Air Filters, Pollution, and Student Achievement

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ABSTRACT

This paper identifies the impact of installing air filters in classrooms for the first time. To do so, I leverage a unique setting arising from the largest gas leak in U.S. history, whereby the offending gas company installed air filters in every classroom within five miles of the leak (but not beyond). Using a spatial regression discontinuity design, I find substantial improvements in student performance: air filters raised mathematics and English scores by 0.20σ. Natural gas was not detected inside schools, implying that the filters improved air quality by removing common pollutants and so these results should extend to other settings.

Keywords: Air Pollution; Human Capital; Air Filters; Spatial Regression Discontinuity; Cost Effectiveness.
***JEL* codes:** I10, I21, I24, I28.

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1 Introduction

A sizeable literature has shown air pollution negatively affects health and cognition, with recent evidence demonstrating that increased levels of air pollution reduce student achievement (Ebenstein, Lavy, and Roth, 2016; Heissel, Persico, and Simon, 2019; Persico and Venator, forthcoming).[1] This evidence, in turn, has prompted calls to reduce children's exposure to airborne pollutants. Large-scale pollution reduction has proved difficult, however, as the required policies are often costly and politically unpopular. In their absence, focused policies that mitigate the negative impacts of polluted air have the potential to improve student achievement *and* be cost effective.

A natural location to reduce children's pollution exposure is at school given that they spend one-half of their waking time there on weekdays. While officials would ideally locate schools in low pollution areas, such policies are often infeasible due to the high levels of pollution throughout many cities.[2] A more feasible policy is to lower air pollution *inside* the school.[3] Given that high-performance air filters can decrease indoor particulate matter by ninety percent (Polidori, Fine, White, and Kwon, 2013), installing air filters in classrooms offers a candidate means to substantially decrease students' air pollution exposure at relatively low cost.

This paper uses a natural experiment arising from the Aliso Canyon gas leak, the largest in US history,[4] to investigate the impact of air filters on student achievement. The gas leak occurred in a wealthy Los Angeles neighborhood and lasted from October 23, 2015 to February 19, 2016. To estimate the effect of air filters, I take advantage of the fact that the

[1]See Graff Zivin and Neidell (2013) and Almond, Currie, and Duque (2018) for in-depth reviews of the literature.

[2]Although every city requires schools, policymakers can try to somewhat mitigate the effect of air pollution by avoiding the most polluted areas within a city: California, for instance, enacted a state law in 2003 that prohibits building schools within 500 feet of a freeway.

[3]In a similar spirit, one could also reduce children's exposure to pollutants in school buses, although students only spend a small fraction of their day in buses. Even so, Austin, Heutel, and Kreisman (2019) and Beatty and Shimshack (2011) find that retrofitting school bus engines increases test scores and improve respiratory health, respectively.

[4]To place the gas leak into perspective, Conley et al. (2016) find that the Aliso Canyon gas leak created greenhouse gas emissions equivalent to the annual emissions of 572,000 passenger cars.

Los Angeles Unified School District (LAUSD) and the owner of the gas well, the Southern California Gas Company, placed air filters in every classroom, office and common area in all schools within five miles of the gas leak at the end of January 2016. The number of air filters installed was substantial: a total of 1,756 plug-in air filters were delivered to just eighteen schools.[5] This variation lends itself naturally to a spatial regression discontinuity design, whereby I compare outcomes for students attending schools just within the five-mile boundary to those just outside.

Using detailed administrative data from the LAUSD, I document significant test score increases in schools receiving air filters. Specifically, I find that air filters raised mathematics scores by 0.20σ, with this increase being statistically significant at the five percent level. Similarly, I find that English scores increase by 0.18σ, although this increase is not statistically significant. Results are robust to choice of bandwidth, functional form of the geographic location control, outliers, and the inclusion of detailed student demographics, including residential ZIP Code fixed effects that help control for a student's exposure to pollution at home. I also find that these test score improvements persist into the following year.

To place the effect size into context, *outdoor* fine particulate concentrations measured by $PM_{2.5}$ – the focus of much of the literature – averaged $7.33\mu g/m^3$ during the January-June 2016 period of interest (recorded by a nearby EPA air monitor). Engineering studies indicate air filters reduce *indoor* particulate matter by ninety percent. Assuming outdoor and indoor air pollution are identical suggests a test score increase of approximately 0.03σ $(= 0.2/(7.33 * 0.9))$ for each $\mu g/m^3$ of fine particulate reduction. In terms of comparison, Ebenstein et al. (2016) find that decreasing *outdoor* $PM_{2.5}$ by one $\mu g/m^3$ on the test day *only* raises test scores by 0.006σ,[6] suggesting the effect identified in this paper is five times the *one day* effect noted in Ebenstein et al. (2016). Indoor particulate levels, however, often exceed

[5] Active carbon filters for all heating and air conditioning units were also installed in these twenty schools.

[6] Ebenstein et al. (2016, pg. 50) report "that a test score in an exam on a day with average pollution (AQI = 59.74) will be lowered relative to an exam taken on a day with the minimum pollution level (AQI = 10.1) by 0.083 standard deviations." Converting AQI into $\mu g/m^3$ units yields the numbers cited.

outdoor levels (Mumovic et al., 2018). Given this, a more direct comparison is Roth (2019) who uses day-to-day variation in *indoor* particulate matter at a public research university within the Greater London Urban Area to calculate the causal effect of *indoor* air quality on test day on student performance. According to his estimates, installing air filters on *only* the day of the test would raise test scores by 0.09σ.[7] Since air filters in my context reduce pollutant exposure for students and teachers for about four months (including the day of the test), it is unsurprising that the estimated effects are two to five times the one (test) day effects previously noted in the literature.

Next, I demonstrate that these test score gains are unlikely to be context-specific. To do so, I use detailed air testing data gathered in schools within the five-mile boundary to show that these schools did not have abnormally high levels of airborne pollutants associated with natural gas. This is also consistent with results from a high-precision natural gas analyzer that looked for traces of natural gas on roads around the gas leak and found that the quantity of airborne natural gas dissipated outside two miles of the leak (Phillips, Ackley, and Jackson, 2016).[8] Given these facts, it is likely that the beneficial effect of the air filters comes from eliminating common airborne pollutants. While Los Angeles faces high levels of air pollution, particulate matter levels (measure by $PM_{2.5}$) in many cities (including New York, Chicago and Houston) exceed those reported by the EPA air monitor closest to the gas leak. Together, these facts suggest that installing air filters in schools throughout many areas of the United States should generate similar test score gains.

The per-year cost to install and maintain air filters throughout a school is around $1,000 per class.[9] Given the large test score increases they generate, installing air filters substantially

[7] Roth (2019) calculates a test score increase of approximately 0.003σ for each $\mu g/m^3$ of fine particulate reduction (measured by PM_{10}). Given the average *indoor* particulate concentration in his sample is $33\mu g/m^3$, air filters should decrease particulate matter by $30\mu g/m^3$ $(= 33 * 0.9)$ and should thus raise test scores by 0.09σ $(= 0.003 * 30)$.

[8] In addition, the primary component of natural gas, methane, is lighter than air and so should generally rise, although in practice the turbulent mixing of gases is an important factor in determining the diffusion of pollutants into the environment.

[9] The air filter itself costs about $700 per unit, although electricity and filter replacement costs add another $600 in costs per year. Assuming a five-year life span for the unit and the need to install 1.5 units for each class to cover common areas leads to the approximate $1,000 per class-year cost.

outperforms other education reforms such as class size reduction on a cost-benefit basis. Indeed, the cost-to-benefit ratio indicates air filter installation is the one of the most cost-efficient (in terms of dollar per test score) educational interventions available to policymakers, outperforming the cost-effectiveness of notable interventions such as high dosage tutoring (Cook et al., 2015), Perry Preschool (Schweinhart et al., 2005), cash transfers from the EITC (Dahl and Lochner, 2012), and Head Start (Ludwig and Phillips, 2007). Air filters thus have the potential to mitigate the negative impact of poor air quality significantly, increasing student performance and – given underprivileged students often reside in high pollution areas (Clark et al., 2014, 2017; Voorheis, 2017; Currie et al., 2020) – helping to reduce the pervasive test score gaps that plague public education.

The rest of the paper is organized as follows: The next section describes the literature along with the Aliso Canyon gas leak and subsequent policy response. This provides the basis for my empirical strategy, which is set out in Section 3, along with the data used. The estimates are presented in Section 4 and are placed in context in Section 5. Section 6 concludes.

2 Background

This section starts by describing the related literature linking air pollution to health and cognition. The setting of this study – the Aliso Canyon gas leak – is then introduced. Particular attention is paid to describing the key policy variation used in this paper whereby air purifiers were provided in every classroom, office, and common area for schools within five miles of the leak.

2.1 Related Literature

Much of the literature on air pollution has focused on particulate matter (PM), which is a mixture of organic and inorganic particles suspended in the air, such as dust, pollen, soot, smoke, and liquid droplets. Particulate pollutants are classified into three categories based on their diameter in micrometers (μm): coarse particles with a diameter between 2.5 and 10μm (PM_{10}), fine particles with a diameter of 2.5μm or less ($PM_{2.5}$), and ultrafine particles which are on the nanoscopic scale (i.e., diameter less than 0.1μm).[10] For comparison, human hair has a diameter of approximately 50-70μm. Epidemiological research has highlighted these particles as being of particular concern. On that basis, much of the literature (including this paper) defines air quality using one of these particulate matter definitions. It is still difficult, however, to attribute the deleterious effects of poor air quality to one specific pollutant since the various measures of particulate matter are highly correlated with each other and the presence of other pollutants such as carbon monoxide, nitrogen oxides, sulfur dioxide, and mercury.

Outdoors, particulate matter is created by a variety of natural and man-made sources such as: fires, construction, power plants, factories, farm activities, and automobiles. Indoors, the concentration of particulate matter is a result of complex interactions between local meteorology, surrounding structures, and building characteristics (e.g., building ventilation, location of air intakes, etc.). Given this, indoor air pollution is highly spatially and temporally variable (Madureira et al., 2012; Mumovic et al., 2018). In addition, a significant source of indoor particulates is human activities that cause the resuspension of settled dust. For instance, Polidori et al. (2013) investigate three Los Angeles area schools and note that indoor particulates in classrooms are highest during the time of day when humans enter or exit classes (e.g., recess). The resuspension of dust by human activities is likely why indoor concentrations of coarse particles in classrooms tend to surpass outdoor levels during the daytime (Mumovic et al., 2018).

An extensive literature has linked outdoor air quality to mortality and health conditions such as bronchitis and asthma. Much of this literature has used short-term (often day-to-

[10] The division of particulate matter into these three categories is based on their ability to penetrate into the lung: coarse particulate matter can permeate the trachea and bronchi, fine particulate can penetrate deeper into the gas exchange regions of the lung (i.e., alveoli), and ultrafine particles are small enough to pass through the lung tissue into the blood stream and affect other organs.

day or *in utero*) variation in air quality to document the negative effects of air pollution. Short-term variation in air quality has come from numerous sources, such as air traffic (Schlenker and Walker, 2015), local weather conditions (Heft-Neal et al., 2019; Deryugina et al., forthcoming), environmental regulation (Sanders and Stoecker, 2015), road traffic (Currie and Walker, 2011; Knittel et al., 2016; Simeonova et al., 2018), within-family (Currie et al., 2009b), and within ZIP code-month-year cells (Neidell, 2004; Currie and Neidell, 2005). An influential literature has also provided convincing estimates of the long-term effects of air pollution by leveraging long-term changes to pollution exposure coming from the Clean Air Act (Chay et al., 2003; Isen et al., 2017), recessions (Chay and Greenstone, 2003), wind patterns (Anderson, forthcoming), industrial plant closings (Currie et al., 2015), and compulsory relocations (Lleras-Muney, 2010).

Likewise, a growing literature has documented the negative effects of outdoor air pollution on human capital formation.[11] Sanders (2012) uses county-level variation in the timing and severity of the early-1980s industrial recession and finds that a standard deviation increase in prenatal particulate exposure is associated with a 0.02-0.06 standard deviation decrease in high school test scores. In a similar spirit, Bharadwaj et al. (2017) use within-family comparisons and document a one standard deviation increase in carbon monoxide exposure *in utero* decreases fourth grade test scores by 0.03-0.05 standard deviations. Marcotte (2017) finds that a $25\mu g/m^3$ increase in particulate matter (measured by $PM_{2.5}$) on the day of the test reduces student performance by about two percent. Similarly, Ebenstein et al. (2016) use variation in test day particulate pollution in Israel and find that every ten $\mu g/m^3$ increase in particulate matter (measured by $PM_{2.5}$) reduces test scores by 0.06 standard deviations.

Some papers have also suggested possible mechanisms underlying these effects. Currie et al. (2009a) use pollution variation in school-year-attendance period cells and estimate that an additional day with carbon monoxide levels above EPA standards increases student absenteeism by 9 percentage points. Persico and Venator (forthcoming) leverage the closing

[11] A related literature has shown air pollution reduces worker productivity on farms (Graff Zivin and Neidell, 2012), in pear-packing plants (Chang et al., 2016a), and at call centers (Chang et al., 2016b).

of large industrial facilities and compare students attending schools nearby to those further away and find the drop in industrial pollution raised test scores by 0.024 of a standard deviation *as well as* reducing the likelihood of absences and school suspensions. Similarly, Heissel et al. (2019) compare students attending schools downwind relative to upwind of highways and determine that increased air pollution from being downwind lowered test scores by 0.04 of a standard deviation along with raising behavioral incidents and absences by 4.1 and 0.5 percentage points, respectively.

Recently, several papers have been able to link *indoor* air quality to reduced cognitive performance. Künn, Palacios, and Pestel (2019) use detailed indoor air quality information from chess tournaments held in Germany to show that a ten μg/m^3 increase in fine particulate matter (measured by $PM_{2.5}$) raises a player's probability of making an erroneous chess move (as determined by a chess engine) by 26.3 percent. Focusing on test scores, Roth (2019) likewise uses day-to-day variation in *indoor* particulate matter at a public research university within the Greater London Urban Area and finds a test score increase of approximately 0.003σ for each μg/m^3 of fine particulate reduction (measured by PM_{10}).

The research also links to the school construction and renovation literature. For instance, Stafford (2015) uses the timing of school renovations throughout a district and finds that mold and ventilation remediation projects increase test scores by 0.07-0.15 of a standard deviation. While beneficial, the costs of these projects are substantial: the average mold remediation and ventilation improvement project cost $500,000 and $300,000, respectively. Similar effects have also been found using new school construction (Neilson and Zimmerman, 2014; Hashim et al., 2018; Lafortune and Schönholzer, 2019) which entail even larger costs. The research here suggests a possible reason for the large gains of school renovation and construction: improved air quality. Given this, district officials may be able to realize the gains of school infrastructure projects at lower costs through focused indoor air quality improvements.

2.2 Aliso Canyon Gas Leak

I now describe the Aliso Canyon gas leak and associated policy responses which provide the identifying variation in this paper whereby air filters were provided to schools within five miles of the gas leak. On October 23, 2015, employees of the Southern California Gas Company (SoCalGas) discovered a natural gas leak at the Aliso Canyon underground storage facility, the second-largest gas storage facility in the United States. The source of the leak was a metal pipe enclosed in a breached 7-inch casing in a well 8,750 feet deep. Initially, SoCalGas believed that the leak would soon be plugged and maintained that "the leak does not pose a health hazard or danger" (Wilcox, 2015). By November 25, however, SoCalGas had attempted six well 'kill' procedures to halt the gas leak with none being successful. At this time, officials realized the gas leak could not be plugged in a timely manner and, on December 4, SoCalGas began to drill a relief well similar to the one used to plug the Deepwater Horizon disaster. At the time, SoCalGas estimated the leak repair would take until the end of March 2016. In the end, the leak was halted ahead of schedule: State officials announced the leak was permanently plugged on February 18, 2016.

The gas leak generated substantial concerns in nearby Porter Ranch, a wealthy majority white neighborhood in the northwest region of Los Angeles,[12] with nearby residents complaining of headaches, nausea, and severe nosebleeds. At the start of December, under court order from the county health department, SoCalGas paid to relocate nearly 350 households. A state of emergency was then declared by county officials on December 15, dramatically raising the number of relocated residents to about 2,500 by the end of December. At the start of January, SoCalGas expanded the voluntary relocation zone of residents to a five-mile radius of the leaking well. According to SoCalGas, this radius was set by the furthest confirmed odor complaint received. Figure A.1 shows reported gas odor complaints as of December 29, 2015 with a circle representing five-miles from the gas leak superimposed. The

[12]The median household income for Porter Ranch in 2016 was reported at $114,826. The demographics of the neighborhood are about 60 percent White, 25 percent Asian, and 7.5 percent Hispanic.

figure indicates a substantial number of odor complaints north of the Ronald Reagan Freeway, which is about two miles south of the gas leak, with the number of complaints quickly dissipating beyond that point.

Residents within this five-mile boundary received assistance in the form of reimbursement for any expenses associated with relocation, including accommodation costs and transportation costs to take their child to and from school. To aid residents that did not wish to relocate, SoCalGas offered services to improve air quality inside homes, including installing air filters or scrubbers and weatherizing homes. Given that residents closer to the gas leak were likelier to evacuate, schools nearer to the gas leak presumably have more students who relocated. If moving negatively affects student performance, this implies that we expect there to be a positive relationship between student performance and distance to the leak, which will need to be controlled for (see Section 3). By the time the gas leak was halted, over 15,000 residents had been relocated, 3,060 homes had received plug-in air filters, 5,300 homes had air scrubbers installed, and 5,200 homes had been weatherized.[13]

Predictably, the gas leak also generated substantial concerns among school officials, especially as two elementary schools, Porter Ranch Community and Castlebay Lane Charter, were only 1.8 miles from the leak (the next closest school was 3.2 miles from the leak). In response, on December 15^{th} LAUSD officials announced that these schools would close after December 18^{th} (the start of winter break). Once winter break ended (January 12), students at these schools were relocated to Northridge Middle School and Sunny Brae Avenue Elementary.[14] The empirical analysis omits students attending the four relocating and receiving schools due to possible disruptions caused by relocation (these four schools also lie outside the region that is 3.5-6.5 miles from the leak that comprises the main analysis sample).

The key policy treatment used in this paper was publicly announced by SoCalGas on January 28^{th},[15] whereby SoCalGas stated they would "provide [plug-in] air purifiers in every

[13] See `https://www.sempra.com/newsroom/press-releases/aliso-canyon-gas-leak-incident-update-february-8-2016`.

[14] To create space for the evacuated students, a substantial number of portable classrooms were used.

[15] While the public announcement was not made until January 28, SoCalGas and the LAUSD had reached

classroom, office, and common area on all 18 campuses" (Laughton, 2016) within five miles of the gas leak. The number of plug-in air filters supplied was substantial: Granada Hills Charter High School, with an enrollment of 4,480 students, had 210 plug-in air purifiers installed in the school according to media reports (Blume, 2016). In addition, these schools could also request to have active carbon filters installed in all heating and air conditioning units if they did not already have them. While the policy was to install air filters in all schools within five miles of the gas leak, distance to the gas leak was rounded to the first decimal point.[16] Given this rounding, I consider all schools within 5.05 miles of the gas leak to be inside the five-mile boundary used to determine whether air filters were received. While district and gas company officials confirmed that the plug-in air filters were delivered to the eighteen schools within five miles of the leak, the exact number of air filters supplied to each school is unknown (with the exception of Granada Hills Charter High School).[17] After the leak was plugged, schools retained possession of the air filters, although it is unknown whether schools continued to use or maintain the units in subsequent years.[18]

Figure 1 shows the region of interest, indicating all LAUSD elementary schools within seven miles of the leak and whether they received an air filter. The figure makes clear that all schools within five miles (rounded to the first decimal) of the gas leak received an air filter while all schools further than five miles did not. Middle schools and the nearest EPA air monitor (about three miles south of the five-mile boundary) are also indicated on the map.

Air sampling was initiated at schools in response to the leak at the behest of the LAUSD. Specifically, Waterstone Environmental was hired to test for the presence of chemicals as-

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an agreement to deliver the plug-in air filters on January 21.

[16]For instance, see Laughton (2016) which clearly rounds distances to the first decimal point. In addition, the only school whose treatment status is affected by the rounding (Andasol Avenue Elementary) received air filters even though it was 5.02 miles from the leak.

[17]While SoCalGas and the LAUSD jointly agreed on the delivery of the plug-in air filters, SoCalGas supplied them. Data on the number of air filters delivered to each school are thus held by SoCalGas who are regrettably unwilling to share data due to (substantial) ongoing litigation.

[18]For instance, one school principal stated that the plug-in air filters were eventually placed in storage as some teachers complained that they made the air too dry.

sociated with natural gas, including volatile organic compounds.[19] The two schools nearest the leak, Porter Ranch Community School and Castlebay Lane Charter School, had their air sampled every school day starting on November 30 until the end of the fall term on December 18.[20] Although no pollutants exceeded regulatory limits, the schools were relocated (as noted) in the spring and so no further testing was conducted in these schools until after the gas leak was plugged.

The remaining eighteen schools within five miles of the leak received air quality testing starting on January 19, 2016. Each school was tested at least twice, with some schools tested up to six times.[21] Again, testing was limited to pollutants associated with natural gas such as methane, ethane, and benzene. Table A.1 displays the results from these tests, which show elevated levels of several pollutants such as ethane and methane in the two (evacuated) schools nearest the leak, but little relationship between distance to the leak and the measured pollutants thereafter. In addition, pollutant levels in these schools were not above normal readings (and well-below regulatory limits), indicating that it is unlikely schools near the five-mile boundary were exposed to above-normal levels of natural gas. This is in line with natural gas concentration readings from a gas analyzer driven around nearby Los Angeles neighborhoods by Phillips et al. (2016) (see Figure A.2).

3 Empirical Design and Data

In this section, I provide a detailed description of my strategy to estimate the effect of air filters on student achievement. The empirical strategy involves a spatial regression discontinuity (RD) design, which relies on the policy agreed by SoCalGas and the LAUSD

[19]Waterstone Environmental tested both directly for methane (the primary component of natural gas) as well as volatile organic compounds often found in natural gas such as benzene, toluene, ethylbenzene and xylene. Tests were conducted using handheld monitors, tedlar bags, and summa canisters.

[20]The only school day testing was not conducted was on December 15 as all LAUSD schools were closed that day due to a terror threat.

[21]Schools appeared to have been tested more than twice for two reasons: (i) schools initially tested on or before Jan 28 were retested in mid-February, and (ii) any school with a benzene reading above 0.92 ppbv was retested soon after.

that all schools within five miles of the gas leak (rounded to the first decimal) receive air filters. I follow with a brief discussion concerning the validity of the RD design in this context and how inference is conducted. The administrative data set that I use is then introduced.

3.1 Empirical Design

Whether a school receives an air filter or not is a deterministic and discontinuous function of distance to the Aliso Canyon gas leak. Such an assignment rule lends itself naturally to a spatial regression discontinuity (RD) design. The design takes advantage of the rule that only schools within five miles (rounded to first decimal point) of the gas leak receive air filters, while schools more than five miles away do not. The essence of the empirical strategy is to compare outcomes in schools just within five miles of the gas leak to those just further than five miles away. Given their geographical proximity, these schools should be similar on observable and unobservable dimensions and thus we can compare outcomes of students on either side of the five-mile policy boundary to capture the effect of air filters on student achievement.

In practice, few schools are 'just' around the five-mile boundary. To increase sample size for inference, the regression discontinuity design includes observations further away from the boundary and controls for the relationship between the outcome and distance to the gas leak. In this context, controlling for this relationship is necessary as the gas company offered reimbursement to families that decided to leave the immediate region due to concerns about the gas leak, but continued to send their children to the same schools (less than one percent of students near the leak switched schools during the 2015-16 academic year). Given that the probability of relocating is higher among residents closer to the leak and that students usually attend the zoned school near their house, schools closer to the gas leak are likely to have more relocated students. If moving affects student performance, this implies that there will be a positive relationship between student performance and distance to the leak that must be accounted for.

The identifying assumption of the RD design is that, with the exception of air filters, all factors determining student outcomes are evolving smoothly with respect to distance from the gas leak. In a spatial RD, both latitude and longitude determine a school's distance to the gas leak and thus we need to take into account that the five-mile policy boundary forms a multidimensional (rather than unidimensional) discontinuity in longitude-latitude space. Specifically, we want to ensure we only compare schools in close geographic proximity rather than just schools near the policy boundary: Intuitively, while a school 4.99 miles north and a school 5.01 miles south of the gas leak are just inside and outside the policy boundary, these schools are not in close geographic proximity (they are almost 10 miles apart) and so should not be directly compared. I deal with this issue in two ways: (i) including boundary segment fixed effects,[22] and (ii) using flexible controls of latitude-longitude space as in Dell (2010).

I thus run the following regression:

$$y_{isb,2015-16} = \alpha + \beta D_s + f(location_s) + g(y_{isb,2014-15}) + \gamma X_{isb} + \phi_b + \epsilon_{isb,2015-16}\ , \qquad (3.1)$$

where $y_{isb,2015-16}$ is the outcome (e.g., test score) of student i in school s along boundary segment b in the 2015-16 school year, D_s is a dummy variable equal to one if student i attends a school within five miles (rounded to first decimal point) of the gas leak, $f(location_s)$ flexibly controls for geographic location (various control functions are explored), $g(y_{isb,2014-15})$ is a flexible cubic polynomial of lagged test scores (interacted with grade dummies), X_{isb} are student demographics and fixed school characteristics, and ϕ_b are boundary segment fixed effects. Our coefficient of interest is β, which represents the effect of being just within five miles of the gas leak (and thus receiving air filters) compared to being just outside (and not receiving air filters).

[22]Specifically, I split the southern side of the five-mile boundary shown in Figure 1 into a western and eastern boundary segment so that there are six elementary schools receiving air filters within 1.5 miles of the boundary for each segment.

To ensure that only nearby schools are compared, I restrict equation (3.1) to schools 3.5-6.5 miles of gas leak, although sensitivity to this bandwidth is explored in Figure A.3 with results being qualitatively and quantitatively similar across various bandwidth selections. For graphical exposition, the paper's main specification controls for geographic location, $f(location_s)$, using unidimensional distance to the gas leak along with boundary segment fixed effects. For robustness, I also always report results controlling for latitude-longitude space and report results using different functional forms in Table A.4.

Validity: The spatial regression discontinuity approach requires that all factors besides air filters that determine test scores are evolving smoothly with respect to distance from the gas leak (conditional on controls). This assumption is needed to ensure that students located just outside five miles of the leak are an appropriate counterfactual for those located just within. For example, it would be problematic if district officials chose the five-mile boundary strategically as student test scores were trending downward in schools just closer than five miles to the gas leak. This appears unlikely, however, as the radius was set by the furthest confirmed *odor* complaint received.

Another concern might arise that students could switch to a school with air filters after they were installed in January. For this reason, I assign students to schools based on the *fall* semester enrollment reports from the LAUSD, which eliminates the ability for students to sort in response to air filter installations (as air filters were not announced until the spring semester).

The plausibility of the assumption can also be assessed by checking whether observable covariates evolve smoothly with respect to distance from the gas leak near the five-mile boundary. To do so, I estimate equation (3.1) using observable student covariates (rather than test scores) as the dependent variable. Table A.2 shows that these covariates evolve smoothly at the five-mile boundary: there are no statistically significant discontinuities at the five-mile boundary in the twelve covariates investigated.

Standard errors: Given that treatment assignment is at the school level, it is natural for standard errors to be clustered at that level. Unfortunately, the main RD sample (with a bandwidth of 1.5 miles) has only twenty-three schools. Such a small number of clusters can lead to overly optimistic standard errors and so all inference in the paper follows from clustering at the school level and using the wild cluster bootstrap procedure from Cameron, Gelbach, and Miller (2008).[23]

3.2 Data

I use detailed administrative data from the Los Angeles Unified School District (LAUSD) which includes all public school students and teachers in the district. They contain information about the number of student absences along with detailed student demographics such as gender, race, age, parental education, English learner status, free or reduced price lunch status and language spoken at home. Crucially, data also contain the ZIP Code of student residence, allowing for residential location to be controlled for using residential ZIP Code fixed effects.[24]

Test scores for each student in mathematics and English Language Arts for grades 3-8 come from state standardized tests. I focus my analysis on the 2014-15 through 2016-17 school years, although data are available from 2005-06 through 2016-17 which I use for a placebo test (see Figure 3). Test score data for 2013-14 are missing, however, due to a change in testing regimes that year to align with the Common Core State Standards. Test score results from 2014-15 through 2016-17 come from online Smarter Balanced Assessments, a comprehensive end-of-year assessment in mathematics and English language arts of grade-level learning that consists of two parts: (i) a computer adaptive test, and (ii) a performance task. These tests are administered each spring[25] to all students except those whose Individ-

[23]The wild clustered bootstrap is implemented using the 'boottest' command from Roodman, Nielsen, MacKinnon, and Webb (2019) with 999 replications.

[24]These ZIP Code boundaries are shown in Figure A.1, with each ZIP Code covering about eight square miles.

[25]Testing dates vary school-to-school with the official testing window for 2015-16 extending from March 9 through June 10. Most schools appear to conduct the tests in May, starting with English in the first two weeks followed by math in the final two weeks of May.

ualized Education Plan requires the student take an alternative assessment and those whose parents opt out.[26] I standardize these tests to have a mean of zero and a variance of one for each grade-year-subject cell.

To assign students to schools, I use the December enrollment reports to eliminate the possibility that students change schools in response to schools installing air filters. End-of-year enrollment reports for June are also available and indicate few students switch schools: only 23/3945 students in the main analysis sample switch schools between the December and June enrollment reports.

I also obtain air quality measures from two sources. First, I gather school-level air testing results from all twenty schools within the five-mile policy boundary conducted in response to the gas leak.[27] Second, I obtain daily pollution readings for the 2015 and 2016 calendar years from the nearest EPA air quality monitor. This air monitor is located approximately 3 miles south of the five-mile gas leak boundary and is indicated on Figure 1. These data are used in Section 5 to interpret the generalizability of the effect of air filters to other settings.

I focus my analysis on elementary schools as there are only seven middle schools in the region of interest 3.5-6.5 miles from the gas leak (there are twenty-three elementary schools), leaving few middle schools in close proximity around the boundary. In addition, two of these middle schools are gifted/high ability magnet schools, which are unlikely to be comparable to other local schools since they draw the highest ability students from throughout Los Angeles. Regardless, I always include results with these schools in the main results table; results become more pronounced with their inclusion.

I make two additional data restrictions. First, due to potential disruptions, I omit students attending the two schools closest to the gas leak who were relocated in January as well as the two schools these students were relocated to (although all these schools lie outside the 3.5-6.5-mile main analysis sample). Second, I omit students attending the two independent

[26] English learners who are in their first 12 months of attending a school in the United States are also not required to take the English language arts test.

[27] Air testing results are available at `https://achieve.lausd.net//site/Default.aspx?PageID=10329`.

elementary charter schools in the region of interest 3.5-6.5 miles from the gas leak as these schools were not part of the LAUSD-SoCalGas agreement due to their independence from the LAUSD.[28]

Summary statistics for the 2015-16 school year are reported in Table 1. Column (1) shows student characteristics for all students in the LAUSD. The LAUSD is a majority Hispanic district (about 75 percent), with white and black students each making up a further ten percent. In terms of socioeconomic status, almost 90 percent of LAUSD students receive free and reduced price lunch, with one-third of their parents being high school dropouts and less than one-quarter graduating college. Column (2) restricts the sample to observations that are within 1.5 miles of the five-mile boundary, which is the main sample that is used for the analysis. There are substantial differences between these students and LAUSD as a whole, coming from the fact the neighborhoods near the gas leak are some of the wealthiest in Los Angeles. Correspondingly, students in this area score 0.35σ higher on end-of-grade standardized tests and are far more advantaged, with almost 40 percent coming from college graduate households and only 75 percent of them receiving free and reduced price lunch. These students are also much more likely to be white and Asian and far less likely to be Hispanic or black. Column (3) further restricts the spatial RD sample to students with valid lagged math and English scores. This sample is similar to that in column (2) and represents the main analysis sample, which consists of 3,945 students.

4 Results

This section starts with descriptive evidence relating to the impact of air filters on pollutants measured by air testing that was conducted inside schools. Then, estimates of the effect of air filters on student achievement along with their persistence are provided. Robustness of the results to outliers, functional form, and bandwidth is also examined along

[28]These schools could, however, have separately requested air filters from SoCalGas although I have no record of the one independent charter school in the five-mile zone receiving air filters. Results are qualitatively and quantitatively similar if these schools are included and are available upon request.

with a placebo test whereby the spatial RD is run each year in the decade preceding the gas leak.

4.1 Main Results

Air Filters and Measured Pollutants: Delivery of plug-in air filters for schools within five miles of the leak was announced on January 28^{th} and air quality testing at these schools was conducted January 19-February 22. Given this, eight schools had their air tested both before *and* after the plug-in air filters were delivered, affording the opportunity to study the impact of the air filters on tested pollutant levels.[29] While air testing was restricted to methane (primary component of natural gas) and volatile organic compounds (namely benzene, toluene, ethylbenzene and xylene) rather than particulate matter which has been the focus of much of the literature, we can still check whether air filters reduced the concentration of these pollutants.

Table 2 reports levels of these pollutants before and after the plug-in air filters were delivered among all these eight schools. A clear pattern emerges whereby pollutant levels fall after the air filters were provided. The final row aggregates these results by regressing pollutant levels on an indicator for the period after the air filters were delivered along with school fixed effects.[30] The reduction in methane and volatile organic compounds concentrations are large and statistically significant: methane levels dropped by 17 percent, while volatile organic compounds levels fell by 60-100 percent (depending on the compound), a number in line with the 52-73 percent removal performance of plug-in air filters for benzene found in Polidori et al. (2013).[31] Given the fall in these pollutants, we would expect the air

[29]The exact date of delivery is unknown, so I omit tests conducted Jan 28-Feb 5 to allow for a one week 'delivery and installation' window. Table A.1 also reports the number of times each school within five miles of the leak was tested and the maximum reading of each pollutant at these schools.

[30]Specifically, it reports the result of the following regression: $pollutant_{st} = \alpha_s + \beta_1 \mathbb{1}\{AfterFilter\}_t + \epsilon_{st}$, where $pollutant_{st}$ is the pollutant level, $\mathbb{1}\{AfterFilter\}_t$ is a post air filter delivery indicator which equals one if date is after Feb 5 (and zero before Jan 28), and α_s are school fixed effects.

[31]Polidori et al. (2013) focus on particulate matter, although do provide limited results for volatile organic compounds. Unfortunately, the data recovery for the summa canisters was "insufficient to guarantee an adequate interpretation of the results" at two of the three schools. Results are therefore only reported for

filters to deliver a similar decrease in particulate matter (although we cannot attribute the effect of air filters to a decline in any particular pollutant).

Air Filters and Student Performance: Figure 2 provides a visual representation of the spatial RD design by plotting test score growth by distance to the Aliso Canyon gas leak. *A priori*, we expect test score growth will be increasing in distance to the gas leak because residents closer to the leak were likelier to relocate, causing a disruption which would presumably lower student performance. As expected, student test score growth is increasing in the distance of their school to the gas leak. Once the distance to the gas leak (rounded to the first decimal point) exceeds five miles, we see a substantial drop in test score growth in both math and English. As this is the point where air filters were no longer installed in schools, this provides clear and convincing evidence that air filters substantially raised test scores.

Table 3 reports these findings in regression form using equation (3.1). As was apparent from Figure 2, students who attend a school within five miles of the gas leak see a substantial increase in test scores. Column (1) reports a basic specification with only lagged test scores as controls, while columns (2) and (3) add demographic controls and residential ZIP Code fixed effects, respectively. Point estimates are remarkably similar across specifications: air filters raised scores by 0.20-0.22σ in math and 0.18-0.20σ in English. Results remain consistent once geographic latitude and longitude controls are added in column (4) and middle schools are included in column (5). Standard errors clustered at the school level are reported in parentheses below the point estimates. Given concerns about the number of clusters, however, I conduct all inference using the wild clustered bootstrap procedure, clustering at the school level (Cameron et al., 2008): p-values from this procedure are reported in square brackets.[32] For all specifications, results are statistically significant at the five percent level for math, although they are generally not statistically significant for English.

one school, with benzene being the only individual volatile organic compound results are reported for.

[32] P-values rather than standard errors are reported for the wild clustered bootstrap since it generates asymmetric confidence intervals.

Persistence: Table 4 reports the effect of air filters installed in January 2016 on student achievement at the end of the *2016-17* school year. Specifically, I alter the regression equation described in equation (3.1) by replacing the dependent variable $y_{isb,2015-16}$ with $y_{isb,2016-17}$. Columns (1) and (2) report the results and show that air filters installed in January 2016 raised *2016-17* test scores by 0.10σ in math, although these results are not statistically significant.

These longer-run results are difficult to interpret, however, for two reasons. First, while schools continue to have the plug-in air filters in future years, it is unclear whether they continued to maintain and operate them. Second, fifth grade students in 2015-16 have transitioned to a new school for 2016-17 and these new schools may be outside the five-mile boundary and so did not receive air filters.[33] Given that, many students who did not have air filters in 2015-16 received air filters in 2016-17 (and vice versa), with 52 percent of fifth grade students in 2015-16 who were in a school without an air filter moving to a middle school with air filters in 2015-16. Since a large number of fifth grade students without air filters in 2015-16 enter middle schools with air filters in 2016-17, there will be a large jump in test scores among these students, causing the estimated discontinuity based on 2015-16 school assignment to fall. Indeed, I find that the impact of air filters in 2016-17 for fifth grade students in 2015-16 is not statistically different from zero (and is actually negative).[34]

Column (3) excludes these students who switch schools due to the transition to middle school, leaving us with only fifth grade students (who were in fourth grade in 2015-16).[35] These students almost entirely remained in the same school, with only one percent of them switching from a school without air filters to schools with them (or vice versa). For these students, I find that the impact of air filters persists into 2016-17: The spatial RD estimate

[33] All elementary schools that are 3.5-6.5 miles from the gas leak have a K-5 grade span.

[34] While not statistically significant, a negative point estimate could potentially arise in this situation for two reasons: (i) test score convergence between 'treated' and 'untreated' students due to their mixing in sixth grade (i.e., SUTVA assumption is clearly violated among these students), or (ii) through behavioral responses if, for instance, students who were surprised by their high scores in 2015-16 reduced their effort.

[35] Fourth grade students in 2016-17 are not included as they lack lagged test scores (as there was no second grade test in 2014-15).

indicates two years of air filter exposure raises math scores by 0.30σ among these students, although this effect is only statistically significant at the ten percent level. The effect does, however, become statistically significant at the five percent level in column (5) once non-transitioning middle school students are also included (e.g., sixth and seventh grade students in 2015-16). A similar story arises for English scores, although the point estimates are smaller and never statistically differ from zero.

4.2 Robustness

I examine robustness to the results above by running placebo tests that estimate the effect of being within five miles of the gas leak in years before the leak actually happened, checking sensitivity to outliers, varying the control function for geographic location, and altering the chosen bandwidth.

Placebo Test: Figure 3 estimates the impact of being within five miles of the gas leak for the preceding decade. Note that the 2013-14 and 2014-15 school years are omitted due to the lack of test score data in 2013-14 (implying no lagged test scores for 2014-15). The figure shows that the largest estimated impact of being within five miles of the gas leak occurs in 2015-16, the year when the air filters were installed. Indeed, the estimated effect of being within five miles of the gas leak in all other years is not statistically different from zero (and is mostly negative).

Outliers: In 2015-16, the school furthest to the gas leak that still received air filters, Andasol Avenue Elementary, had a tremendous 0.35σ and 0.20σ growth in math and English scores, respectively. To ensure that results are not driven entirely from this one outlier, I rerun the results excluding the 133 students at this school from the analysis. Table A.3 recreates the main RD results from Table 3 omitting students from Andasol Avenue Elementary. For mathematics, estimates fall but remain statistically significant across all specifications considered. For instance, the preferred estimate from column (3), which controls for demographics and ZIP Code fixed effects, falls from 0.20σ to 0.13σ with Andasol Avenue

Elementary excluded, but remains statistically significant at the five percent level using the wild clustered bootstrap procedure for inference (p-value=0.031). English scores similarly fall from 0.18σ to 0.10σ (and remain statistically insignificant).

Functional Form: Table A.4 shows robustness of the main results to using various functional forms to control for geographic location. Columns (2) and (3) show estimates controlling for distance from the five-mile boundary using a quadratic and a triangular kernel as the functional form (rather than linear). Estimates using these functional forms are larger (although not statistically significantly so), as they give greater weight to schools nearest the boundary, one of which had a very large increase in test score growth (see 'outliers' heading regarding this observation). Column (4) interacts the linear functional form with the boundary fixed effects, while column (5) uses a quadratic latitude-longitude control: both these estimates are similar to those using the linear distance control. Overall, estimates appear consistent across different functional forms and range between 0.2-0.3σ and 0.15-0.35σ for math and English, respectively.

Bandwidth: Figure A.3 plots spatial RD estimates using various bandwidths from 0.75 to 2.5 miles.[36] For both math and English, magnitudes decline with bandwidth size since larger bandwidths reduce the impact of the final school within the five-mile radius with the large test score increase (see outliers heading regarding this observation). The effect for math remains statistically different from zero for all bandwidths considered, with the effect size ranging from 0.15-0.3σ. English scores similarly range between 0.1-0.35σ, but are only significantly different from zero at bandwidths below 1.25 miles.

5 Discussion

While the results above indicate air filters substantially improve student achievement in this particular context, a natural question arises as to whether these effects extend to other

[36] I stop the figure at 2.5 miles as there are no schools closer than 2.5 miles from the leak that were not evacuated.

settings. Here, I highlight two context-specific features of this study and discuss whether these limit external validity: (i) the presence of the gas leak, and (ii) the level of ambient air pollution. I end the section with a suggestive cost-benefit exercise.

5.1 External Validity

Presence of Natural Gas: One particular concern for external validity is that schools in this setting are situated near the largest gas leak in United States history, which might make air filters particularly effective since they are filtering out pollutants from the natural gas leak (e.g., methane) that are unlikely to be in such concentrations elsewhere. To investigate this, I use the fact that air testing was conducted at all schools within five miles of the leak to check for the presence of dangerous levels of pollutants associated with natural gas. Here, as noted, these air quality tests checked for air pollutants associated with natural gas rather than indoor air quality in general.

Air testing initially began in the two schools nearest to the leak at the end of November. These schools were tested every school day from November 30 until December 18, when they were closed for Christmas break and students were subsequently relocated. Both schools showed elevated levels of methane, ethane and xylenes, although all were well-below the regulatory limit from the California Office of Environmental Health Hazard Assessment. After Christmas break, air testing was done for the remaining eighteen schools within five miles of the gas leak between mid-January through mid-February. Many of these tests were thus conducted before the plug-in air filters were delivered around January 28. For each school, testing was conducted at least two times, with five schools receiving three or four tests and three schools receiving five or six tests.

Table A.1 reports the maximum reported value for six tested pollutants over the tests at a given school. While methane, ethane and xylenes levels appear elevated for the two schools nearest the gas leak (that were subsequently closed), the remainder of the schools do not appear to have inflated levels of pollutants. In addition, no relationship is apparent between the distance of the school to the leak and air pollutants, suggesting that pollution from the gas leak was not substantially affecting air quality within these schools.

These air testing results agree with results from a very accurate laser-based methane detector that was driven around Los Angeles neighborhoods, as documented in Phillips et al. (2016). The researchers reported these results with images on the Home Energy Efficiency Team (HEET) website,[37] with Figure A.2 showing one such visualization. The image makes clear that the natural gas is concentrated north of the Ronald Reagan Freeway, which is about two miles south of the gas leak. Since the schools that are analyzed are all over 3.5 miles from the gas leak, it appears that methane concentrations are not abnormally high for these schools, aligning with the results from the in-school air testing.

Pollution Levels in Los Angeles: Air quality in Southern California is known to be some of the worst in the United States, indicating that air filters might be particularly effective in this region. The gas leak occurred in Porter Ranch, however, which is known for having some of the cleanest air in the San Fernando Valley. Readings from the nearest air monitor to the gas leak indicate $PM_{2.5}$ concentrations of $7.33\mu g/m^3$ from January to June 2016 and an annual mean $PM_{2.5}$ concentration for 2016 of $9.12\mu g/m^3$. In comparison, annual mean $PM_{2.5}$ concentrations in 2018 for other highly-populated cities in the United States were: $9.54\mu g/m^3$ in New York City, $9.63\mu g/m^3$ in Chicago, $10.63\ \mu g/m^3$ in Houston, and $7.95\mu g/m^3$ in Philadelphia.[38] Ambient air pollution (as measure by $PM_{2.5}$) thus exceeds that in our region of analysis in three of the four largest cities in the United States (excluding Los Angeles), indicating that air filters have the potential to benefit a substantial number of schools across the country.

[37] Photographs from this imaging are available at `https://web.archive.org/web/20160712201258/http://www.heetma.org/porter-ranch-gas-leak-images/` and a video showing these visualizations is also available at `https://www.youtube.com/watch?v=aU1pmzKPCcE`.

[38] Annual $PM_{2.5}$ concentrations for these cities came from the air monitor nearest to the city center.

5.2 Cost-Benefit Analysis

In order to assess whether installing air filters in schools is worthwhile, the cost of filters must also be considered. The air filters that were installed cost approximately \$700 per unit,[39] which I assume (conservatively) last five years.[40] In addition, the activated carbon in these air filters must be replaced yearly at a cost of \$300, and running the filter adds around \$24 a month to the electricity bill in high-cost electricity regions.[41] The cost of installing and operating a single air filter during the academic year is thus approximately \$680 ($\approx$700/5 + 300 + 24*10). Air filters in this setting were also installed in common areas and offices in the school: Given this, I calculate that 1.5 air filters are required for each classroom.[42] I therefore (conservatively) estimate that the yearly cost per class to install air filters throughout a school is \$1,000.

Consequently, air filters raise test scores by about 0.2σ per \$1,000 of expenditure. This benefit-to-cost ratio is extraordinarily high when compared to other expenditures policymakers might consider to raise test scores. Krueger (1999), for instance, finds that reducing class sizes by seven students (from a base of twenty-two) raises test scores by 0.2σ. To reduce class size by this amount requires about one additional teacher for every two classes, signifying a substantial cost as teacher earn, on average, almost \$75,000 per year in Los Angeles (excluding benefits). The benefit-to-cost ratio of air filters is therefore over twenty times that of the class size reduction policy considered by Krueger (1999). Indeed, a benefit-to-cost ratio of 0.2σ per \$1,000 of expenditure indicates air filter installation might well be the most cost-efficient (in terms of dollar per test score) educational intervention available to poli-

[39] The \$700 per unit cost comes from statements made by SoCalGas' Vice President of Customer Services (Gillian Wright) during meetings with the Porter Ranch Community Advisory Committee. Minutes of these meetings are available at `http://www.prcac.com/committee-meetings/`.

[40] This is a very conservative assumption given that high-end air filters often come with a ten-year warranty.

[41] Electricity cost estimates come from `https://ww3.arb.ca.gov/research/indoor/aircleaners/air_cleaners_gas_leak.htm`.

[42] Unfortunately, the number of air filters supplied to each school is only known for Granada Hills Charter High School (from a press release), which received 210 plug-in air filters. Given average class size at this school is 30.5 and there were 4,480 students, this suggests delivery of 1.43 (= 210/(4480/30.5)) air filters per classroom to cover offices and common areas. Conservatively, this suggests schools need about 1.5 air filters per classroom.

cymakers, outperforming the cost-effectiveness of notable interventions such as high dosage tutoring (Cook et al., 2015), Perry Preschool (Schweinhart et al., 2005), cash transfers from the EITC (Dahl and Lochner, 2012), and Head Start (Ludwig and Phillips, 2007).

6 Conclusion

This paper has taken advantage of a unique policy setting arising from the largest gas leak in United States history to estimate the effect of air filters on student achievement. To do so, I used a spatial regression discontinuity design to exploit the fact that all schools within five miles of the leak received air filters. I found that installing air filters in schools raised student achievement substantially, increasing test scores in mathematics and English by 0.20σ.

Next, I showed that the unique setting analyzed does not limit the external validity of the results. I found few pollutants associated with natural gas in schools in the region of analysis, suggesting that the air filters are not generating large improvements in test scores by filtering out abnormal amounts of natural gas pollutants that are unlikely to be present elsewhere. The ambient air pollution near the leak is also relevant for many large cities, with the three largest cities in the United States (excluding Los Angeles) having higher levels of particulate air pollution.

My analysis complements prior research which has established that air pollution negatively affects student health and cognition by analyzing a policy that can improve the air quality faced by students. Furthermore, air filter installation is low in cost, allowing for the negative effects of pollution to be partially offset at costs far lower than large-scale air improvement policies. Indeed, with a benefit-to-cost ratio of 0.2σ increase in test scores per $1,000 of expenditure, air filter installation is one of the most cost-effective education policies available to policymakers today. In addition, the negative effects of air pollution are not spread evenly across the United States population. Specifically, economically disadvantaged students disproportionately attend schools in highly-polluted regions. Given this fact, installing air filters in polluted regions should both raise student achievement and reduce the pervasive test score gaps that plague public education.

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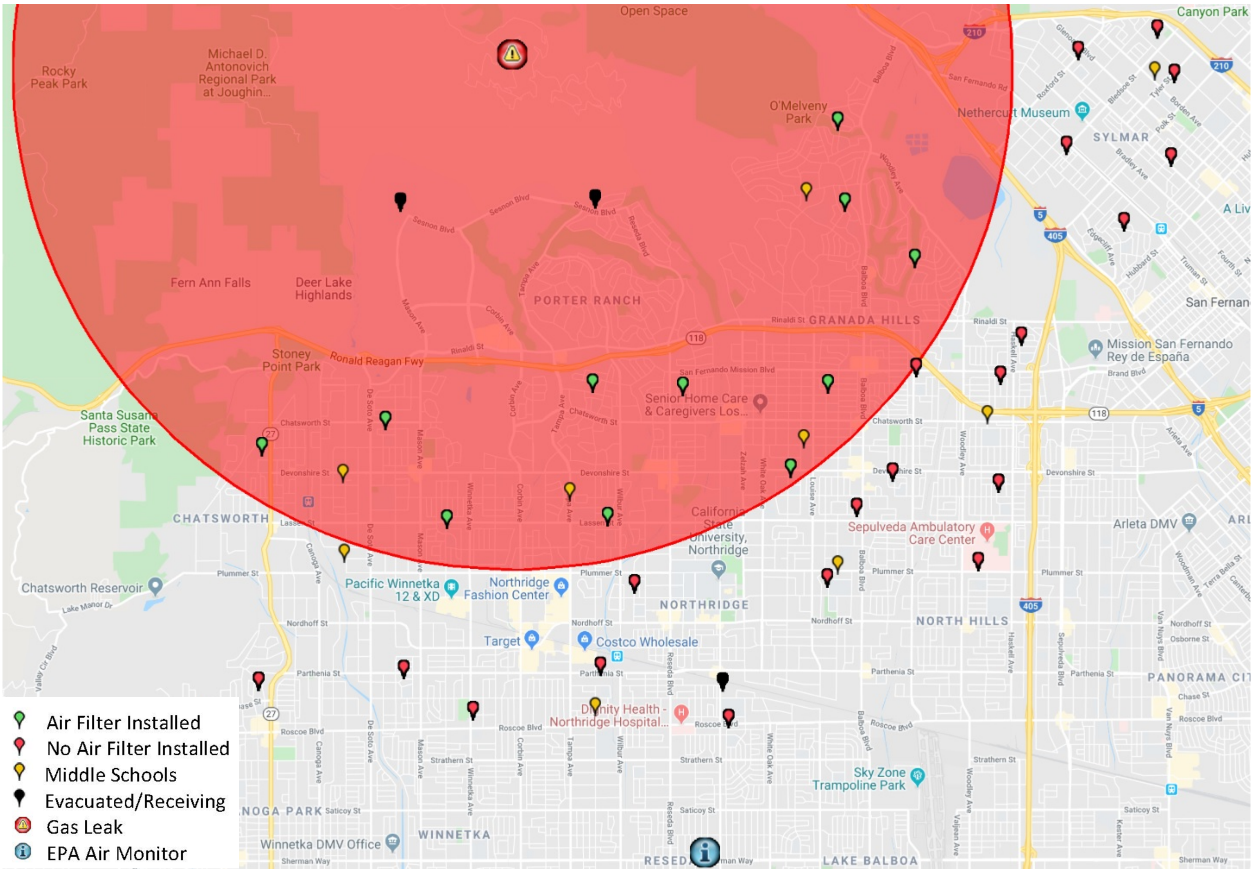
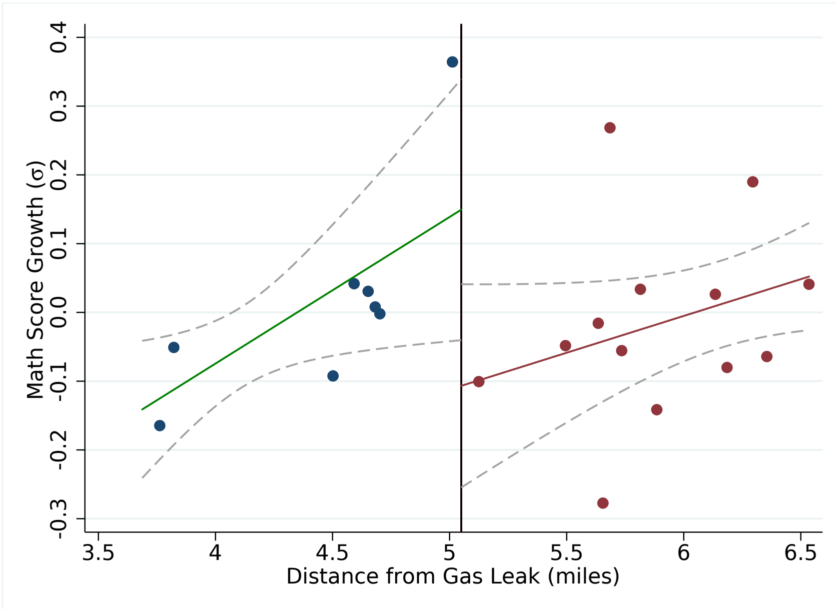
Figure 1: Map of Region of Interest



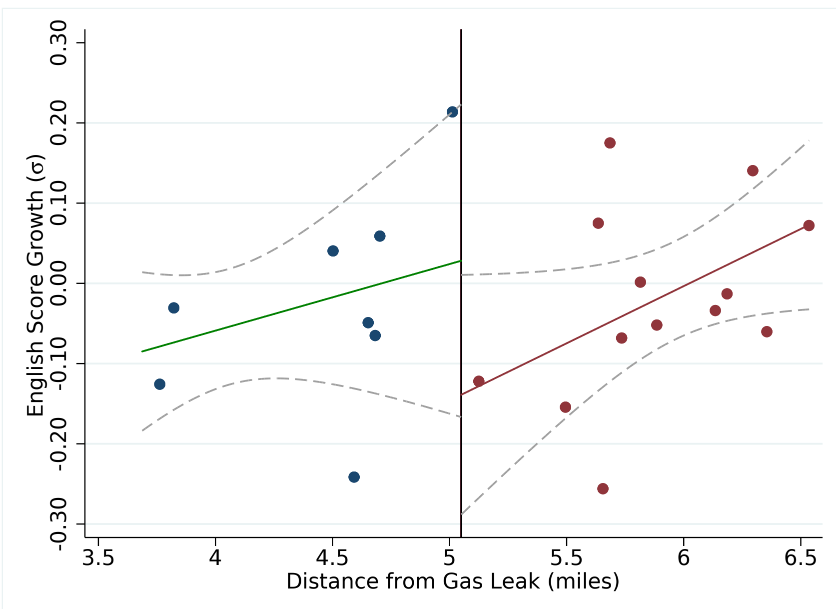
Notes: This figure shows the location of all 34 elementary schools in the Los Angeles Unified School District within seven miles of the Aliso Canyon gas leak. The 11 elementary schools that received air filters are denoted with a green pin, while I denote the 20 schools that did not receive air filters with a red pin (of which 12 are within 6.5 miles of the leak and so are included in the main analysis sample). Schools that were evacuated (two schools nearest to the gas leak) or received evacuated students (only one school noted in figure as the other school receiving evacuees is further than 7 miles from the leak) are denoted with black pins and are excluded from all analysis. The 9 middle schools within seven miles of the leak are indicated with an orange pin (of which 7 are within 3.5-6.5 miles of the leak). Five independent charter schools (two elementary and three middle schools) were omitted from the figure as they were not part of the LAUSD-SoCalGas air filter agreement (of these, only two schools are within the 3.5-6.5-mile main analysis region). The red circle indicates a five mile (rounded to first decimal point) radius from the gas leak. The location of the gas leak and the location of the nearest EPA air monitor are also shown.

Figure 2: Test Score Growth by Distance to Leak

(a) Math Score Growth



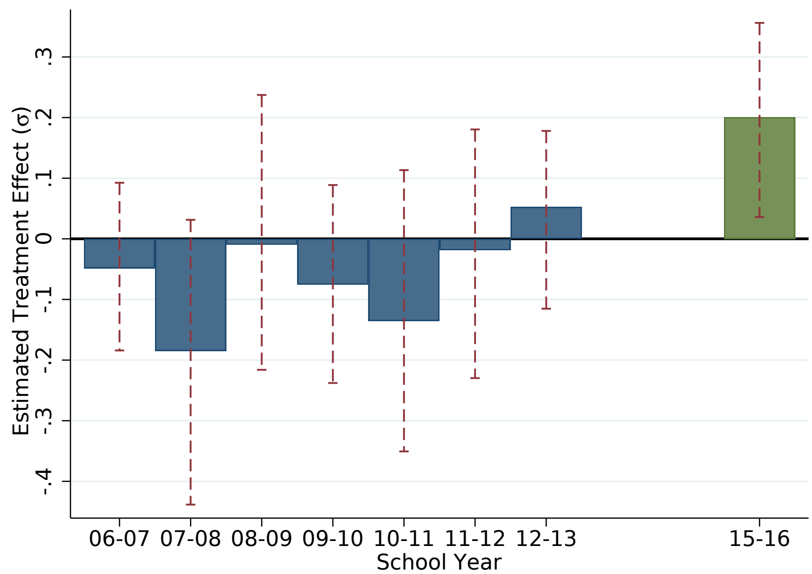
(b) English Score Growth



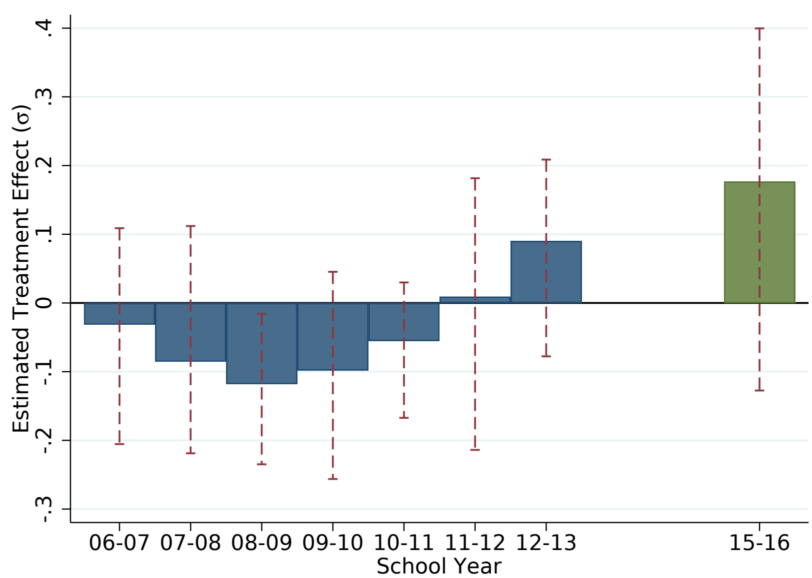
Notes: Figures show test score growth for individual students from 2014-15 to 2015-16 (e.g., current minus prior year test score) by distance to the Aliso Canyon gas leak. Figures 2(a) and 2(b) are based on 3,940 and 3,945 observations, respectively. The vertical line represents five miles (rounded to first decimal point) from the gas leak after which air filters were no longer installed in schools. Dashed lines represent 95% confidence intervals with standard errors clustered at the school level.

Figure 3: Robustness: Placebo Years

(a) Math Score



(b) English Score



Notes: This figure plots spatial RD estimates from equation (3.1) by year from 2006-07 through 2015-16. School years 2013-14 and 2014-15 are omitted due to no test scores being available in 2013-14. Controls for lagged test scores, demographics and residential ZIP Code fixed effects are used and thus the point estimate for the 2015-16 school year is the same of that reported in column (3) of Table 3. The dashed whiskers represent 95 percent confidence intervals with inference done clustering at the school level and using the wild cluster bootstrap procedure from Cameron et al. (2008).

Table 1: Summary Statistics for 2015-16

	Full Sample[1]	RD Sample[2] (3.5-6.5 miles)	Test Score RD Sample[3] (3.5-6.5 miles)
	(1)	(2)	(3)
Mean of Student Characteristics			
Math Score (σ)	0.00	0.35	0.36
English Score (σ)	0.00	0.36	0.37
Lagged Math Score (σ)	0.02	0.37	0.37
Lagged Reading Score (σ)	0.01	0.38	0.38
Days Absent	6.38	5.96	5.88
% Hispanic	73.6	59.2	59.5
% White	10.9	21.2	21.0
% Black	8.8	4.5	4.4
% Asian	4.4	9.9	9.8
% Free/Reduced Price Lunch[4]	88.5	74.9	74.6
% English Learners	28.4	16.2	15.7
Parental Education:[5]			
% High School Dropout	29.2	11.9	11.8
% High School Graduate	30.2	24.6	24.4
% Some College	18.1	24.6	24.8
% College Graduate	22.5	37.4	39.0
# of Students	90,042	4,215	3,945

[1] Data cover grades 4-5 in the Los Angeles Unified School District during the 2015-16 school year.

[2] RD Sample is restricted to students attending LAUSD schools within 3.5 and 6.5 miles of the Aliso Canyon gas leak.

[3] Test Score RD Sample is the same as column (2), but further restricted to students with valid lagged math and English language arts scores.

[4] Data are missing in the full sample for eleven percent of observations, increasing to eighteen percent in the RD sample.

[5] Data are missing in the full sample for twenty-five percent of observations where parental education was recorded as "Decline to Answer," dropping to thirteen percent in the RD sample. College graduate also incorporates those with post-graduate education.

Table 2: Air Testing Results Before and After Air Filter Delivery

School Name		Times Tested	Methane (ppbv) (1)	Benzene (ppbv) (2)	Toluene (ppbv) (3)	Ethylbenzene (ppbv) (4)	Xylenes (ppbv) (5)
Robert Frost Middle	**Before:**	2	3,525	0.565	3.7	0.53	3.6
	After:	1	3,470	0.23	0.8	None	0.26
Van Gogh Charter	**Before:**	2	3,290	0.365	3	0.28	1.5
	After:	1	3,670	None	0.45	None	0.24
Beckford Charter	**Before:**	3	4,183	0.41	1.2	0.35	2.33
	After:	2	3,575	0.23	0.31	None	1.4
El Oro Way Charter	**Before:**	1	2,920	0.45	2.4	0.24	1.2
	After:	1	3,220	0.24	0.21	None	None
Darby Avenue Charter	**Before:**	3	4,795	0.65	8.21	1.63	5.35
	After:	2	3,210	0.23	0.37	None	1.7
Germain Academy	**Before:**	2	4,130	0.96	2.65	0.63	4.05
	After:	3	2,990	0.59	4.43	None	1.67
Knollwood Preparatory	**Before:**	1	3,230	0.54	4.2	0.49	3.1
	After:	1	2,900	0.20	0.33	None	None
Superior St. Elementary	**Before:**	2	4,215	0.71	7.4	0.95	5.2
	After:	2	3,245	0.22	1.01	None	0.47
All Schools	**Before:**	16	3,907	0.58	4.27	0.71	3.50
	After:	13	3,275	0.29	1.42	None	0.97
Regression Result: Pollutant Regressed on 'After Filter' Indicator with School Fixed Effects:							
After Filter			-646.4*	-0.34***	-3.09	-0.71***	-2.64***
[p-value]			[0.08]	[0.00]	[0.13]	[0.00]	[0.00]

Notes: This table shows pollutant readings from the air testing conducted by Waterstone Environmental as part of the air testing program conducted by the LAUSD in response to the Aliso Canyon gas leak before and after the plug-in air filters were delivered. Only schools with tests conducted *both* before and after the air filters were delivered are included. I omit all tests conducted from Jan 28 - Feb 5 to allow one week for the delivery and installation of plug-in air filters after the Jan 28^{th} announcement date. 'After' thus captures tests conducted Feb 9 - Feb 22, while 'before' includes tests conducted Jan 19- Jan 27 and also incorporates one Dec 2 test conducted at Beckford Charter. 'Regression Result' reports the result of the following regression: $pollutant_{st} = \alpha_s + \beta_1 \mathbb{1}\{AfterFilter\}_t + \epsilon_{st}$, where $pollutant_{st}$ is the pollutant level, $\mathbb{1}\{AfterFilter\}_t$ is an post air filter delivery indicator which equals one if date is after Feb 5 (and zero before Jan 28), and α_s are school fixed effects. The coefficient on 'After Filter' (β_1) is reported and represents the change in concentration of the pollutant after the plug-in air filters were delivered. Pollutant units are in parts per billion by volume (ppbv). Given there are only eight clusters, p-values clustered at the school level using the wild clustered bootstrap procedure from Cameron et al. (2008) are reported below the standard errors in square brackets. Using inference from the wild clustered bootstrap procedure, ***,** and * denote significance at the 1%, 5% and 10% levels, respectively. Air testing results are available at `https://achieve.lausd.net//site/Default.aspx?PageID=10329`.

Table 3: Regression Discontinuity Estimates

	Elementary Schools Only				Middle Schools Included
	(1)	(2)	(3)	(4)	(5)
Panel A. Outcome: Math Scores					
Within 5 Miles	0.223**	0.202**	0.201**	0.186**	0.228**
(clustered s.e.)	(0.094)	(0.076)	(0.062)	(0.059)	(0.064)
[wild cluster bootstrap p-value]	[0.041]	[0.028]	[0.027]	[0.046]	[0.012]
Panel B. Outcome: English Scores					
Within 5 Miles	0.204	0.180	0.177	0.179	0.253*
(clustered s.e.)	(0.116)	(0.099)	(0.089)	(0.086)	(0.083)
[wild cluster bootstrap p-value]	[0.239]	[0.233]	[0.195]	[0.188]	[0.059]
Controls					
Lagged Test Scores	Yes	Yes	Yes	Yes	Yes
Demographic Controls	No	Yes	Yes	Yes	Yes
Residential ZIP Code FEs	No	No	Yes	Yes	Yes
Latitude-Longitude Controls	No	No	No	Yes	No
Observations	3,945	3,945	3,945	3,945	12,587

Notes: Estimates report the effect of air filters on student achievement as described in equation (3.1). Column (5) reports results including the seven middle schools within 3.5-6.5 miles of the gas leak. Each cell is a separate RD estimate from a local linear regression allowing for different functions on either side of the threshold, except column (4) where a second-order polynomial control for latitude-longitude space is used instead. The bandwidth used is 1.5 miles. Effect sizes are in terms of standard deviations of the student test score distribution. 'Lagged test scores' control for a cubic of lagged math and English scores interacted with grade dummies. 'Demographic controls' include gender, ethnicity, free and reduced price lunch status, English learner status, age and age squared interacted with grade, and language spoken at home. Missing indicators are used to control for missing demographics or lagged other-subject scores. 'Residential ZIP Code FEs' are fixed effects for the ZIP Code of student residence. All regressions include grade and boundary segment fixed effects and control for a school's magnet and affiliated charter status. Number of observations are reported for panel B; panel A has five fewer observations as these students lack lagged math scores. Standard errors clustered at the school level are reported in brackets. Given there are only twenty-three clusters, p-values clustered at the school level using the wild clustered bootstrap procedure from Cameron et al. (2008) are reported below the standard errors in square brackets. Conducting inference using the wild clustered bootstrap procedure, ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.

Table 4: Regression Discontinuity Estimates for 2016-17 Outcomes

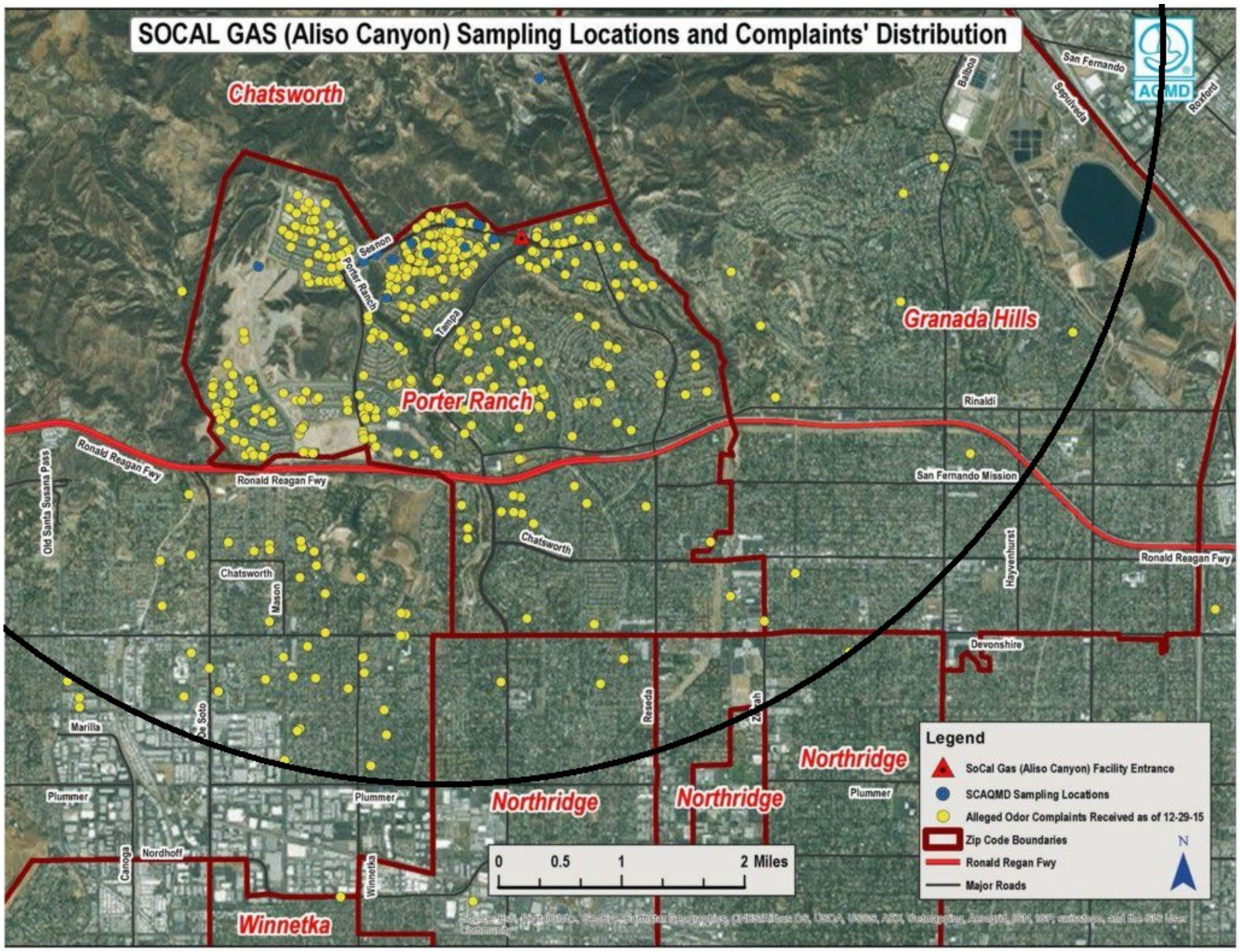
	Elementary Schools Only			*Middle Schools Included*	
	All Grades	All Grades	Transition Grade Excluded[1]	All Grades	Transition Grade Excluded[1]
	(1)	(2)	(3)	(4)	(5)
Panel A. Outcome: 2016-17 Math Scores					
Within 5 Miles	0.105	0.103	0.300*	0.128	0.304**
(clustered s.e.)	(0.093)	(0.067)	(0.112)	(0.076)	(0.115)
[wild cluster bootstrap p-value]	[0.395]	[0.222]	[0.054]	[0.163]	[0.035]
Panel B. Outcome: 2016-17 English Scores					
Within 5 Miles	-0.020	-0.025	0.007	0.054	0.138
(clustered s.e.)	(0.120)	(0.076)	(0.113)	(0.085)	(0.114)
[wild cluster bootstrap p-value]	[0.929]	[0.824]	[0.954]	[0.609]	[0.338]
Controls					
2014-15 Test Scores	Yes	Yes	Yes	Yes	Yes
Demographic Controls	No	Yes	Yes	Yes	Yes
Residential ZIP Code FEs	No	Yes	Yes	Yes	Yes
Observations	3,465	3,465	1,855	8,910	7,330

[1] 'Transition' grade refers to fifth grade students in 2015-16 who have transitioned to a new school in 2016-17 because of the grade span of elementary schools (all elementary schools have a K-5 grade span).

Notes: Estimates report the effect of air filters installed in January 2016 on student achievement at the end of the *2016-17* school year. The regression equation is the same as equation (3.1), but with the dependent variable $y_{isb,2015-16}$ being replaced by $y_{isb,2016-17}$. Columns (4) and (5) report results including the seven middle schools within 3.5-6.5 miles of the gas leak. Columns (3) and (5) exclude students that were in fifth grade during the 2015-16 school year as they transitioned to a new (potentially non air filtered) school. Each cell is a separate RD estimate from a local linear regression allowing for different functions on either side of the threshold. The bandwidth used is 1.5 miles. Effect sizes are in terms of standard deviations of the student test score distribution. '2014-15 test scores' control for a cubic of 2014-15 (i.e., twice-lagged) math and English scores interacted with grade dummies. 'Demographic controls' include gender, ethnicity, free and reduced price lunch status, English learner status, age and age squared interacted with grade, and language spoken at home. Missing indicators are used to control for missing demographics or lagged other-subject scores. 'Residential ZIP Code FEs' are fixed effects for the ZIP Code of student residence. All regressions include grade and boundary segment fixed effects and control for a school's magnet and affiliated charter status. Standard errors clustered at the school the student attended in 2015-16 and are reported in brackets. Given there are only twenty-three clusters, p-values clustered at the school attended in 2015-16 using the wild clustered bootstrap procedure from Cameron et al. (2008) are reported below the standard errors in square brackets. Conducting inference using the wild clustered bootstrap procedure, ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.

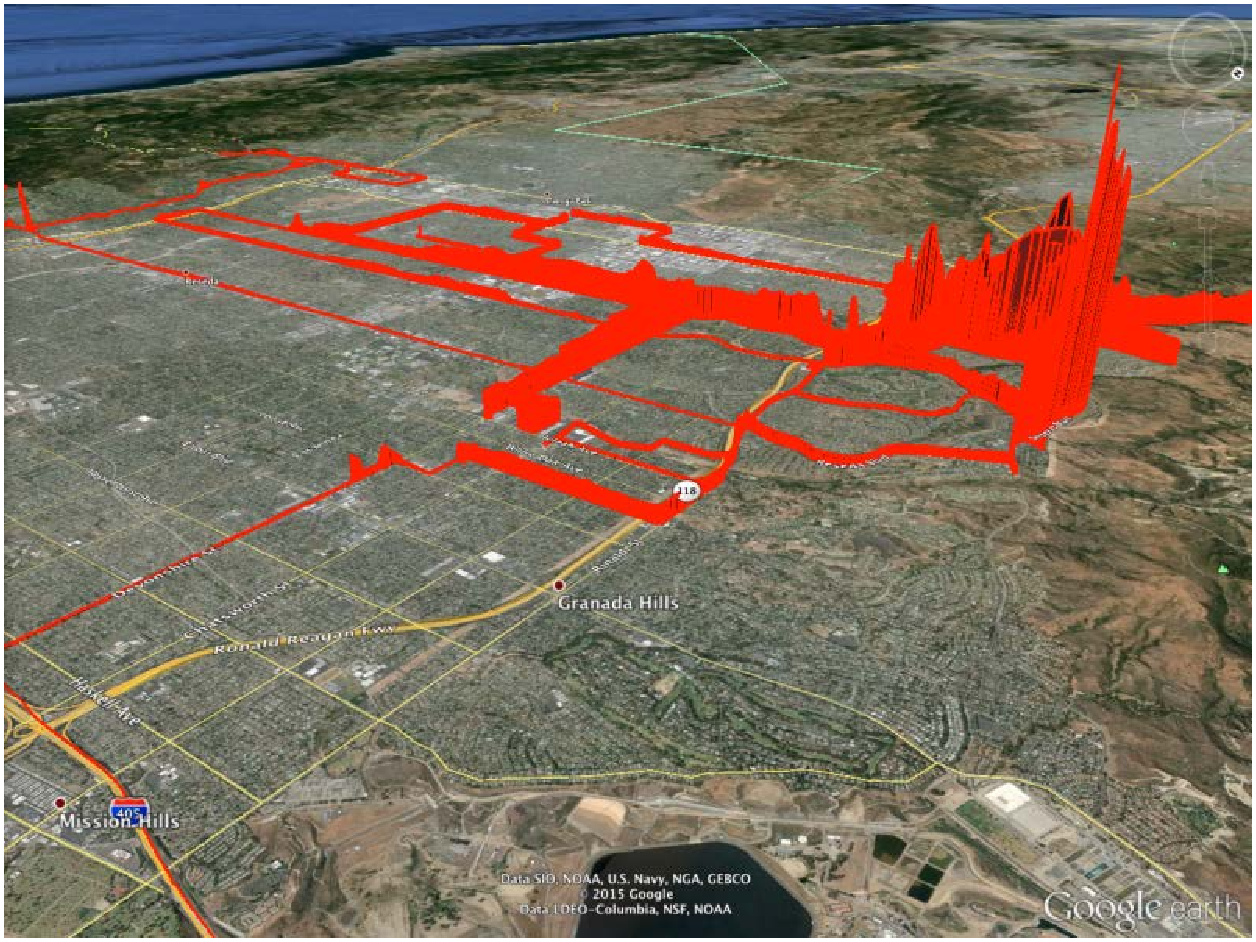
A Appendix Figures and Tables

Figure A.1: Map of Resident Odor Complaints



Notes: This figure shows alleged odor complaints reported to SoCalGas as of December 29, 2015. A black circle representing five miles from the gas leak is superimposed over the figure. Zip Code boundaries are also shown. The figure comes from an interoffice correspondence from the Los Angeles Unified School District Office of Environmental Health and Safety and is available at `https://achieve.lausd.net/cms/lib/CA01000043/Centricity/Domain/135/Informative%20re%20Aliso%20Canyon%20Gas%20LeakUpdate%20%2001%2021%2016.pdf`.

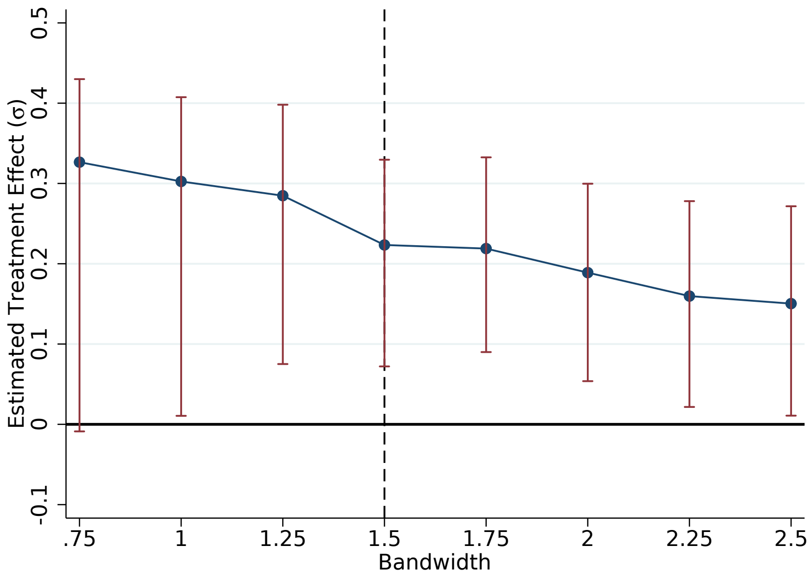
Figure A.2: Map of Methane Measurements



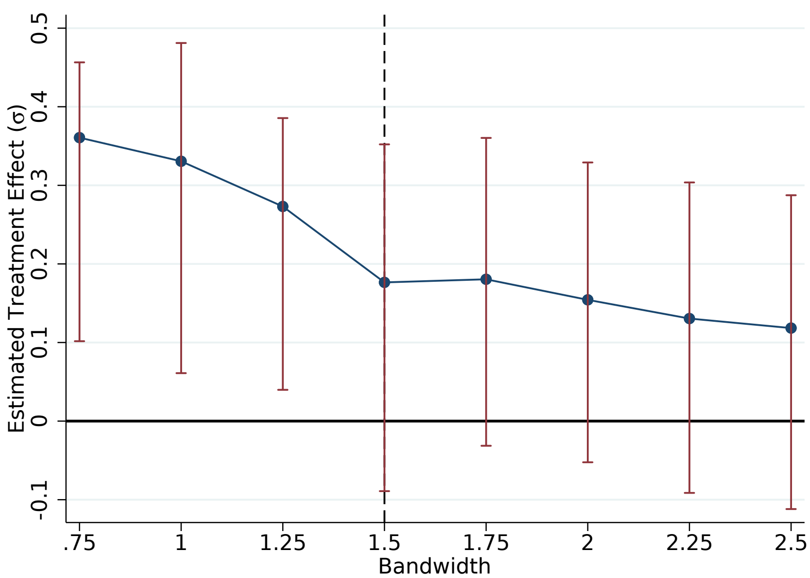
Notes: This figure is directed southwestward and shows estimated natural gas presence from a laser-based methane detector used by researchers Rob Jackson, Nathan Phillips, and Bob Ackley to document the extent of the Aliso Canyon gas leak. The vertical height of the bars indicate the amount of natural gas detected. Visually, the natural gas presence appears concentrated north of the Ronald Reagan Freeway which is about two miles south of the Aliso Canyon gas leak.

Figure A.3: Robustness: Bandwidth

(a) Math Score



(b) English Score



Notes: This figure plots spatial RD estimates using various bandwidths from 0.75 to 2.5 miles. Controls for lagged test scores, demographics and residential ZIP Code fixed effects are used. The vertical dashed line represents a bandwidth of 1.5 miles which is used for the main analysis (with its point estimate being the same of that reported in column (3) of Table 3). The whiskers represent 95 percent confidence intervals with inference done clustering at the school level using the wild cluster bootstrap procedure from Cameron et al. (2008). Note that the wild clustered bootstrap procedure generates asymmetric confidence intervals.

Table A.1: Air Testing Results from Schools within 5 Miles

School Name	Distance to Leak (miles) (1)	Times Tested (2)	Methane (ppbv) (3)	Ethane (ppbv) (4)	Benzene (ppbv) (5)	Toluene (ppbv) (6)	Ethyl-benzene (ppbv) (7)	Xylenes (ppbv) (8)
Castlebay Lane Charter[1]	1.7	15	6,400	120	0.92	14.4	11.37	39.9
Porter Ranch Community[1]	1.8	15	12,940	460	0.73	1.8	0.24	1.7
Robert Frost Middle	3.2	3	3,970	None	0.60	4.7	0.54	3.6
Van Gogh Charter	3.3	3	3,670	None	0.38	3.1	0.29	1.6
Beckford Charter	3.4	5	5,050	None	0.73	1.8	0.55	3.7
El Oro Way Charter	3.7	3	3,220	None	0.45	2.6	0.24	1.2
Darby Avenue Charter	3.8	5	5,950	None	1.10	17.0	2.80	8.2
Germain Academy	3.9	6	4,300	None	1.20	9.9	0.78	5.0
Granada Hills Charter High	4.2	2	3,440	None	0.50	4.3	None	3.1
Nobel Charter Middle	4.4	2	3,240	None	0.47	12.0	None	3.1
Chatsworth Charter High[2]	4.5	2	5,040	None	0.56	7.6	None	2.1
Knollwood Preparatory	4.5	4	3,420	None	1.60	12.0	0.50	3.5
Ernest Lawrence Middle	4.6	2	3,980	None	0.57	9.8	0.67	5.4
Granada Community Charter	4.6	2	3,320	None	0.38	9.8	0.44	2.9
Chatsworth Park Elementary	4.6	2	3,090	None	0.34	8.4	6.20	4.4
Superior Street Elementary	4.7	4	4,280	None	0.84	7.5	1.10	6.3
Topeka Drive Charter	4.7	2	3,120	None	0.64	7.1	None	1.6
Patrick Henry Middle	4.8	2	3,420	None	0.54	13.0	0.29	1.4
Andasol Avenue Elementary	5.0	2	3,050	None	0.37	7.4	None	4.7
Regulatory Limit[3]	-	0.03	500,000	1,000,000	0.92	80	450	160

[1] Castlebay Lane Charter and Porter Ranch Community were tested every school day from Nov 30-Dec 18 (except Dec 15 as all LAUSD were closed due to a terrorist threat) as well as February 22.

[2] Due to their proximity, Chatsworth Charter High and Stoney Point Continuation were tested as one school.

[3] Regulatory limits for methane and ethane are from the National Institute for Occupational Safety and Health, while the regulatory limits for benzene, toluene, ethylbenzene and xylenes are from the California Office of Environmental Health Hazard Assessment Chronic Reference Exposure Level.

Notes: This table shows the *maximum* reading of six pollutants that were tested Waterstone Environmental as part of the air testing program conducted by the LAUSD in response to the Aliso Canyon gas leak. Pollutant units are in parts per billion by volume (ppbv). The two schools nearest to the leak, Castlebay Lane Charter and Porter Ranch Community, were tested every schoolday from Nov 30-Dec 18 and then were relocated to new schools outside the five-mile boundary after Dec 18. Every other school within five miles of the gas leak was tested at least twice starting on Jan 19 as part of the program, although several schools were tested more often and Beckford Charter was also tested on Dec 2. Schools appeared to have been tested more than twice for two reasons: (i) schools initially tested on or before Jan 28 were retested in mid-February, and (ii) any school with a benzene reading above 0.92 ppbv were retested soon after. Air testing results are available at `https://achieve.lausd.net//site/Default.aspx?PageID=10329`.

Table A.2: Tests of Discontinuities in Observable Covariates

	Percent Hispanic (1)	Percent White (2)	Percent Asian (3)	Percent Black (4)	Percent FRPM[1] (5)	Percent EL[2] (6)
Within 5 Miles	0.62	0.33	2.52	-1.88	-3.06	0.81
[p-value]	[0.98]	[0.97]	[0.80]	[0.56]	[0.83]	[0.94]
Observations	3,945	3,945	3,945	3,945	3,355	3,945
Mean Dep. Var.	59.4	21.1	9.9	4.4	74.7	16.0

	Student has Parent with: Some College or Graduate (7)	High School Graduate (8)	High School Dropout (9)	Lagged Absences (10)	Lagged Math Score (11)	Lagged English Score (12)
Within 5 Miles	3.87	-0.86	-3.01	0.39	-0.16	-0.05
[p-value]	[0.85]	[0.95]	[0.79]	[0.70]	[0.70]	[0.88]
Observations	3,443	3,443	3,443	3,945	3,945	3,945
Mean Dep. Var.	63.8	24.5	11.8	5.81	0.37	0.38

[1] FRPM is an acronym for 'free or reduced price meal eligible.'
[2] EL is an acronym for 'English learners.'

Notes: Estimates report the discontinuity in observable covariates by running equation (3.1) with a covariate as the dependent variable (rather than test scores). Sample is restricted to elementary school students without missing lagged math or English scores. Each cell represents results from a separate local linear regression allowing for different functions on either side of the threshold. The bandwidth used is 1.5 miles and grade fixed effects are included. This table reports p-values (rather than standard errors) using the wild clustered bootstrap procedure from Cameron et al. (2008) given that there are only twenty-three clusters. ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.

Table A.3: Outlier Robustness

	Elementary Schools Only				Middle Schools Included
	(1)	(2)	(3)	(4)	(5)
Panel A. Outcome: Math Scores					
Within 5 Miles	0.109*	0.112**	0.133**	0.129**	0.191**
(clustered s.e.)	(0.054)	(0.046)	(0.043)	(0.049)	(0.054)
[wild cluster bootstrap p-value]	[0.086]	[0.046]	[0.031]	[0.048]	[0.038]
Panel B. Outcome: English Scores					
Within 5 Miles	0.078	0.069	0.093	0.086	0.217
(clustered s.e.)	(0.100)	(0.091)	(0.097)	(0.096)	(0.093)
[wild cluster bootstrap p-value]	[0.505]	[0.523]	[0.449]	[0.508]	[0.188]
Controls					
Lagged Test Scores	Yes	Yes	Yes	Yes	Yes
Demographic Controls	No	Yes	Yes	Yes	Yes
Residential ZIP Code FEs	No	No	Yes	Yes	Yes
Latitude-Longitude Controls	No	No	No	Yes	No
Observations	3,812	3,812	3,812	3,812	12,454

Notes: To ensure that results are not driven by an outlier, this table recreates results from Table 3 but omits the outlier observation, Andasol Avenue Elementary, located 5.02 miles from the leak (and thus received air filters given the first digit rounding convention) which had a tremendous 0.35σ and 0.20σ growth in math and English scores, respectively. This drops 133 observations relative to the results in Table 3. As in Table 3, estimates report the effect of air filters on student achievement as described in equation (3.1). Column (5) reports results including the seven middle schools within 3.5-6.5 miles of the gas leak. Each cell is a separate RD estimate from a local linear regression allowing for different functions on either side of the threshold, except column (4) where a second-order polynomial control for latitude-longitude space is used instead. The bandwidth used is 1.5 miles. Effect sizes are in terms of standard deviations of the student test score distribution. 'Lagged test scores' control for a cubic of lagged math and English scores interacted with grade dummies. 'Demographic controls' include gender, ethnicity, free and reduced price lunch status, English learner status, age and age squared interacted with grade, and language spoken at home. Missing indicators are used to control for missing demographics or lagged other-subject scores. 'Residential ZIP Code FEs' are fixed effects for the ZIP Code of student residence. All regressions include grade and boundary segment fixed effects and control for a school's magnet and affiliated charter status. Number of observations are reported for panel B; panel A has five fewer observations as these students lack lagged math scores. Standard errors clustered at the school level are reported in brackets. Given there are only twenty-two clusters, p-values clustered at the school level using the wild clustered bootstrap procedure from Cameron et al. (2008) are reported below the standard errors in square brackets. Conducting inference using the wild clustered bootstrap procedure, ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.

Table A.4: Functional Form Robustness

	Control for Geographic Location				
	Linear	Quadratic	Triangular Kernel	Linear + Boundary FE Interactions	Quadratic Lat-Lon
	(1)	(2)	(3)	(4)	(5)
Panel A. Outcome: Math Scores					
Within 5 Miles	0.201**	0.319*	0.324**	0.221**	0.186**
(clustered s.e.)	(0.062)	(0.055)	(0.062)	(0.066)	(0.059)
[wild cluster bootstrap p-value]	[0.027]	[0.063]	[0.043]	[0.036]	[0.046]
Panel B. Outcome: English Scores					
Within 5 Miles	0.177	0.318	0.355*	0.168	0.179
(clustered s.e.)	(0.089)	(0.072)	(0.054)	(0.105)	(0.086)
[wild cluster bootstrap p-value]	[0.195]	[0.218]	[0.078]	[0.333]	[0.188]
Controls					
Lagged Test Scores	Yes	Yes	Yes	Yes	Yes
Demographic Controls	Yes	Yes	Yes	Yes	Yes
Residential ZIP Code FEs	Yes	Yes	Yes	Yes	Yes
Observations	3,945	3,945	3,945	3,945	3,945

Notes: This table shows robustness to the functional form that controls for geographic location by estimating the effect of air filters on student achievement as described in equation (3.1) using various functional forms. Column (1) is identical to column (3) in Table 3 as both control for geographic location using linear distance to gas leak and feature the same set of controls. Columns (2) and (3) control for geographic location using a quadratic and triangular kernel functional form to control for distance to gas leak. Column (4) is the same as column (1) but interacts the linear distance control with boundary segment fixed effects. Finally, Column (5) uses a second-order polynomial in latitude-longitude to control for geographic location. 'Lagged test scores' control for a cubic of lagged math and English scores interacted with grade dummies. 'Demographic controls' include gender, ethnicity, free and reduced price lunch status, English learner status, age and age squared interacted with grade, and language spoken at home. 'Residential ZIP Code FEs' are fixed effects for the ZIP Code of student residence. All regressions include grade and boundary segment fixed effects and control for a school's magnet and affiliated charter status. Number of observations are reported for panel B as five observations lack lagged math scores. Standard errors clustered at the school level are reported in brackets. Given there are only twenty-three clusters, p-values clustered at the school level using the wild clustered bootstrap procedure from Cameron et al. (2008) are reported below the standard errors in square brackets. Conducting inference using the wild clustered bootstrap procedure, ***,** and * denote significance at the 1%, 5% and 10% levels, respectively.