale beginning in the mid 1800s, especially in larger cities. Research on the early 20th century, when water distribution systems were relatively new, shows high water acidity in cities with lead pipes impaired cognitive performance among World War II enlistees and increased infant mortality in the early 1900s (Ferrie et al., 2012; Clay et al., 2014). Feigenbaum and Muller (2016) show that cities' use of lead service pipes exposed entire city populations to higher doses of lead and significantly increased city-level homicide rates.

Although most cities in the US were moving away from installing lead pipes by the 1920s, it was not until 1986 that Congress amended the Safe Drinking Water Act to prohibit the use of pipes, solder or flux that were not "lead free" in public water systems. Despite the prohibition of newly installed lead pipes, existing lead pipes in the water distribution systems typically had built up protective scales over time and were allowed to remain in place. However, lead can enter drinking water when these lead plumbing materials corrode. A number of factors influence the degree to which lead enters the water, including the acidity of water, the types and amounts of minerals present, the amount of lead, the temperature of the water, the age of the pipes, the duration that water is stagnant in the pipes, and the presence of protective scales or coatings inside the pipes.

As most lead water mains have already been replaced, lead service lines are typically the greatest source of lead in drinking water, but lead can also be found in faucets, fixtures, and plumbing with lead solder. Service lines deliver water from the water main to the customer's home and consist of two segments. The "public" service line segment runs under the street from the property line to the water main and is owned by the water system. The "private" service line segment begins at the property line and is the responsibility of the homeowner (see Appendix 8.1.1 for more detail).

[5] www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water

Instead of mandating the removal of existing lead pipes, the EPA issued the Lead and Copper Rule (LCR) in 1991 to attempt to control the corrosivity of the water and prevent lead leaching from pipes into drinking water. The regulation requires community water systems to test for lead in tap water by collecting samples from homes that are more likely to have lead plumbing materials. For each water system, if 10 percent of the samples from homes exceed the EPA's action level of 15 parts per billion (ppb), the water system must undertake a number of actions to control corrosion. These actions include taking additional steps to optimize corrosion control treatment, educating the public about lead in drinking water, and replacing lead service lines owned by the water system. More than 5,000 water systems violated the testing requirements of the Lead and Copper Rule in 2015, and over 1,000 systems serving nearly 4 million people reported exceeding the EPA's lead action level between 2013 and 2015 (Olson and Fedinick, 2016).

1.3 Lead in Drinking Water in Rhode Island

In Rhode Island, lead exposure has consistently been a large concern. The aging distribution system has lead service lines dating back to the 1800s. Providence Water, the largest community water supply system in RI, routinely samples 300 locations in each compliance sample round for Lead and Copper Rule compliance. For the first 15 years after the Lead and Copper Rule was established, the 90th percentile of lead compliance samples in Providence were consistently between 10 and 15 ppb, just below the EPA's action level, as shown in Figure 1. In an effort to reduce lead levels, Providence Water commissioned a study to assess their corrosion control. Based on the EPA's research findings, the study recommended reducing the pH level of the water from 10.2 to 9.7, which was expected to be the optimal level to reduce lead solubility in water. Contrary to expectations, after this change was implemented in 2006, the 90th percentile of lead samples exceeded the action level for the first time. Between 2006 and 2017, the lead testing results were at or exceeded the lead action level in 16 of 23 testing periods. Figure 1 shows the 90th percentile of lead tests for Providence Water from 1997 to 2017.

Exceeding the lead action level in 2006 triggered the EPA's requirement for Providence Water to begin a lead service line replacement program in 2007. Under the EPA's Lead and

Copper Rule, water systems exceeding the lead action level were required to replace 7 percent of public lead service lines per year until all were replaced or until the system returned to compliance with the lead action level. As Providence Water had 25,600 lead service lines in 2006, they were required to replace about 1,792 annually, costing about $8 million per year. Between 2007 and 2010, Providence Water replaced about 10,000 lead service lines as part of their LSL Replacement Program. Figure 2 shows the density of service lines installed among older homes by year of installation.[6] The figure clearly shows the dramatic rise in service line replacements between 2007 and 2010 driven by the LSL Replacement Program, which is the variation leveraged in this study.

Requirements to replace lead service lines applied only to the public portion of service lines owned by the water system. The private portion was also commonly made of lead and usually remained in place. While Providence Water was required to offer to replace the property owners' portion of the service line, these private-side replacements were done at the owners' expense, which was about $3,800 on average (Providence Water, 2021).[7] In practice, very few owners (only 1-2 percent) chose to replace their private lead service lines during this time due to the cost. Therefore, most of the service line replacements made through this program were partial lead service line replacements, as they typically replaced only the public lead service lines.

Starting in 2010, with the release of a new CDC study, the efficacy of partial lead service line replacements came under question. Cross-sectional estimates in Brown et al. (2011) suggested partial replacement of lead service lines was associated with elevated blood lead levels, possibly due to disturbance of the mineral coating that increases lead in water. However, with only cross-sectional variation, any characteristics of households impacting lead levels and correlated with partial LSL replacement, such as lead paint remediation, would bias estimates. Nevertheless, this correlational evidence led the EPA's Science Advisory Board to report in 2011 that there was "inadequate" evidence to determine the effectiveness of partial LSL replacement (US EPA, 2011). Given these concerns, the Rhode Island Department

[6]Older homes built before 1937 are more likely to have had lead service lines and to be affected by the LSL Replacement Program (see Appendix 8.1.4 for detail). While data on the year homes were built is not available for the whole sample, the figure looks remarkably similar in the full sample, without restricting to homes built prior to 1937, which is shown in Appendix Figure A4.

[7]At the time, a 1% interest loan was made available, but take-up was low.

of Health granted a stay of the LSL replacement program in 2012. Since then, Providence Water has focused on increasing full LSLRs (i.e. simultaneously replacing both the public and private side). Beginning in 2018, Providence Water implemented a policy to conduct only full LSLRs. Appendix 8.1.4 provides more details and changes to the program that have occurred since the study period.

Other sources of lead exposure, such as lead paint, have also been a problem in Rhode Island. Lead-based paints were banned for residential use in 1978, but homes built prior to 1978 are likely to still have some lead-based paint. In Rhode Island, the Lead Hazard Mitigation and Lead Poisoning Prevention Acts require all pre-1978 non-exempt rental homes to be inspected for lead in order to obtain a "lead safe" certificate, but inspections focus primarily on lead paint and do not necessarily require testing the tap water.[8] Rhode Island law requires owners of properties built before 1978 to disclose information about known and potential lead exposure hazards before the sale or rental of residential property. For example, sellers should provide a copy of all lead inspection reports to potential buyers. Because of broad public concern about lead exposure in Rhode Island, it is also common for home buyers to conduct a lead inspection before the sales contract takes effect.

2 Data Description

Data for this project come from several sources, including public water service lines data, census data, blood lead test results with address information, and tax parcel data on home sales. I describe each of the data sources in detail below.

Service Line Data

[8] Exemptions include (1) temporary housing; (2) elderly housing; (3) one, two and three-unit homes, one unit of which is occupied by the property owner; and (4) units that have been found to be lead-safe or lead-free through the proper certification. The most common types of certificates are the Certificate of Lead Conformance and the Conditional Lead Safe Certificate. The Certificate of Lead Conformance is required for most pre-1978 rental units and involves an Independent Clearance Inspection, which is limited to a visual assessment of painted surfaces and dust wipe sampling. The Conditional Lead Safe Certificate is required for properties with RIDOH violations and involves a Comprehensive Environmental Lead Inspection (CELI), which determines the presence of lead in paint, dust, soil, and water. If a CELI detects lead in drinking water, owners must label taps with a warning message in the primary language of the occupants, must provide bottled water for drinking and cooking until the water reaches a lead-safe level, and replace lead-containing pipes with lead free materials (216-RICR-5015-3.16.16).

Service line data comes from the Providence Water Supply Board (Providence Water), which serves about 60 percent of all Rhode Island residents with drinking water. These data contain the spatial location of all public service lines, year of installation for each line, line material (e.g. lead, copper, etc.), and line type (e.g. commercial, residential, etc.). These data include information on only the public-side of each service line, and I limit the sample to residential lines. Unfortunately, I lack information on private-side service line replacements and interior plumbing and fixture material, which may also be important sources of lead exposure for children. However, replacing both the public and private sides simultaneously was infrequent, less than 2 percent, during the LSL Replacement program.

Figure 3 shows the location of public service lines. Non-lead lines are shown in light peach, lead lines that had not yet been replaced as of 2017 are shown in medium brown, and non-lead lines that were installed during the Lead Service Line Replacement program (between 2007 and 2010) are shown in dark brown. Replacements appear to be concentrated in certain neighborhoods. Appendix 8.3.1 combines replacements with census data to explore whether neighborhoods receiving replacements were demographically or economically different. Replacements are driven mostly by the concentration of older homes and the density of lead service lines, but even conditional on these characteristics, suggestive results indicate that neighborhoods with many renters and more black households may have received fewer replacements.

Service line data are combined with additional tax parcel data from the cities of Providence and Cranston, which contain information on the year homes were built.[9] Using year of service line installation, Appendix 8.1.4 and Figure A3 show that lead service lines were frequently installed up until about 1937. After 1937, almost none of newly installed service lines were made of lead. This is consistent with historical records that show LSL installation was discontinued in 1937 when copper tubing was adopted (Providence Water, 2021). Therefore, homes built prior to 1937 were more likely to have had a lead service line.

Child Blood Lead Level Data

[9]Over 60 percent of child observations are from locations in Providence and Cranston. Tax parcel data was not available for other cities that were served by Providence Water, such as North Providence, Johnston, and Pawtucket. Analysis using year built data is therefore based on the smaller sample of parcels located in either Providence or Cranston.

Blood lead level test results for children come from the Rhode Island Department of Health (RIDOH). These data contain all blood lead test results from 2005 to 2016 for children ages 0 to 6 years old. In Rhode Island, healthcare providers are required by law to conduct at least two blood lead screening tests on all children by the age of three. Children should then be screened annually through age six. Children between age 3 and 6 with all previous blood lead tests under 5 $\mu g/dL$ can be screened using risk assessment questions (see Appendix 8.1.3 for detail). For example, children living in newer homes with fewer sources of potential lead exposure may not need to take a blood lead test.[10] Results of blood lead tests must be reported to the RIDOH within 10 days of testing. Lead screening tests for children under age six are free.

The blood lead test data include information on year tested, test result, and test method. Two types of blood lead testing methods are used. Capillary tests use a small amount of blood taken from the capillaries close to the skin in a child's arm, finger, or heel. Venous tests require a withdrawal of blood from the child's arm and are more accurate than capillary tests. The main estimates restrict the sample to venous test results, but are robust to including capillary tests. Confidential information on residential addresses of children allow linkages between children and public water service lines. Importantly, a unique identifier for each child makes it possible to observe blood lead test results for the same child over time. I observe the age at which each test was taken and, if there are multiple tests per year of age, I measure blood lead level as the average of all tests for a child at that age. I show that the results are robust to using the minimum value or maximum value as well.

In general, blood lead levels were trending down over this time period, from an average of about 4.34 $\mu g/dL$ in 2005 to about 2.18 $\mu g/dL$ in 2016, as seen in Figure A5a. Yet, these levels remain much higher than the nation-wide average of 0.8 $\mu g/dL$ based on NHANES data from 2011-2016 (Egan et al., 2021). The BLL distribution in Rhode Island also has a long right tail. About 13 percent of children had elevated blood lead levels over 5 $\mu g/dL$, and 3 percent had blood lead levels over 10 $\mu g/dL$.[11] Moreover, Table 1 shows a stark racial gap in average blood lead levels. The average for all children in the sample is about 2.9

[10] Appendix 8.3.2 explores changes in the probability of testing after lead service line replacements. Results are consistent with screening requirements that require fewer tests for children living in newer homes.

[11] Appendix 8.1.5 provides some additional detail.

$\mu g/dL$, with Black children having a higher average at 3.2 $\mu g/dL$. Exposure to lead through drinking water may contribute to this gap, as Black households are more exposed to lead service lines.

As children living in homes built before 1937 are more likely exposed to a lead service line, it is useful to compare average child blood lead levels by the age of their house, as shown in Figure 4. In panel a, the vertical line denotes the year 1937 and squares show the mean BLL for children living in homes built in each 5-year bin of home age. The line shows the smoothed BLLs over years of home age. Blood lead levels are higher for children living in homes built before 1937. On average, BLLs are about 3.37 and 2.07 $\mu g/dL$ for children in homes built before 1937 and after 1937, respectively. There is a decrease in average BLLs around 1937, suggesting that some of this difference in means may be driven by exposure through lead service lines.[12] Panel b of Figure 4 shows the smoothed blood lead levels by year of home age for tests taken before treatment or for children that were never treated (long dashed line) and for tests taken after treatment (short dashed line). The decline in blood lead levels is concentrated in older homes, which would be expected if the line installations reduce exposure to lead through lead service lines in older homes. These results provide descriptive evidence consistent with the hypothesis that the LSLR Program led to reduced BLLs for children, but section 4.2.1 tests for this more formally.

Home Sales Data

Data on home sales come from the Rhode Island Tax Assessor and include sales from 2002 to 2018. I restrict the sample to residential homes and arms-length sales. Spatial information on tax parcel locations are used to combine home sale data with service line replacements. I exclude sales for new construction homes, defined as homes built after 2000 where the year built is equal to the year of service line installation. Service lines installed at old homes during the LSLR Program, from 2007 to 2010, are most likely to be lead service line replacements. I focus on these treatment cohorts and define installations as part of the LSLR Program if they occur between 2007 and 2010 at homes built before 1937. Service line replacements before

[12]Figure A7 plots average blood lead levels by home age separately by race. Both Black and White children in homes built before 1937 have higher blood lead levels than children in newer homes. The racial gap in blood lead concentrations generally persists across all home ages. See Appendix 8.1.5 for more detail.

or after the program, or at new homes, may be lead service line replacements or may be associated with home remodels or new construction. These non-LSLR Program installations may be endogenous to home remodels.

Data on home characteristics include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade.[13] I condition on these covariates in all regressions to account for differential trends in home prices based on house characteristics.

Census Data

Census data is used to understand the distribution of lead service line exposure and replacements across demographic groups in Providence. Data comes from the 5-year sample of the American Community Survey (ACS) from 2013. Observations are at the block-group level and include information on median year homes were built, household size, home ownership type (owned, mortgaged, rented, or vacant), household type (single headed, married, single person, or non-family), education level, unemployment, public assistance, median household income, race/ethnicity, and presence of children.

Additional census data is used to explore neighborhood changes before and after the LSLR Program in areas that receive many replacements relative to those that do not. Data at the census tract level comes from the 2000 Decennial Census and the 5-year ACS from 2015 and includes information on rental prices, home ownership type, education level, percent below poverty, median household income, race/ethnicity, and presence of children.

3 Empirical Strategy

I exploit variation in child exposure to lead service lines from differential timing and location of lead service line replacements. The vast majority of these replacements were conducted as part of the Lead Service Line Replacement program, a requirement which was triggered when 10 percent of tap samples exceeding the 15 ppb lead action level in 2006. As the decision regarding time and location of the public lead service line replacements was made by the utility owner, rather than the homeowner, it is likely to be exogenous to other household-

[13] Grade is the original quality and construction of the house when built.

level changes. Moreover, very few households (less than 2 percent) chose to replace the private portion of the service line at the same time as the public portion replacements were made, because homeowners were responsible for this extra cost, about $3,800 on average. As other lead-reducing interventions tend to be even more costly, it is unlikely that homeowners were simultaneously investing in other lead-related interventions.[14] To support this assumption, Appendix 8.2.2 shows that the timing of replacements is not systematically related to property-level characteristics.

Given this variation in treatment timing and location from lead service line replacements, a traditional two-way fixed effects (TWFE) design would estimate the following,

$$BLL_{ia} = \beta^{TWFE} AfterInstall_{ia} + \pi_i + \delta_a + X + \varepsilon_{ia} \tag{1}$$

where the outcome is the average blood lead level for child i at age a for the panel of children tested between ages 0 and 6. The main variable of interest, $AfterInstall_{iat}$ is equal to one after a service line is replaced. The sample is restricted to non-moving households in order to abstract away from any endogenous moving behavior, which I examine directly in a separate analysis. Age indicators, δ_a, control for trends and shocks common to all children at different ages. Additional controls could be included in the vector X.

However, a recent literature has demonstrated that the estimate given by β^{TWFE} can only be interpreted as a weighted average of causal effects, and problematically, some of these weights can be negative (Callaway and Sant'Anna, 2020; Goodman-Bacon, 2021; Borusyak and Jaravel, 2017; De Chaisemartin and d'Haultfoeuille, 2020). In the presence of dynamic treatment effects, for example, comparisons of newly treated children to already treated children are not a valid comparison, as already treated children may still be responding to their past treatment and, therefore, cannot provide a valid counterfactual to represent potential outcomes in the absence of treatment. As lead in the body can accumulate over time and can be re-mobilized into the blood, it is likely that the effect of lead service line replacements may grow over time.

Therefore, I follow Callaway and Sant'Anna (2020) to summarize the effect of lead service

[14] For example, the EPA estimates that lead-based paint removal costs about $8 to $15 per square foot or about $9,600 to $30,000 for a 1,200 to 2,000 square foot house.

line replacements on child blood lead levels by estimating group-time average treatment effects, $ATT(g,t)$, for groups g and time periods t where there are T periods. Groups comprise all units that are treated at a particular age. I drop all units that were already treated by the time they were first observed in the data. These already treated units cannot be used as valid counterfactuals in the presence of dynamic treatment effects.

I estimate the group-time average treatment effect for each group g in each time period t by comparing units in g to one of two control groups: never treated units or units that were not-yet-treated in time t. Depending on the comparison group, I assume that the blood lead levels of children in houses with LSL replacements would have trended the same in the absence of treatment as the blood lead levels of children of the same age in houses with never replaced LSL or not-yet-replaced LSL (see Assumptions 5 and 6 in Callaway and Sant'Anna (2020)). To account for general trends in blood lead levels over time, I also condition on calendar year using the doubly robust estimator (Callaway and Sant'Anna, 2020; Sant'Anna and Zhao, 2020). Equations 2 and 3 show the group-time average treatment effect for group g at time t using the never treated and not-yet-treated units as a comparison group, respectively,

$$ATT^{nev}(g,t) = \mathbb{E}[BLL_t - BLL_{g-1}|G_g = 1] - \mathbb{E}[BLL_t - BLL_{g-1}|C = 1] \tag{2}$$

$$ATT^{ny}(g,t) = \mathbb{E}[BLL_t - BLL_{g-1}|G_g = 1] - \mathbb{E}[BLL_t - BLL_{g-1}|D_t = 0] \tag{3}$$

where BLL_t is the blood lead level at time t, G_g is an indicator equal to one for units in treatment group g, C is an indicator equal to one for the never treated units, and D_t is an indicator equal to one after treatment and equal to zero for not-yet-treated units.[15] I estimate $ATT^{nev}(g,t)$ and $ATT^{ny}(g,t)$ with $\widehat{ATT^{nev}(g,t)}$ and $\widehat{ATT^{ny}(g,t)}$, which are the sample analogues of equations 2 and 3. In practice, $\widehat{ATT^{nev}(g,t)}$ and $\widehat{ATT^{ny}(g,t)}$ estimate a classic 2x2 difference-in-difference without variation in treatment timing by comparing the relative difference in outcomes for group g and a control group between period t and the reference period prior to treatment, $g-1$. Group-time average treatment effects are aggregated by

[15] Note that, unless otherwise indicated, I impose the "no-anticipation" assumption, such that I assume the lead service line replacements are unanticipated. This is a reasonable assumption as the choice to replace a particular lead service line is made by the utility owner, not the homeowner.

simple aggregation, event-time aggregation, and group aggregation (see Appendix 8.2.1 for more detail). Standard errors are clustered at the child level with a multiplier bootstrap procedure (see Callaway and Sant'Anna (2020) for details). Unlike the commonly used pointwise confidence bands, this approach obtains simultaneous confidence bands that asymptotically cover the entire path of the group-time average treatment effects with a fixed probability and takes into account the dependency across different group-time average treatment effect estimators, which is arguably more suitable for visualizing the overall estimation uncertainty.

In addition to studying the effect of LSL replacements on child blood lead levels, I also estimate the effect on housing prices. For this analysis, observations are at the property-year level. Similar to the BLL results, I estimate the group-time average treatment effects, $ATT(g, t)$, where groups comprise all homes that received a replacement in a particular year. I drop all homes that were already treated by the time they were first observed in the data. I aggregate group-time average treatment effects based on either the never-treated or not-yet-treated control group and use the analogous simple, event, and group aggregations. To account for differential trends in housing prices by home type over time, I also use the doubly robust estimator and condition on a variety of home characteristics, including total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade.

4 Results

4.1 Environmental Justice and Distributional Impacts

Next, I explore the demographic characteristics of the population in Rhode Island that are exposed to lead service lines and replacements using data from the 2013 5-year ACS at the block-group level.[16] Table 2 shows detailed demographic, economic, and housing characteristics for neighborhoods with lead exposure and those that were targeted by the LSLR Program.

First, I explore who is more likely exposed to lead service lines. Comparing column 1

[16] I define public-side service lines as lead if they are recorded as made of lead as of 2017 or if they were replaced during the LSLR Program from 2007 to 2010.

to either columns 2 or 3, shows the difference in characteristics for block-groups unexposed and exposed to lead service lines. Exposure to LSL is not uniformly distributed across the population. As with many other environmental hazards, disadvantaged groups are more likely exposed to lead service lines. Neighborhoods with LSLs, in columns 2 and 3, are more likely to be renters, to be single headed households, to have a high school education or less, to be unemployed, to receive public assistance, to have a lower household income, to be non-white, and to be Hispanic. This is consistent with Vivier et al. (2011) who show that children in high poverty neighborhoods are almost four times more likely to have elevated BLLs than those in low poverty neighborhoods in Rhode Island.

Next, I explore who is more likely to receive replacements of lead service lines. Comparing columns 2 and 3 in Table 2 shows the difference in characteristics for neighborhoods with lead that received no LSL replacements or any replacements, respectively. While most differences are relatively small, two characteristics stand out. Neighborhoods targeted by the LSLR Program had an older housing stock and higher concentrations of lead service lines. Providence's housing stock is known to be some of the oldest in the country with about 45 percent of block-groups having a median year of home age before 1939.[17] About 50 percent of neighborhoods with LSL replacements (column 3) had a median year of home age before 1939, as compared to only about 28 percent in neighborhoods with lead but no replacements (column 2). Another important factor is the density of lead service lines. Neighborhoods with replacements seem to have had a higher concentration of lead service lines, which likely reduced the efficiency of replacements. Neighborhoods with lead but without any replacements (column 2) had about 21 percent of lines made of lead, while neighborhoods with replacements (column 3) had about 41 percent of lines made of lead. Appendix 8.3.1 explores these patterns in more detail and similarly finds that the distribution of replacements appears to be driven mostly by the concentration of older homes and the density of lead service lines, but even conditional on these characteristics, suggestive results indicate that neighborhoods with many renters and more black households may have received fewer replacements.

[17] I use 1939 instead of 1937 (when RI stopped installing LSL), because the median year of home age in the ACS is truncated at 1939.

4.2 Impacts of Place-Based Policy on Targeted Households

In this section, I explore how the lead service line replacement program impacted targeted households and neighborhoods. First, I estimate the effect of replacements on child blood lead levels among non-moving households. Second, I explore whether households living in homes receiving replacements remain in those homes after the program. Third, I study whether homeowners benefit from replacements through increased home sales prices. Finally, I explore broader changes in neighborhood demographics in response to the program.

4.2.1 Effects on Child Blood Lead Levels

I begin with exploring how partial lead service line replacements affected child blood lead levels. As mineral buildup may limit lead from leaching into drinking water and disturbance of pipes during a partial replacement may increase lead in drinking water, it is not obvious *a priori* whether replacements will reduce blood lead levels in children. Table 3 shows the overall summary aggregations of the average treatment effects. The sample includes only non-moving households. Columns 1 and 4 show the simple aggregation, columns 2 and 5 show the aggregation over event time, and columns 3 and 6 show the group aggregation (see Appendix 8.2.1 for aggregation detail). The counterfactual is set to the never treated group in columns 1-3 and the not-yet-treated group in columns 4-6. Across all aggregation methods and counterfactual groups in Panel A, the estimates consistently show a significant decline in average child blood lead levels of about 0.3-0.4 $\mu g/dL$ following a public-side lead service line replacement.

This represents a sizable decline in child blood lead levels. Relative to the mean of 2.89 $\mu g/dL$, the estimates represent a decline of about 12-14 percent. Alternatively, the 0.4 $\mu g/dL$ decline accounts for about 19 percent of the overall downward trend in child blood lead levels during the study period or 31 percent of the gap in average child blood lead levels for children living in homes built before and after 1937, when LSL were no longer installed in Rhode Island. Based on existing literature, a 0.4 unit decline in BLL is expected to reduce the probability of school suspension by 2.4% and juvenile detention by 23% (Aizer and Currie, 2019), and reduce the probability of being substantially below proficient in reading and math by 3.2% and 2%, respectively (Aizer et al., 2018). The magnitude is also about twice as large as the estimated decline of 0.17 $\mu g/dL$ from deleading NASCAR and ARCA races, although this is a conservative estimate (Hollingsworth and Rudik, 2020).

Panels B and C report results for binary indicators equal to one if a child's blood lead level is over 5 $\mu g/dL$ or over 10 $\mu g/dL$, respectively. The results show replacements led to a significant decline in elevated blood lead levels across all aggregation methods and counterfactual groups. Replacements led to a 5-6 percentage point decline in the probability of having a blood lead level over 5 $\mu g/dL$, or 38-45 percent from the mean. Replacements also had a significant impact on blood lead levels over 10 $\mu g/dL$, which declined by about 1-2 percentage points after replacement, or 50-84 percent from the mean.

Table 4 explores heterogeneity in these results by gender, race, and ethnicity. While the coefficients by gender and ethnicity are similar in magnitude, some interesting patterns arise by race. The effects on overall blood lead levels are driven by White children in Panel a. However, Black children have the largest point estimates for reductions in elevated blood lead levels over 5 and over 10 $\mu g/dL$ in Panels b and c, respectively. These larger reductions in elevated lead levels for Black children may have helped contribute to closing the racial gap in lead exposure. Figure 6 shows the cumulative distribution for blood lead test results by race before and after the LSLR program. Although blood lead levels remain higher for Black children, the Black-White gap in lead levels is smaller in years after the program.

Next, I explore heterogeneity in the treatment effects by event-time in Figure 5.[18] The event-study style aggregation, given by equation 5, provides information on trends prior to treatment and the evolution of the effects after treatment. The pre-treatment periods, in orange, show fairly flat and insignificant estimates. The lack of pre-treatment trends gives support for the assumption that blood lead levels would have trended similarly in children with LSL replacements and among children in the counterfactual group, in the absence of treatment. For all three measures, the estimates show a decline in blood lead levels after LSL replacements, which appears to grow somewhat over time. It is not surprising that the decrease in child BLL grows over time, since lead accumulates as it is stored in the body

[18]While Figure 5 uses the never treated group as the counterfactual, Figure A13 shows the figures using the not-yet-treated group as the counterfactual and finds very similar results.

over time, such that it may take time for reductions in BLL to arise.

These results are robust to a number of alternative specifications, as shown in Table 5. Column 1 replicates the main results for each of our BLL measures: average BLL result in panel A, an indicator for over 5 in panel B, and an indicator for over 10 in panel C.[19] First, I explore the robustness of the results to alternative measures of child BLL. Rather than using the yearly average of test results for children with multiple tests in a given year, using the maximum or minimum values within the year, in columns 2 and 3, produces very similar estimates. The magnitude of the effects are slightly larger (smaller) when using the maximum (minimum) values, which is not surprising.

Next, to ensure that the estimates are not driven by outliers of very high blood lead test results, column 4 shows the estimates after dropping the top percentile of test results. Column 5 includes capillary tests in addition to venous tests in the sample. As capillary tests are less accurate than venous tests, it is not surprising that the estimates are somewhat attenuated.

Next, I show the robustness of the results to alternate samples. Column 6 of Table 5 shows estimates based only on the sample of children that were treated during the LSL Replacement program from 2007 to 2010. These treatment cohorts are most likely to contain LSL replacements and are unlikely to be related to household-level changes. In column 7, I show the effects after dropping homes built after 1937 that were unlikely to have had a lead service line.[20] The estimates are very similar to the baseline specification, which provides some reassurance that the results are driven by older homes that were likely to have had lead service lines prior to the new installation. In column 8 of Table 5, I drop any BLL tests that occur in the same year of treatment, but before the lead service line is replaced. This ensures that the first year of treatment is based only on BLL tests that are taken after treatment begins. Finally, column 9 conditions on the year a child's home was built to account for any differential trends in blood lead levels by age of the house. Across all specifications, the

[19] All results are reported for the simple aggregation and never treated counterfactual group, but are robust to using the not yet treated group and other aggregation methods. Table A8, for example, shows similar results for the event study aggregation.

[20] As shown in Figure A3, lead service lines were commonly installed by Providence Water until 1937. This specification keeps all homes with missing information on year the home was built. As described in the data section, year built data was available only for Providence and Cranston.

estimates are consistent with the baseline specification and indicate a statistically significant decline in child BLL following a lead service line replacement.

4.2.2 Moving Behavior

Results show that LSL replacements reduced blood lead concentrations among non-moving children. While the racial gap in BLLs was diminished over this period, it was not eliminated. Therefore, it is useful to consider whether the program was successful in reaching the targeted households by looking first at endogenous moving behavior.

First, I explore whether households moved in response to replacements. I use a child's location at each blood test to look at the moving behavior of families after public LSL replacement, which will capture moves by renters as well as homeowners. Figure 7 shows the event study aggregation estimates. The outcome variable is equal to one if a child has ever moved from their first observed residential location. The pre-treatment coefficients in orange are statistically insignificant, suggesting there is little evidence of differential moving behavior prior to a LSL replacement. After replacement, the blue coefficients show an increase in the probability that a child has ever been observed at a new residential location. Table 6 shows the effect of lead service line replacements on the probability of moving across various aggregation methods and control groups. The estimates consistently show a statistically significant increase in moving of about 8-9 percent.

To better understand whether moving behavior is driven by homeowners or renters, I look at the probability that a home is sold in response to LSL replacement. I focus on replacements that occur during the LSLR Program, as defined in section 2. Figure 8 shows the event study aggregation estimates for the probability of a home being sold. Estimates use the never treated control group and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, and initial land assessment, and home grade in order to control for differential trends in home sales during the sample period by housing characteristics. Figure 8a shows that there is little evidence of a change in the probability that a home is sold either before or after the LSL replacement. Pre-treatment coefficients in orange and post-treatment coefficients in blue are not statistically different from zero.[21] Panel a of Table 7 presents the corresponding regression results. Across all aggregations and counterfactual groups the coefficients in panel a are small and statistically insignificant.

As there is no increase in the probability of a home sale, these results suggest that the moving behavior is driven primarily by renters. Renters are an especially important group in this setting, as the proportion of renters is high in neighborhoods with many lead service lines. Table 2 reports that over half of houses are rented in census block groups with at least some lead service lines. Renters also tend to be lower income and are more likely to be minorities.

Renters and homeowners are likely to differ along a number of relevant dimensions. Renters may have less information about the presence of lead service lines, as landlords are only required to inform renters of "known" lead sources. Renters are also reliant on their landlords to make any home improvements, such as replacing the remaining private-side lead service lines. Landlords may have little incentive to make such costly investments. Alternatively, renters may also have a different willingness to pay for replacements. Renters also have a lower cost of moving, relative to homeowners. Appendix 8.3.4 explores some potential mechanisms behind this moving behavior.

4.2.3 Effects on Home Sales Price

To capture the indirect benefits to homeowners from the program, I focus the effect of public lead service line replacements on home prices. The expected effect of LSL replacements on home values is not obvious and depends both on home buyers prior knowledge of LSLs and their valuation of public LSL replacements.

I focus on replacements that occur during the LSLR Program, as defined in section 2. The outcome variable is the log of the sales price, as described in section 2. Estimates use

[21] It is reassuring that we do not find spike in the probability of home sale in the same year as the replacement, as this could indicate that replacement timing is endogenously related to homeowner renovations at the time of sale. Appendix 8.3.3 shows that installations that occur outside of the LSLR Program increase in the probability of a home sale in the same year as the service line installation. If these replacements are endogeneously related to other home improvements, any price changes would be difficult to interpret because they would simultaneously capture both the effect of the home renovation and the reduced lead exposure from the lead service line. However, the lack of effect on the probability of sale in Figure 8a suggests that replacements made as part of the LSLR Program are likely exogenous.

the never treated control group and include year and parcel fixed effects. The doubly robust estimator conditions on a variety of housing characteristics in order to control for differential trends in home sales during the sample period by housing characteristics. Figure 8b shows that after LSL replacement, there is an increase in the sale price, suggesting that new home buyers value the replacements. There is little evidence of pre-trends in the periods before replacement, as shown by flat and insignificant pre-treatment coefficients in orange.

Regression results are reported in panel b of Table 7 where the outcome is the log of sale price. Results show LSL replacements are associated with a 7-8 percentage increase in the price of a home. Using the average home sales price of $238,000, this is an increase of about $16,000 to $19,000 per public-side LSLR. The magnitude of this effect is reasonable relative to the existing literature, which has documented even larger effects on housing prices for other lead hazards. Christensen et al. (2022) find a 27-43 percent reduction in the average home value in Flint, MI since the lead crisis, Billings and Schnepel (2017) find that lead paint remediation increases home values by 32 percent, and Gazze (2021) find that state mandates requiring the mitigation of lead hazards in old homes decreases the price of those homes by about 7 percent.[22]

This effect is robust to various aggregations and counterfactual groups, as shown across columns in Table 7. In Table A9, I show these results are robust to alternative specifications. First, columns 2-4 document that the results are not driven by outliers in home sale price. Next, in order to address concerns that different neighborhoods may have differential home price trends during the recession, column 5 adds census tract to the conditional parallel trends assumption, such that comparisons are made within tracts, and finds very similar results. Finally, column 6 of Table A9 shows there is no effect of LSL replacement on the probability of foreclosure, which provides additional evidence that the the housing crisis is uncorrelated with the timing of lead service line replacements.

[22]Theising (2019) find an increase of 3-4 percent for mandated private-side lead service line replacements in Madison, WI. Unlike in Madison, homeowners in Providence did not have to pay for these public LSL replacements, thus the changes in home values I observe in this setting are more likely to represent home buyers' valuation of the reduced risk of lead exposure.

4.2.4 Neighborhood Changes

Previous results suggest that LSL replacements led to existing renters moving out and increased value for homeowners. Given the clustered nature of these replacements, it is useful to use neighborhood characteristics to better understand what types of buyers and renters move into these neighborhoods targeted by the LSLR Program. To do so, I use census tract level data from 2000 and 2015, as described in section 2.

In principle, we could expect neighborhoods to be changing in different ways. Homes that received public lead service line replacements may attract buyers with a high willingness to pay for clean drinking water, since replacing any remaining private-side lead would be relatively straightforward during a renovation. Neighborhoods may also benefit from improved curb appeal from repaving the street after replacements are complete. Alternatively, if the information about the presence of lead service lines is new, the incoming residents may have lower willingness or ability to pay for clean drinking water. We might also expect households with children to respond differently, given that lead exposure is especially harmful to children.

Using a simple 2x2 difference in difference model, I compare demographic changes before and after the replacement program in tracts with many relative to few replacements. Regressions include tract fixed effects and a year indicator, and are weighted by the total number of service lines eligible for replacement. Tables 8 and 9 show the results where treatment is measured continuously as the percent of lines replaced in panel a, and treatment is measured as a binary variable equal to one for tracts above the 75th percentile of percent of lines replaced in panel b. Patterns are generally consistent across both panels.

In Table 8, I find slight increase in the percent white households living in LSLR neighborhoods, although the coefficient is only marginally significant. Coefficients on the percent black and other race are negative, but not significant. The coefficient on percent of under age 5 is negative, but insignificant, perhaps reflecting parental concern over lingering lead in these neighborhoods. Results are also suggestive of an overall decline in highly educated households and an increase in low income households, but these coefficients are not significant. Results on rental prices shown in Table 9 indicate an increase in rent in these targeted neighborhoods, perhaps reflecting that renters moving in have a higher valuation for these replacements.

Broadly, these neighborhood patterns are only suggestive and may mask important heterogeneities at the property level. Without more granular data, it is difficult to know exactly who moves into homes that received a LSL replacement. Nevertheless, these results, along with the increased moving behavior among renters, suggest that place-based policies, such as the removal of public lead service lines, may not reach the targeted households.

5 Discussion & Conclusion

This paper provides evidence of the effect of partial public-side lead service line replacements on child blood lead levels, moving behavior, housing prices, and neighborhood changes. Replacement of public-side lead service lines, conducted as part of Providence Water's LSLR Program, significantly reduced child blood lead levels by about 0.4 $\mu g/dL$, or 13 percent from the mean. Considering that public-side replacements would not entirely eliminated exposure to lead through drinking water if private-side lead lines or lead interior plumbing remained, this is likely an underestimate of the contribution of drinking water to children's overall lead exposure. Current policy efforts focus on fully replacing both the private and public side simultaneously. Extrapolating the estimates to fully replacing lead service lines could conservatively reduce blood lead levels by about 0.6 $\mu g/dL$, or 22 percent from the mean.[23] This closely mirrors the EPA's estimates that drinking water can make up 20 percent or more of a person's total exposure to lead.[24]

I also find that LSLRs increase home values by about 7-8 percent, suggesting that home buyers value the public-side LSL replacements more than the cost. Using the average home sales price of $238,000, this suggests a valuation of about $16,000 to $19,000 per public-side LSLR, which is about three to four times as large as the average cost of a public-side replacement, $4,800 (Providence Water, 2021). Replacing the entire LSL is likely to

[23]In Appendix 8.1.2 I estimate that privately owned service lines are about 0.61-1.27 times the length of publicly owned service lines. I use 0.61 as a conservative estimate. Using 1.27 would lead to a reduction of about 0.9 $\mu g/dL$, or 31 percent of the mean.

[24]https://www.epa.gov/ground-water-and-drinking-water/basic-information-about-lead-drinking-water

benefit homeowners even more than the partial replacements studied here. Yet, if we take a conservative estimate of the increase in home value of $16,000, replacing the 6 to 10 million remaining lead service lines could generate benefits of $96-$160 billion.

Despite the benefits to homeowners, I find that renters living in homes targeted by the LSLR Program are more likely to move out after replacements. Renters are an especially important group in this context, as they are disproportionately exposed to lead service lines, but are reliant on landlords to pay for private-side replacements. Demographic changes at the neighborhood level are mixed, with some evidence that new residents are more white and paying higher rent, but other estimates suggestive of a decline in income. Yet, these results indicate that not all households living in homes targeted by the program receive the benefits. Renters, especially, are more likely to move out and do not receive any benefit from increased property values.

These findings show that even partial lead service line replacements can reduce child blood lead levels and that lead service lines are an important contributor to overall child blood lead levels. As no level of lead exposure is considered safe, it is important to address lead exposure through drinking water in addition to other channels of exposure, such as lead paint. The Infrastructure Investment and Jobs Act a step in this direction by funding full lead service line replacements, but current funding is insufficient to replace all LSLs. Providing funding for full lead service line replacements at all homes will lower child blood lead levels and also help protect renters and other disadvantaged groups that do not own or cannot afford to replace private-side lead service lines, yet are disproportionately exposed to lead service lines.

References

Aizer, Anna and Janet Currie, "Lead and juvenile delinquency: new evidence from linked birth, school, and juvenile detention records," *Review of Economics and Statistics*, 2019, *101* (4), 575–587.

_ , _ , Peter Simon, and Patrick Vivier, "Do low levels of blood lead reduce children's future test scores?," *American Economic Journal: Applied Economics*, 2018, *10* (1), 307–41.

Bae, Hyunhoe, "Reducing environmental risks by information disclosure: Evidence in residential lead paint disclosure rule," *Journal of Policy Analysis and Management*, 2012, *31* (2), 404–431.

Banzhaf, H Spencer and Randall P Walsh, "Segregation and Tiebout sorting: The link between place-based investments and neighborhood tipping," *Journal of Urban Economics*, 2013, *74*, 83–98.

Banzhaf, Spencer, Lala Ma, and Christopher Timmins, "Environmental justice: The economics of race, place, and pollution," *Journal of Economic Perspectives*, 2019, *33* (1), 185–208.

Billings, Stephen B and Kevin T Schnepel, "The value of a healthy home: Lead paint remediation and housing values," *Journal of Public Economics*, 2017, *153*, 69–81.

_ and _ , "Life after lead: Effects of early interventions for children exposed to lead," *American Economic Journal: Applied Economics*, 2018, *10* (3), 315–44.

Borusyak, Kirill and Xavier Jaravel, "Revisiting event study designs," *Available at SSRN 2826228*, 2017.

Boslett, Andrew and Elaine Hill, "Shale gas transmission and housing prices," *Resource and Energy Economics*, 2019, *57*, 36–50.

Brown, Mary Jean, Jaime Raymond, David Homa, Chinaro Kennedy, and Thomas Sinks, "Association between children's blood lead levels, lead service lines, and water disinfection, Washington, DC, 1998–2006," *Environmental research*, 2011, *111* (1), 67–74.

Callaway, Brantly and Pedro HC Sant'Anna, "Difference-in-differences with multiple time periods," *Journal of Econometrics*, 2020.

Chaisemartin, Clément De and Xavier d'Haultfoeuille, "Two-way fixed effects estimators with heterogeneous treatment effects," *American Economic Review*, 2020, *110* (9), 2964–96.

Chay, Kenneth Y and Michael Greenstone, "Does air quality matter? Evidence from the housing market," *Journal of political Economy*, 2005, *113* (2), 376–424.

Christensen, Peter, David Keiser, and Gabriel Lade, "Economic effects of environmental crises: Evidence from Flint, Michigan," *Forthcoming at American Economic Journal: Economic Policy*, 2022.

Clay, Karen, Margarita Portnykh, and Edson Severnini, "The legacy lead deposition in soils and its impact on cognitive function in preschool-aged children in the United States," *Economics & Human Biology*, 2019, *33*, 181–192.

_ , _ , and _ , "Toxic truth: Lead and fertility," *Journal of the Association of Environmental and Resource Economists*, 2021, *8* (5), 975–1012.

_ , Werner Troesken, and Michael Haines, "Lead and mortality," *Review of Economics and Statistics*, 2014, *96* (3), 458–470.

Currie, Janet, "Inequality at birth: Some causes and consequences," *American Economic Review*, 2011, *101* (3), 1–22.

_ , Joshua Graff Zivin, Katherine Meckel, Matthew Neidell, and Wolfram Schlenker, "Something in the water: Contaminated drinking water and infant health," *Canadian Journal of Economics/Revue canadienne d'économique*, 2013, *46* (3), 791–810.

_ , Lucas Davis, Michael Greenstone, and Reed Walker, "Environmental health risks and housing values: evidence from 1,600 toxic plant openings and closings," *American Economic Review*, 2015, *105* (2), 678–709.

Dave, Dhaval M and Muzhe Yang, "Lead in drinking water and birth outcomes: A tale of two water treatment plants," *Journal of Health Economics*, 2022, p. 102644.

Davis, Lucas W, "The effect of power plants on local housing values and rents," *Review of Economics and Statistics*, 2011, *93* (4), 1391–1402.

Dignam, Timothy A, Jose Lojo, Pamela A Meyer, Ed Norman, Amy Sayre, and W Dana Flanders, "Reduction of elevated blood lead levels in children in North Carolina and Vermont, 1996–1999," *Environmental health perspectives*, 2008, *116* (7), 981–985.

Egan, Kathryn B, Cheryl R Cornwell, Joseph G Courtney, and Adrienne S Ettinger, "Blood lead levels in US children ages 1–11 years, 1976–2016," *Environmental health perspectives*, 2021, *129* (3), 037003.

Feigenbaum, James J and Christopher Muller, "Lead exposure and violent crime in the early twentieth century," *Explorations in economic history*, 2016, *62*, 51–86.

Ferrie, Joseph P, Karen Rolf, and Werner Troesken, "Cognitive disparities, lead plumbing, and water chemistry: Prior exposure to water-borne lead and intelligence test scores among World War Two US Army enlistees," *Economics & Human Biology*, 2012, *10* (1), 98–111.

Gamper-Rabindran, Shanti and Christopher Timmins, "Does cleanup of hazardous waste sites raise housing values? Evidence of spatially localized benefits," *Journal of Environmental Economics and Management*, 2013, *65* (3), 345–360.

Gazze, Ludovica, "The price and allocation effects of targeted mandates: evidence from lead hazards," *Journal of Urban Economics*, 2021, p. 103345.

_ **and Jennifer Heissel**, "Infrastructure upgrades and lead exposure: Do cities face trade-offs when replacing water mains?," *Journal of Environmental Economics and Management*, 2021, *108*, 102472.

Goodman-Bacon, Andrew, "Difference-in-differences with variation in treatment timing," *Journal of Econometrics*, 2021, *225* (2), 254–277.

Goyer, Robert A, "Nutrition and metal toxicity," *The American journal of clinical nutrition*, 1995, *61* (3), 646S–650S.

Greenstone, Michael and Justin Gallagher, "Does hazardous waste matter? Evidence from the housing market and the superfund program," *The Quarterly Journal of Economics*, 2008, *123* (3), 951–1003.

Grönqvist, Hans, J Peter Nilsson, and Per-Olof Robling, "Understanding How Low Levels of Early Lead Exposure Affect Children's Life Trajectories," *Journal of Political Economy*, 2020, *128* (9), 3376–3433.

Grossman, Daniel S and David JG Slusky, "The impact of the Flint water crisis on fertility," *Demography*, 2019, *56* (6), 2005–2031.

Hill, Elaine L, "Shale gas development and infant health: evidence from Pennsylvania," *Journal of health economics*, 2018, *61*, 134–150.

Hollingsworth, Alex and Ivan Rudik, "The effect of leaded gasoline on elderly mortality: Evidence from regulatory exemptions," 2020.

_ **, Mike Huang, Ivan J Rudik, and Nicholas J Sanders**, "Lead Exposure Reduces Academic Performance: Intensity, Duration, and Nutrition Matter," Technical Report, National Bureau of Economic Research 2020.

Jones, David J, "Primary prevention and health outcomes: Treatment of residential lead-based paint hazards and the prevalence of childhood lead poisoning," *Journal of Urban economics*, 2012, *71* (1), 151–164.

Keiser, David A and Joseph S Shapiro, "US water pollution regulation over the past half century: burning waters to crystal springs?," *Journal of Economic Perspectives*, 2019, *33* (4), 51–75.

Lanphear, Bruce P, "Low-level toxicity of chemicals: No acceptable levels?," *PLoS biology*, 2017, *15* (12), e2003066.

Marcus, Michelle, "Going beneath the surface: Petroleum pollution, regulation, and health," *American Economic Journal: Applied Economics*, 2021, *13* (1), 1–37.

_ , "Testing the water: Drinking water quality, public notification, and child outcomes," *The Review of Economics and Statistics*, 2021, pp. 1–45.

— **and Pedro HC Sant'Anna**, "The role of parallel trends in event study settings: An application to environmental economics," *Journal of the Association of Environmental and Resource Economists*, 2021, *8* (2), 235–275.

Muehlenbachs, Lucija, Elisheba Spiller, and Christopher Timmins, "The housing market impacts of shale gas development," *American Economic Review*, 2015, *105* (12), 3633–59.

Olson, Erik and Kristi Pullen Fedinick, "What's in your water? Flint and beyond," *NRDC, June*, 2016.

Providence Water, "Providence Water Supply Board's Lead Service Line Replacement Program for Disadvantaged Communities," 2021.

Rabin, Richard, "The lead industry and lead water pipes "A Modest Campaign"," *American journal of public health*, 2008, *98* (9), 1584–1592.

Rau, Tomás, Sergio Urzúa, and Loreto Reyes, "Early exposure to hazardous waste and academic achievement: Evidence from a case of environmental negligence," *Journal of the Association of Environmental and Resource Economists*, 2015, *2* (4), 527–563.

Reyes, Jessica Wolpaw, "Environmental Policy as Social Policy? The Impact of Childhood Lead Exposure on Crime," *The BE Journal of Economic Analysis & Policy*, 2007, *7* (1), 1–43.

— , "Lead exposure and behavior: effects on antisocial and risky behavior among children and adolescents," *Economic Inquiry*, 2015, *53* (3), 1580–1605.

Sant'Anna, Pedro HC and Jun Zhao, "Doubly robust difference-in-differences estimators," *Journal of Econometrics*, 2020, *219* (1), 101–122.

Sorensen, Lucy C, Ashley M Fox, Heyjie Jung, and Erika G Martin, "Lead exposure and academic achievement: Evidence from childhood lead poisoning prevention efforts," *Journal of Population Economics*, 2019, *32* (1), 179–218.

Theising, Adam, "Lead pipes, prescriptive policy and property values," *Environmental and Resource Economics*, 2019, *74* (3), 1355–1382.

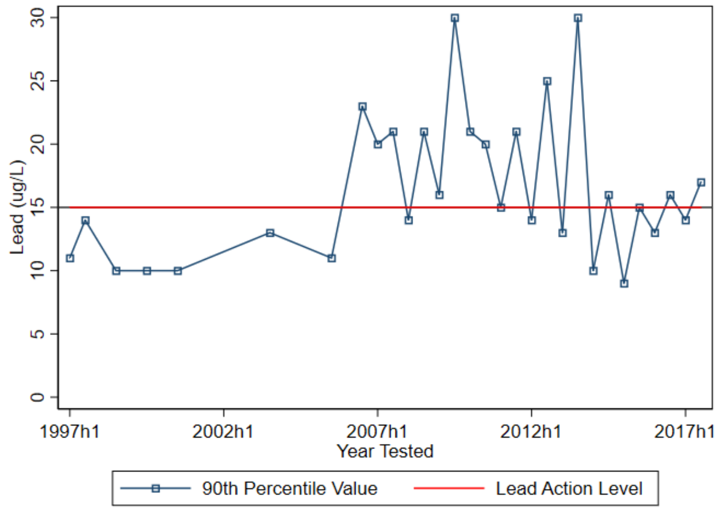
US EPA, "SAB Evaluation of the Effectiveness of Partial Lead Service Line Replacements," 2011.

Vivier, Patrick M, Marissa Hauptman, Sherry H Weitzen, Scott Bell, Daniela N Quilliam, and John R Logan, "The important health impact of where a child lives: neighborhood characteristics and the burden of lead poisoning," *Maternal and child health journal*, 2011, *15* (8), 1195–1202.

Zahran, Sammy, Terrence Iverson, Shawn P McElmurry, and Stephan Weiler, "The effect of leaded aviation gasoline on blood lead in children," *Journal of the Association of Environmental and Resource Economists*, 2017, *4* (2), 575–610.

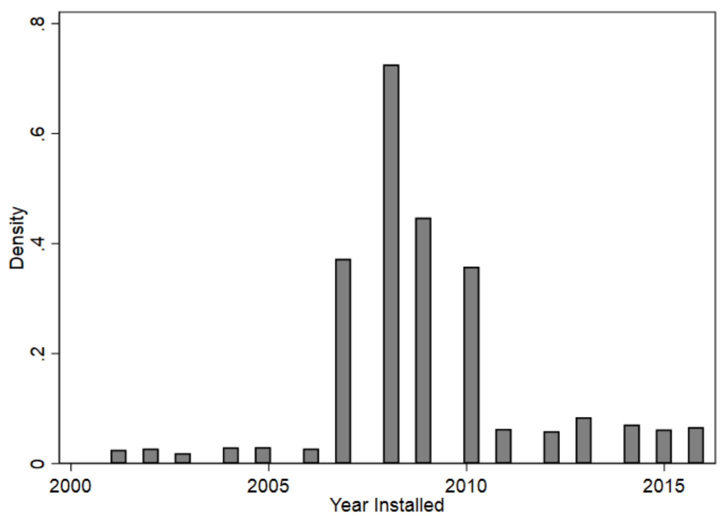
6 Figures

Figure 1: Providence Water LCR Compliance History



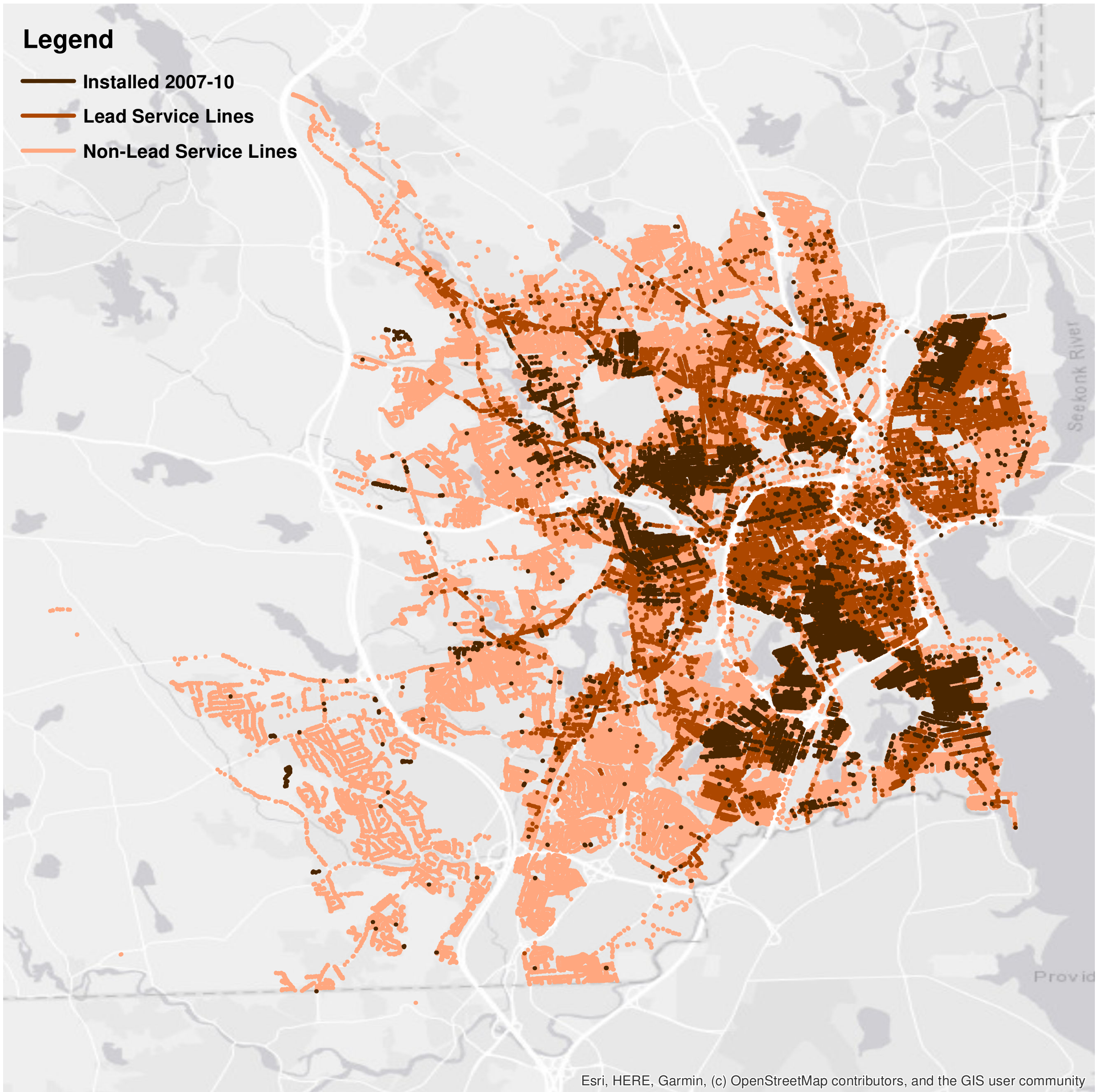
Notes: EPA's Lead and Copper Rule establishes a lead action level of 15 $\mu g/L$, shown by the red line. As approved by the Rhode Island Department of Health (RIDOH), the sampling frequency has changed over time.

Figure 2: Year service lines installed among old homes



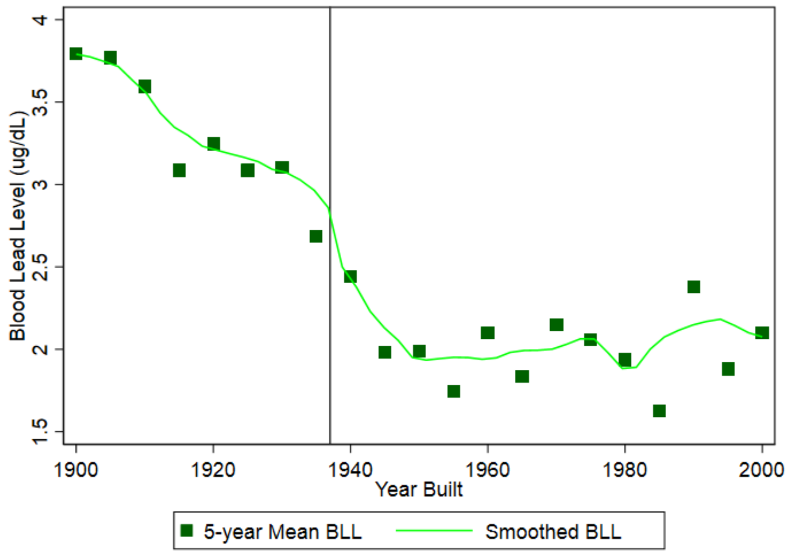
Notes: Figure shows the histogram of service lines installed after 2000 by year of installation among homes built before 1937. The dramatic rise in installations between 2007 and 2010 corresponds to the lead service line replacement program. Lead service lines were commonly installed prior to 1937, making homes built before 1937 more likely to have lead service lines. While data on year homes were built is not available for the whole sample, the figure looks remarkably similar in the full sample, without restricting to homes built prior to 1937, which is shown in Appendix Figure A4.

Figure 3: Lead and Non-lead Service Lines

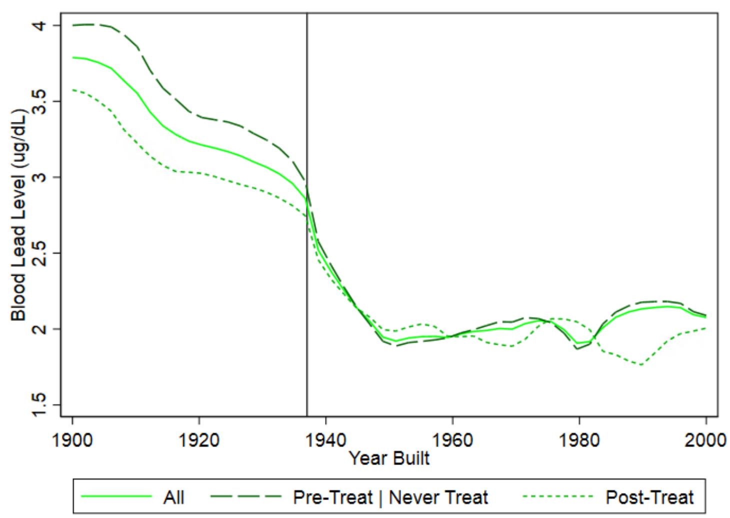


Notes: Figure shows the location of Providence Water public service lines in Rhode Island. Non-lead service lines are shown in light peach, lead service lines that had not yet been replaced by 2017 are shown in medium brown, and service lines that were installed during the Lead Service Line Replacement program (between 2007 and 2010) are shown in dark brown.

Figure 4: Child BLL by Year Home Built



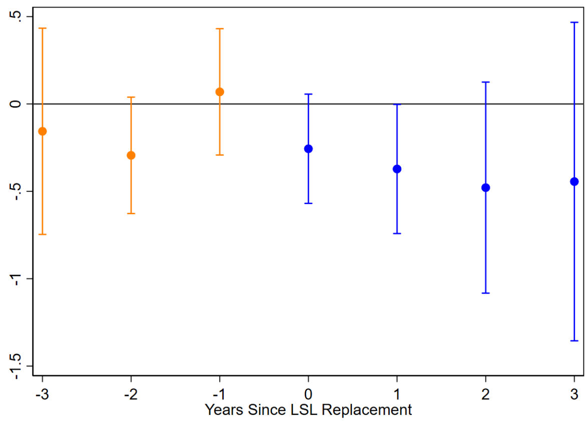
(a) BLL By Year Built



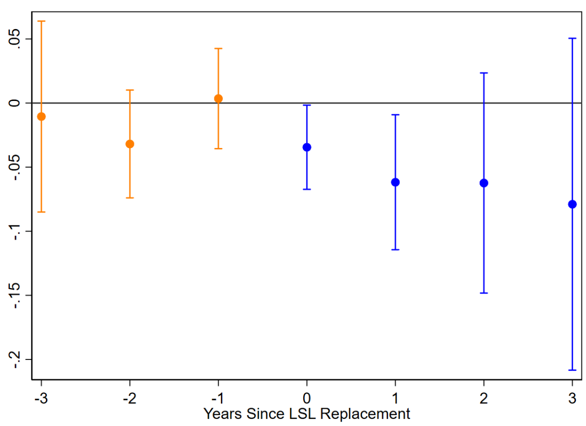
(b) BLL By Year Built, Pre/Post

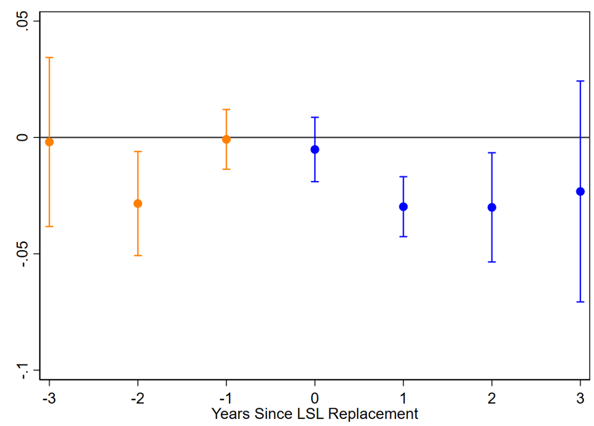
Notes: Panel a shows the mean blood lead level by year of home construction from 1900 to 2000. Squares represent the mean BLL for each 5-year bin. Binned endpoints include homes built 1900 or earlier and 2000 or later. The line shows the smoothed relationship between blood lead levels and age of the house using 'lpoly'. The vertical line denotes 1937, the year in which lead service lines were no longer installed. Panel b shows the smoothed relationship between blood lead levels and the age of the house using 'lpoly'. The solid line represents all observations, the long dashed line represents blood lead tests of children before line replacement or who were never treated, and the short dashed line represents blood lead tests of children after line replacement.

Figure 5: Effect of LSLR on Child BLL



(a) BLL Test Result



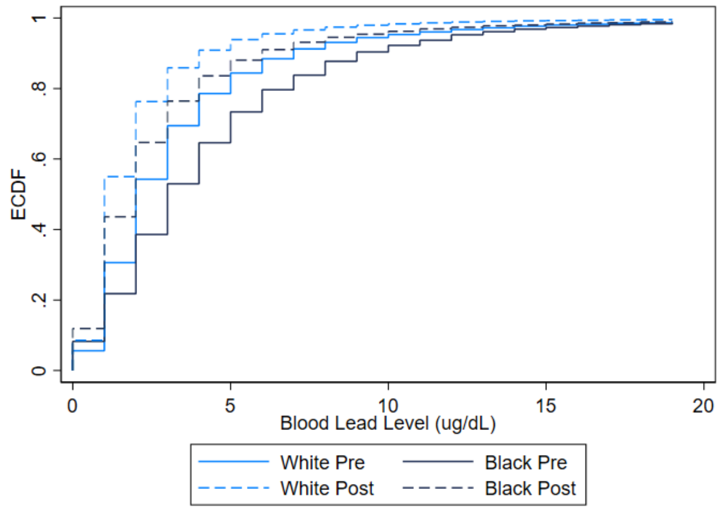


(b) BLL Over 5

(c) BLL Over 10

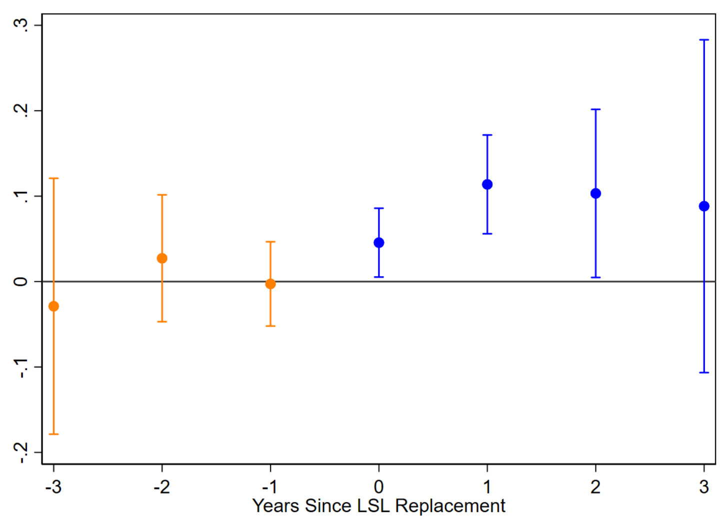
Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is never treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (c) show results for the BLL test result, an indicator for BLL over 5 $\mu g/dL$ and an indicator for BLL over 10 $\mu g/dL$, respectively.

Figure 6: Black-White Gap in Blood Lead Levels



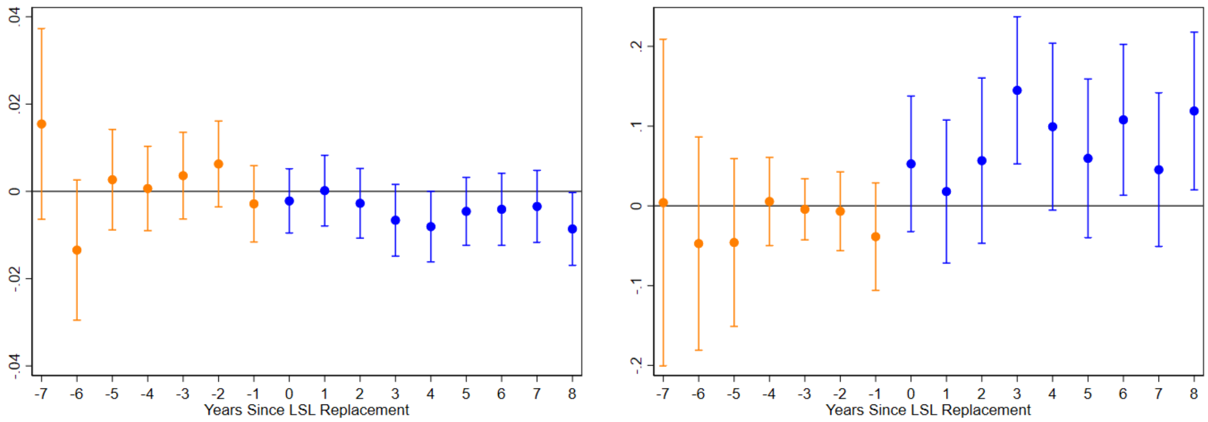
Notes: Figure shows the empirical cumulative distribution function for blood lead test results by race before and after the LSLR program. Pre is denoted with solid lines and is defined as tests before 2007, and Post is denoted with dashed lines and is defined as after 2010. Light blue lines show BLLs for white children and dark blue lines show the BLLs for black children. The distribution is truncated at 20 ug/dL.

Figure 7: Effect of LSLR on Moving



Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is never treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. The outcome is an indicator equal to one if the child ever moved from the original location.

Figure 8: Effect of LSLR on Home Sales



(a) Any Sale

(b) Log(Price)

Notes: Event study aggregation estimates reported for LSL replacements made during the LSLR Program. The x-axis reports years since the service line was replaced. The outcome in panel a is equal to one if the home sold in each year. The outcome in panel b is the log of the sale price. Post-treatment estimates in blue are relative to period -1. Pre-treatment estimates in orange are relative to the previous period. Estimates use the "never treated" control group and include year and parcel fixed effects. Anticipation is set to zero periods. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals are clustered at the parcel level.

7 Tables

Table 1: BLL Summary Statistics

	Obs	Mean	Std. Dev.	Min	Max
BLL in $\mu g/dL$	14,583	2.886	2.943	0	49
BLL Over 5 $\mu g/dL$	14,583	0.131	0.338	0	1
BLL Over 10 $\mu g/dL$	14,583	0.026	0.160	0	1
Years of Age	14,583	2.273	1.460	0	5
BLL | Male	7,629	2.932	2.957	0	40.5
BLL | Female	6,954	2.837	2.926	0	49
BLL | White	3,940	2.974	2.891	0	35.25
BLL | Black	1,738	3.187	3.165	0	49
BLL | Other Race	6,986	2.751	2.924	0	40.5
BLL | Hispanic	4,453	2.685	2.640	0	40.5
BLL | Non-Hispanic	9,764	3.020	3.080	0	49

Notes: The sample is restricted to non-movers. Observations are at the child-age level. For children with multiple tests per year of age, the mean is reported.

Table 2: Characteristics of Population Exposed to Lead Service Lines and Replacements

	(1)	(2)	(3)	(4)
	No Lead	Lead		Total
		None Replaced	Any Replaced	
Lead Lines (%)	0	0.210	0.411	0.367
Median year built	1964.5	1957.3	1949.0	1950.7
Median built before 1939	0	0.278	0.504	0.452
Average household size	2.315	2.043	2.647	2.582
Houses owned (%)	0.683	0.427	0.495	0.504
Houses mortgaged (%)	0.694	0.733	0.736	0.732
Houses rented (%)	0.317	0.573	0.505	0.496
Vacant (%)	0.0606	0.0921	0.121	0.114
Single Headed HHs (%)	0.243	0.333	0.412	0.394
Non-family HHs (%)	0.360	0.544	0.397	0.404
Single person HHs (%)	0.859	0.829	0.766	0.777
HS Educ or less (%)	0.346	0.371	0.468	0.452
Bachelors Degree (%)	0.215	0.200	0.164	0.170
Masters or Doctorate Degree	0.129	0.189	0.125	0.129
Unemployed (%)	0.0763	0.126	0.130	0.125
Public Assistance(%)	0.00955	0.0352	0.0400	0.0374
Median HH income	62419.6	52563.6	49933.5	51033.7
White (%)	0.902	0.737	0.634	0.661
Black (%)	0.0381	0.0876	0.123	0.114
Other (%)	0.0813	0.192	0.275	0.255
Hispanic (%)	0.0354	0.156	0.278	0.251
Under age 18 (%)	0.179	0.136	0.218	0.210

Notes: Means are reported from the 2013 5-year American Community Survey and observations are at the block group level. Column (1) includes block groups without any lead service lines. Column (2) includes block groups with some lead service lines, but none were replaced during the LSLR Program. Column (3) includes block groups with some lead service lines and some replacements during the LSLR Program. Column (4) shows the full sample of block groups.

Table 3: Effect of Lead Service Line Replacements on Child Blood Lead Levels

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.	*Outcome: BLL*					
After Install	-0.364**	-0.388*	-0.431***	-0.343**	-0.371*	-0.416**
	(0.152)	(0.199)	(0.164)	(0.150)	(0.197)	(0.177)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$					
After Install	-0.054***	-0.059***	-0.053***	-0.051***	-0.057**	-0.050***
	(0.019)	(0.024)	(0.019)	(0.019)	(0.026)	(0.019)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$					
After Install	-0.021***	-0.022**	-0.014*	-0.019***	-0.020**	-0.013*
	(0.007)	(0.009)	(0.007)	(0.007)	(0.009)	(0.007)
Observations	6,375	6,375	6,375	6,375	6,375	6,375
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Year Control	yes	yes	yes	yes	yes	yes
Non-movers	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and condition on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level.

Table 4: Heterogeneity of BLL Results

	(1) Baseline	(2) Male	(3) Female	(4) White	(5) Black	(6) Other	(7) Hisp	(8) Non-Hisp
Panel A.	*Outcome: BLL*							
After Install	-0.364**	-0.364	-0.378*	-0.912***	-0.759	-0.004	-0.285	-0.354
	(0.152)	(0.242)	(0.214)	(0.316)	(0.523)	(0.182)	(0.231)	(0.267)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$							
After Install	-0.054***	-0.051*	-0.054**	-0.041	-0.077	-0.038	-0.052*	-0.041
	(0.019)	(0.030)	(0.026)	(0.044)	(0.052)	(0.025)	(0.029)	(0.031)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$							
After Install	-0.021***	-0.019*	-0.021**	-0.030**	-0.047*	-0.021**	-0.016*	-0.022**
	(0.007)	(0.012)	(0.010)	(0.014)	(0.027)	(0.009)	(0.009)	(0.010)
Observations	6,375	3,336	3,039	1,785	791	2,901	1,742	4,463
Aggregation	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple
Control Group	Never	Never	Never	Never	Never	Never	Never	Never
Year Control	yes	yes	yes	yes	yes	yes	yes	yes

Notes: Notes: Results show the overall summary aggregations of the average treatment effects based on simple aggregation using the never treated control group. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Column 1 replicates the baseline results, and columns 2 to 8 show sub-samples by gender, race, and ethnicity.

Table 5: Robustness of BLL Results to Alternate Specifications

	(1) Baseline	(2) Max	(3) Min	(4) No Outliers	(5) With Capillary	(6) 2007-10	(7) Drop 1937+	(8) Fix After	(9) Year Built Control
Panel A.	*Outcome: BLL*								
After Install	-0.364**	-0.477***	-0.256*	-0.295**	-0.281**	-0.453**	-0.329**	-0.348**	-0.380**
	(0.152)	(0.164)	(0.147)	(0.147)	(0.142)	(0.201)	(0.162)	(0.160)	(0.155)
Panel B.	*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$								
After Install	-0.054***	-0.061***	-0.047**	-0.053***	-0.047***	-0.054**	-0.050**	-0.058***	-0.056***
	(0.019)	(0.020)	(0.019)	(0.019)	(0.019)	(0.026)	(0.020)	(0.022)	(0.019)
Panel C.	*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$								
After Install	-0.021***	-0.027***	-0.017***	-0.019***	-0.017**	-0.023***	-0.020***	-0.014*	-0.022***
	(0.007)	(0.008)	(0.006)	(0.006)	(0.008)	(0.007)	(0.007)	(0.009)	(0.007)
Observations	6,375	6,375	6,375	6,371	6,955	15,859	5,921	6,357	6,375
Aggregation	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple	Simple
Control Group	Never	Never	Never	Never	Never	Never	Never	Never	Never
Year Control	yes	yes	yes	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects based on simple aggregation using the never treated control group. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Columns 2-3 use the maximum and minimum BLL values for children with multiple tests per year, respectively. Column 4 excludes the top 1% of BLL tests. Column 5 includes capillary tests. Column 6 uses only treatment cohorts with lines installed during the LSLR Program (2007-2010). Note that the sample is larger because other households with installations outside of the LSLR Program are allowed to act as a counterfactual. Column 7 excludes homes built after 1937 that are less likely to have had lead service lines. Column 8 excludes BLL tests taken in the same year as treatment but before the line was replaced. Column 9 also conditions on the year a child's home was built.

Table 6: Effect of Lead Service Line Replacements on Moving Behavior

	(1)	(2)	(3)	(4)	(5)	(6)
After Install	0.082***	0.088*	0.079***	0.082***	0.088**	0.079***
	(0.033)	(0.045)	(0.024)	(0.032)	(0.045)	(0.025)
Observations	12,613	12,613	12,613	12,613	12,613	12,613
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Year Control	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Anticipation is set to zero. Estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Treatment timing is based on the child's first observed location. The outcome is an indicator equal to one if a child ever moved from their initial location. Observations are set to missing in the first year a child is observed.

Table 7: Effects on Home Sales

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.	*Outcome:* $\mathbb{1}$[*Any Home Sale*]					
After Install	-0.0045	-0.0045	-0.0043	-0.0044	-0.0044	-0.0043
	(0.0032)	(0.0030)	(0.0031)	(0.0032)	(0.0030)	(0.0031)
Observations	13,767	13,767	13,767	13,767	13,767	13,767
Panel B.	*Outcome: Log(Sale Price)*					
After Install	0.067**	0.078**	0.075**	0.070**	0.081**	0.077**
	(0.031)	(0.034)	(0.036)	(0.032)	(0.035)	(0.036)
Observations	7,258	7,258	7,258	7,258	7,258	7,258
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Controls	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta_{simple}^{overall}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta_{es}^{overall}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Sample includes LSL replacements made during the LSLR Program at old homes. The outcome is any sale in panel a and the log of home price in panel b. Estimates have zero anticipation and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals and clustered at the parcel level are reported in parentheses.

Table 8: Changes in Demographics

	Under Age 5	White	Black	Other Race	Hispanic	High Educ	Median Inc	Below Poverty	Renters
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Panel A.									
LSLRs × Post	-1.750	8.934*	-5.404	-5.360	3.397	-3.897	-8,892	8.335**	1.635
	(1.153)	(5.282)	(3.647)	(4.816)	(5.595)	(3.644)	(5,812)	(3.554)	(2.755)
Observations	132	132	117	117	121	132	132	132	132
R-squared	0.772	0.958	0.909	0.945	0.956	0.974	0.941	0.933	0.982
Panel B.									
High LSLRs × Post	-0.601	2.941	-2.829	-0.986	1.327	-2.016	-491.4	0.586	-0.812
	(0.549)	(2.523)	(1.734)	(2.327)	(2.651)	(1.717)	(2,795)	(1.750)	(1.300)
Observations	132	132	117	117	121	132	132	132	132
R-squared	0.768	0.957	0.910	0.944	0.956	0.974	0.939	0.927	0.982
Tract FE	yes	yes	yes	yes	yes	yes	yes	yes	yes
Mean	5.995	68.86	12.14	23.20	23.62	34.33	43359	20.15	50.79

Notes: Data at the tract-year level comes from the 2000 Census and 2015 ACS. Outcomes are measured as percentages, except for median household income. High education is defined as those with an associates, bachelors or graduate degree. Post is equal to one in 2015, after the lead service line replacement program ends, and zero in 2000. Panel A uses the number of lines installed during the lead service line replacement program as a continuous measure of treatment, while Panel B uses a binary measure equal to one if the number of lines installed during the program is greater than the 75th percentile. Regressions are weighted by the total number of service lines eligible for replacement, which includes lines that were installed during the lead service line replacement program (2007-2010) or were still made of lead.

Table 9: Changes in Rental Prices

		Rent Amount (%)				
	Median Rent	<$200	$200-499	$500-999	$1000-1499	≥$1500
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.						
LSLRs × Post	29.89	1.786	-12.03**	23.18**	-8.967	-4.038
	(68.75)	(3.995)	(5.724)	(11.26)	(5.985)	(3.398)
Observations	131	132	132	132	132	132
R-squared	0.939	0.761	0.844	0.656	0.825	0.737
Panel B.						
High LSLRs × Post	10.54	1.461	-7.996***	13.10**	-4.450	-2.143
	(32.47)	(1.880)	(2.604)	(5.233)	(2.820)	(1.599)
Observations	131	132	132	132	132	132
R-squared	0.939	0.763	0.855	0.667	0.825	0.739
Tract FE	yes	yes	yes	yes	yes	yes
Mean	761	9.762	20.30	53.51	12.88	3.549

Notes: Data at the tract-year level comes from the 2000 Census and 2015 ACS. Post is equal to one in 2015, after the lead service line replacement program ends, and zero in 2000. Panel A uses the number of lines installed during the lead service line replacement program as a continuous measure of treatment, while Panel B uses a binary measure equal to one if the number of lines installed during the program is greater than the 75th percentile. Regressions are weighted by the total number of service lines eligible for replacement, which includes lines that were installed during the lead service line replacement program (2007-2010) or were still made of lead.

8 Online Appendix

Contents

8.1 Additional Background

8.1.1 Public and Private Service Lines

Lead service lines were regularly installed in the US for water distribution on a major scale beginning in the mid 1800s, especially in larger cities. While lead pipes were more expensive than iron, they were more durable and malleable. When originally installed, they were expected to last about 35 years, relative to 16 years for iron, and could be bent around existing structures. While early concern about the potential toxicity of lead from water passing through lead pipes is documented into the early 1900s, it was not until the 1920s that many cities started revising local and state plumbing codes to prohibit or limit the use of lead in pipes for water distribution (Rabin, 2008). Although most cities in the US were moving away from installing lead pipes by the 1920s, it was not until 1986 that Congress amended the Safe Drinking Water Act to prohibit the use of pipes, solder or flux that were not "lead free" in public water systems.[25]

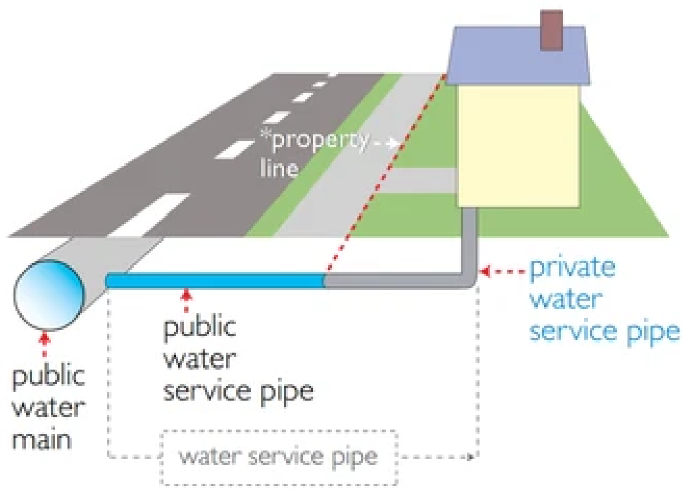
Figure A1 shows a simple illustration of the public water delivery system. Water mains typically run under the street, whereas service lines deliver water from the water main to the customer's home and consist of public and private-owned segments. The "public" service line segment runs under the street from the property line to the water main and is owned by the water system. The "private" service line segment begins at the property line and is the responsibility of the homeowner. As shown in Figure 3, this paper uses data on the

[25] At the time, "lead free" pipes were still allowed to contain up to 8 percent lead. In 2011, the definition of "lead free" was revised by lowering the maximum lead content of the wetted surfaces of plumbing products to a weighted average of 0.25 percent.

location of public service lines. Unfortunately, there is no systematic collection of data on the privately owned portion of service lines.

Providence Water began converting their service line information into GIS data in the mid-2000s from both paper records and a digital work order system. The service line material for the public side of the service line was taken from the old records and transferred to the geocoded service line data. This information is updated as part of the work order process when services are added, removed, or replaced (Providence Water, 2021).

Figure A1: Service Lines: Public and Private Portions



Notes: Figure shows an example of a service line that connects homes to water mains. The privately owned portion connects from the home to the property line and the publicly owned portion connects from the property line to the water main.

8.1.2 Estimating Relative Length of Private and Public Service Lines

Under current guidelines, most new lead service lines replacements will replace the full lead service line, including both public and private portions. Removing a longer length of lead pipe should have a larger effect on child blood lead levels, as lead levels are a function of the amount of lead that is in contact with water.[26] In an effort to extrapolate the findings from this study focused on partial public-side replacements to the effects of full replacements, it is useful to estimate the relative length of public and private service line segments.

To do so, I use geocoded public service line data from the Providence Water Supply Board and building footprint data from the University of Rhode Island Environmental Data Center and the Rhode Island Geographic Information System (RIGIS). The building footprint data provide information on the location of buildings within each parcel of property. As water must be delivered to each building, rather than the perimeter of the property, this should provide a more accurate measure of private service line length. The building footprint shapefile contains representative, computer generated building footprints for Rhode Island and was

[26] It is important to note that this relationship may not be linear, as many other factors influence lead levels in water, including acidity, temperature, presence of minerals and protective scales on pipes, and the duration that water stays in contact with pipes.

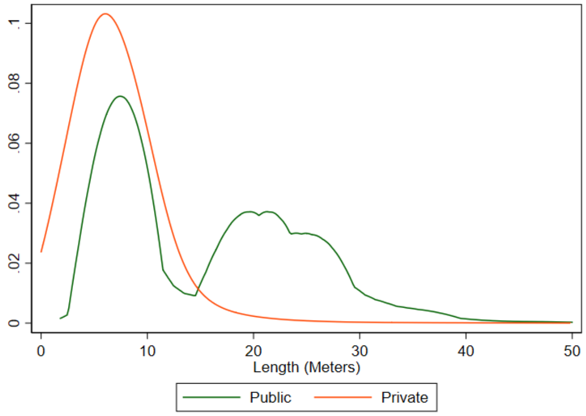
originally developed by Microsoft. The data were released by Microsoft as open source data in June 2018. The data are available at https://www.rigis.org/datasets/edc::building-footprints/about.

The length of private side service lines is estimated by calculating the distance between public side service lines and the nearest building footprint within 50 meters. I use either the distance to the edge or distance to the centroid of the nearest building footprint polygon. Distance to the edge is a more conservative measure. Both measures are only proxies for the length of private service lines and neither measure will accurately reflect the amount of interior plumbing, which may also contain lead.

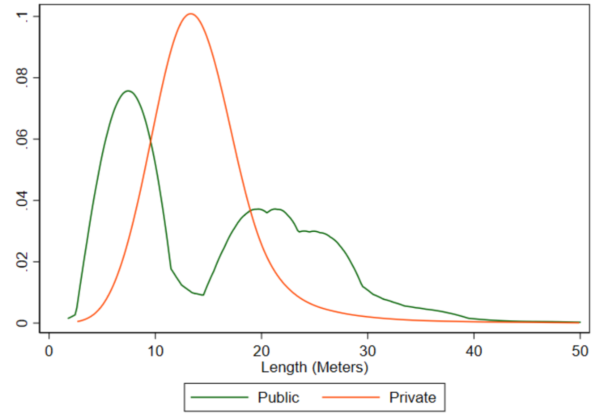
In Figure A2, I plot the length and ratio of public service lines and the estimated length of private service lines. In panels (a) and (c), I plot the length of public side service lines and a proxy for length of private side service lines based on either distance to the edge or centroid of building footprints. I exclude public service lines in the upper tail of the distribution, above 50 meters long. The distribution of public side lines is bimodal. When water mains do not run down the middle of the road, homes on one side of the street will be closer, while homes on the other side of the street will be further away. This is consistent with the bimodal distribution. In panel (a), the distance between the end of the public segment and the building perimeter is about 7 meters. In panel (c), the distance between the end of the public segment and the building centroid is about 14 meters.

In panels (b) and (d), I show the distribution of the ratio between the length of public and private segments. On average, privately owned service lines are about 0.61 times the length of publicly owned service lines when using distance to the building perimeter as a proxy, and 1.27 times the length when using distance to the building centroid as a proxy.

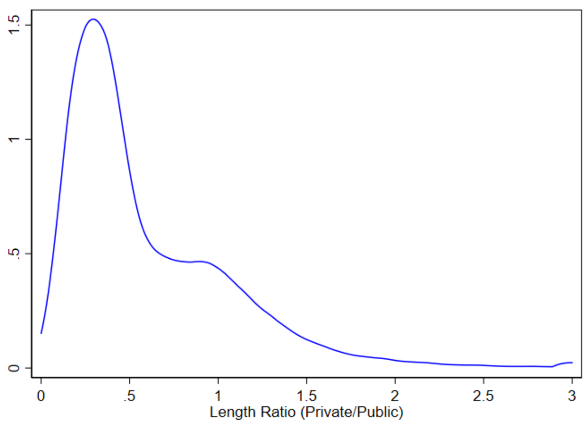
Figure A2: Estimated Length of Private Side Service Lines



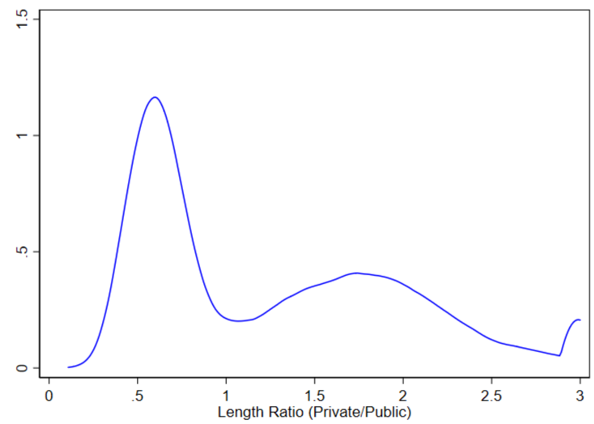
(a) Length using Building Perimeter



(c) Length using Building Centroid



(b) Ratio using Building Perimeter



(d) Ratio using Building Centroid

Notes: Panels (a) and (c) plot the length of public side service lines and a proxy for length of private side service lines based on either distance to the edge or centroid of building footprints, respectively. Kdensity distributions are shown with a bandwidth of 2. Panels (b) and (d) show the distribution of the ratio between the length of public and private segments based on either the distance to the edge or centroid of building footprints, respectively. Kdensity distributions are shown with a bandwidth of 0.05. On the x-axis, 3 includes all service lines with a ratio of 3 or above. I restrict to private and public segments under 50 meters.

8.1.3 Blood Lead Screening in Rhode Island

In Rhode Island, healthcare providers are required by law to conduct at least two blood lead screening tests on all children by the age of three. Children should then be screened annually through age six. Children between age 3 and 6 with all previous blood lead tests under 5 $\mu g/dL$ can be screened using risk assessment questions shown in Table A1. For example, children living in newer homes with fewer sources of potential lead exposure may not need to take a blood lead test. Results of blood lead tests must be reported to the RIDOH within 10 days of testing. Lead screening tests for children under age six are free. Rhode Island insurance companies and Medicaid fully cover the costs of lead tests, and children without insurance can obtain a free test at St. Joseph Hospital Health Center.

Table A1: Rhode Island Blood Lead Screening

Panel A. Universal Blood Lead Screening
Screen all children from nine months to six years of age (9 to 72 months) for lead poisoning at least once annually.
Children age 9-36 months:
–Screen once between 9-15 months of age, and
–Screen again 12 months later, between 21 and 36 months of age.
Children age 36-72 months:
–If a child was screened at least twice prior to 36 months of age, and any test was greater than or equal to 5 $\mu g/dL$, continue to order a blood lead test at least once a year until the child is six years old.
–If a child was screened at least twice prior to 36 months of age, and ALL tests were lower than 5 $\mu g/dL$, the Risk Assessment Questions below can be used instead of a blood lead test to screen for lead.
–If a child was NOT screened at least twice prior to 36 months of age, order a blood lead test. If the blood lead level is higher than or equal to 5 $\mu g/dL$, follow the recommended actions and screen annually. If the blood lead level is lower than 5 $\mu g/dL$, the Risk Assessment Questions below can be used instead of a blood lead test, to screen for lead, in the future.
Panel B. Risk Assessment Questions
If the answer to ANY of these questions is YES, order a blood lead test. If the answer to ALL of these questions is NO, blood lead testing can be discontinued, but the Risk Assessment Questions should be asked annually until the child is six years old.
1. Does your child live in or regularly visit a house built before 1978 with peeling or chipping paint (daycare center, pre- school, home of babysitter, friend, or relative)?
2. Does your child live in or regularly visit a house built before 1978 that has been renovated or remodeled in the last six months?
3. Does your child have a brother, sister, housemate, or playmate who has or did have lead poisoning?
4. Does your child live near an active smelter, battery recycling plant, or other industry likely to release lead?
5. Does your child live with an adult whose job (i.e., construction, painting) or hobby (i.e. pottery, stained glass, furniture refinishing, automotive bodywork, or boat refinishing) involves exposure to lead?

Source: Rhode Island Department of Health, Childhood Lead Poisoning Prevention Program Referral Intervention Process (2019).

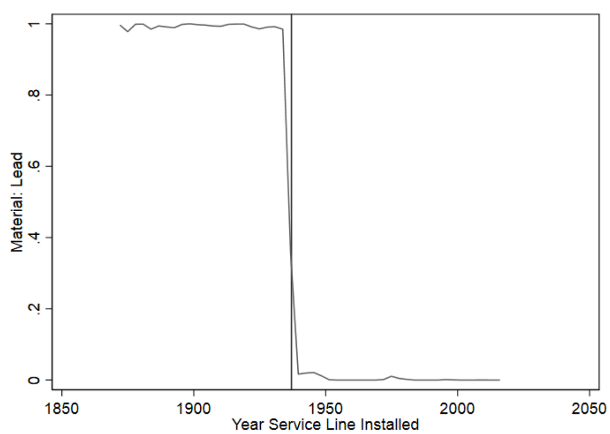
8.1.4 Replacement Program in Rhode Island

Exceeding the lead action level in 2006 triggered the EPA's requirement for Providence Water to begin a lead service line replacement program in 2007. Under the EPA's Lead and Copper Rule, water systems with 10 percent of samples exceeding the 15 ppb lead action level were required to replace 7 percent of public lead service lines per year until all were replaced or until the system returned to compliance with the lead action level. As Providence Water had 25,600 lead service lines in 2006, they were required to replace about 1,792 annually, costing about $8 million per year. Between 2007 and 2010, Providence Water replaced about 10,000 lead service lines as part of their LSL Replacement Program.

Older homes are more likely to have had lead service lines and to be affected by the LSL Replacement Program. Using year of service line installation, Figure A3 shows that lead service lines were frequently installed up until about 1937. After 1937, almost none of newly installed service lines were made of lead. This is consistent with historical records that show LSL installation was discontinued in 1937 when copper tubing was adopted (Providence Water, 2021). However, it is important to note that information on service line material may not have been well recorded at the time of installation, especially in the early 1900s. If recorded service line material was inferred from home age, this discontinuity may not be as sharp is it appears. Because of this uncertainty, I do not employ a regression discontinuity design.

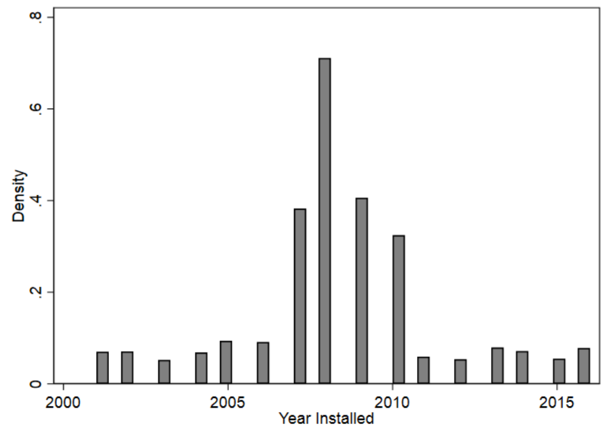
Nevertheless, homes built prior to 1937 are more likely to have had lead service lines and new installations at these homes are likely driven by the LSL Replacement Program. Using this information, Figure 2 shows the density of service lines installed among older homes by year of installation. The figure clearly shows the dramatic rise in service line replacements between 2007 and 2010 driven by the LSL Replacement Program, which is the variation leveraged in this study. While data on the year homes were built is not available for the whole sample, the figure looks remarkably similar in the full sample, without restricting to homes built prior to 1937, shown in Figure A4 below.

Figure A3: Service line material by year installed



Notes: Figure shows the proportion of newly installed service lines constructed from lead by year of service line installation based on service line installation data from Providence Water. The vertical line denotes year 1937, after which lead service lines were no longer regularly installed.

Figure A4: Year service lines installed, full sample



Notes: Figure shows the histogram of service lines installed after 2000 by year of installation for the full sample. The dramatic rise in installations between 2007 and 2010 corresponds to the lead service line replacement program.

Several updates have been made to the replacement program in Rhode Island since the time period of this study. Beginning in 2018, Providence Water implemented a policy to conduct only full LSLRs. At the same time, they began to offer a 3-year 0% interest loan program for homeowners to replace their private side lead service lines. This was funded through a $1 million loan from the Rhode Island Infrastructure Bank and through additional water rate increases to customers. More recently, the loan term was extended to 5 years. In addition, Providence Water currently offers free lead testing to all of their retail customers. Customers can request a lead testing kit, which is sent through the mail. Samples are returned through the mail and the results of the test are provided to the customers. Because temporary spikes in particulate lead levels can be common for up to several months after construction of both partial and full LSLR, Providence Water promotes free post-LSLR lead testing for customers and provides a counter-type filter and a 6-month supply of NSF 53 certified filters.[27] To the extent that these protective actions were performed in the early years of the LSLR program, before the CDC report generated concerns about partial LSLRs, they are likely to mitigate households' exposure to spikes in lead levels immediately after LSLR. As only a 6-month supply of filters is provided, these protective actions are unlikely to persist beyond the first 6 months after replacement.

8.1.5 Trends and Distribution of BLLs

In general, blood lead levels were trending down over this time period from an average of about 4.34 $\mu g/dL$ in 2005 to about 2.18 $\mu g/dL$ in 2016, as seen in Figure A5a. One goal of this paper is to test whether public-side LSL replacements helped contribute to this overall decline and to what extent. Figure A5b shows the trends in average blood lead levels by age of the home. These trends show some suggestive evidence that during the Lead Service Line Replacement Program, from 2007 to 2010, declines in BLLs were largest for children most

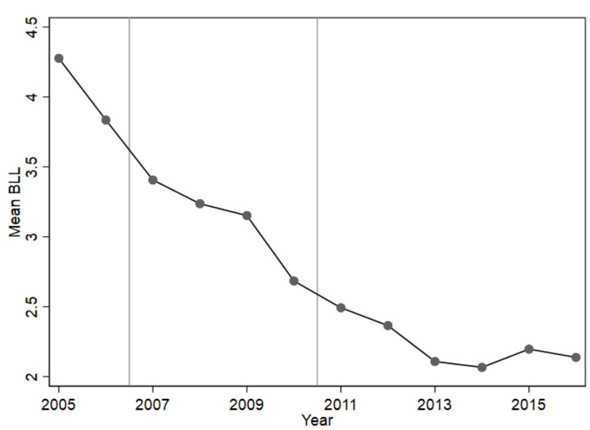
[27] Filters and instructions are distributed by the inspectors prior to the LSLR. The construction inspector collects the water samples, and sends them to an outside laboratory for analysis(Providence Water, 2021).

likely exposed to the program, those who lived in homes built before 1937.

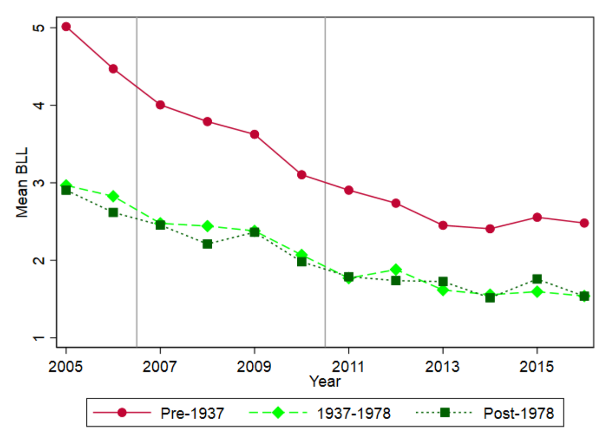
Although blood lead levels were relatively low during this time, especially compared to historical periods, the BLL distribution still showed a long right tail. Table 1 shows the average blood lead level for children in the sample is about 2.9 $\mu g/dL$, with Black children having a higher average at 3.2 $\mu g/dL$. These levels are much higher than the nation-wide average of 0.8 $\mu g/dL$ based on NHANES data from 2011-16 (Egan et al., 2021). Since 2012, the CDC has lowered the blood lead reference value to 3.5 $\mu g/dL$, which is based on the 97.5th percentile of the blood lead values among US children ages 1-5 years. Many children in RI have even higher BLLs. About 13 percent of children had elevated blood lead levels over 5 $\mu g/dL$, and 3 percent had blood lead levels over 10 $\mu g/dL$. Figure A6 shows the distribution of blood lead levels by the year a child's home was built. Children living in homes built before 1937, when LSL were commonly installed, had higher blood lead levels. The solid line shows the distribution of BLL was shifted to the right for these children. On the other hand, children in homes build between 1937 and 1978 or after 1978, when lead paint was banned, had lower blood lead levels. Interestingly, there was little difference in the distribution of blood lead levels between children in homes that may have lead paint and children in homes built after the lead paint ban, which is consistent with existing work showing that lead paint remediation efforts have been effective and may have helped close this gap.

Finally, I replicate Figure 4 separately for White and Black children. Figure A7 plots average blood lead levels by home age separately by race. Both Black and White children in homes built before 1937 have higher blood lead levels than children in newer homes. For both groups, there appears to be a drop around the vertical solid line at 1937, when lead service lines were no longer installed. For Black children only, there also appears to be a decline in blood lead levels around the dashed vertical line at 1978, when lead paint was banned. The racial gap in blood lead concentrations generally persists across all home ages.

Figure A5: Trend in Child BLLs over Time



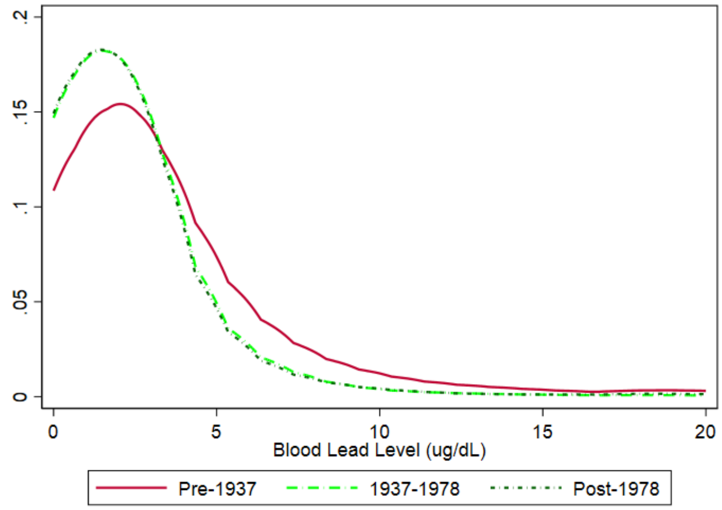
(a) Mean BLL



(b) Mean BLL by Home Age

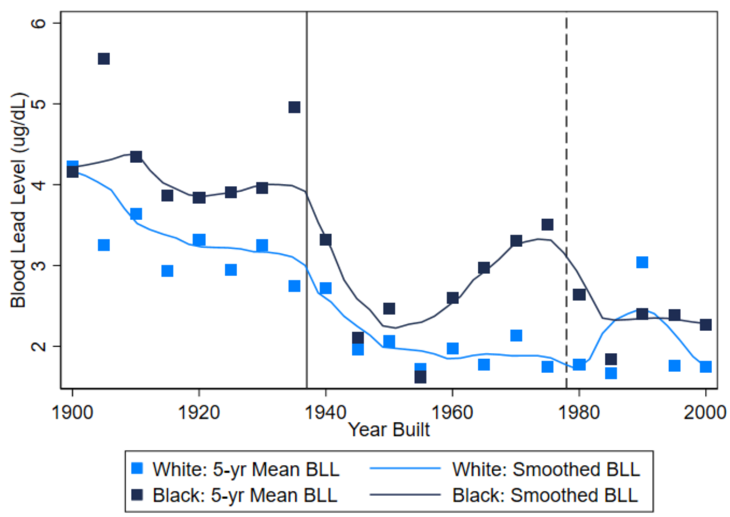
Notes: Vertical lines denote the start and end of the Lead Service Line Replacement Program in Providence, RI. Panel a shows the average blood lead levels for all children tested from 2005 to 2016 in Rhode Island. Panel b shows the average blood lead levels by age of home construction: built before 1937, built from 1937 to 1978, and built after 1978.

Figure A6: Distribution of Child BLLs by Home Age



Notes: The figure shows the distribution of blood lead levels for children in homes built before 1937 (solid line), between 1937 and 1978 (dashed line), and after 1978 (dotted line). Lead service lines were primarily installed before 1937 and lead paint was banned for residential use in 1978. The figure focuses on BLLs below 20 $/mug/dL$, but a small fraction are even higher, as shown in Table 1.

Figure A7: Child BLL by Year Home Built: By Race



Notes: Figure shows the mean blood lead level for White and Black children by year of home construction from 1900 to 2000. Squares represent the mean BLL for each 5-year bin. Binned endpoints include homes built 1900 or earlier and 2000 or later. The line shows the smoothed relationship between blood lead levels and age of the house using 'lpoly'. The solid vertical line denotes 1937, the year in which lead service lines were no longer installed. The dashed vertical line denotes 1978, the year in which lead paint was banned.

8.2 Methodology Detail

8.2.1 ATT Aggregation

Group-time average treatment effects are aggregated by simple aggregation, event-time aggregation, and group aggregation. First, simple aggregation summarizes an overall effect:

$$\theta_{simple}^{overall} = \frac{1}{\kappa} \sum_{g \in G} \sum_{t=1}^{5} \mathbb{1}(t \geq g) ATT(g,t) P(G = g | G \leq T) \tag{4}$$

where $\kappa = \sum_{g \in G} \sum_{t=1}^{5} \mathbb{1}(t \geq g) P(G = g | G \leq T)$, which ensures that the weights on $ATT(g,t)$ in the second term sum to one. This method of aggregating average treatment effects eliminates the negative weighting issue that plagues the TWFE estimate of β^{TWFE} from equation 1 in the presence of dynamic treatment effects.

Next, I use the event-study style aggregation to look at trends prior to treatment and the evolution of the effects after treatment. Null estimates in pre-treatment periods give support for the assumption that parallel trends would have continued in the absence of treatment.[28] Let e denote event-time (i.e. $e = t - g$ which is the time elapsed since treatment occurred at time g). Treatment effect heterogeneity by event-time can be highlighted with the following aggregation.

$$\theta_{es}(e) = \sum_{g \in G} \mathbb{1}(g + e \leq T) P(G = g | G + e \leq T) ATT(g, g + e) \tag{5}$$

As an alternative to the simple aggregation of treatment effects, θ_{simple}, I also report an overall treatment effect parameter that averages $\theta_{es}(e)$ over all event times:

$$\theta_{es}^{overall} = \frac{1}{T-1} \sum_{e=0}^{T-2} \theta_{es}(e) \tag{6}$$

Finally, I report the overall group aggregation, which may be preferable as an overall treatment effect aggregation relative to the simple aggregation method, because $\theta_{simple}^{overall}$ systematically places more weight on groups that experience treatment longer. Following Callaway and Sant'Anna (2020), $\theta_{group}(\tilde{g})$ is the average effect of a lead service line replacements among units in group $\tilde{g}$, across all their post-treatment periods. Then, $\theta_{group}^{overall}$ averages these effects together across groups to summarize the overall effect.

$$\theta_{group}(\tilde{g}) = \frac{1}{T - \tilde{g} + 1} \sum_{t=\tilde{g}}^{T} ATT(\tilde{g}, t) \tag{7}$$

$$\theta_{group}^{overall} = \sum_{g \in G} \theta_{group}(g) P(G = g | G + e \leq T) \tag{8}$$

[28] Note that when using the never treated comparison group (invoking Assumption 4 of Callaway and Sant'Anna (2020)), the assumption does not restrict pre-treatment trends across groups. Whereas using the not-yet-treated comparison group (invoking Assumption 5 of Callaway and Sant'Anna (2020)), pre-treatment trends are restricted. See Marcus and Sant'Anna (2021) for further discussion.

8.2.2 Exogeneity of LSL Replacement Timing

As the decision regarding time and location of the public lead service line replacements was made by the utility owner, rather than the homeowner, it is likely to be exogenous to other household-level changes. Although we cannot observe household-level behaviors or characteristics at the address level, we do observe property characteristics at the address level. To support the assumption that replacement timing is uncorrelated with other important drivers of child blood lead levels, Table A2 regresses year of treatment on a variety of property characteristics.

Columns 1 and 2 show that treatment timing not systematically related to a variety of property characteristics, including total bedrooms, bathrooms, assessment value, living area, and building quality, among others. This supports our assumption that treatment timing is unrelated to household-level changes, as it does not appear that certain homes were targeted earlier. The only significant predictor in column 1 is home age. However, this becomes insignificant in Column 2, which includes broader census block controls for the density of lead service lines and average home age for each block. As expected, both neighborhood characteristics are predictive of replacement timing. The utility likely targeted neighborhoods where replacements would be efficient, such as neighborhoods with many lead service lines in need of replacement. As these are broader neighborhood characteristics and the choices were made by the utility, it is unlikely that they are related to household-specific changes driving blood lead levels.

Table A2: Replacement Timing and House Characteristics

	(1)	(2)
Total bedrooms	0.0219	0.0126
	(0.0139)	(0.0136)
Total full baths	0.0458	0.0169
	(0.0346)	(0.0338)
Total half baths	-0.0154	-0.0110
	(0.0327)	(0.0318)
ln(Assessment)	0.0790	0.0161
	(0.0493)	(0.0481)
Living area	-4.61e-05	-3.60e-05
	(3.18e-05)	(3.09e-05)
Total land area	-0.0553	-0.199
	(0.370)	(0.366)
Total rooms	-0.00115	0.0113
	(0.00996)	(0.00972)
Total kitchens	0.0508	0.0335
	(0.0369)	(0.0359)
Grade	-0.0127	-0.0139
	(0.0191)	(0.0188)
Year built	-0.00870***	0.00108
	(0.000841)	(0.00104)
% Lead in Census Block		-0.770***
		(0.0662)
Mean Year built in Census Block		-0.0235***
		(0.00161)
Observations	6,043	6,038
R-squared	0.033	0.088

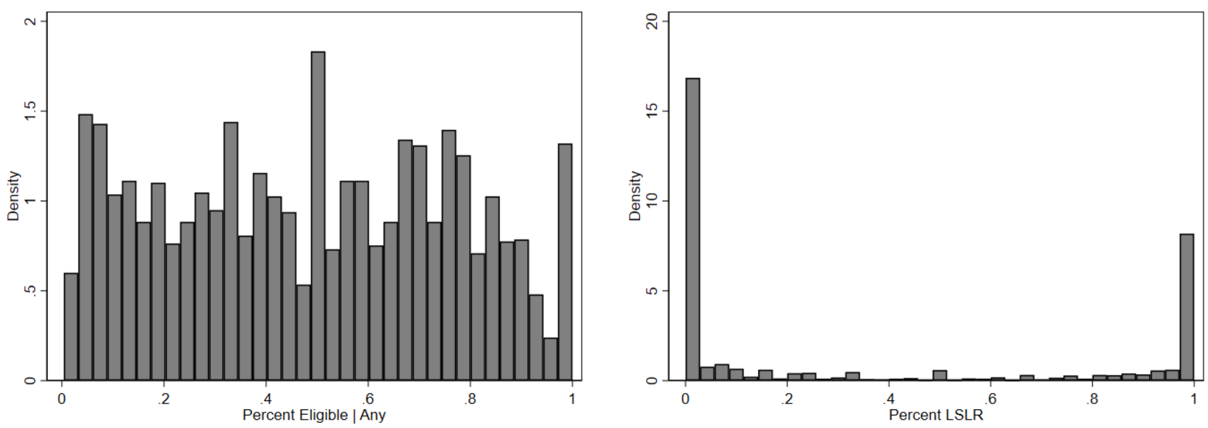
Notes: Sample includes tax assessor sales data for properties that received a replacement during the LSLR Program. The outcome is the year of replacement.

8.3 Additional Results

8.3.1 Characteristics of Exposed Neighborhoods

Figure 3 indicated that exposure to lead service lines and exposure to the replacement program is spatially concentrated. The distribution of the percent of lead service lines within census blocks covers a wide range, as shown in panel a of Figure A8. While many neighborhoods have very low levels of lead service lines, some blocks have over 75 percent of total service lines that were likely made of lead. However, panel b shows that, conditional on having some lead service lines, the percent replaced during the LSLR Program is most likely to be 0 or 100 percent. This suggests that the replacements were concentrated in certain neighborhoods, which is visually consistent with Figure 3. Even when looking at bigger geographic areas, such as census block groups shown in Figure A9, the pattern is very consistent.

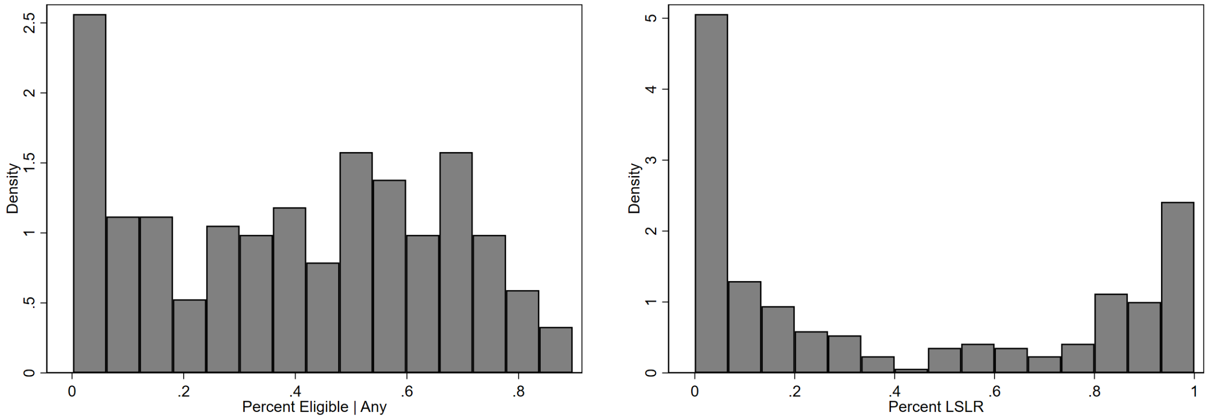
Figure A8: Distribution of Treatment at Block Level



(a) Percent Lines Eligible (Lead) if Any (b) Percent of Eligible Lines Replaced

Notes: Observations are at the block level. Panel a shows the distribution of the percent of total service lines that were "eligible" for replacement, conditional on having any eligible lines. Eligible lines are defined as service lines that were still lead in 2017 or lines installed during the LSLR Program from 2007 to 2010. Panel b shows the distribution of the percent of total "eligible" lines that were replaced during the LSLR Program.

Figure A9: Distribution of Treatment at Block Group Level



(a) Percent Lines Eligible (Lead) if Any

(b) Percent of Eligible Lines Replaced

Notes: Observations are at the block group level. Panel a shows the distribution of the percent of total service lines that were "eligible" for replacement, conditional on having any eligible lines. Eligible lines are defined as service lines that were still lead in 2017 or lines installed during the LSLR Program from 2007 to 2010. Panel b shows the distribution of the percent of total "eligible" lines that were replaced during the LSLR Program.

Given the spatial concentration of both lead service lines and replacements. It is useful to consider what characteristics describe these neighborhoods. First, Table 2 in the paper shows that neighborhoods with lead service lines tend to be more disadvantaged, which is similar to the existing environmental justice literature. I explore these patterns more in Table A3 which uses census data at the block group level. To proxy for the percent of lead service lines prior to the replacement program, the outcome for all regressions is the percent of census block group's service lines that were still lead in 2017 or lines installed during the LSLR Program from 2007 to 2010. Regressions are weighted by the number of total lines, such that rural neighborhoods without many service lines receive lower weight. Explanatory variables include a variety of household characteristics, measures of income and education, and demographic characteristics. It is important to note that many of these characteristics are correlated and these patterns are simply descriptive. Column 1 focuses on household characteristics and shows a positive and significant association between lead exposure and household size, percent of homes rented and percent vacant. Columns 2 focuses on income and education. Lower income neighborhoods tend to have higher exposure to lead service lines. Lead exposure is positively related to the percent unemployed and the percent on public assistance, and negatively related to the median household income. Interestingly, there is a positive correlation between high education and lead service line exposure. Column 3 focuses on demographics, showing consistently higher exposure among non-white households. Higher percentages of Black and other race households are associated with increased exposure to lead, relative to white households. Similarly, Hispanic households experience greater exposure to lead than non-Hispanic households. Column 4 includes all these characteristics in the same regression and still finds a strong correlation between the percent of homes rented and vacant, education, unemployment, and race/ethnicity. In columns 5-6, I add an additional control for the age of housing stock, which is equal to one if the neighborhood's median home age was earlier than 1939. Unsurprisingly, the correlation is strongly significant and diminishes somewhat the magnitude and/or significance of several other characteristics in the regression. Nevertheless, it is interesting to see that many variables remain statistically significant even conditional on living the age of housing stock, such as correlations with percent of homes rented and vacant, high education, and the percent black. Finally, column 6 presents unweighted results, which show very similar patterns.

Second, Table A4 uses the same data to explore what characteristics describe neighborhoods that received lead service line replacements and whether replacements systematically targeted certain neighborhoods. The outcome for all regressions is the percent of a census block group's service lines that were installed during the LSLR Program from 2007 to 2010. Regressions are weighted by the total number of lines "eligible" for replacement, defined as either still lead as of 2017 or replaced during the LSLR program. I use the same explanatory variables as the previous table. Column 1 shows that replacements were more common for neighborhoods with bigger households and single headed households, and less common in neighborhoods with a higher percentage of rentals. Column 2 shows that replacements were more common for neighborhoods with lower education and higher unemployment. Column 3 shows that replacements were only marginally significantly more common in neighborhoods with large Hispanic populations. Column 4 includes all these characteristics in the same regression and still finds the strongest correlation between the percent of homes rented. In columns 5-6, I add additional controls for the density of lead lines eligible for replacement and the age of housing stock, which is equal to one if the neighborhood's median home age was earlier than 1939. These variables are highly correlated, so I add them separately and find strong and consistently positive associations, reinforcing the idea that replacements occurred in neighborhoods with an older housing stock and a high density of lead service lines. Interestingly, when conditioning on age of housing stock and density of lead lines, the coefficient on the percent black becomes statistically significantly negative, suggesting predominately black neighborhoods may receive fewer replacements. Neighborhoods with many renters are also less likely to receive replacements, even conditional on the presence of lead and an older housing stock. Finally, columns 7-8 present unweighted results, which show very similar patterns.

Table A3: Lead Service Line Exposure and Local Demographics

	(1)	(2)	(3)	(4)	(5)	(6)
Built before 1939					0.219***	0.217***
					(0.0270)	(0.0274)
Average HH size	0.0844***			0.0337	0.0265	0.0305
	(0.0236)			(0.0327)	(0.0293)	(0.0285)
Houses rented (%)	0.427***			0.228***	0.136*	0.117*
	(0.0672)			(0.0771)	(0.0699)	(0.0663)
Vacant (%)	0.627***			0.409***	0.268**	0.282**
	(0.140)			(0.130)	(0.118)	(0.117)
Single Headed HHs (%)	0.0668			0.110	0.144**	0.120*
	(0.0732)			(0.0765)	(0.0686)	(0.0697)
High Education (%)		0.408***		0.560***	0.281***	0.190**
		(0.0878)		(0.0854)	(0.0838)	(0.0840)
Unemployed (%)		1.210***		0.484***	0.240	0.186
		(0.205)		(0.175)	(0.160)	(0.158)
Public Assistance (%)		0.783**		-0.0639	0.0612	0.0610
		(0.312)		(0.272)	(0.244)	(0.233)
Median HH income		-0.00227***		-5.68e-05	-5.11e-05	0.000331
		(0.000681)		(0.000741)	(0.000663)	(0.000673)
Black (%)			0.532***	0.367***	0.229**	0.235**
			(0.128)	(0.125)	(0.113)	(0.111)
Other (%)			0.411***	0.257**	0.109	0.134
			(0.116)	(0.105)	(0.0960)	(0.0950)
Hispanic (%)			0.229**	0.204**	0.135	0.117
			(0.103)	(0.104)	(0.0931)	(0.0922)
Under age 18 (%)			-0.204	0.0957	0.151	0.141
			(0.182)	(0.185)	(0.165)	(0.162)
Observations	275	274	275	274	274	274
R-squared	0.366	0.235	0.348	0.532	0.626	0.589

Notes: Regressions use data from the 5-year ACS 2013 at the census block group level. The outcome is the percent of lines likely made of lead prior to the program, defined as the percent of census block group's service lines that were still lead in 2017 or lines installed during the LSLR Program from 2007 to 2010. Built before 1939 is equal to one of the median home age was before 1939. High education is defined as having a bachelors or graduate degree. Median household income is measured in thousands. Columns 1-5 are weighted by the total number of service lines and column 6 is unweighted.

Table A4: Lead Service Line Replacements and Local Demographics

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Lead Lines (%)					0.819***		0.319***	
					(0.136)		(0.121)	
Built before 1939						0.134**		0.132**
						(0.0572)		(0.0582)
Average HH size	0.134***			-0.0219	-0.0603	-0.0305	-0.00971	-0.00649
	(0.0426)			(0.0603)	(0.0567)	(0.0599)	(0.0599)	(0.0601)
Houses rented (%)	-0.303**			-0.591***	-0.723***	-0.622***	-0.532***	-0.509***
	(0.131)			(0.148)	(0.140)	(0.148)	(0.145)	(0.145)
Vacant (%)	0.364			0.311	0.0637	0.226	-0.0547	-0.00927
	(0.246)			(0.247)	(0.234)	(0.247)	(0.250)	(0.249)
Single Headed HHs (%)	0.263*			0.127	0.115	0.164	-0.00141	0.0429
	(0.136)			(0.161)	(0.150)	(0.160)	(0.149)	(0.149)
High Education (%)		-0.395***		-0.0299	-0.451**	-0.173	-0.298*	-0.319*
		(0.145)		(0.171)	(0.174)	(0.180)	(0.171)	(0.178)
Unemployed (%)		0.589*		0.339	0.0797	0.222	-0.0284	-0.0192
		(0.323)		(0.333)	(0.313)	(0.333)	(0.336)	(0.338)
Public Assistance (%)		-0.719		-0.882*	-0.654	-0.804*	-0.453	-0.402
		(0.461)		(0.475)	(0.445)	(0.472)	(0.488)	(0.491)
Median HH income		0.000667		-0.00145	-0.00108	-0.00151	-0.000318	-0.000182
		(0.00122)		(0.00142)	(0.00133)	(0.00141)	(0.00144)	(0.00145)
Black (%)			-0.308	-0.340	-0.507**	-0.413*	-0.626***	-0.596**
			(0.205)	(0.235)	(0.221)	(0.235)	(0.240)	(0.240)
Other (%)			0.257	0.427**	0.182	0.327	0.174	0.167
			(0.197)	(0.203)	(0.194)	(0.205)	(0.199)	(0.201)
Hispanic (%)			0.317*	0.324	0.259	0.297	0.219	0.233
			(0.173)	(0.200)	(0.187)	(0.198)	(0.195)	(0.196)
Under age 18 (%)			0.202	0.200	0.0429	0.230	0.284	0.366
			(0.319)	(0.350)	(0.328)	(0.347)	(0.343)	(0.344)
Observations	255	254	255	254	254	254	254	254
R-squared	0.079	0.077	0.112	0.189	0.296	0.207	0.170	0.164

Notes: Regressions use data from the 5-year ACS 2013 at the census block group level. Lead Lines (%) is the percent of lines likely made of lead prior to the program, defined as the percent of census block group's service lines that were still lead in 2017 or lines installed during the LSLR Program from 2007 to 2010. Built before 1939 is equal to one of the median home age was before 1939. High education is defined as having a bachelors or graduate degree. Median household income is measured in thousands. Columns 1-6 are weighted by the total number of lead lines and columns 7-8 are unweighted.

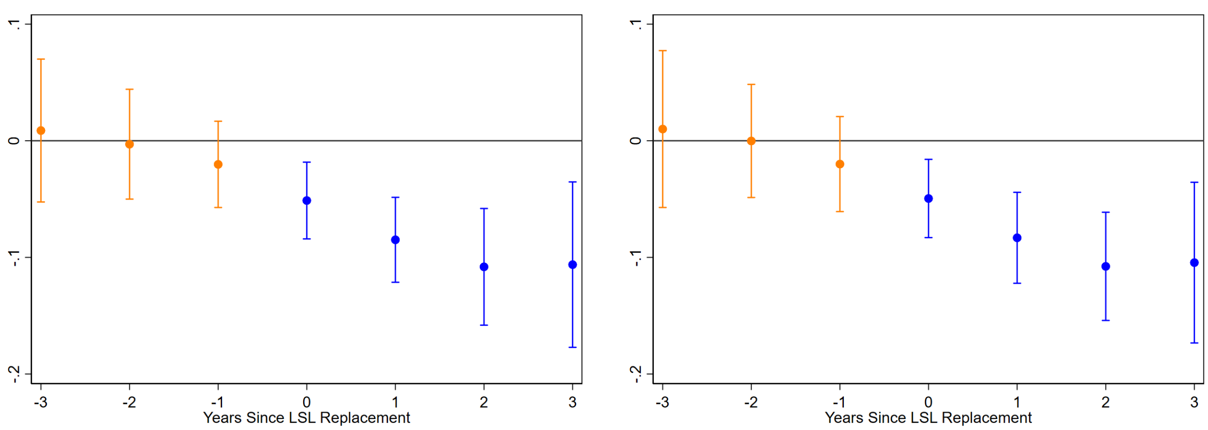
8.3.2 Probability of Testing

In this section, I explore whether LSL replacements have an impact on the probability of receiving a blood lead test. Rhode Island's testing requirements indicate that children over 36 months old may be asked risk assessment questions to determine whether they must receive a blood lead test. Children living at homes built before 1978 with peeling or chipping paint are required to have a lead test (see Appendix 8.1.3). Given that results from Table 6 show that children are moving away from older homes, it may be the case that the probability of testing goes down since these children may not be required to have a lead test.

First, I show the effect of LSL replacements on the probability of testing in Figure A10 and Table A5. The outcome is equal to one if a child has any blood lead test at a given age. The sample includes movers and defines LSL replacement timing based on the child's first observed location. Figure A10 shows a decline in the probability of testing after a child's LSL is replaced. Table A5 shows that after LSL replacements, a child is about 5 percentage points less likely have a lead test. The estimate is consistent across aggregation methods and control groups reported in columns 1-6.

Given that children are moving away from older homes, it is not surprising that the frequency of testing declines slightly as children living at new homes are not necessarily required to have a lead test. Although the sample of movers is unlikely to be random, our main results restrict the sample to non-moving households, such that this is unlikely to bias our main estimates of the effect of LSL replacements on child blood lead levels.

Figure A10: Effect of LSLR on the Probability of Testing



(a) Never treated

(b) Not yet treated

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is never treated in panel (a) and not yet treated in panel (b). The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. The outcome is an indicator for whether a child had any BLL test at each age from 0 to 5.

Table A5: Effect of LSLR on the Probability of Testing

	(1)	(2)	(3)	(4)	(5)	(6)
After Install	-0.049***	-0.051***	-0.049***	-0.046***	-0.048***	-0.047***
	(0.010)	(0.011)	(0.009)	(0.010)	(0.010)	(0.009)
Observations	25,267	25,267	25,267	25,267	25,267	25,267
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Year Control	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta_{simple}^{overall}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta_{es}^{overall}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Anticipation is set to zero. Estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Treatment timing is based on the child's first observed location. The outcome is an indicator for whether a child had any BLL test at each age from 0 to 5.

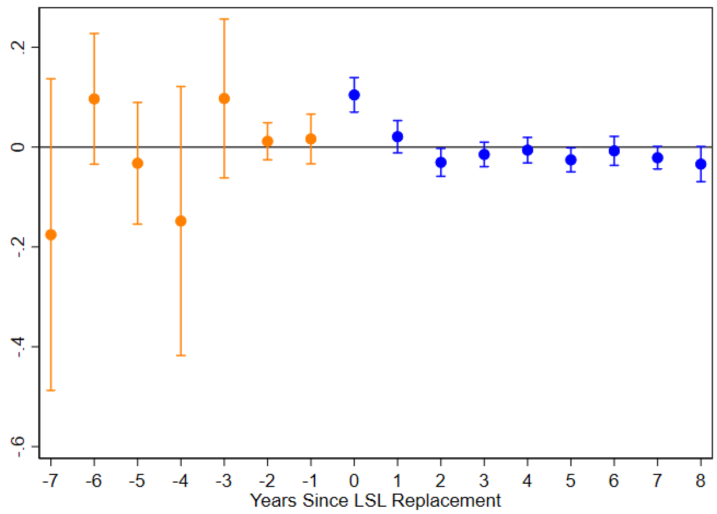
8.3.3 Effects of Non-LSLR on Home Sales

LSL Replacements that occur as part of the LSLR Program are likely exogenous to the homeowners' decision making process because they are conducted by the water system in response to the regulatory requirement. Alternatively, replacements that occur at other times are likely to be endogenously related to a request by the homeowner. For example, during a home renovation project, a homeowner may choose to replace the private-side of their lead service line and request that the water supply company replace the public-side at the same time. As these replacements are endogeneously related to other home improvements, any price changes would be difficult to interpret because they would simultaneously capture both the effect of the home renovation and the reduced lead exposure from the lead service line. In this section, we present results for these endogenous replacements that occur outside the LSLR Program.

Figure A11 shows the event study aggregation estimates for the probability of a home being sold. Estimates allow for 1 period of anticipation and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, and initial land assessment, and home grade in order to control for differential trends in home sales during the sample period by housing characteristics.

In Figure A11, there is a clear increase in the probability of that a home is sold around the time of replacement for replacements performed outside of the LSLR Program. The coefficient in period 0 is positive and statistically significant. Because these replacements may be associated with home remodels and remodels often occur just before or just after a home is sold, it is not surprising that the replacement timing is associated with an increase in the probability of a home sale. These results are consistent with what we would expect to find if replacements are endogenously related to home remodels outside of the LSLR Program.

Figure A11: Effect on Probability of Home Sale: Not LSLR Program



Notes: Event study aggregation estimates reported for LSL replacements not made during the LSLR Program. The x-axis reports years since the service line was replaced. The outcome is equal to one if the home sold in each year. Post-treatment estimates in blue are relative to period -1. Pre-treatment estimates in orange are relative to the previous period. Estimates use the "never treated" control group and include year and parcel fixed effects. Anticipation is set to one period. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals are clustered at the parcel level.

8.3.4 Moving Mechanisms

Increased moving among renters may be driven through a number of channels. First, landlords may increase rent if LSL replacements are a valuable amenity or if replacements increased a neighborhood's desirability. Lower income renters or renters with lower willingness to pay for this amenity may move out. Second, replacements may bring new information to some renters about the presence of lead remaining in the private-side portion of the service line that is owned by the landlord and was not replaced by the water utility.

While landlords are required to inform renters of any known lead sources, there are no requirements to determine whether a home has a lead service line if it is unknown to the landlord. When public-side lead service line replacements are conducted, the utility can check the material of the private side and inform the resident.[29] Therefore, lead service line replacements may have provided new information that their service line was made of lead. To the extent that this induced avoidance through moving, we might expect renters to move to homes with fewer lead hazards, such as newer homes.

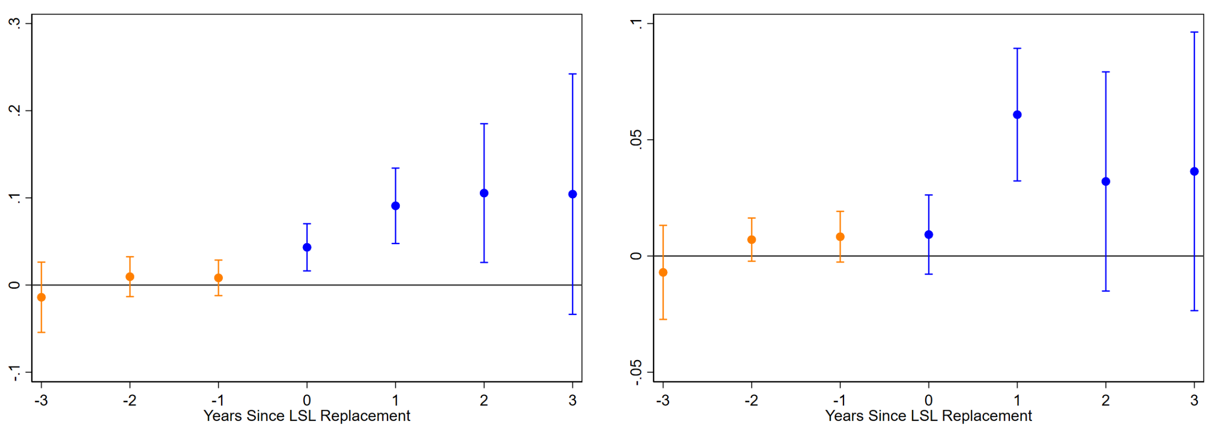
As renting households were likely to have heterogeneous levels of information and heterogeneous valuations of this amenity, it is difficult to identify a single mechanism driving this

[29] In addition, Providence Water conducted a variety of tap water sampling tests for lead around the time of replacement and the results were shared with residents.

effect. While it would be useful to have more descriptive information on the locations renters moved to, I only observe information on home age. I provide some suggestive evidence that rental prices increased and renters moved to newer homes.

First, I explore whether these children are more or less likely to move to a newer home. Homes built after 1937 are less likely to have lead service lines. Figure A12a and Panel A of Table 6 show there is a significant increase in the probability of living in a home built after 1937 of about 8-9 percentage points. Movers may also prefer to live in a home without risk of lead service lines and lead paint, which was banned in 1978. Figure A12b and Panel B of Table A6 show there is a significant increase in the probability of living in a home built after 1978 of about 3 percentage points. The estimates are consistent across aggregation methods and control groups reported in columns 1-6. These results suggest that the LSL replacements may act as an information channel to renters that increases their probability of moving to a newer home to avoid lead exposure. However, lacking data on other measures of home quality, such as other health hazards, it is difficult to know if moving households are better or worse off overall.

Figure A12: Effect of LSLR on Moving to Newer Homes



(a) Live in Post-1937 Home

(b) Live in Post-1978 Home

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is never treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. The outcome in panels a and b is an indicator equal to one if the home was built after 1937 and 1978, respectively.

Table A6: Effect of Lead Service Line Replacements on Moving to Post-1978 Home

	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.			$Outcome: \mathbb{1}[Live\ in\ Post-1937\ Home]$			
After Install	0.089***	0.086***	0.074***	0.089***	0.086***	0.074***
	(0.018)	(0.027)	(0.016)	(0.019)	(0.025)	(0.015)
Observations	16,079	16,079	16,079	16,079	16,079	16,079
Panel B.			$Outcome: \mathbb{1}[Live\ in\ Post-1978\ Home]$			
After Install	0.034***	0.035***	0.031***	0.033***	0.034***	0.031***
	(0.011)	(0.012)	(0.010)	(0.010)	(0.011)	(0.010)
Observations	16,079	16,079	16,079	16,079	16,079	16,079
Aggregation	Simple	Event	Group	Simple	Event	Group
Control Group	Never	Never	Never	Not yet	Not yet	Not yet
Year Control	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Columns 1 and 3 show the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Columns 2 and 4 show the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. Columns 3 and 6 show the aggregation over groups. Columns 1-3 use the never treated group as a counterfactual, whereas columns 4-6 use the not-yet-treated group as a counterfactual. Anticipation is set to zero. Estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Treatment timing is based on the child's first observed location. The outcomes is an indicator equal to one if the child lives in a home built after 1978.

Next, I explore changes in rental prices in neighborhoods with many lead service line replacements using census data at the census tract level. Using a simple 2x2 difference-in-difference specification, I compare rental prices before and after the lead service line replacement in tracts with higher relative to lower replacements. Regressions include tract fixed effects and a year indicator, and are weighted by the total number of service lines eligible for replacement. Table A7 shows the results where treatment is measured continuously as the percent of lines replaced in panel a, and treatment is measured as a binary variable equal to one for tracts above the 75th percentile of percent of lines replaced in panel b. Across both specifications, results are very similar. Although statistically insignificant, column 1 shows a positive coefficient for median rent, suggesting that rental prices may be increasing in neighborhoods with higher portions of replacements after the program. Columns 2-6 show changes in the amount of rent across the distribution. Columns 3 and 4 show a statistically significant decrease in rents $200-499 and an increase in rents $500-999, respectively. These patterns may reflect increased rental prices for homes with LSL replacements, perhaps suggesting that renters moving in have a higher valuation for these replacements or that existing renters are pushed out due to increases in rent. However, it is difficult to disentangle these patterns without more granular data on rental prices, which is unfortunately unavailable.

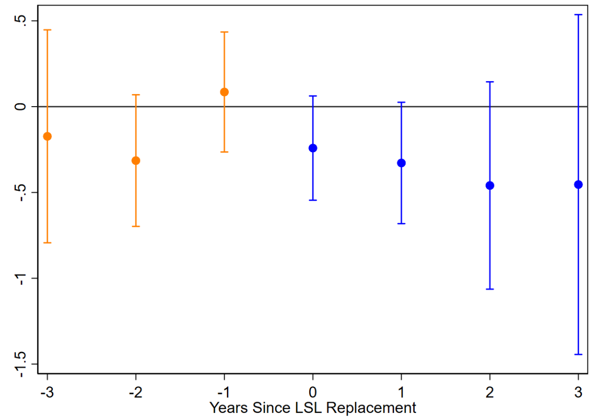
Table A7: Changes in Rental Prices

		Rent Amount (%)				
	Median Rent	<$200	$200-499	$500-999	$1000-1499	≥$1500
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A.						
LSLRs × Post	29.89	1.786	-12.03**	23.18**	-8.967	-4.038
	(68.75)	(3.995)	(5.724)	(11.26)	(5.985)	(3.398)
Observations	131	132	132	132	132	132
R-squared	0.939	0.761	0.844	0.656	0.825	0.737
Panel B.						
High LSLRs × Post	10.54	1.461	-7.996***	13.10**	-4.450	-2.143
	(32.47)	(1.880)	(2.604)	(5.233)	(2.820)	(1.599)
Observations	131	132	132	132	132	132
R-squared	0.939	0.763	0.855	0.667	0.825	0.739
Tract FE	yes	yes	yes	yes	yes	yes
Mean	761	9.762	20.30	53.51	12.88	3.549

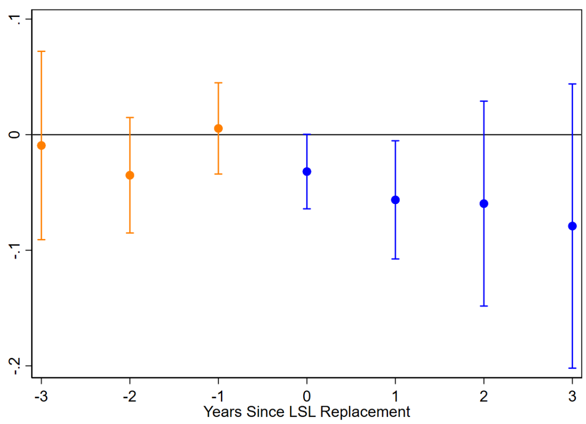
Notes: Data at the tract-year level comes from the 2000 Census and 2015 ACS. Post is equal to one in 2015, after the lead service line replacement program ends, and zero in 2000. Panel A uses the number of lines installed during the lead service line replacement program as a continuous measure of treatment, while Panel B uses a binary measure equal to one if the number of lines installed during the program is greater than the 75th percentile. Regressions are weighted by the total number of service lines eligible for replacement, which includes lines that were installed during the lead service line replacement program (2007-2010) or were still made of lead.

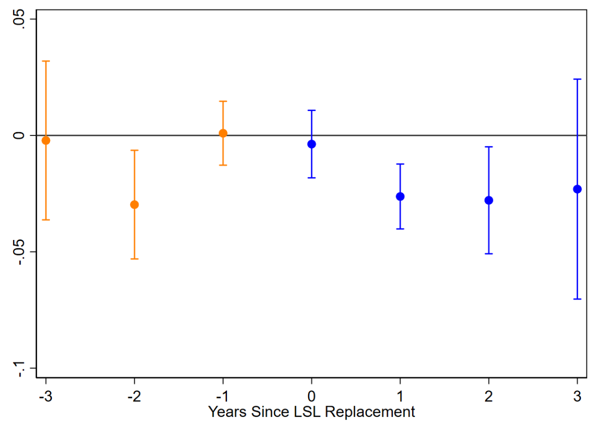
8.3.5 Alternative Counterfactuals and Specifications

Figure A13: Effect of LSLR on Child BLL, not yet treated



(a) BLL Test Result



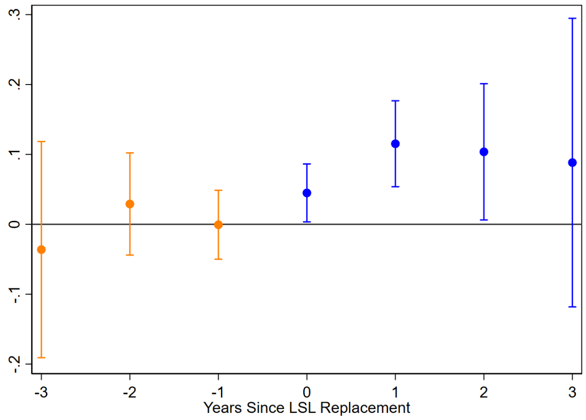


(b) BLL Over 5

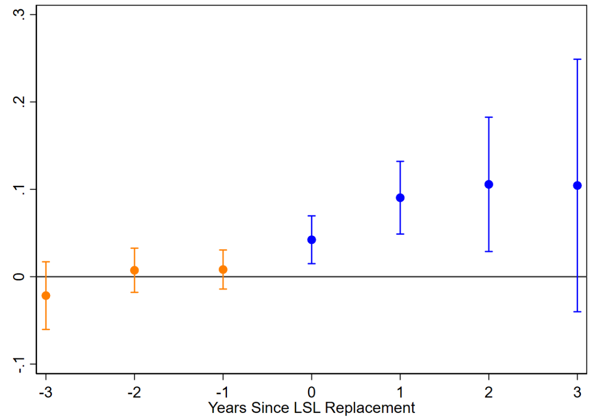
(c) BLL Over 10

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is not yet treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (c) show results for the BLL test result, an indicator for BLL over 5 $\mu g/dL$ and an indicator for BLL over 10 $\mu g/dL$, respectively.

Figure A14: Effect of LSLR on Moving, not yet treated



(a) Ever Moved



(b) Live in Post-1937 Home

Notes: Figures show the event-study aggregation given by equation 5 where average treatment effects are aggregated by event time. The control group is not yet treated. The post-treatment period is shown in blue and estimates are relative to period -1. The pre-treatment periods in orange are estimated relative to the previous period. 95 percent confidence intervals are included. Panels (a) - (b) show results for an indicator equal to one if the child ever moved from the original location, and an indicator equal to one if the home was built after 1937, respectively.

Table A8: Robustness of BLL results to alternate specifications, event aggregation

	(1) Baseline	(2) Max	(3) Min	(4) No Outliers	(5) With Capillary	(6) 2007-10	(7) Drop 1937+	(8) Fix After	(9) Year Built Control
Panel A.					*Outcome: BLL*				
After Install	-0.388*	-0.506**	-0.274	-0.329*	-0.321*	-0.487*	-0.329**	-0.368*	-0.406**
	(0.199)	(0.206)	(0.191)	(0.186)	(0.172)	(0.254)	(0.162)	(0.213)	(0.199)
Panel B.					*Outcome:* $\mathbb{1}[BLL\ Over\ 5]$				
After Install	-0.059***	-0.064***	-0.049**	-0.058**	-0.054**	-0.060*	-0.055**	-0.059**	-0.061**
	(0.024)	(0.024)	(0.024)	(0.025)	(0.023)	(0.032)	(0.026)	(0.024)	(0.025)
Panel C.					*Outcome:* $\mathbb{1}[BLL\ Over\ 10]$				
After Install	-0.022**	-0.028***	-0.017**	-0.020**	-0.017*	-0.023***	-0.021**	-0.016*	-0.023***
	(0.009)	(0.009)	(0.008)	(0.008)	(0.010)	(0.009)	(0.009)	(0.010)	(0.008)
Observations	6,375	6,375	6,375	6,371	6,955	15,859	5,921	6,357	6,375
Aggregation	Event	Event	Event	Event	Event	Event	Event	Event	Event
Control Group	Never	Never	Never	Never	Never	Never	Never	Never	Never
Year Control	yes	yes	yes	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects based on event study aggregation using the never treated control group. Anticipation is set to zero. The sample is restricted to non-movers and estimates include age and child fixed effects. The doubly robust estimator is used and conditions on year. Bootstrapped 95% uniform confidence intervals shown in parentheses are clustered at the child level. Columns 2-3 use the maximum and minimum BLL values for children with multiple tests per year, respectively. Column 4 excludes the top 1% of BLL tests. Column 5 includes capillary tests. Column 6 uses only treatment cohorts with lines installed during the LSLR Program (2007-2010). Column 7 excludes homes built after 1937 that are less likely to have had lead service lines. Column 8 excludes BLL tests taken in the same year as treatment but before the line was replaced. Column 9 also conditions on the year a child's home was built.

Table A9: Robustness of Home Price Results to Alternate Specifications

	(1) Baseline	(2) $> \$10k$	(3) $< \$1m$	(4) $> \$10k$ & $< \$1m$	(5) Tract Control	(6) Any Foreclosure
Panel A.	*Aggregation: Simple*					
After Install	0.064**	0.060**	0.073**	0.069**	0.093***	-0.001
	(0.032)	(0.031)	(0.034)	(0.030)	(0.037)	(0.002)
Observations	7,259	7,253	7,207	7,201	7,259	13,767
Panel B.	*Aggregation: Event*					
After Install	0.074**	0.069**	0.085**	0.080**	0.108***	-0.001
	(0.035)	(0.032)	(0.035)	(0.032)	(0.036)	(0.002)
Observations	7,259	7,253	7,207	7,201	7,259	13,767
Control Group	Never	Never	Never	Never	Never	Never
Controls	yes	yes	yes	yes	yes	yes

Notes: Results show the overall summary aggregations of the average treatment effects. Panel A shows the simple aggregation, $\theta^{overall}_{simple}$, from equation 4. Panel B shows the aggregation over event time, $\theta^{overall}_{es}$, from equation 6. The counterfactual is the nevertreated group. Column 1 replicates the baseline results. Columns 2-4 limit the sample to sales prices above \$10,000, below \$1 million, and with both restrictions. Column 5 also conditions the parallel trends assumption on census tract, such that comparisons are made within tract. Column 6 shows that there is no change in the probably of foreclosure after replacement. Sample includes LSL replacements made during the LSLR Program at old homes. The outcome is the log of home price. Estimates have zero anticipation and include year and parcel fixed effects. The doubly robust estimator is used and covariates include total bedrooms, total bathrooms, year built, living area, initial building assessment, initial land assessment, and home grade. Bootstrapped 95% uniform confidence intervals and clustered at the parcel level are reported in parentheses.