The Long-Lasting Effects of Early Childhood Lead Exposure: Evidence from Piston-Engine Aircraft Emissions*

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Abstract

This paper estimates the short- and long-term effects of low-level lead exposure in early childhood, leveraging a natural experiment stemming from the sharp decline in piston-engine aircraft traffic—the largest source of airborne lead emissions—following the 9/11 attacks. Exploiting variation in lead exposure across schools, kindergarten cohorts, and wind patterns, we employ both difference-in-differences and instrumental variable approaches to estimate the causal effects of lead exposure on educational, behavioral, and labor market outcomes using longitudinal student-level data from Texas. Our findings reveal that one unit increase in lead exposure from kindergarten through third grade significantly reduces educational attainment, evidenced by lower test scores, decreased high school graduation rates, and reduced college enrollment. Additionally, lead exposure has marginally significant effects on increasing school absenteeism and the likelihood of expulsion. Furthermore, these adverse effects extend into adulthood, with lead exposure significantly reducing adult earnings.

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1 Introduction

Lead is a highly toxic metal with well-documented effects on health, cognitive development, and behavior, particularly in children (EPA, 2013; Reyes, 2015; Aizer and Currie, 2019). Since the 1970s, environmental regulations in the United States, particularly by the Environmental Protection Agency (EPA), have significantly reduced lead exposure by eliminating key sources such as leaded gasoline, paint, and plumbing (EPA, 2021). These policies have resulted in a more than 90% decline in blood lead levels and a 99% reduction in airborne lead levels. Yet, despite these achievements, concerns remain regarding the safety of current exposure levels. The Centers for Disease Control and Prevention (CDC) has consistently lowered the reference value for elevated blood lead levels, most recently to 3.5 µg/dL in 2021, underscoring growing evidence that even low-level exposure can harm children's development.

While the adverse effects of high levels of lead exposure on health, cognition, and behavior are well-established (Reyes, 2015; Aizer and Currie, 2019; Grönqvist et al., 2020; Gazze et al., 2024), the consequences of low-level exposure are less clear and have received less attention in the literature. A limited number of studies have found that even low levels of lead exposure significantly reduce test scores (Aizer et al., 2018; Hollingsworth et al., 2022). However, much less is known about whether these adverse short-term effects persist, influencing long-term educational attainment and labor market outcomes. The broader literature on health and education interventions often finds that initial improvements in test scores fade over time, raising the question of whether similar patterns exist for the effects of early childhood lead exposure.

One of the challenges in studying the long-term impacts of lead exposure is the difficulty in obtaining longitudinal data that tracks individuals from early exposure through adulthood. Another challenge is the potential for unobserved household characteristics to confound estimates of lead's impact on children's outcomes. Additionally, accurately measuring lead exposure has proven difficult; prior studies typically rely on blood lead levels, which only capture temporary lead exposure, while lead accumulates in bones and other tissues. These limitations may result in an underestimation of the true effects of low-level lead exposure.

This paper addresses these challenges by leveraging unique longitudinal administrative data from the Texas Education Research Center (ERC) and exploiting a natural experiment in the sharp decline of piston-engine aircraft (PEA) traffic following the 9/11 terrorist attacks. PEA, which is the only type of aircraft still using leaded fuel, is currently the largest remaining contributor to airborne lead emissions in the U.S. Figure 8 demonstrates the dramatic drop in lead emissions following the post-9/11 decline in PEA traffic. Using this variation, we develop two measures of lead exposure: (1) lead emissions based on fuel used during PEA takeoff and landing and (2) lead pollution levels detected by the monitors across Texas. These measures allow us to track exposure levels for schools located near airports.

To estimate the causal effects of lead exposure, we employ multiple identification strategies, including difference-in-differences (DID) models and instrumental variable (IV) techniques. First, we leverage variation in lead exposure across kindergarten cohorts and school proximity to airports to implement a DID approach. This method estimates the effects of cumulative lead exposure from kindergarten through third grade, controlling for school and cohort fixed effects. It also adjusts for key confounders such as jet traffic and student-level characteristics like gender, race, economic status, English proficiency, special education status, and risk of dropout. A limitation of this approach is that we only have two years of pre-9/11 data due to the PEA traffic data being available only from 2000 onward. To further strengthen our estimates, we use an instrumental variable (IV) approach, leveraging the interaction of PEA traffic from kindergarten through third grade with wind direction as an instrument for lead exposure. The underlying assumption is that wind patterns drive higher lead deposition in downwind areas, but these patterns are unrelated to student performance. This combination of wind direction and the variation in PEA traffic across cohorts, induced by the exogenous 9/11 shock, serves as a robust IV for lead exposure.

The DID results show that increased PEA traffic and associated lead emissions have significant negative effects on educational outcomes. Specifically, we find that a unit increase in PEA traffic significantly reduces reading and math scores, lowers high school graduation rates, and decreases both overall and on-time college enrollment. Additionally, lead exposure significantly increases behavioral problems, including school absenteeism, disciplinary incidents, and severe offenses such as violence and crime, which in turn raise the likelihood of suspension and expulsion. Most importantly, the detrimental effects of PEA traffic and lead exposure persist into adulthood, with significant reductions in labor market earnings. The DID estimates align with our IV results, both showing adverse effects of lead exposure from kindergarten through third grade on educational achievement and earnings outcomes, while the IV estimates for school absence and expulsion are only marginally significant.

This paper contributes to the literature by providing new evidence on the short- and long-term effects of low-level lead exposure on a broad range of outcomes, including academic performance, behavior, and labor market success. In particular, we extend the scope of previous studies by linking early childhood lead exposure to long-term educational achievement and adult earnings—a key contribution. Additionally, this is the first study to estimate the causal effects of lead emissions from PEA, an under-researched but significant source of modern lead pollution. Our findings also have important policy implications. As the EPA reviews its air quality standards for lead, our results underscore the need to reevaluate current regulations, particularly for lead emissions from PEA, which continue to expose many children to harmful lead pollution.

2 Background

Lead is a highly toxic metal that causes adverse health impacts once it enters the body. In the modern setting of this paper, the largest sources of lead emissions in the U.S. have already been eliminated, and piston-engine aircraft is one of the very few unregulated lead emissions. The exogenous reduction in lead emissions due to declined PEA operations after 9/11 provides us with a unique quasi-experiment to examine the immediate and enduring effects of low lead exposure.

2.1 Background of lead

Lead is a highly poisonous heavy metal widely used in several products, including gasoline, paint, water pipes, batteries, etc. (NIH, 2007). Tetraethyl lead (TEL) is the toxic lead compound in gasoline. In the past, there were incidents where TEL caused severe lead poisoning that even led to mortality. For example, after Du Pont's first TEL plant opened in New Jersey, several workers died from lead poisoning. In 1924, more than 80 percent of Standard Oil workers died or suffered severe poisoning (Kitman, 2000).

Lead can enter the human body by inhalation or the digestive tract. In some cases, lead can get into the body through the skin, such as the type of lead used in gasoline or lead dust/particles. Once taken in the body, lead enters the bloodstream and can be deposited in hard (e.g., bone) and soft (e.g., brain) tissues. Half of the lead in the blood (called the half-life) is excreted in approximately 30 days. Lead has a half-life of 40 days for soft tissue, up to 10 years or longer in bones and teeth.

Because lead is stored in the body, a person can develop lead poisoning from exposure to minimal amounts over a long period. Even when the exposure ends, lead will still internally affect the person. It usually takes months or years for lead to be entirely excreted after the actual exposure ends.

Lead exposure leads to serious health consequences, particularly for young children. It can adversely affect kidney function, the immune system, reproductive and developmental systems, and the cardiovascular system. Even though lead affects almost every organ in the body, the nervous system is the most affected area in children and adults. This is particularly salient for young children because they often absorb more lead than adults, and their nervous systems are still in the development stage.

Lead exposure has been linked to not only severe health issues but also non-health consequences. Particularly, lead has been shown to lower IQ scores and decrease success in school (EPA, 2013). In addition, lead can cause many mental and behavioral issues, such as hyperactivity, anxiety, lack of attention, and depression in children (EPA, 2013). Previous studies have shown the striking effect of lead exposure on crimes (Aizer and Currie, 2019).

Despite massive success in reducing lead exposure in the US, lead exposure remains a public health concern. It is estimated that 170 million Americans were exposed to high lead levels during childhood (McFarland et al., 2022). Additionally, a study by Hauptman et al. (2021) finds that 1 in 2 children in the U.S. under the age of 6 have detectable lead levels in their blood. According to CDC (2012), there is no safe amount of lead exposure because even small levels of lead can lead to hazardous health problems. The difficulty with lead is that once emitted into the environment, there is no known way to destroy it or reverse its effects on human health. Hence, it is crucial to reduce lead from its source of emission properly.

2.2 Background of leaded aviation fuel

The U.S. has taken significant steps to transition away from leaded fuels. In the 70s, one of the largest lead sources in the U.S. is emissions from automobiles. The U.S. Congress founded the U.S. Environmental Protection Agency (EPA) in 1970 and adopted the Clean Air Act, which set air quality standards (EIA, 2020). By 1975 all new cars must have catalytic converters that only used lead-free fuel (EPA, 1996). In 1976, the U.S. Environmental Protection Agency (EPA) started an effort to phase out leaded gasoline by mandating gas stations to offer unleaded gasoline. Over a decade after this deleading effort, the amount of lead used in automotive gasoline fell dramatically (99 percent). Effective January 1, 1996, the EPA altogether banned leaded gasoline for on-road vehicles (EIA, 2020).

Piston-engine aircraft (PEA) is one of the very few off-road vehicles that are still allowed to use leaded gasoline called aviation gasoline (avgas). PEAs are small planes used by flight schools, businesses, and individuals for personal flying, training, sightseeing, recreation, and search and rescue. Aviation gasoline (avgas) is the specialized fuel for PEA. TEL is added to avgas to raise fuel octane and prevent engine knock and other issues in high-performance engines. Jet aircraft and turbine-power do not use avgas but use lead-free fuels similar to kerosene (FAA, 2019).

Despite the recent discovery of unleaded avgas (Billing, 2014), leaded avgas remains the most used fuel for PEA. Today, the most common avgas in the U.S. market is 100 MON low lead (100LL). However, even the low-lead type of avgas still contains up to 0.56 grams of lead per liter. This is equivalent to 2.12 grams of lead per gallon.

With the elimination of lead emission from cars and trucks, PEA operating on avgas is the largest source of ambient lead concentration (AOPA, 2016). Around 70 percent of airborne lead emissions in the U.S. result from PEA operations (County, 2021). It is estimated that avgas is widely used in approximately 170,000 PEA in 20,000 airports across the U.S. (FAA, 2019).

Lead emission from PEA endangers public health and welfare. Sixteen million people live, and 3 million children attend school within 1km of an airport with piston-engine aircraft operating on avgas (EPA, 2010). Children living or attending school near airports can inhale airborne lead directly or ingest lead settled in soil or dust. Previous research by EPA (2010) and Agency (2002) indicates that lead emissions from these small airplanes can negatively impact children's health, especially those who live or attend school near airports.

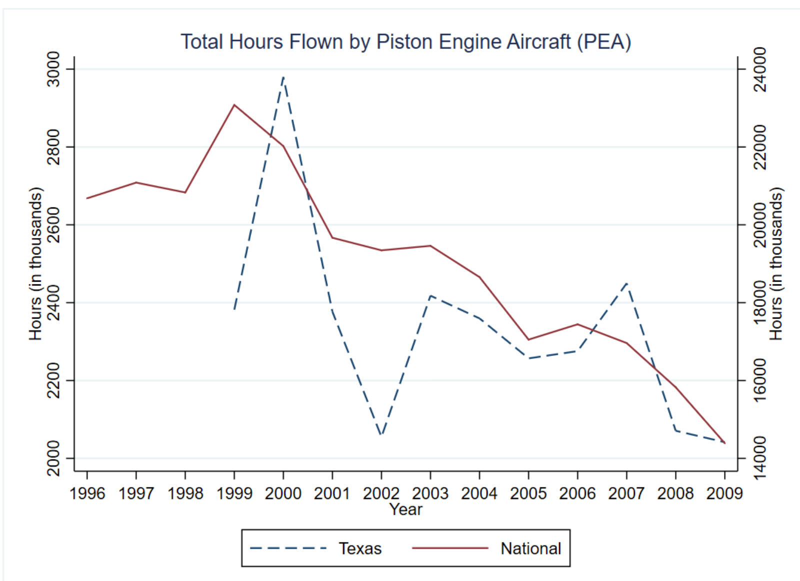
The lack of regulation of lead emissions from PEA raised concerns among policymakers, environmentalists, and non-profit organizations. In 2006, Friends of the Earth filed a petition asking the EPA to begin rule-making to address general aviation lead emissions. Since then, several more community groups and non-profit organizations continue calling for the EPA to take the necessary step in piston aircraft's lead emission regulation. Most recently, the county of Santa Clara in California and 39 organizations filed a petition urging the EPA to initiate a nationwide ban on leaded avgas (EarthJustice, 2021). In response to the rising concern over lead emissions from PEA, the EPA has been actively investigating whether lead emissions from PEA cause air pollution and endanger society's welfare (EPA, 2015). In addition, the EPA has called for further research evidence on the impacts of piston aircraft lead emission on air quality and analysis of the impacted population.

2.3 Background of the general aviation industry and 9/11 aftermath

General aviation is often used to describe all aviation activities that do not fall under military operation, major cargo, or commercial aviation (Shetty, 2012). General aviation covers a wide range of activities. Personal flying accounts for 40 percent of total hours flown. Instructional flying accounts for 17 percent of total hours flown, followed by business (12 percent) and corporate (11 percent) uses (FAA, 2009).

In the history of the GA industry (Figure 2), there were two times that GA operation fell dramatically (Shetty, 2012). The first time happened in 1979 when the operations declined by 32 percent from 40,000,000 flights down to 27,500,000 in only three years. After this sharp decline, GA operations began to recover to the peak level of 40,000,000 flights in 2000. However, starting in 2001, total operation experienced a long and consistent decline. By 2010, total GA operation was only 25,000,000, a 35 percent decline from 2000. The total hours flown[1] by PEA also declined nationally between 2000 and 2009 (Figure 1).

Figure 1: Total Hours Flown by PEA in Texas and nationally

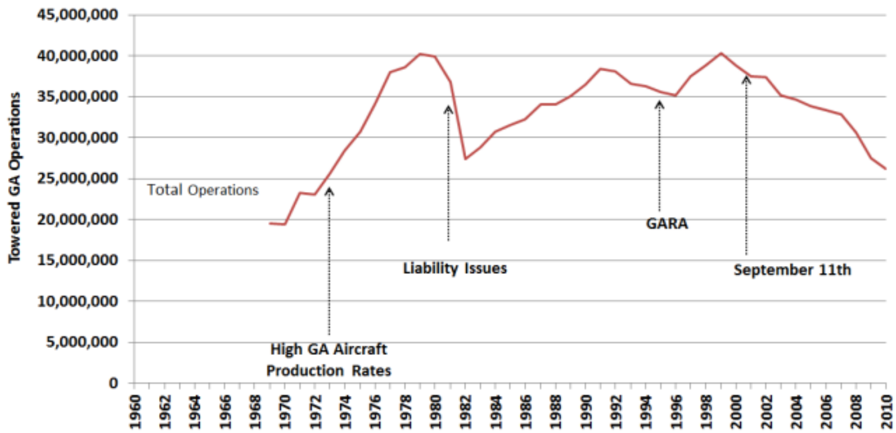


Notes: Data collected from FAA's General Aviation and Part 135 Activity Surveys

According to a study by Shetty (2012), this dip in GA operations started in 2001 is most likely a result of the 9/11 terrorist attacks. On September 11, 2001,

[1]Data collected from FAA's General Aviation and Part 135 Activity Surveys: www.faa.gov/general_aviation. Data for Texas in this report is available starting from 1999.

Figure 2: Events affecting total operations in the history of the general aviation industry



Notes: The source of this figure comes from Shetty (2012).

four coordinated suicide terrorist attacks were carried out by 19 militants associated with the Islamic extremist group al Qaeda. The first two planes crashed into the twin towers of the World Trade Center in New York City. The third plane hit the Pentagon in Arlington, Virginia, and the fourth plane crashed in Shanksville, Pennsylvania. All aircraft were ordered to land at the nearest airports immediately. On September 13, 2001, the FAA reopened the National Airspace System to commercial and private aviation.

After 9/11, government and agency reports linked general aviation to terrorism (Lichtblau, 2005). This is because 9/11 hijackers learned to fly at flight schools in the US and considered using small planes for their missions. According to the CIA, the hijackers reported wanting to use small planes to spread biological or chemical agents and carry explosives. In the years following 9/11, DHS and FBI issued a security advisory that al-Qaeda considered small aircraft for the terrorist attack on the U.S. consulate in Pakistan (Tillery, 2006). The fears surrounding GA and greater awareness that GA can be used in criminal activity hit the industry hard, particularly flight schools (Summers Walker, 2011).

Due to its link to terrorism, general aviation not only saw an immediate decline in aviation activity in the following months but also experienced more prolonged effects. These effects include increased security procedures, tighter airspace regulation, and poor public perceptions of aviation in general.

Before 9/11, GA's regulation was always less stringent than commercial aviation. FAA was responsible for GA security and implemented requirements for pilot certification. However, there was no requirement for background checks when an individual sought a pilot license. Most of the FAA's safety regulations were operational procedures such as takeoffs, landings, or flight patterns (Tillery, 2006).

Immediately after 9/11, under the enactment of the Aviation and Transportation Security Act, Congress created the TSA to increase the security of all modes of transportation, particularly general aviation security. The Homeland Security Act passed on November 25, 2002, officially put TSA responsible for aviation security (GAO, 2004). Federal agencies, public and private entities, and industry stakeholders implemented several security initiatives. First, regardless of citizenship and aircraft type, flight school applicants must undergo an extensive background check under TSA's requirement. In 2003, the FAA eliminated paper certificates and issued a new security-enhanced pilot license to both active and new pilots (Tillery, 2006). Different states and GA airports themselves also implemented new security measures and procedures.

The number of temporary flight restrictions (TFRs) issued by the FAA increased significantly after 9/11. Before the terrorist attack, TFRs were often used to protect airspace during important events of short duration when air traffic is considered threatening to people, pilots, or aircraft and property (Zuschlag, 2005). For example, TFRs were issued for forest fires, natural disasters, shuttle launches, and visits by the President or other VIPs (FAA, 2004). However, after 9/11, TFRs rapidly increased in amount, size, and duration (GAO, 2004). First, in addition to visiting VIPs, TFRs were extended to areas around military installations, large public gatherings, attractions, nuclear power stations, and on some occasions, the entire city. Second, the size of some TFRs also increased (Figure 5). For example, before the attack, TFRs for a presidential visit had a radius of 3 miles with a ceiling of 3,000 feet. After 9/11, presidential TRFs extended to 30 miles with a ceiling of 8,000 feet (GAO, 2004). Third, the duration of TFRs was also extended (Zuschlag, 2005). This is particularly salient for the national capital region and selected military installations (Figure 4). For example, the security TFR over military installation in Texarkana, Texas, was put in place briefly after the terrorist attacks but was only canceled in June 2003 (GAO, 2004).

This significant increase in TFRs led to a rise in accidental violations, which resulted in 15-90 days suspension of pilot's license (GAO, 2004). In some cases, the pilot was under interrogation by law enforcement. In addition, there were incidents where a military aircraft was sent to intercept a violating aircraft (Zuschlag, 2005). Since September 2001, the number of TFR violations increased dramatically: 1,969 violations from September 2001 to 2003 compared to 116 violations from 1998 to August 2001 (Figure 3). Piston engine aircraft accounted for over 80 percent of the TFR violations after 9/11. This rise in air traffic restrictions and violations caused significant disruption for GA passengers and firms. Between 9/11 and March 2004, the rise in TFRs resulted in 11,000 GA flights canceled, 74,000 GA flights postponed, and 100,000 flights diverted to more circuitous routes (GAO, 2004). In short, post-9/11 security and air operation restrictions negatively affected general aviation operations and traffic count. According to a survey of 1,250 pilots conducted by Shetty (2012), 1 in 2 say security and restrictions post 9/11 have a significant negative impact on their flying.

Figure 3: Violations of TFRs between 1998 and 2004 (GAO (2004))

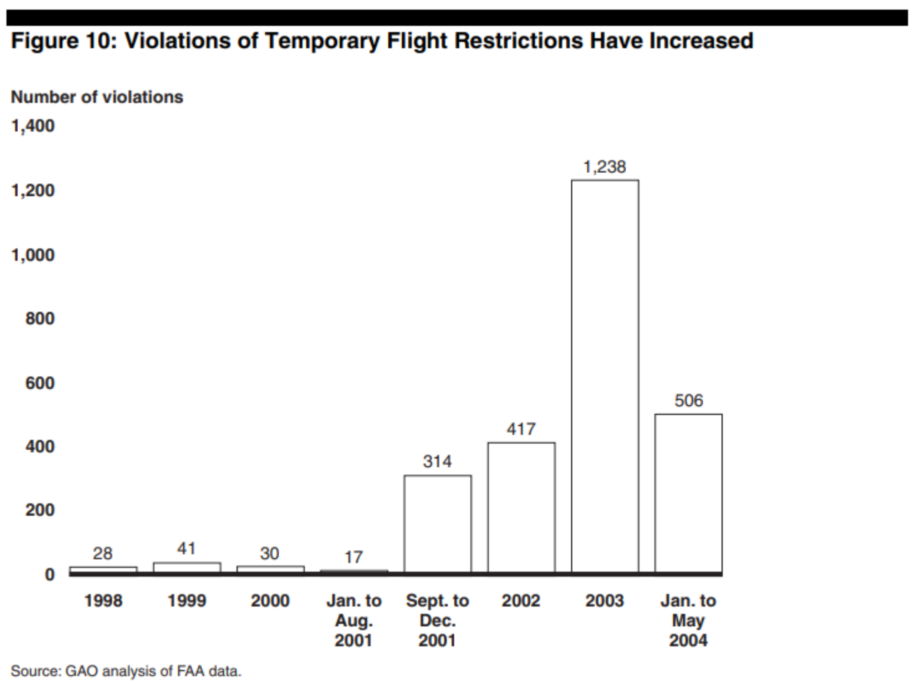


Figure 4: Security TFRs over Military Installations (GAO (2004))

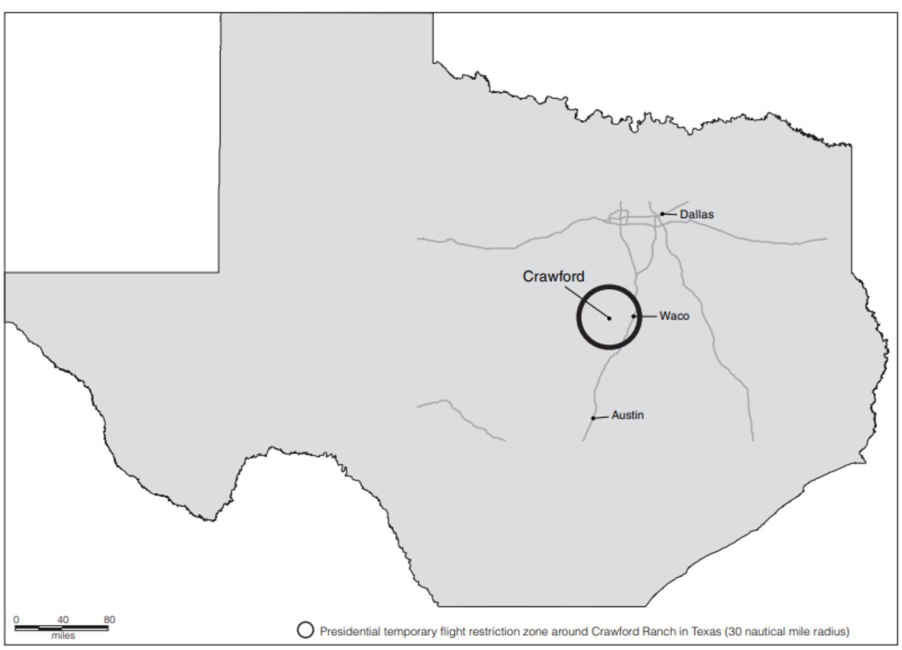
Figure 9: Remaining and Cancelled Security TFRs Over Military Installations

	Still in Effect	Canceled	Date canceled
U.S. Army	Anniston, AL	Augusta, GA	1/29/2002
	Richmond, KY	Kingsport, TN	4/05/2002
	Newport, IN	Taxarkana, TX	6/20/2003
	Pine Bluff, AR		
	Pueblo, CO		
	Tooeloe, UT		
	Hermiston, OR		
U.S. Air Force		Wright Patterson, OH	9/27/2001
		Knob Knoster, MO	5/02/2003
		Valdez, AK	6/10/2003
U.S. Navy	Bremerton, WA	Mayport, FL	3/18/2002
	Everett, WA	Crane, IN	11/23/2003
	Bangor, WA		
	Port Townsend, WA		
	St. Mary's, GA		
	Honolulu, HI		

Source: FAA.

Figure 5: Extended area for a presidential TFR in Texas (GAO (2004))

Figure 7: Temporary Flight Restriction over the Crawford Ranch in Texas when the President Is Present



Source: GAO.

3 Data

In this section, we describe four sources of data used in this paper. We combine PEA operation, lead pollution, wind direction, and administrative educational and labor market outcomes data to build an individual-level dataset that links lead exposure with short- and long-term outcomes.

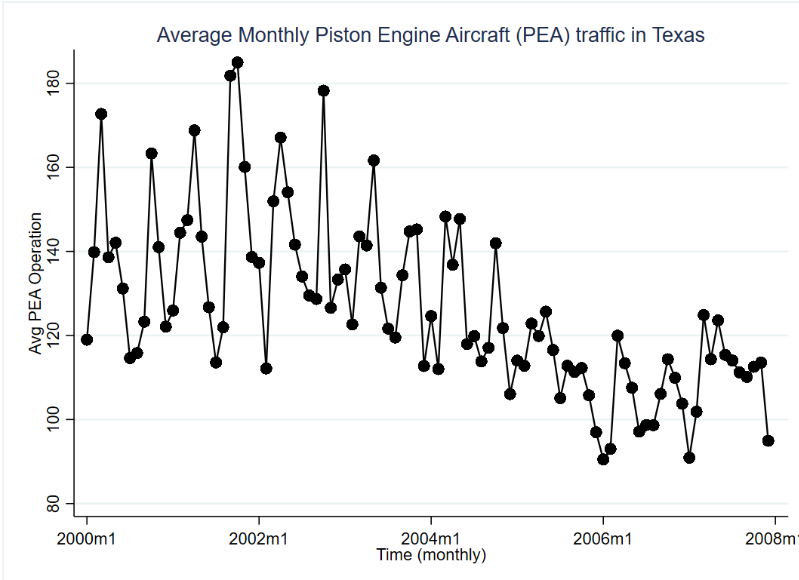
3.1 Piston-Engine Aircraft (PEA) Operation Data

Our construction of students' cumulative exposure to lead emission requires airport location and PEA operation. We collected PEA operation data from the Federal Aviation Administration (FAA)'s Traffic Flow Management Systems Counts (TFMSC). The TFMSC database provides traffic count data by the airport for different aircraft types by day. The TFMSC collects flight data through pilots' flight plans and the National Airspace System (NAS) via RADAR. TFMSC data are available from January 2000 to the present and are updated monthly. In the TFMSC system, the data are divided into many categories, including flight type (domestic/foreign), source-provided use class (commercial/military/general aviation/etc.), and aircraft type (piston/turbine/jet/helicopter/etc.).

We aggregate the data to have annual operation counts for PEA and other lead-free aircraft for every airport in Texas between 2000 and 2007. Total operation is defined as the sum of departures and arrivals. TFMSC reported total piston-engine aircraft (PEA) operation for over 180 airports during this period. However, we will only use data from 133 airports with PEA traffic counts every day/month in this period. We combined PEA operations at Texas airports with information on these airports' locations (such as longitude and latitude) collected from the Aircraft Owner and Pilot Association (AOPA) and confirmed with the Texas Airport Directory by the Texas Department of Transportation.

Figure 6 shows Texas's average monthly piston engine aircraft (PEA) traffic between 2000 and 2007. PEA operations in Texas followed the national trend, gradually falling in the years that followed the 9/11 attacks. The average monthly PEA operation is 140 flights between 2000 and 2001. This number decreased to 120 flights between 2002 and 2007. There has been a long and consistent decline in PEA operations as well as a decline in total hours flown. On average, the total hours flown by PEA in Texas between 1999 and 2001 was 2,600 thousand hours. This number reduces to about 2,200 thousand hours between 2002 and 2009.

Figure 6: Average monthly piston engine aircraft (PEA) traffic in Texas



3.2 Airborne Lead Concentration Data

We employ two methods to measure lead exposure in schools from kindergarten through third grade. First, we use daily airborne lead concentration data from the EPA's AirNow database, which provides lead levels for each reading day at air monitors across the U.S. In this study, we focus on daily lead concentration data from Texas monitors between 2000 and 2007. To align with our analysis, we aggregate this data to the monitor-year level. During this period, 10 to 13 air monitors reported lead levels in Texas annually. For our IV analysis, we limit the sample to schools within 50 miles of an air monitor. As shown in Table 2, the average distance of schools to the nearest air monitor is 18 miles. The cumulative lead exposure from kindergarten through third grade averages 0.04 g/m^3 for the 2000-2001 cohorts and 0.01 g/m^3 for the 2002-2004 cohorts. However, a limitation of this measure is that it does not cover all public schools in Texas, given the limited number of monitors.

To complement this measure, we estimate lead emissions from PEA takeoff and landing based on fuel consumption. According to the FAA's General Aviation and Part 135 Activity Surveys, a piston-engine aircraft consumes an average of 14.2 gallons of fuel per flight. OAG data shows that 30-40% of this fuel is used during takeoff and landing: 20-25% for takeoff (including taxiing, takeoff, and climb) and 10-15% for landing (including approach and taxiing). This corresponds to 2.84 to 3.55 gallons consumed during takeoff and 1.42 to 2.13 gallons during landing. With an average lead content of 2.4 grams per gallon of avgas, takeoff emits approximately 8.52 grams of lead, and landing emits about 5.11 grams. We calculate lead exposure by multiplying these emission levels by the total number of PEA takeoffs and landings.

3.3 Wind Data

We construct a downwind index for each school during the study period following Duque and Gilraine (2022). We first obtain wind direction from the National Oceanic and Atmospheric Administration (NOAA)'s Normals Hourly data. These data report hourly wind direction from 33 wind stations in Texas between 2000 and 2011. Wind direction is highly persistent so using 2000-2011 to calculate downwind index for each school in our study period is reasonable. We restrict wind observations to those that occur during school hours (8 am-3 pm) and during the school year (September-May). We then collapse the wind data by the angle of wind according to an 8-directional wind-rose, which includes four cardinals (N, E, S, W) plus four intercardinal directions (NE, SE, SW, NW). For each wind station, we observe wind direction for each hour of each day. To match the level of analysis, we further collapse this data to find the proportion of time the wind blows toward one of the directions for a station each year.

Using location information from NOAA data, we match each airport to the nearest wind station. Hence, for each airport-wind station pair, we have the proportion of time the wind blows toward one of the eight directions each year. To ensure that we adequately capture the direction wind is blowing at the airport, we restrict the airport-wind station distance to 50 miles. The closest wind station is within 18 miles on average. However, our results are robust to different distance bands.

We use the coordinates of each school and its closest airport to calculate the direction of the school relative to the airport. We discretize the direction the school is located relative to the airport into one of eight cardinal and intercardinal directions (N, E, S, W, NE, SE, SW, NW) to match the wind direction. We calculate the angle between the two location points ranging between 0-360 degrees and then categorize the direction based on the degree on the compass. Table 1 gives the direction corresponding to different degree ranges.

Next, we calculate the proportion of time the wind blows from airport A towards school S either directly or from an adjacent direction. Following Duque and Gilraine (2022), we allow full weight in the direct wind direction and half a weight in the adjacent direction. Figure 7 is an example of how we calculate how downwind a school is from the nearest airport. The circular format of the wind rose represents the direction the wind is blowing toward, and the length of each segment shows the proportion of time the wind blows toward that direction.

In this example, the wind blows North 27.5 percent of the time. So, a school north of the airport will be affected by the pollution from the airport from the North direction and from the 2 adjacent directions (NW and NE). This school is then having the probability of being downwind of $0.275 + 0.5 \times 0.1625 + 0.5 \times 0.1625 = 0.4375$. Similarly, another school located east of the airport will have a lower downwind probability: $0.05 + 0.5 \times 0.1625 + 0.5 \times 0.075 = 0.168$.

Table 1: Direction Category

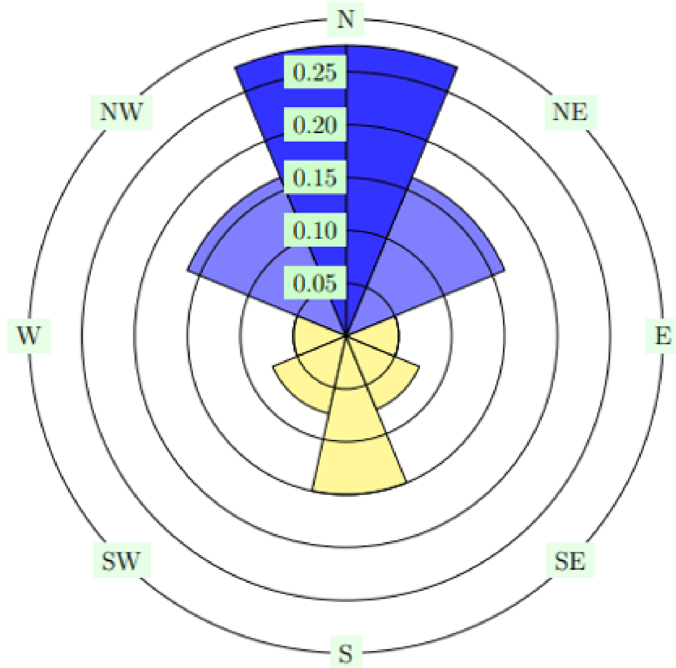
Bearing Range (Degrees)	**Direction**
0° - 22.5°	North
22.5° - 67.5°	Northeast
67.5° - 112.5°	East
112.5° - 157.5°	Southeast
157.5° - 202.5°	South
202.5° - 247.5°	Southwest
247.5° - 292.5°	West
292.5° - 337.5°	Northwest
337.5° - 360°	North

Notes: This table shows how we categorize the direction after calculating the angle between a school and airport locations. We use the following formula to calculate the angle between two location points: $\theta = \text{atan2}(\sin \Delta\lambda \cdot \cos \phi_2, \cos \phi_1 \cdot \sin \phi_2 - \sin \phi_1 \cdot \cos \phi_2 \cdot \cos \Delta\lambda)$ where ϕ_1, λ_1 are the latitude and longitude of the start point and ϕ_2, λ_2 are the latitude and longitude of the end point. $\Delta\lambda$ is the difference in longitude. Since atan2 returns values in the range $-\pi ... +\pi$ (that is, -180° ... +180°), we normalize the result to a compass bearing (in the range 0°-360°).

3.4 Longitudinal Student Level Data

The Texas Education Research Center (ERC), maintains the administrative data for each student attending the Texas public schools. Specifically, the Texas ERC compiles pre-kindergarten through the twelfth grade (PK-12) educational records from the Texas Education Agency (TEA), the post-secondary education records within Texas from the Texas Higher Education Coordinating Board (THECB), the post-secondary

Figure 7: An Example of Constructing Downwind Index



Note: This figure, adapted from Duque and Gilraine (2022), shows how the downwind index is constructed. The wind rose has 8 directions (N, NE, E, SE, S, SW, W, NW), and each circle represents the proportion of time the wind blows toward that direction. In this example, the wind blows North 27.5% of the time and toward NW and NE 16.25% each. For a school located North of the airport, the downwind index includes the contribution from the North (0.275) and half the contributions from NW and NE. This gives a total downwind index of: $0.275 + 0.5 \times 0.1625 + 0.5 \times 0.1625 = 0.4375$. This index represents the probability of the school being downwind and exposed to pollution from the airport.

education records from other states via the National Student Clearinghouse (NSC), and the Texas employment earnings data from the Texas Workforce Commission (TWC). Each dataset incorporates a uniquely generated identifier, denoted as ID2. This ID2 serves as a unique substitute for Social Security Numbers (SSNs), enabling longitudinal tracking of a student across these diverse datasets. The brief introduction of each dataset and the definitions for key outcome variables used in this study are documented below.

3.5 TEA 2000-2022

Reading and math scores are important measurements of educational performance. These test scores data come from the Texas standardized assessment, the Texas Assessment of Knowledge and Skills (TAKS). The TAKS had been administered from

2003 to 2011. It is required for students in grades 3 to 11 to assess reading and math skills, with the raw scores reflecting the number of correctly answered multiple-choice questions. In this paper, we estimate the impacts of lead pollution on test scores from grade 4 to 8. [2]This is because beginning from grade 9, students could start to take the end of year test, which is a requirement for high school graduation. Due to the fact that students can take this end-of-year test in any grade from 9 to 12 like student A takes this test in grade 9 while another pass this test in grade 12, which makes it less comparable due to the difference in the timing of the test. Additionally, the test scores are standardized with zero mean and one standard deviation by cohort.

High school graduation is another critical measure of educational achievement. In this study, we define "ever graduating from high school" as obtaining a high school diploma (excluding a GED) within a fifteen-year window from 2007 through 2022. Additionally, we categorize high school graduation based on its timing relative to the expected schedule. For example, graduating on time refers to graduating from a high school by the twelfth year post kindergarten.

Except for educational attainment, we also investigate the effect of lead pollution on behavioral outcomes. The TEA includes data for days absent from school, percent of school absence, and the reasons and actions for student disciplinary incidents. Particularly, there are variables that document whether a disciplinary incident belongs to crime or violent behavior. This study uses the violence and crime variables to estimate the impacts of retention on severe behavior outcomes.

Other school-level information, like school location, including longitude and latitude, also comes from the Texas Education Agency (TEA). Using location information, we match schools to the nearest airport, which is, on average, 7.5 miles away.

3.6 THECB 2010-2021 and NSC 2011-2019

Using the longitudinal data, we are able to track the effect of lead pollution on college enrollment outcomes within and outside of Texas. Specifically, the post-secondary outcomes are combined from THECB and NSC, including college enrollment and the types of institutions attended. We have developed two metrics for college enrollment: one tracking any enrollment from 2010 to 2021 and another assessing on-time enrollment, which we define as enrollment in college by the thirteenth year post-kindergarten.

[2]For the last cohort, kindergarteners in 2004, their grade 8 test scores are missing because they would take the grade 8 test in 2012 when Texas adopts a new assessment, STAAR. To avoid the effect generated from different version of the assessment, we only use TAKS test scores.

3.7 TWC Wages Data 2007-2022

We are also able to observe students' earnings outcomes, which come from the TWC. The TWC dataset covers wages paid within Texas, while earnings obtained from other states are not documented in the TWC data.[3]A lack of positive earnings in the dataset might reflect unemployment within Texas or employment outside the state. Missing wage records are coded as zero in this study. The outcomes of interest are annual earnings at each age from 23 to 27. We can observe the annual earnings up to age 27 for kindergarteners in 2000, while we can only observe the earnings up to age 23 for the last cohort, kindergarteners in 2004.

Our main sample includes kindergarteners from 2000 through 2004. We further restrict the sample to these kindergarteners who attend a school within 50 miles of the airport.[4]A statistics summary of students' characteristics and key outcome variables by cohorts who attend kindergarten from 2000 through 2004 is presented in Table 2. The Kindergarteners of the 2000 and 2001 cohorts are exposed to higher levels of PEA traffic and lead pollution compared to those post-2001, and they are also more likely to be White and are less likely to be economically disadvantaged and at risk of dropout compared to those post-2001 cohorts. Previous literature studying lead emitted from water pipeline and old house faces the selection issue that lead exposure is associated poor household characteristics. In our study, we do not have this selection issue. Instead, students with higher level of lead exposure are more likely coming from area and families with good economic status. This could be due to the fact that the number of PEA flights is associated with economic growth. Even for those children from areas with good economic status, low levels of lead exposure are correlated with worse short- and long-term outcomes, like decreased high school graduation rates, increased behavioral issues, and lower earnings. However, they have relatively high college enrollment rates.

[3]TWC requires all employers to report Unemployment Insurance (UI) wages and to pay their quarterly UI taxes electronically. Employers that do not file and pay electronically may be subject to penalties as prescribed in Sections 213.023 and 213.024 of the Texas Unemployment Compensation Act (TUCA).

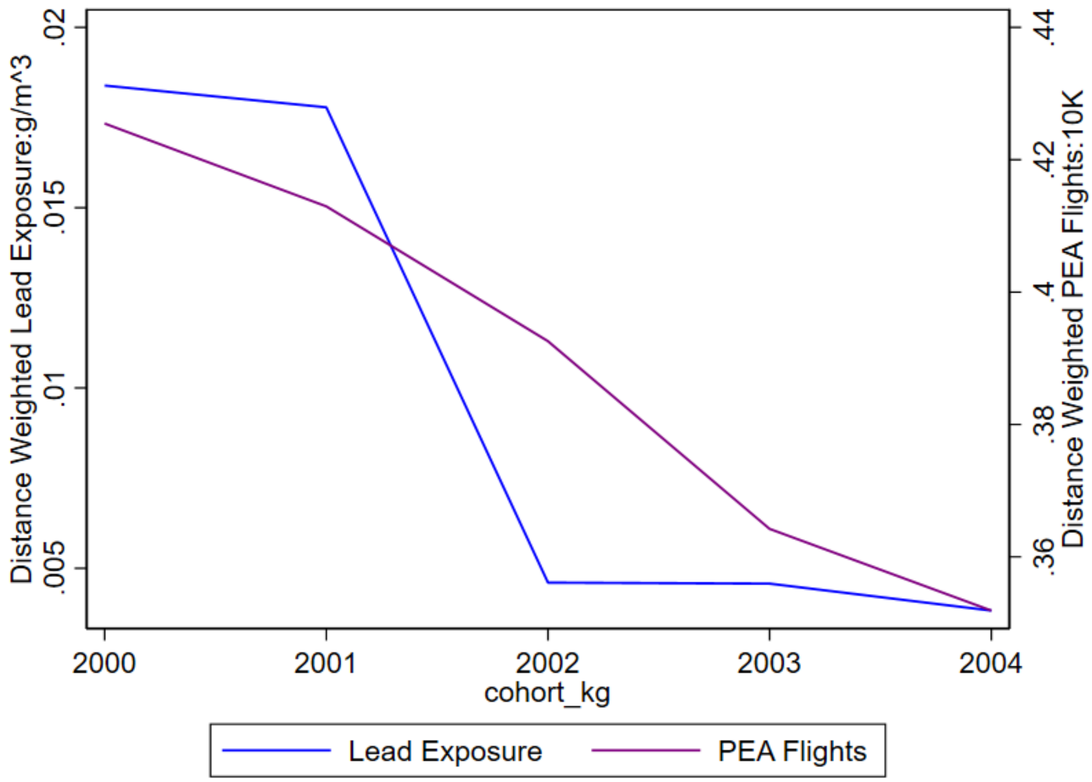
[4]Lead pollution could have impacts on areas up to 50 miles to the emission sources (Hollingsworth et al., 2022).

Table 2: Summary Statistics

	(1) 2000	(2) 2001	(3) 2002	(4) 2003	(5) 2004
Students' Characteristics					
Female	0.50	0.50	0.50	0.50	0.50
African	0.13	0.13	0.13	0.13	0.13
Hispanic	0.44	0.46	0.46	0.47	0.48
White	0.40	0.39	0.38	0.36	0.36
Bilingual program	0.14	0.13	0.14	0.15	0.16
Economically disadvantaged	0.55	0.56	0.57	0.58	0.57
Special Education	0.10	0.10	0.10	0.09	0.09
At risk of dropout	0.38	0.39	0.43	0.44	0.45
Airport Characteristics					
Distance of school to airport	7.59	7.57	7.51	7.46	7.43
Min distance from monitor to school	18.37	18.46	18.46	18.55	18.64
Distance weighted lead (g/m^3)	0.01	0.01	0.00	0.00	0.00
Lead (g/m^3)	0.04	0.04	0.01	0.01	0.01
Distance weighted PEA (10k)	0.34	0.34	0.32	0.30	0.29
PEA(10k)	1.52	1.49	1.42	1.34	1.28
JET(10k)	19.10	19.49	20.08	20.80	21.03
Lead from PEA(kg)	103.58	102.00	96.92	91.20	87.08
Educational Attainment					
Grade 4 reading scores	0.00	0.00	-0.00	-0.00	-0.00
Grade 4 math scores	0.00	0.00	0.00	0.00	0.00
Ever graduated from high school	0.80	0.81	0.81	0.82	0.83
Ontime high school graduation	0.73	0.75	0.75	0.76	0.77
Ever enrolled in any university	0.64	0.63	0.62	0.60	0.59
Ontime enrollment in any university	0.56	0.56	0.56	0.53	0.54
Ever enrolled in a 4 year university	0.35	0.35	0.35	0.33	0.32
Ontime enrollment in a 4 year university	0.26	0.26	0.26	0.25	0.25
Ever enrolled in a 2 year university	0.55	0.54	0.53	0.50	0.49
Ontime enrollment in a 2 year university	0.46	0.46	0.45	0.43	0.43
Earnings Outcomes					
Wage23	18,688.52	19,225.53	18,420.75	19,574.33	20,344.93
Wage24	21,257.02	20,295.26	21,797.96	22,599.55	18,312.12
Wage25	22,117.88	23,480.97	24,601.74	19,781.56	6,646.28
Wage26	25,125.45	26,002.81	21,049.28	5,957.53	14,381.75
Wage27	27,332.28	22,430.41	6,869.48	16,276.05	7,552.25
Disciplinary Incidents					
Days absent	64.64	62.89	61.70	66.66	61.70
Percent of absence	43.97	42.55	41.29	44.28	40.97
Any disciplinary incidents	5.27	5.18	4.84	4.70	4.42
Violence	0.41	0.42	0.40	0.41	0.40
Crime	0.20	0.20	0.20	0.20	0.20
Suspension	4.96	4.89	4.57	4.44	4.17
Expulsion	0.33	0.31	0.28	0.27	0.25
Observations	228858	233955	240751	251111	259933

Notes: The sample includes kindergartners from 2000 through 2004 cohorts who attended schools within 50 miles of the nearest airport. Both lead exposure and PEA traffic are measured as cumulative totals from kindergarten through third grade.

Figure 8: Distance Weighted Lead and PEA from Kindergarten to Grade 3 by Cohorts



Notes: This figure shows the correlation between cumulative lead exposure and PEA traffic from kindergarten through third grade for cohorts from 2000 to 2004. The sample includes kindergartners from these cohorts who attended schools within 50 miles of the nearest airport. Both lead exposure and PEA traffic are measured as cumulative totals from kindergarten through third grade weighted by the distance to the nearest airport.

4 Empirical Strategy

4.1 DID

We estimate the short and long-term effects of lead exposure on student outcomes by exploiting variation in lead concentrations across cohorts mainly due to the sudden reduction of lead emission in the air after 2001 caused by the drop of PEA operations following the 9/11 events. In addition, the lead concentration level varies by the distance of a school to the airport, with students attending schools closer to the airport experiencing higher levels of lead exposure. Utilizing the variation in lead concentration across cohorts and schools, this paper estimates the impacts of PEA operation and lead exposure using the model inspired by the framework in Hollingsworth et al.

(2022).

First, we estimate the effects of the cumulative number of PEA operations from Kindergarten through third grade on student's outcomes, using equation (1).

$$Y_{ics} = \alpha_0 + \alpha_1 \text{Cumulative PEA}_{ics} + JET_{sc} + Z_i + \delta_s + \gamma_c + \epsilon_{ics} \tag{1}$$

where i, c, and s represent the student, cohort, and school dimensions. Y_{ics} denotes the outcome of interest, such as test scores, high school graduation, college enrollment, and earnings. Cumulative PEA_{ics}, captures the total number of PEA operations from Kindergarten to grade 3, weighted by the distance of schools to the nearest airport, adjusting the fact that PEA operation primarily influences surrounding areas, and the impacts become weaker as the distance increases. To address the confounding factors caused by the operation of other types of aircraft, we control for the cumulative number of jet aircraft operations in JET_{sc}. In Z_i, we further control for student's demographic characteristics, including gender, race, economically disadvantaged status, participation in a bilingual program, participation in a special education program, and the status of being at risk of dropout, to adjust for the influence of students' background. Furthermore, we add the school fixed effects (δ_s), controlling for the factors invariant over time within a school but different across schools. In addition, we control for Kindergarten cohort fixed effects (γ_c) that control for the trends that are the same across schools for the same cohorts but variant across cohorts. ϵ_{ics} is the error term, and we cluster the standard error at the school level since students who attend the same schools share similar levels of lead exposure and education quality. Under the validity of the assumption, α_1 captures the effect of a 10,000 increase in the number of PEA operations between kindergarten and third grade on student outcomes.

We then examine the effects of lead concentrations from kindergarten through third grade emitted from PEA takeoff and landing, which accounts for about 35% of the total lead emission within one flight. The model is specified in equation (2) below:

$$Y_{ics} = \theta_0 + \theta_1 \text{Cumulative lead exposure}_{ics} + Z_i + \delta_s + \gamma_c + \epsilon_{ics} \tag{2}$$

where Cumulative lead exposure_{ics} represents the total lead exposure emitted from PEA takeoff and landing from Kindergarten to grade 3, weighted by the distance of schools to the nearest airport, adjusting the fact that lead concentration from aviation fuel primarily influences surrounding areas and the impacts become weaker as the distance increases.[5]The coefficient θ_1 quantifies the impact of an incremental one kg of lead exposure from Kindergarten to grade three on student outcomes. A limitation of this method is the short period before 2002, which restricts our ability to examine the pre-trend assumption—a key requirement for DID validity.

4.2 IV

To address potential biases and further strengthen our estimates, we employ an instrumental variable (IV) approach, exploiting the unexpected decline in PEA traffic and the randomness of wind direction. Specifically, we employ the interaction of cumulative PEA traffic with the downwind index as an IV for lead exposure from kindergarten through grade three collected from the nearest monitor. The main assumption is that the value of the downwind index in an area where the school is located is not associated with school quality. However, the schools in downwind areas have higher lead deposition from PEA. Additionally, lead exposure across cohorts is quasi-random due to air flight restrictions and strengthened security checks on general aviation pilots post-9/11. We start the analysis with the reduced form estimate in (3), showing the impacts of PEA in downwind areas compared to relative upwind areas. The IV model is constructed in the 2SLS format. Equation (4) shows the first-stage estimate, which measures the impacts of the instrumental variable, the interaction of cumulative PEA with the downwind index, on cumulative lead exposure. The second stage estimate is expressed in equation (5), where we estimate the effect of lead exposure predicted by equation (4) on student outcomes.

$$Y_{ics} = \alpha_0 + \alpha_1 \text{PEA*Downwind}_{ics} + Z_i + JET_{cs} + \delta_s + \gamma_c + \eta_{ics} \tag{3}$$

$$Lead_{ics} = \alpha_0 + \alpha_1 \text{PEA*Downwind}_{ics} + Z_i + JET_{cs} + \delta_s + \gamma_c + \epsilon_{ics} \tag{4}$$

[5]Based on data from the FAA's General Aviation and Part 135 Activity Surveys and a report from OAG, piston-engine aircraft, which typically consume about 14.2 gallons of fuel per hour, use a 20-25% portion of this fuel during takeoff phases and 10-15% for landing. Specifically, takeoff processes consume approximately 2.84 to 3.55 gallons, while landing processes consume about 1.42 to 2.13 gallons. Lead content in avgas ranges from 0.14 to 1.12 grams per litter (Technical Support Document: Lead Emissions from the Use of Leaded Aviation Gasoline in the United States), which is equivalent to 0.53-4.23 grams per gallon. Taking the average, 2.4 grams per gallon, we estimate that the PEA takeoff phase emits about 8.52 grams of lead, and the landing phase emits approximately 5.11 grams of lead. Using the annual number of PEA takeoff and landing data, we calculate the lead emitted from PEA between Kindergarten and third grade.

$$Y_{ics} = \beta_0 + \beta_1 \widehat{Lead_{ics}} + Z_i + JET_{cs} + \delta_s + \gamma_c + \mu_{ics} \tag{5}$$

where Y_{ics} denotes the outcome of interest, such as test scores, high school graduation, college enrollment, and earnings for kindergartener (i) of the cohort (c) in school (s). $Lead_{ics}$ measures the cumulative lead exposure from kindergarten through grade three collected from the nearest monitor. PEA*Downwind$_{ics}$ represents the interaction of cumulative PEA traffic from kindergarten through grade three with the downwind index, which is the instrumental variable for cumulative lead exposure. In Z_i, we further control for student's demographic characteristics, including gender, race, economically disadvantaged status, participation in a bilingual program, participation in a special education program, and the status of being at risk of dropout, to adjust for the influence of students' background. To address the confounding factors caused by other types of aircraft operations, we control for the cumulative number of jet aircraft operations in JET_{sc}. Furthermore, we add the school fixed effects (δ_s), controlling for the factors invariant over time within a school but different across schools, like school quality. In addition, we control for Kindergarten cohort fixed effects (γ_c) that control for the trends that are the same across schools but variant across cohorts. μ_{ics} is the error term, and we cluster the standard error at the school level since students who attend the same schools share similar levels of lead exposure and education quality.

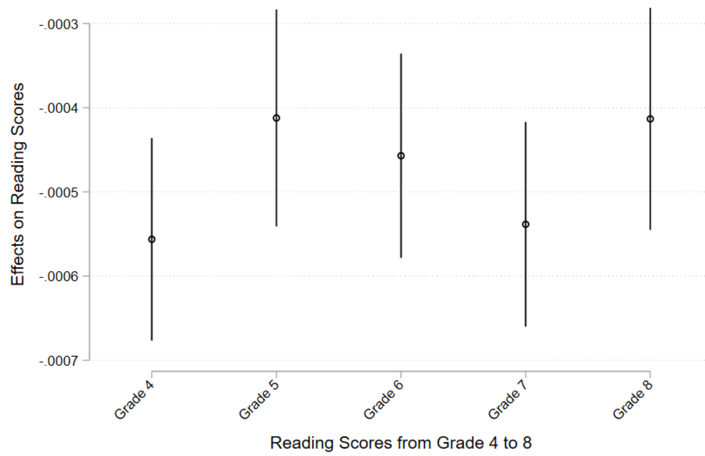
5 Results

5.1 DID Results

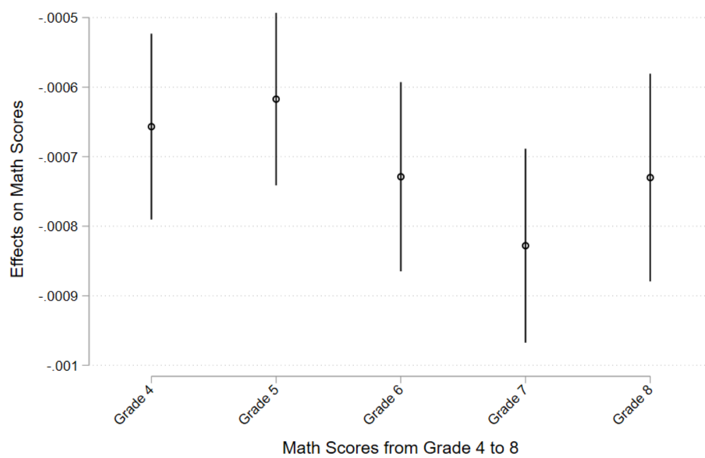
5.1.1 Effects on Test Scores

Even at low levels, lead exposure has a measurable negative impact on children's cognitive development. Figure 9 illustrates that an increase of one kilogram of lead exposure from kindergarten through third grade leads to a reduction in both reading and math scores in the fourth grade. These adverse effects persist, with reading and math scores continuing to decline through eighth grade. Notably, while the decline in reading scores narrows slightly in the later grades, the reduction in math scores becomes more pronounced, particularly after fifth grade.

Figure 9: Cumulative Effects of Lead Exposure on Test Scores



(a) Reading Scores (σ)



(b) Math Scores (σ)

Notes: These figures illustrate the effects of cumulative lead pollution from PEA takeoff and landing during kindergarten through third grade on standardized math and reading scores. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport.

Table 3 provides the estimated effects of PEA operations and lead emissions on test scores. Panel A shows that a 10,000 increase in PEA flights reduces reading scores by 0.03 of a standard deviation in fourth grade. The annual traffic of PEA flights is 15,000 in 2000, which would reduce the reading scores by 0.045 standard deviation. This negative impact persists across grades four through eight, albeit with slightly diminishing magnitudes. A similar pattern is observed for math scores, with an initial decline of 0.039 of a standard deviation in fourth grade. The negative impact on math scores intensifies in the later grades, culminating in a 0.04 decline by the eighth grade. All these estimates are statistically significant at the 1% level.

In Panel B, we examine the effect of lead exposure, specifically the amount of lead emitted during PEA takeoffs and landings from kindergarten through third grade, adjusted for the distance from the school to the nearest airport. Given that takeoffs and landings account for 30%-40% of the fuel used in a PEA flight, the results are particularly telling. An increase of one kilogram of lead concentration corresponds to a 0.0006 decline in reading scores for students attending schools located one mile closer to PEA-operated airports. The effect size implies that the total lead (103 kg) emitted from PEA in 2000 would reduce reading scores by 0.06 standard deviation. This adverse effect on reading scores remains consistent from the fourth through eighth grades, with all estimates reaching statistical significance at the 1% level.

A similar negative trend is observed for math scores, with a decline of 0.0007 of a standard deviation in fourth grade. This detrimental effect continues through eighth grade, with all estimates statistically significant at the 1% level.

Table 3: Effect of Cumulative Lead Exposure on Test Scores

	Grade 4	Grade 5	Grade 6	Grade 7	Grade 8
Panel A: effects of an increase of 10k PEA					
PEA(10k):Reading	-0.0315***	-0.0211***	-0.0260***	-0.0307***	-0.0257***
	(0.0045)	(0.0047)	(0.0044)	(0.0045)	(0.0049)
N	1122490	1091634	1094754	1084137	833436
PEA(10k):Math	-0.0394***	-0.0351***	-0.0436***	-0.0487***	-0.0437***
	(0.0050)	(0.0046)	(0.0051)	(0.0052)	(0.0056)
N	1122490	1039606	1094754	1084137	806738
Panel B: effects of an increase of one kg lead exposure					
Lead(kg):Reading	-0.0006***	-0.0004***	-0.0005***	-0.0005***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	1122490	1091634	1094754	1084137	833436
Lead(kg):Math	-0.0007***	-0.0006***	-0.0007***	-0.0008***	-0.0007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	1122490	1039606	1094754	1084137	806738

Notes: This table shows the effect of PEA traffic and lead exposure on reading and math scores from grades 4 through 8. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. PEA traffic is measured as the cumulative total from kindergarten through third grade. Lead emissions from PEA takeoff and landing are calculated as follows: The FAA reports that piston-engine aircraft consume an average of 14.2 gallons of leaded fuel per flight. According to OAG, 30-40% of this fuel is burned during takeoff and landing, with 20-25% for takeoff and 10-15% for landing. With an average lead content of 2.4 grams per gallon, takeoff emits approximately 8.52 grams of lead, and landing emits about 5.11 grams. Lead exposure is then calculated based on the total lead emissions from PEA takeoff and landing during kindergarten through third grade. The standard errors clustered at the school level are in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns.

5.1.2 Effects on Behavioral Issues

The negative effects of lead exposure on test scores found in this study align with existing research on the impact of low-level lead pollution (Hollingsworth et al., 2022). This paper extends the current literature by presenting new evidence on the effects of low-level lead exposure on outcomes beyond test scores, including behavioral outcomes.

Table 4 presents the estimated effects of PEA flights and lead pollution from PEA fuel on school absences and disciplinary incidents during the one to nine years following third grade. Panel A shows that an increase of 10,000 PEA flights increases total days absent from school by 3 days, the absence rate by 3.34%. In addition to these academic disruptions, PEA flights are associated with a rise in behavioral issues. Specifically, total disciplinary incidents increase by 0.4, with severe incidents, such as violence and crime, rising by 0.04 and 0.02, respectively. Consequently, the probability of suspension and expulsion increases by 39 and 3.4 percentage points, respectively.

Panel B of Table 4 further highlights the impact of lead pollution from PEA takeoffs and landings on school absences and disciplinary incidents. An increase of one kilogram in lead concentration leads to a 0.05-day rise in total school absences and a 5.76% increase in absence rates over the same period. This exposure also results in an additional 0.008 disciplinary incidents, with violent behaviors and crimes increasing by 0.0007 and 0.0004, respectively. Consequently, the likelihood of suspension and expulsion rises by 0.007 and 0.0005 percentage points, respectively.

Table 4: Effect of Cumulative Lead Exposure on Disciplinary Incidents

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	School Absence		Disciplinary Types			Disciplinary Action	
	Days absent	Absence%	Any Disci.	Violence	Crime	Suspension	Expulsion
Panel A: effects of an increase of 10k PEA							
PEA(10k):Total	3.1499***	3.3401***	0.4237***	0.0405***	0.0241***	0.3918***	0.0341***
	(0.3361)	(0.3209)	(0.0555)	(0.0067)	(0.0041)	(0.0520)	(0.0049)
N	1188904	1188904	1188904	1188904	1188904	1188904	1188904
Panel B: effects of an increase of one kg lead exposure							
Lead(kg):Total	0.0543***	0.0576***	0.0078***	0.0007***	0.0004***	0.0073***	0.0005***
	(0.0047)	(0.0045)	(0.0008)	(0.0001)	(0.0001)	(0.0007)	(0.0001)
N	1188904	1188904	1188904	1188904	1188904	1188904	1188904

This table shows the effect of PEA traffic and lead exposure on school absence and disciplinary incidents. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. PEA traffic is measured as the cumulative total from kindergarten through third grade. Lead emissions from PEA takeoff and landing are calculated as follows: The FAA reports that piston-engine aircraft consume an average of 14.2 gallons of leaded fuel per flight. According to OAG, 30-40% of this fuel is burned during takeoff and landing, with 20-25% for takeoff and 10-15% for landing. With an average lead content of 2.4 grams per gallon, takeoff emits approximately 8.52 grams of lead, and landing emits about 5.11 grams. Lead exposure is then calculated based on the total lead emissions from PEA takeoff and landing during kindergarten through third grade. The standard errors clustered at the school level are in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns.

A growing body of literature on education and health interventions highlights the potential for short-term effects to differ substantially from long-term outcomes. This paper contributes to the literature on low-level lead exposure by providing new evidence on its impact on long-term educational achievement and earnings outcomes. Utilizing longitudinal administrative data, we estimate the effects of lead exposure on outcomes that extend beyond test scores, focusing on educational attainment and long-term earnings.

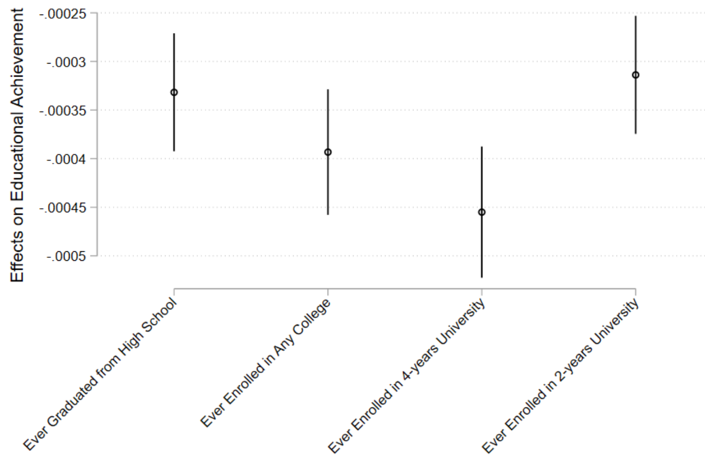
5.1.3 Effects on Long-Term Educational Achievement

Figure 10 demonstrates that an increase of one kilogram of lead exposure from kindergarten through third grade significantly decreases the likelihood of ever graduating from high school and enrolling in any college, with particularly strong effects on enrollment in four-year universities. Similarly, Figure 11 shows comparable negative impacts on on-time high school graduation (within nine years after third grade) and on-time college enrollment (within ten years after third grade).

Table 5 provides the estimated effects of PEA flights and lead emissions on educational attainment. Panel A shows that an increase of 10,000 PEA takeoffs or landings reduces the probability of ever graduating from high school by 1.93 percentage points and on-time graduation by 2.45 percentage points. PEA flights also decrease the likelihood of ever enrolling in college by 2.28 percentage points and on-time enrollment by 2.62 percentage points. These effects are all statistically significant at the 1% level. The negative impact on college enrollment is more pronounced for four-year universities compared to two-year programs.

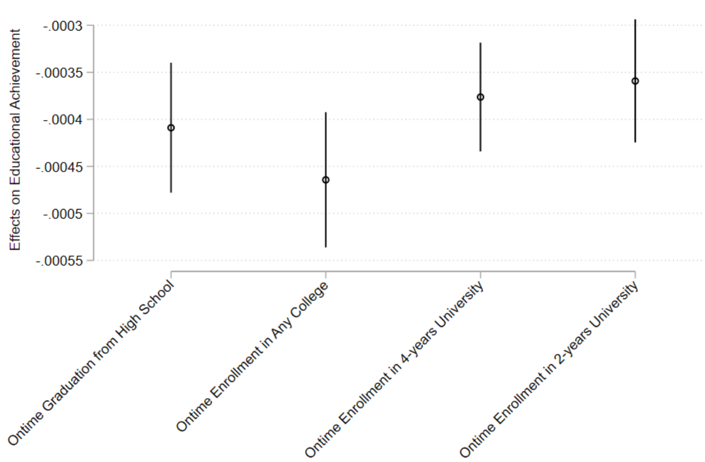
Panel B of Table 5 further reveals that an increase of one kilogram of lead emissions from PEA takeoffs and landings results in a 0.03 percentage point decrease in the probability of ever graduating from high school and a 0.04 percentage point decrease in college enrollment. On-time high school graduation and college enrollment also decline by 0.04 and 0.05 percentage points, respectively. The adverse effects on university enrollment are particularly significant for four-year programs, with a 0.05 percentage point reduction in ever enrolling and a 0.04 percentage point decrease in on-time enrollment. Similar, though slightly smaller, effects are observed for two-year programs.

Figure 10: Effects of Lead Exposure on Ever Obtaining Educational Achievement



Note: This figure shows the impact of cumulative lead exposure from PEA takeoff and landing on long-term educational attainment, including ever graduating from high school and enrolling in college.

Figure 11: Effects of Lead Exposure on On-Time Educational Achievement



Note: This figure shows the impact of cumulative lead exposure from PEA takeoff and landing on the timing of obtaining long-term educational attainment.

Table 5: Effect of Cumulative Lead Exposure on Educational Attainment

	Ever HG	Ontime HG	Any Coll.	Ontime Coll.	Ever 4years	Ontime 4years	Ever 2years	Ontime 2years
Panel A: effects of an increase of 10k PEA								
PEA(10k)	-0.0193***	-0.0245***	-0.0228***	-0.0262***	-0.0256***	-0.0216***	-0.0180***	-0.0200***
	(0.0022)	(0.0025)	(0.0023)	(0.0026)	(0.0025)	(0.0021)	(0.0022)	(0.0023)
N	1191003	1191003	1191003	1191003	1191003	1191003	1191003	1191003
Panel B: effects of an increase of one kg lead exposure								
Lead(kg)	-0.0003***	-0.0004***	-0.0004***	-0.0005***	-0.0005***	-0.0004***	-0.0003***	-0.0004***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	1191003	1191003	1191003	1191003	1191003	1191003	1191003	1191003

Notes: This table shows the effect of PEA traffic and lead exposure on high school graduation and post-secondary educational outcomes. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. PEA traffic is measured as the cumulative total from kindergarten through third grade. Lead emissions from PEA takeoff and landing are calculated as follows: The FAA reports that piston-engine aircraft consume an average of 14.2 gallons of leaded fuel per flight. According to OAG, 30-40% of this fuel is burned during takeoff and landing, with 20-25% for takeoff and 10-15% for landing. With an average lead content of 2.4 grams per gallon, takeoff emits approximately 8.52 grams of lead, and landing emits about 5.11 grams. Lead exposure is then calculated based on the total lead emissions from PEA takeoff and landing during kindergarten through third grade. The standard errors clustered at the school level are in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns.

5.1.4 Effects on Long-Term Earnings Outcomes

This section examines whether the adverse effects of lead pollution from PEA takeoffs and landings extend to long-term earnings outcomes. The results indicate a persistent negative impact on adult earnings attributable to PEA operations and the associated lead emissions.

Table 6 presents the estimated effects of PEA flights and lead exposure on earnings from ages 23 through 27. Specifically, an increase of 10,000 PEA flights results in a significant reduction in annual wages, with declines of $777 at age 23 and $814 at age 24. These losses intensify with age, reaching $1,164 by age 27. All estimates are statistically significant at the 1% level.

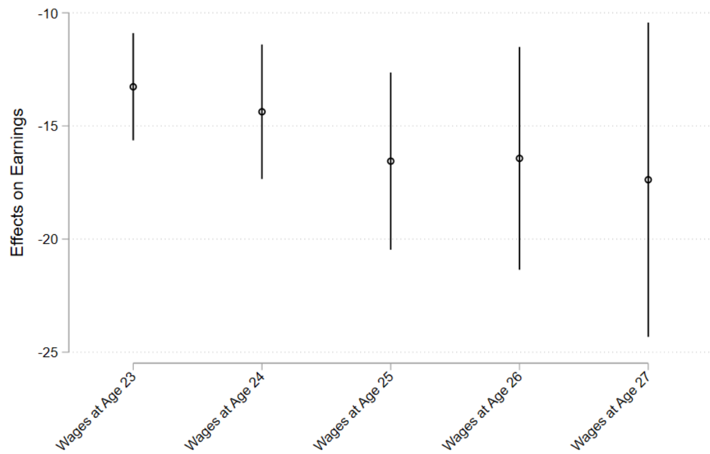
Similarly, an increase of one kilogram of lead emissions from PEA operations leads to a reduction in annual earnings, starting with a $13 and $14 decline at early ages like 23 and 24. The reduction escalates to a $17 reduction at later ages from 25 through 27. These estimated effects, also significant at the 1% level, underscore the long-lasting impacts of lead exposure. Figure 12 visually illustrates this downward trend in the reduction in annual earnings caused by lead exposure. These findings suggest that the harmful effects of lead pollution are not only immediate but also have lasting economic consequences.

Table 6: Effect of Cumulative Lead Exposure on Earnings Outcomes

	Wages at age 23	Wages at age 24	Wages at age 25	Wages at age 26	Wages at age 27
Panel A: effects of an increase of 10k PEA					
PEA(10k)	-777***	-814***	-959***	-1008***	-1164***
	(89)	(112)	(149)	(191)	(287)
N	1190844	950333	703164	466413	235531
Panel B: effects of an increase of one kg lead exposure					
Lead(kg)	-13***	-14***	-17***	-16***	-17***
	(1)	(2)	(2)	(3)	(4)
N	1190844	950333	703164	466413	235531

This table shows the effect of PEA traffic and lead exposure on earnings outcomes. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. PEA traffic is measured as the cumulative total from kindergarten through third grade. Lead emissions from PEA takeoff and landing are calculated as follows: The FAA reports that piston-engine aircraft consume an average of 14.2 gallons of leaded fuel per flight. According to OAG, 30-40% of this fuel is burned during takeoff and landing, with 20-25% for takeoff and 10-15% for landing. With an average lead content of 2.4 grams per gallon, takeoff emits approximately 8.52 grams of lead, and landing emits about 5.11 grams. Lead exposure is then calculated based on the total lead emissions from PEA takeoff and landing during kindergarten through third grade. The standard errors clustered at the school level are in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns.

Figure 12: Effects of Lead Exposure on Earnings Outcomes



Note: This figure illustrates the effects of cumulative lead pollution from PEA takeoff and landing during kindergarten through third grade on earnings outcomes. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport.

5.2 IV Results

5.2.1 Effects on Test Scores

Consistent with the DID results, the IV estimates also show adverse effects of low levels of lead exposure on short- and long-term outcomes. The IV estimates further demonstrate that even low levels of lead pollution reduce the performance on test scores. Panel A presents the 2SLS and reduced-form estimates for reading scores, while Panel B reports the results for math scores. The 2SLS estimates in Panel A indicate that a one g/m^3 increase in lead concentration leads to a 1.3 standard deviation reduction in fourth-grade reading scores, with the effect statistically significant at the 1% level. Notably, this negative effect persists through later grades, including grade 8, although the estimate for grade 5 is less precise.[6] While prior research on education interventions often finds transitory gains in test scores, our results suggest that reducing one unit of lead exposure can yield lasting improvements in academic performance. Furthermore, the reduced-form estimates align closely with the 2SLS results, showing that an increase of 10,000 PEA flights decreases fourth-grade reading scores by 0.06 standard deviations in relatively downwind areas.

The effect of lead exposure on math scores is even more pronounced, as shown

[6]The 2004 kindergarten cohort lacks grade 8 test scores due to the transition from TAKS to STAAR assessments in 2012. To avoid inconsistencies between assessment formats, STAAR scores for the 2004 cohort are excluded.

in Panel B. A one g/m^3 increase in lead concentration reduces fourth-grade math scores by about 1.8 standard deviations, with the effect significant at the 1% level. This negative impact persists across subsequent grades, with reductions of 1.8 and 1.3 standard deviations in grades 7 and 8, respectively, both statistically significant at the 10% level. Notably, the reduced-form estimates suggest larger effects on math scores compared to reading. Specifically, an increase of 10,000 PEA flights reduces math scores by 0.078 standard deviations in downwind areas compared to upwind areas. This negative effect remains consistent across subsequent grades and is statistically significant at the 1% level.

Table 7: IV Estimate of the Effect of Lead Exposure on Test Scores

	(1) First stage: Lead (g/m^3)	(2) G4	(3) G5	(4) G6	(5) G7	(6) G8
Panel A: Effects on Reading Scores						
2SLS: Lead (g/m^3)		-1.3453***	-0.1101	-1.0286**	-1.0776**	-0.9190*
		(0.4568)	(0.5202)	(0.4156)	(0.4568)	(0.5236)
N		625856	606701	609241	601910	461604
Reduced form: PEA (10k)*downwind	0.040***	-0.0604***	-0.0193	-0.0398***	-0.0505***	-0.0356**
	(0.007)	(0.0136)	(0.0192)	(0.0124)	(0.0128)	(0.0150)
N	625,856	1025884	996829	999589	989569	759922
Panel B: Effects on Math Scores						
2SLS:Lead (g/m^3)		-1.7793***	-0.9406**	-1.6311***	-1.8113***	-1.3249**
		(0.4866)	(0.4262)	(0.4331)	(0.5303)	(0.6396)
N		625856	578692	609241	601910	447459
Reduced form: PEA*downwind	0.040***	-0.0777***	-0.0505***	-0.0700***	-0.0841***	-0.0645***
	(0.007)	(0.0140)	(0.0136)	(0.0142)	(0.0146)	(0.0184)
N	625,856	1025884	949871	999589	989569	735769

Notes: This table shows the first stage, 2SLS, and reduced form estimates of the effects of lead exposure on reading and math scores from grades 4 through 8. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Lead exposure and PEA traffic are measured as the cumulative total from kindergarten through third grade. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns. The standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*** $p < 0.01$.

5.2.2 Effects on Behavioral Issues

Lead exposure also exacerbates behavioral problems. The results are shown in Table 8, which displays the 2SLS and reduced form estimates on behavioral outcomes, including school absence, disciplinary incidents, violence, crime, and disciplinary action, including suspension and expulsion. The 2SLS estimates demonstrate that a one g/m^3 increase in lead concentration raises 80 days absent (125% increase relative to the mean) from school and 79% (183% increase compared to the mean) in the absence rate, with these effects statistically significant at the 10% level. Prior research has shown that chronic absenteeism worsens long-term academic achievement and labor market outcomes. The increase in school absence suggests that lead exposure harms long-term outcomes by disrupting children's ability to engage with the educational environment.

While lead exposure increases total disciplinary incidents and more severe issues, such as violence and crime, the estimates are not statistically significant. This could indicate that lead exposure has heterogeneous effects on different types of behavioral issues, potentially influencing absenteeism more than other forms of disciplinary issues. However, a one g/m^3 increase in lead exposure significantly raises the likelihood of expulsion by 0.8. The effect size is 295% increase relative to the mean, and the estimate is statistically significant at 10% level. Expulsions could lead to further disengagement from school and increased involvement with the adult criminal justice system, which we are not able to capture in this paper.

Table 8: Effect of Cumulative Lead Exposure on Disciplinary Incidents

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
		School Absence		Disciplinary Types			Disciplinary Action	
	First stage:Lead (g/m^3)	Days absent	Absence%	Any Disci.	Violence	Crime	Suspension	Expul
2SLS: Lead (g/m^3)		79.9968*	78.5078*	9.2473	0.4146	0.3481	8.4727	0.8272*
		(46.1053)	(42.1393)	(6.1838)	(0.5737)	(0.2972)	(5.7689)	(0.4826)
Mean (0-50 miles)		64	43	5	0.41	0.20	5	0.28
Effect Size		125%	183%	185%	101%	174%	169%	295%
N		660924	660924	660924	660924	660924	660924	660924
Reduced form: PEA*downwind	0.039***	4.8442***	4.9694***	0.5418***	0.0402*	0.0273**	0.4981***	0.0467***
	(0.007)	(1.4089)	(1.3420)	(0.1963)	(0.0220)	(0.0118)	(0.1832)	(0.0159)
N	660,924	1086024	1086024	1086024	1086024	1086024	1086024	1086024

Notes: This table shows the first stage, 2SLS, and reduced form estimates of the effects of lead exposure on behavioral outcomes. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Lead exposure and PEA traffic are measured as the cumulative total from kindergarten through third grade. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns. The standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.2.3 Effects on Long-Term Educational Attainment

The negative impacts of lead exposure extend to long-term educational attainment. The results come from Table 9, which displays the results of lead exposure on high school graduation and college enrollment and graduation outcomes based on ever and on-time definitions. The findings show that one g/m^3 increase in lead concentration reduces the probability of ever graduating from high school from 2009 through 2022 by 55 percentage points and on-time (within 12 years post-kindergarten) high school graduation by 77 percentage points. These estimates correspond to 68% and 103% decline, separately, which are statistically significant at 5% level. Similarly, college enrollment is adversely affected, with a 107 percentage point reduction in the likelihood of ever enrolling in college from 2010 through 2022 and a 120 percentage points reduction in on-time (within 13 years post-kindergarten) college enrollment. The estimated effects are 176% and 218% declines compared to the average. These negative effects are also evident across both 4-year and 2-year institutions. Specifically, one g/m^3 increase in lead exposure decreases the probability of ever enrolling in a 4-year university by 109 percentage points and on-time enrollment by 93 percentage points. The effect sizes are large, which are 320% and 356% decrease compared to the average. A slightly smaller effect is observed for 2-year college enrollment, with reductions of 0.84 percentage points for ever enrolling and 88 percentage points for on-time enrollment. All of these estimates are statistically significant at the 5% level. The findings demonstrate that early childhood lead exposure not only reduces educational attainment but also delays the timing of achieving them.

Table 9: IV Estimate of the Effect of Lead Exposure on Educational Attainment

	(1) First stage: Lead (g/m^3)	(2) Ever HG	(3) Ontime HG	(4) Any Coll.	(5) Ontime Coll.	(6) Ever 4years	(7) Ontime 4years	(8) Ever 2years	(9) Ontime 2years
2SLS:Lead (g/m^3)		-0.5491**	-0.7700**	-1.0740**	-1.2011**	-1.0885**	-0.9254**	-0.8405***	-0.8830**
		(0.2714)	(0.3408)	(0.4269)	(0.4895)	(0.4718)	(0.3846)	(0.3040)	(0.3658)
Mean (0-50 miles)		0.81	0.75	0.61	0.55	0.34	0.26	0.52	0.44
Effect Size		-68%	-103%	-176%	-218%	-320%	-356%	-162%	-201%
N		662201	662201	662201	662201	662201	662201	662201	662201
Reduced form: PEA*downwind	0.039***	-0.0298***	-0.0388***	-0.0415***	-0.0480***	-0.0441***	-0.0372***	-0.0328***	-0.0366***
	(0.007)	(0.0079)	(0.0092)	(0.0088)	(0.0105)	(0.0109)	(0.0090)	(0.0067)	(0.0085)
N	662,201	1087993	1087993	1087993	1087993	1087993	1087993	1087993	1087993

Notes: This table shows the first stage, 2SLS, and reduced form estimates of the effects of lead exposure on educational attainment outcomes. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Lead exposure and PEA traffic are measured as the cumulative total from kindergarten through third grade. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns. The standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

5.2.4 Effects on Earnings Outcomes

Lead exposure has a pronounced and growing negative impact on adult earnings, as presented in Table 10. While a one g/m^3 increase in lead concentration reduces annual earnings at ages 23, 24, and 25 by $25,419, $30,308, and $40,811, these negative effects become more pronounced in the following years. By age 26, the annual earnings are reduced by $52,989 (208% reduction relative to the mean), and by age 27, the decrease remains substantial at $50960 (188% decline relative to the mean). These findings suggest that the adverse impacts of early childhood lead exposure not only persist but intensify over time, reflecting the cumulative disadvantage that lead exposure imposes on career trajectories and wage growth. The larger impact on earnings at later ages highlights the long-term barriers to economic mobility and labor market success caused by lead pollution in early childhood.

The pathways through which lead exposure reduces earnings include a combination of lower educational attainment and increased behavioral problems. As evidenced in earlier sections, lead exposure significantly reduces test scores, high school graduation rates, and college enrollment and graduation rates. Educational achievement is a critical predictor of labor market outcomes. Moreover, behavioral issues, such as increased absenteeism and disciplinary actions, may impair non-cognitive skills, such as persistence, teamwork, and adaptability, which are increasingly important in labor markets.

Table 10: IV Estimate of the Effect of Lead Exposure on Earnings Outcomes

	(1) First stage:Lead (g/m^3)	(2) Wages23	(3) Wages24	(4) Wages25	(5) Wages26	(6) Wages27
2SLS: Lead (g/m^3)		-25419***	-30308***	-40811***	-52989***	-50960**
		(7651)	(9566)	(13325)	(15362)	(23115)
Mean (0-50 miles)		19276	21459	23344	25435	27076
Effect Size		-132%	-141%	-175%	- 208%	-188%
N		662093	526555	388071	255944	128016
Reduced form: PEA*downwind	0.043***	-1350***	-1733***	-1964***	-2574***	-2726***
	(0.005)	(250)	(318)	(417)	(584)	(845)
N	388071	1087840	867052	640885	424714	214301

Notes: This table shows the first stage, 2SLS, and reduced form estimates of the effects of lead exposure on earnings outcomes. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Lead exposure and PEA traffic are measured as the cumulative total from kindergarten through third grade. Student demographics, jet aircraft operations, and school and cohort fixed effects are included in all columns. The standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.*** $p < 0.01$.

6 Robustness Checks

6.1 Including Weather Controls

Given that weather factors can influence pollution dispersion and learning (Park et al. (2020)), we re-estimate our DID and IV models controlling for outdoor temperature and wind patterns. Wind speed could affect the spread of lead particulates, while outdoor temperature may impact student concentration, attendance, and performance. By including these variables, we ensure that the estimated effects of lead exposure are not confounded by other environmental factors that vary across regions and time periods, providing a more precise measure of lead's direct impact.

We estimate the exact model specification in Eq (2) and Eq (5) for DID and IV models. However, we add the average outdoor temperature and wind speed in Texas for the year each cohort attended grade 3 as additional controls. Table 11 shows the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes when incorporating weather controls. Refer to the Appendix for the full set of results for this robustness check.

This robustness check yields results consistent with the main analysis, reinforcing the validity of our findings. Across both DID and IV specifications, the adverse effects of lead exposure on educational, behavioral, and labor market outcomes remain evident. Increased lead exposure significantly lowers G4 reading and math scores and increases absenteeism. For instance, a one g/m^3 increase in lead exposure reduces reading and math scores by 1.34 and 1.78 standard deviations, respectively (both significant at a 1% level). Furthermore, a one g/m^3 increase in lead exposure increases the number of days absent by 80 days (significant at a 10% level).

Lead exposure continues to reduce the likelihood of high school completion, college enrollment, and future earnings. A one g/m^3 increase in lead exposure lowers high school completion and college enrollment rates by 0.55 and 1.07 percentage points. Annual earnings at age 24 were reduced by $30,247 for every g/m^3 increase in lead exposure. The robustness of the results across different empirical strategies and different outcomes, even with these additional weather controls, strengthens the conclusion that the effects of low-level lead exposure during childhood are not limited to short-term outcomes but extend into long-term economic well-being.

Table 11: Robustness Check with Weather Controls

	(1) G4 Reading	(2) G4 Math	(3) Days Absent	(4) Ever HS	(5) Any College	(6) Wages at age 24
DID: Lead (kg)	-0.0006***	-0.0007***	0.0543***	-0.0003***	-0.0004***	-14***
	(0.0001)	(0.0001)	(0.0047)	(0.0000)	(0.0000)	(2)
N	1,122,468	1,122,468	1,188,904	1,190,974	1,190,974	950,305
2SLS: Lead (g/m^3)	-1.3469***	-1.7827***	80.0395*	-0.5494**	-1.0740**	-30247***
	(0.4561)	(0.4852)	(46.0773)	(0.2714)	(0.4268)	(9586)
N	625,856	625,856	660,924	662,201	662,201	526,555

Notes: This table reports the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes when controlling for weather conditions. The top and bottom panels show the estimates from Eq(2) and Eq(5), respectively with the addition controls of the average outdoor temperature and wind speed in Texas for the year each cohort attended grade 3. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

6.2 Different Distance Bands

To confirm the validity of our findings, we conducted a robustness check by re-estimating the DID and IV models using varying distance bands around the airports. The reasons for this robustness check are twofold. First, this analysis helps address potential concerns about the confounding effects of close proximity to the airport. Students attending school within a few miles of the airport may experience lead exposure from PEA operations and significant noise pollution, which could affect their educational and behavioral outcomes. By excluding students only a few miles away from the airport, we aim to isolate the effect of lead exposure and ensure that our results are not driven by other factors associated with proximity to airports. Second, the distribution of lead deposition might vary across distance bands. Testing different distance bands confirms whether the results hold across different exposure levels.

We estimate the same model specification in Eq (2) and Eq (5) for DID and IV models, restricting the data to observations within 1-50, 3-50, and 5-50 miles. Table 12 shows the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes across different distance bands. Refer to the Appendix for the full set of results for this robustness check.

The results, presented in Table 12, remain consistent with the main analysis across all distance bands, supporting the robustness of our findings. When restricted to 1-50 miles, the DID and IV estimates for the effect of lead exposure on educational, behavioral, and labor market outcomes are highly significant. A one g/m^3 increase in lead exposure decreases reading and math scores by 1.47 and 1.82 standard deviations and increases absenteeism by 80 days. Additionally, for every unit increase in lead exposure, the likelihood of high school graduation and college enrollment declines by 0.54 and 1.07 percentage points, resulting in a large decrease in future wages of $32,853. Even with larger exclusion zones, the results uphold their significance and direction.

These robustness checks' results demonstrate that the estimated impacts of lead exposure are consistent across different distance bands, lending further credibility to the main findings. By accounting for possible confounding factors such as noise pollution and varying lead concentration levels, we confirm that the adverse effects of lead exposure on educational, behavioral, and labor market outcomes persist even when excluding students closest to the airport.

Table 12: Robustness Check with Different Distance Bands

	(1) G4 Reading	(2) G4 Math	(3) Days Absent	(4) Ever HS	(5) Any College	(6) Wages at age 24
Panel A: Restricting to 1-50 miles						
DID: Lead (kg)	-0.0006***	-0.0007***	0.0665***	-0.0004***	-0.0005***	-17***
	(0.0001)	(0.0001)	(0.0053)	(0.0000)	(0.0000)	(2)
N	1,109,538	1,109,538	1,175,156	1,177,198	1,177,198	939,152
2SLS: Lead (g/m^3)	-1.4754***	-1.8205***	80.0335*	-0.5440**	-1.0712**	-32853***
	(0.4846)	(0.5042)	(47.3892)	(0.2770)	(0.4375)	(10056)
N	625,116	625,116	660,157	661,434	661,434	525,929
Panel B: Restricting to 3-50 miles						
DID: Lead (kg)	-0.0008***	-0.0009***	0.1176***	-0.0005***	-0.0007***	-28***
	(0.0001)	(0.0002)	(0.0092)	(0.0001)	(0.0001)	(4)
N	909,926	909,926	962,222	963,879	963,879	769,742
2SLS: Lead (g/m^3)	-1.7914***	-2.1723***	79.4483	-0.5796*	-1.0217**	-32001***
	(0.5850)	(0.6084)	(48.8260)	(0.3001)	(0.4367)	(10226)
N	609,353	609,353	643,656	644,905	644,905	512,776
Panel C: Restricting to 5-50 miles						
DID: Lead (kg)	-0.0008***	-0.0011***	0.1184***	-0.0005***	-0.0008***	-37***
	(0.0002)	(0.0003)	(0.0156)	(0.0001)	(0.0001)	(6)
N	649,648	649,648	686,076	687,234	687,234	548,988
2SLS: Lead (g/m^3)	-3.1740***	-3.7498***	219.8525***	-1.3496***	-2.0135***	-49564***
	(0.7055)	(0.7051)	(41.4478)	(0.3027)	(0.3244)	(14642)
N	580,184	580,184	613,157	614,362	614,362	488,525

Notes: This table reports the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes using different distance bands. The DID and 2SLS estimates from Eq(2) and Eq(5) are reported for each distance band. The sample consists of kindergartners from the 2000 to 2004 cohorts. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

6.3 Heterogeneity Effects

Understanding how low-lead exposure's impact varies across different demographic groups is critical. Since different populations may have varying levels of vulnerability to pollution due to biological, social, and economic factors, identifying the heterogeneity effects allows for equitable policy interventions. In addition, since disparities in educational and labor market outcomes are well-documented, it is important for public policy design to examine how environmental stressors such as lead exposure might contribute to these disparities.

6.3.1 By Gender

Table 13: Heterogeneity Effects by Gender

	(1) G4 Reading	(2) G4 Math	(3) Days Absent	(4) Ever HS	(5) Any College	(6) Wages at age 24
Panel A: Female						
DID: Lead (kg)	-0.0005***	-0.0007***	0.0518***	-0.0003***	-0.0004***	-14***
	(0.0001)	(0.0001)	(0.0054)	(0.0000)	(0.0000)	(-2)
N	566,438	566,438	594,135	595,135	595135	472,549
2SLS: Lead (g/m^3)	-1.5186***	-2.3280***	73.3757	-0.5303*	-1.117**	-33162**
	(0.4331)	(0.5220)	(47.8262)	(0.2966)	(0.4679)	(13081)
N	316,182	316,182	330,939	331,562	331,562	262,628
Panel B: Male						
DID: Lead (kg)	-0.0006***	-0.0006***	0.0572***	-0.0003***	-0.0003***	-15***
	(0.0001)	(0.0001)	(0.0055)	(0.0000)	(0.0000)	(2)
N	556,007	556,007	594,742	595,812	595,812	477,680
2SLS: Lead (g/m^3)	-1.2076*	-1.2457**	87.5385*	-0.5735*	-1.0318**	-27125**
	(0.6418)	(0.5767)	(48.2277)	(0.2976)	(0.4258)	(12251)
N	309,664	309,664	329,978	330,632	330,632	263,892

Notes: This table reports the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes for female and male. The DID and 2SLS estimates from Eq(2) and Eq(5) are reported for each panel. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

We estimate the same model specification in Eq (2) and Eq (5) for DID and IV models, restricting the data to either male or female students. Table 13 shows the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes by gender. Refer to the Appendix for the full set of results for this robustness check.

The results indicate that both females and males are adversely affected by low-lead exposure. For female students, increased lead exposure reduces reading and math scores by 1.52 and 2.33 standard deviations (both significant at the 1% level). Although the effect on absenteeism is positive, it is not statistically significant. Regarding long-term outcomes, lead exposure significantly decreases the likelihood of high school completion by 0.53 percentage points and college attendance by 1.12 percentage points. Additionally, lead exposure leads to a substantial wage reduction of approximately $33,162 at age 24.

Similarly, the IV estimates for male students show a significant reduction in reading and math scores of 1.21 and 1.25 standard deviations for every unit increase in lead exposure. The number of days absent increases by 87.54 days, which is significant at the 10% level. Lead exposure also reduces the likelihood of high school and college completion by 0.57 and 1.03 percentage points, respectively. In the labor market, males experience an earning loss of $27,125 at age 24 due to lead exposure.

These results deepen the main analysis by highlighting the gender differences in the magnitude of lead exposure's impact. While both male and female students face reduced long-term economic losses, females experience a larger earning loss[7]. These findings suggest that lead exposure may affect the genders differently due to variations in biological or social responses to environmental stressors. This calls for gender-specific policy interventions to mitigate the long-term effects of lead exposure.

6.3.2 By Race

We estimate the same model specification in Eq (2) and Eq (5) for DID and IV models, restricting the data to either White, Hispanic, or Black students. Table 14 shows the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes by race. Refer to the Appendix for the full set of results for this robustness check.

The heterogeneity analysis by race reveals notable differences in the impact of lead exposure on educational, behavioral, and labor market outcomes for White, Hispanic, and Black students. White students see a large and significant reduction in reading and math scores (by 4.48 and 4.71 standard deviation) for every unit increase in lead exposure. Additionally, lead exposure increases absenteeism by about 313 days and decreases the likelihood of high school completion and college attendance by 1.29 and 2.46 percentage points, respectively. Notably, the wage penalty for White students is substantial, approximately $132,765 by age 24.

Hispanic students also experience adverse effects from lead exposure on test scores

[7] We test the null hypothesis that the adverse effect on wages for males is the same as that for females. We reject the equality hypothesis at a 1% level.

and college enrollment. However, absenteeism and high school completion do not show statistically meaningful effects. The earning loss for Hispanic students is not statistically significant in the IV model.

Similarly, for Black students, the findings demonstrate a significant negative impact on math scores, with a reduction of 2.82 points. Absenteeism also increases significantly, by approximately 255 days, while high school completion and college attendance decrease by 2.13 and 3.16 percentage points, respectively. The earning loss for Black students is not statistically significant in the IV model.

These findings enrich the main analysis by underscoring the varying impacts of lead exposure across different racial groups. While all groups experience detrimental effects, the magnitude of these effects varies, with White students suffering significantly larger reduction[8] in educational attainment and future earnings. Policymakers can use this information to develop race-specific policy interventions to mitigate the harmful effects of lead exposure on long-term outcomes.

6.3.3 By Income

We estimate the same model specification in Eq (2) and Eq (5) for DID and IV models, restricting the data to students who belong and are not included in the economic disadvantage group separately. Table 15 shows the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes by income group. Refer to the Appendix for the full set of results for this robustness check.

The findings indicate that lead exposure negatively affects educational outcomes for economically disadvantaged students. A one-unit increase in lead concentration leads to a decline in reading and math scores by 0.64 and 0.78 standard deviations, respectively. Additionally, the findings reveal a substantial increase in days absent (by 40 days) and negative impacts on high school graduation rates (by 0.36 percentage points) and college attendance (by 0.83 percentage points). Furthermore, economically disadvantaged students also see a significant earning loss of $17,794 at the age of 24. These results highlight the severe consequences of lead exposure on both academic performance and long-term economic prospects for this vulnerable population.

Similarly, the IV results reveal significant adverse effects of lead exposure for students not classified as economically disadvantaged. Reading and math scores decline

[8] We test the hypothesis that the adverse effects on higher education attainment and wage loss for White students equal that for non-White students. We reject the equality hypothesis at a 1% level for both outcomes.

Table 14: Heterogeneity Effects by Race

	(1) G4 Reading	(2) G4 Math	(3) Days Absent	(4) Ever HS	(5) Any College	(6) Wages at age 24
Panel A: White						
DID: Lead (kg)	-0.0005***	-0.0005***	0.0570***	0.0004***	-0.0003***	-28***
	(0.0001)	(0.0001)	(0.0067)	(0.0001)	(0.0001)	(3)
N	420,193	420,193	446,118	223,318	223,318	363,587
2SLS: Lead (g/m^3)	-4.4841***	-4.7068***	312.9934***	-1.2915**	-2.4646***	-132756***
	(1.0224)	(0.9816)	(60.6253)	(0.5178)	(0.5688)	(35886)
N	209,870	209,870	222,733	223,318	223,318	181,578
Panel B: Hispanic						
DID: Lead (kg)	-0.0006***	-0.0007***	0.0523***	-0.0003***	-0.0004***	-11***
	(0.0001)	(0.0001)	(0.0064)	(0.0000)	(0.0000)	(2)
N	524,806	524,806	552,180	552,817	552,817	435,301
2SLS: Lead (g/m^3)	-0.8925**	-1.0081***	20.6881	-0.1644	-0.4810*	-11946
	(0.3638)	(0.3248)	(31.2589)	(0.1666)	(0.2780)	(7399)
N	295,421	295,421	309,626	310,025	310,025	243,411
Panel C: Black						
DID: Lead (kg)	-0.0005***	-0.0006***	0.0713***	-0.0004***	-0.0004***	-9***
	(0.0001)	(0.0001)	(0.0082)	(0.0001)	(0.0001)	(3)
N	140,366	140,366	151,557	151,877	151,877	120,661
2SLS: Lead (g/m^3)	-1.8409	-2.8214**	254.6865***	-2.1317***	-3.1573***	-29229
	(1.3434)	(1.4298)	(88.2053)	(0.6271)	(0.6835)	(27197)
N	92,043	92,043	98,693	98,909	98,909	78,059

Notes: This table reports the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes by race. The DID and 2SLS estimates from Eq(2) and Eq(5) are reported for each panel. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

by 3.77 and 4.38 standard deviations, respectively (both significant at the 1% level). There is also a considerable increase in days absent (by 214 days) and a negative impact on high school graduation rates (by 0.99 percentage points) and college attendance (by 1.85 percentage points). Moreover, these students experience a significant earning loss of $72,084 at age 24.

These heterogeneity findings add depth to the main analysis by demonstrating that the negative impacts of lead exposure extend beyond economically disadvantaged students. The consistent declines in educational performance and significant income losses across both income groups emphasize the widespread implications of lead exposure as a public health issue. This finding underscores the urgent need for comprehensive policies to reduce lead exposure for all students, regardless of socioeconomic status.

Table 15: Heterogeneity Effects by Income

	(1) G4 Reading	(2) G4 Math	(3) Days Absent	(4) Ever HS	(5) Any College	(6) Wages at age 24
Panel A: Economic Disadvantage						
DID: Lead (kg)	-0.0005***	-0.0006***	0.0546***	-0.0003***	-0.0004***	-11***
	(0.0001)	(0.0001)	(0.0061)	(0.0000)	(0.0000)	(2)
N	633,245	633,245	675,004	676,006	676,006	537,315
2SLS: Lead (g/m^3)	-0.6452*	-0.7799*	39.8404	-0.3561*	-0.8267**	-17794**
	(0.3802)	(0.4217)	(39.2006)	(0.2041)	(0.3419)	(7669)
N	348,290	348,290	369,205	369,797	369,797	292,514
Panel B: Not Economic Disadvantage						
DID: Lead (kg)	-0.0007***	-0.0007***	0.0541***	-0.0003***	-0.0004***	-23***
	(0.0001)	(0.0001)	(0.0050)	(0.0000)	(0.0001)	(3)
N	489,179	489,179	513,849	514,917	514,917	412,899
2SLS: Lead (g/m^3)	-3.7745***	-4.3851***	213.8656***	-0.9939**	-1.8475***	-72084**
	(1.1726)	(1.3683)	(52.8642)	(0.4840)	(0.6627)	(28053)
N	277,538	277,538	291,694	292,379	292,379	233,995

Notes: This table reports the effects of cumulative lead exposure on representative educational, behavioral, and labor market outcomes by income group. The DID and 2SLS estimates from Eq(2) and Eq(5) are reported for each panel. The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

7 Conclusion

This paper provides new causal evidence on the short- and long-term effects of low-level lead exposure on children's outcomes, with a focus on one of the largest remaining sources of airborne lead emissions—piston-engine aircraft (PEA). Leveraging the sharp decline in PEA traffic following the 9/11 attacks, wind direction, and a rich longitudinal dataset from the Texas Education Research Center (ERC), we trace the impacts of early childhood lead exposure on educational, behavioral, and labor market outcomes.

Our findings reveal that even low levels of lead exposure during kindergarten through third grade have profound and lasting adverse effects. Lead exposure significantly reduces reading and math test scores, increases behavioral problems, and negatively impacts long-term educational attainment by reducing the likelihood of graduating from high school and enrolling in college. These effects persist into adulthood, where we observe substantial reductions in labor market earnings for those exposed to higher lead levels in early childhood. Notably, these persistent adverse effects challenge the "fade-out" phenomenon often documented in education interventions, demonstrating that the detrimental impacts of lead exposure could endure over time. Furthermore, the adverse effects of lead exposure cannot be easily mitigated by socioeconomic advantages, even for high-income children living near airports, despite their access to greater resources.

This study contributes to the growing body of literature linking lead exposure to adverse health and human capital outcomes, extending the analysis to low-level lead pollution from a modern low-level, yet under-researched, source. By providing new causal evidence, we highlight the critical need for policymakers to address the risks posed by even low thresholds of lead pollution. With many children still exposed to airborne lead near airports, reducing emissions from PEA could yield significant public health and economic benefits by improving educational outcomes and enhancing labor market productivity. While our study focuses on educational and labor market outcomes, future research could explore the broader health implications of low-level lead exposure, offering further insights for targeted policy interventions.

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8 Appendix

8.1 Tables

Table A1: Summary Statistics Before and After 2001

	(1) 2000-2001	(2) 2002-2004	3 Diff.(Pre-Post)	4 P-values	5 N
Students' Characteristics					
Female	0.50	0.50	0.00	0.745	1192570
African	0.13	0.13	0.00***	0.000	1192425
Hispanic	0.45	0.47	-0.02***	0.000	1192425
White	0.39	0.37	0.02***	0.000	1192425
Bilingual program	0.13	0.15	-0.02***	0.000	1191884
Economically disadvantaged	0.56	0.57	-0.02***	0.000	1191883
Special Education	0.10	0.09	0.01***	0.000	1192117
At risk of dropout	0.39	0.44	-0.05***	0.000	1192022
Airport Characteristics					
Distance of school to airport	7.58	7.47	0.12***	0.000	1214608
Min distance btw monitor and school	18.42	18.55	-0.14***	0.000	704668
Distance weighted lead (g/m^3)	0.01	0.00	0.01***	0.000	1214608
Lead (g/m^3)	0.04	0.01	0.03***	0.000	1214608
Distance weighted PEA (10k)	0.34	0.30	0.04***	0.000	1214608
PEA(10k)	1.50	1.34	0.16***	0.000	1214608
JET(10k)	19.29	20.65	-1.35***	0.000	1214608
Lead from PEA(kg)	102.78	91.60	11.18***	0.000	1214608
Educational Attainment					
Grade 4 reading scores	0.00	-0.00	0.00	0.829	1132908
Grade 4 math scores	0.00	0.00	0.00	0.769	1132908
Ever graduated from high school	0.80	0.82	-0.02***	0.000	1214608
Ontime high school graduation	0.74	0.76	-0.02***	0.000	1214608
Ever enrolled in any university	0.63	0.60	0.03***	0.000	1214608
Ontime enrollment in any university	0.56	0.54	0.02***	0.000	1214608
Ever enrolled in a 4 year university	0.35	0.33	0.02***	0.000	1214608
Ontime enrollment in a 4 year university	0.26	0.25	0.01***	0.000	1214608
Ever enrolled in a 2 year university	0.55	0.51	0.04***	0.000	1214608
Ontime enrollment in a 2 year university	0.46	0.43	0.02***	0.000	1214608
Earnings Outcomes					
Wage23	18959.98	19471.15	-511.17***	0.000	1214437
Wage24	20770.85	22087.28	-1316.43***	0.000	970080
Wage25	22806.93	24317.46	-1510.53***	0.000	718071
Behavioral Outcomes					
Days absent	63.75	63.36	0.39***	0.000	1211430
Percent of absence	43.25	42.18	1.07***	0.000	1211430
Any disciplinary incident	5.22	4.65	0.58***	0.000	1211430
Violence	0.41	0.41	0.01***	0.004	1211430
Crime	0.20	0.20	0.00**	0.020	1211430
Suspension	4.92	4.39	0.53***	0.000	1211430
Expulsion	0.32	0.27	0.05***	0.000	1211430

Notes: The sample includes kindergartners from 2000 through 2004 cohorts who attended schools within 50 miles of the nearest airport. Both lead exposure and PEA traffic are measured as cumulative totals from kindergarten through third grade.

Table A2: DID: Effect of Lead Exposure on Short- and Long-term Outcomes

	Reading	Math	Pct_absence	Total Disc	Ever HG	Any Coll.	4 year U	2 year U	Wage 25
Lead*Post2001	-1.2001***	-2.6040***	63.4928***	6.3999**	-0.2371*	-0.4526***	-0.8137***	0.1891	-28498.7747**
	(0.3856)	(0.4921)	(15.2527)	(3.1704)	(0.1310)	(0.1592)	(0.1603)	(0.1499)	(12955.5921)
N	653810	653810	690903	690903	692216	692216	692216	692216	405932

Notes: standard errors clustered at school level in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A3: Robustness Check with Weather Controls: Effect of Lead Exposure on Test Scores

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: Effects on Reading Scores					
DID: Lead(kg)	-0.0006***	-0.0004***	-0.0005***	-0.0005***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	1122468	1091611	1094732	1084114	833413
2SLS: Lead (g/m^3)	-1.3469***	-0.1080	-1.0304**	-1.0771**	-0.9168*
	(0.4561)	(0.5210)	(0.4149)	(0.4571)	(0.5255)
N	625856	606701	609241	601910	461604
Panel B: Effects on Math Scores					
DID: Lead (kg)	-0.0007***	-0.0006***	-0.0007***	-0.0008***	-0.0007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	1122468	1039584	1094732	1084114	806716
2SLS: Lead (g/m^3)	-1.7827***	-0.9405**	-1.6351***	-1.8116***	-1.3234**
	(0.4852)	(0.4265)	(0.4318)	(0.5303)	(0.6412)
N	625856	578692	609241	601910	447459

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, weather controls (including outdoor temperature and wind speed), and school- and cohort-fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A4: Robustness Check with Weather Controls: Effect of Lead Exposure on Disciplinary Incidents

	(1) Days absent	(2) Absence%	(3) Any Disci.	(4) Violence	(5) Crime	(6) Suspension	(7) Expul
DID: Lead (kg)	0.0543***	0.0576***	0.0078***	0.0007***	0.0004***	0.0073***	0.0005***
	(0.0047)	(0.0045)	(0.0008)	(0.0001)	(0.0001)	(0.0007)	(0.0001)
N	1188904	1188904	1188904	1188904	1188904	1188904	1188904
2SLS: Lead (g/m^3)	80.0395*	78.5429*	9.2336	0.4144	0.3475	8.4607	0.8255*
	(46.0773)	(42.1197)	(6.1877)	(0.5736)	(0.2973)	(5.7723)	(0.4830)
N	660924	660924	660924	660924	660924	660924	660924

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, weather controls (including outdoor temperature and wind speed), and school- and cohort-fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A5: Robustness Check with Weather Controls: Effect of Lead Exposure on Educational Attainment

	(1) Ever HG	(2) Ontime HG	(3) Any Coll.	(4) Ontime Coll.	(5) Ever 4years	(6) Ontime 4years	(7) Ever 2years	(8) Ontime 2years
DID: Lead (kg)	-0.0003***	-0.0004***	-0.0004***	-0.0005***	-0.0005***	-0.0004***	-0.0003***	-0.0004***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	1190974	1190974	1190974	1190974	1190974	1190974	1190974	1190974
2SLS: Lead (g/m^3)	-0.5494**	-0.7701**	-1.0740**	-1.2012**	-1.0890**	-0.9254**	-0.8401***	-0.8830**
	(0.2714)	(0.3408)	(0.4268)	(0.4893)	(0.4715)	(0.3844)	(0.3040)	(0.3657)
N	662201	662201	662201	662201	662201	662201	662201	662201

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, weather controls (including outdoor temperature and wind speed), and school- and cohort-fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A6: Robustness Check with Weather Controls: Effect of Lead Exposure on Earning Outcomes

	(1) Wages at age 23	(2) Wages at age 24	(3) Wages at age 25	(4) Wages at age 26	(5) Wages at age 27
DID: Lead (kg)	-13***	-14***	-17***	-16***	-17***
	(1)	(2)	(2)	(3)	(4)
N	1190815	950305	703145	466398	235524
2SLS: Lead (g/m^3)	-25365***	-30247***	-40751***	-52968***	-51116**
	(7669)	(9586)	(13358)	(15388)	(23115)
N	662093	526555	388071	255944	128016

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, weather controls (including outdoor temperature and wind speed), and school- and cohort-fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A7: Robustness Check with Different Distance Bands: Effect of Lead Exposure on Reading Scores

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: Restricting to 1-50 miles					
DID: Lead (kg)	-0.0006***	-0.0005***	-0.0005***	-0.0006***	-0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	1109538	1079018	1082212	1071722	823705
2SLS: Lead (g/m^3)	-1.4754***	-0.2165	-1.0834**	-1.1480**	-0.9036*
	(0.4846)	(0.5605)	(0.4388)	(0.4827)	(0.5388)
N	625116	605991	608521	601201	461054
Panel B: Restricting to 3-50 miles					
DID: Lead (kg)	-0.0008***	-0.0006***	-0.0007***	-0.0009***	-0.0006***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
N	909926	884996	887205	878776	676205
2SLS: Lead (g/m^3)	-1.7914***	-0.4036	-1.2115***	-1.4210**	-1.1043*
	(0.5850)	(0.6400)	(0.4535)	(0.5835)	(0.6095)
N	609353	590883	593223	586202	449528
Panel C: Restricting to 5-50 miles					
DID: Lead (kg)	-0.0008***	-0.0005**	-0.0005*	-0.0006***	-0.0006**
	(0.0002)	(0.0002)	(0.0002)	(0.0002)	(0.0003)
N	649648	632212	633052	627562	482840
2SLS: Lead (g/m^3)	-3.1740***	-1.8555***	-2.2654***	-2.6581***	-1.9709***
	(0.7055)	(0.6153)	(0.6597)	(0.5865)	(0.5600)
N	580184	563141	564975	558436	428259

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts. Student demographics and school and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A8: Robustness Check with Different Distance Bands: Effect of Lead Exposure on Math Scores

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: Restricting to 1-50 miles					
DID: Lead (kg)	-0.0007***	-0.0006***	-0.0008***	-0.0010***	-0.0009***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	1109538	1027631	1082212	1071722	797334
2SLS: Lead (g/m^3)	-1.8205***	-0.9744**	-1.7173***	-1.8638***	-1.2369*
	(0.5042)	(0.4406)	(0.4589)	(0.5528)	(0.6373)
N	625116	578004	608521	601201	446923
Panel B: Restricting to 3-50 miles					
DID: Lead (kg)	-0.0009***	-0.0008***	-0.0010***	-0.0013***	-0.0011***
	(0.0002)	(0.0001)	(0.0002)	(0.0002)	(0.0002)
N	909926	843498	887205	878776	655013
2SLS: Lead (g/m^3)	-2.1723***	-1.2920**	-2.0971***	-2.2597***	-1.6505**
	(0.6084)	(0.5171)	(0.5624)	(0.6863)	(0.7571)
N	609353	563684	593223	586202	435803
Panel C: Restricting to 5-50 miles					
DID: Lead (kg)	-0.0011***	-0.0008***	-0.0007**	-0.0012***	-0.0006**
	(0.0003)	(0.0002)	(0.0003)	(0.0003)	(0.0003)
N	649648	603072	633052	627562	468065
2SLS: Lead (g/m^3)	-3.7498***	-2.3919***	-3.7164***	-3.8384***	-3.2374***
	(0.7051)	(0.6527)	(0.7064)	(0.7228)	(0.6901)
N	580184	537354	564975	558436	415328

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts. Student demographics and school and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A9: Robustness Check with Different Distance Bands: Effect of Lead Exposure on Disciplinary Incidents

	(1) Days absent	(2) Absence%	(3) Any Disci.	(4) Violence	(5) Crime	(6) Suspension	(7) Expul
Panel A: Restricting to 1-50 miles							
DID: Lead (kg)	0.0665***	0.0691***	0.0093***	0.0009***	0.0005***	0.0087***	0.0007***
	(0.0053)	(0.0051)	(0.0009)	(0.0001)	(0.0001)	(0.0008)	(0.0001)
N	1175156	1175156	1175156	1175156	1175156	1175156	1175156
2SLS: Lead (g/m^3)	80.0335*	81.4178*	10.3579	0.6221	0.4011	9.5027	0.9120*
	(47.3892)	(44.2999)	(6.6484)	(0.6129)	(0.3127)	(6.2004)	(0.5149)
N	660157	660157	660157	660157	660157	660157	660157
Panel B: Restricting to 3-50 miles							
DID: Lead (kg)	0.1176***	0.1125***	0.0153***	0.0017***	0.0011***	0.0141***	0.0012***
	(0.0092)	(0.0087)	(0.0017)	(0.0002)	(0.0001)	(0.0016)	(0.0001)
N	962222	962222	962222	962222	962222	962222	962222
2SLS: Lead (g/m^3)	79.4483	83.7161*	11.0552	0.7496	0.3764	10.2556	0.8485*
	(48.8260)	(46.8853)	(7.1787)	(0.6666)	(0.3164)	(6.7305)	(0.5136)
N	643656	643656	643656	643656	643656	643656	643656
Panel C: Restricting to 5-50 miles							
DID: Lead (kg)	0.1184***	0.1000***	0.0136***	0.0018***	0.0011***	0.0128***	0.0008***
	(0.0156)	(0.0145)	(0.0030)	(0.0004)	(0.0002)	(0.0028)	(0.0003)
N	686076	686076	686076	686076	686076	686076	686076
2SLS: Lead (g/m^3)	219.8525***	221.3903***	32.0182***	2.8013***	0.9327*	29.9684***	2.0632***
	(41.4478)	(40.9782)	(7.1946)	(0.8621)	(0.5325)	(6.6979)	(0.7347)
N	613157	613157	613157	613157	613157	613157	613157

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts. Student demographics and school and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A10: Robustness Check with Different Distance Bands: Effect of Lead Exposure on Educational Attainment

	(1) Ever HG	(2) Ontime HG	(3) Any Coll.	(4) Ontime Coll.	(5) Ever 4years	(6) Ontime 4years	(7) Ever 2years	(8) Ontime 2years
Panel A: Restricting to 1-50 miles								
DID: Lead (kg)	-0.0004***	-0.0005***	-0.0005***	-0.0006***	-0.0006***	-0.0005***	-0.0004***	-0.0004***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	1177198	1177198	1177198	1177198	1177198	1177198	1177198	1177198
2SLS: Lead (g/m^3)	-0.5440**	-0.7957**	-1.0712**	-1.2086**	-1.1139**	-0.9505**	-0.8433***	-0.8897**
	(0.2770)	(0.3585)	(0.4375)	(0.5057)	(0.4942)	(0.4040)	(0.3132)	(0.3782)
N	661434	661434	661434	661434	661434	661434	661434	661434
Panel B: Restricting to 3-50 miles								
DID: Lead (kg)	-0.0005***	-0.0007***	-0.0007***	-0.0008***	-0.0008***	-0.0007***	-0.0006***	-0.0007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	963879	963879	963879	963879	963879	963879	963879	963879
2SLS: Lead (g/m^3)	-0.5796*	-0.8699**	-1.0217**	-1.1883**	-1.0945**	-0.9428**	-0.7954***	-0.8604**
	(0.3001)	(0.3988)	(0.4367)	(0.5199)	(0.5080)	(0.4185)	(0.3075)	(0.3830)
N	644905	644905	644905	644905	644905	644905	644905	644905
Panel C: Restricting to 5-50 miles								
DID: Lead (kg)	-0.0005***	-0.0006***	-0.0008***	-0.0010***	-0.0009***	-0.0007***	-0.0007***	-0.0008***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	687234	687234	687234	687234	687234	687234	687234	687234
2SLS: Lead (g/m^3)	-1.3496***	-1.8586***	-2.0135***	-2.4423***	-2.3008***	-1.9103***	-1.4923***	-1.7594***
	(0.3027)	(0.3516)	(0.3244)	(0.3721)	(0.3586)	(0.3007)	(0.3030)	(0.3240)
N	614362	614362	614362	614362	614362	614362	614362	614362

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts. Student demographics and school and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A11: Robustness Check with Different Distance Bands: Effect of Lead Exposure on Earning Outcomes

	(1) Wages at age 23	(2) Wages at age 24	(3) Wages at age 25	(4) Wages at age 26	(5) Wages at age 27
Panel A: Restricting to 1-50 miles					
DID: Lead (kg)	-16***	-17***	-20***	-21***	-23***
	(1)	(2)	(2)	(3)	(4)
N	1177045	939152	694776	460850	232682
2SLS: Lead (g/m^3)	-27299***	-32853***	-41603***	-53834***	-50321**
	(8041)	(10056)	(13918)	(16154)	(25226)
N	661326	525929	387624	255638	127841
Panel B: Restricting to 3-50 miles					
DID: Lead (kg)	-26***	-28***	-36***	-36***	-44***
	(3)	(4)	(5)	(6)	(8)
N	963768	769742	569866	378264	191162
2SLS: Lead (g/m^3)	-25597***	-32001***	-41268***	-54063***	-55609**
	(7774)	(10226)	(14417)	(16984)	(26774)
N	644800	512776	377891	249265	124645
Panel C: Restricting to 5-50 miles					
DID: Lead (kg)	-41***	-37***	-42***	-41***	-47***
	(5)	(6)	(10)	(11)	(14)
N	687164	548988	406684	270054	136281
2SLS: Lead (g/m^3)	-36893***	-49564***	-56872***	-65117***	-75169**
	(12988)	(14642)	(16048)	(17836)	(30642)
N	614260	488525	359875	237306	118669

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts. Student demographics and school and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A12: Heterogeneity Effect of Lead Exposure on Test Scores (by Gender)

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: Reading Scores (for Female)					
DID: Lead (kg)	-0.0005***	-0.0004***	-0.0005***	-0.0005***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	566438	548173	550475	544753	419702
2SLS: Lead (g/m^3)	-1.5186***	-0.6107	-1.3278***	-0.8040*	-0.8888
	(0.4331)	(0.5762)	(0.4939)	(0.4654)	(0.6451)
N	316182	305106	306681	302877	232879
Panel B: Reading Scores (for Male)					
DID: Lead (kg)	-0.0006***	-0.0004***	-0.0004***	-0.0006***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	556007	543416	544238	539349	413688
2SLS: Lead (g/m^3)	-1.2076*	0.3690	-0.7369	-1.3892**	-0.9324
	(0.6418)	(0.6282)	(0.5757)	(0.5769)	(0.6560)
N	309664	301591	302557	299029	228717
Panel C: Math Scores (for Female)					
DID: Lead (kg)	-0.0007***	-0.0006***	-0.0007***	-0.0009***	-0.0007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	566438	518110	550475	544753	404567
2SLS: Lead (g/m^3)	-2.3280***	-1.3891***	-1.9531***	-1.9914***	-1.0995
	(0.5220)	(0.5131)	(0.5075)	(0.5667)	(0.7365)
N	316182	288842	306681	302877	224844
Panel D: Math Scores (for Male)					
DID: Lead (kg)	-0.0006***	-0.0006***	-0.0007***	-0.0008***	-0.0008***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	556007	521451	544238	539349	402128
2SLS: Lead (g/m^3)	-1.2457**	-0.5297	-1.3366***	-1.6618***	-1.5954**
	(0.5767)	(0.5072)	(0.5144)	(0.6151)	(0.7059)
N	309664	289842	302557	299029	222608

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A13: Heterogeneity Effect of Lead Exposure on Disciplinary Incidents

	(1) Days absent	(2) Absence%	(3) Any Disci.	(4) Violence	(5) Crime	(6) Suspension	(7) Expul
Panel A: Female							
DID: Lead (kg)	0.0518***	0.0559***	0.0047***	0.0005***	0.0002***	0.0045***	0.0002***
	(0.0054)	(0.0052)	(0.0006)	(0.0001)	(0.0001)	(0.0006)	(0.0001)
N	594135	594135	594135	594135	594135	594135	594135
2SLS: Lead (g/m^3)	73.3757	73.2433	3.9530	0.0777	-0.0352	3.9108	0.0915
	(47.8262)	(44.8846)	(3.3892)	(0.3856)	(0.1869)	(3.2147)	(0.2511)
N	330939	330939	330939	330939	330939	330939	330939
Panel B: Male							
DID: Lead (kg)	0.0572***	0.0597***	0.0109***	0.0010***	0.0006***	0.0101***	0.0008***
	(0.0055)	(0.0051)	(0.0012)	(0.0002)	(0.0001)	(0.0012)	(0.0001)
N	594742	594742	594742	594742	594742	594742	594742
2SLS: Lead (g/m^3)	87.5385*	84.8240**	14.7685	0.7204	0.7059	13.2239	1.6116*
	(48.2277)	(42.6895)	(10.2719)	(0.9583)	(0.5306)	(9.5903)	(0.8478)
N	329978	329978	329978	329978	329978	329978	329978

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A14: Heterogeneity Effect of Lead Exposure on Educational Attainment

	(1) Ever HG	(2) Ontime HG	(3) Any Coll.	(4) Ontime Coll.	(5) Ever 4years	(6) Ontime 4years	(7) Ever 2years	(8) Ontime 2years
Panel A: Female								
DID: Lead (kg)	-0.0003***	-0.0004***	-0.0004***	-0.0005***	-0.0005***	-0.0004***	-0.0004***	-0.0004***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	595135	595135	595135	595135	595135	595135	595135	595135
2SLS: Lead (g/m^3)	-0.5303*	-0.6686*	-1.1177**	-1.2918***	-1.3016**	-1.0660**	-0.7999***	-0.7786***
	(0.2966)	(0.3536)	(0.4679)	(0.4992)	(0.5888)	(0.4420)	(0.2892)	(0.3004)
N	331562	331562	331562	331562	331562	331562	331562	331562
Panel B: Male								
DID: Lead (kg)	-0.0003***	-0.0004***	-0.0003***	-0.0004***	-0.0004***	-0.0003***	-0.0003***	-0.0003***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	595812	595812	595812	595812	595812	595812	595812	595812
2SLS: Lead (g/m^3)	-0.5735*	-0.8833**	-1.0318**	-1.1174**	-0.8665**	-0.7701**	-0.8709**	-0.9900**
	(0.2976)	(0.3770)	(0.4258)	(0.5163)	(0.3880)	(0.3518)	(0.3714)	(0.4716)
N	330632	330632	330632	330632	330632	330632	330632	330632

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A15: Heterogeneity Effect of Lead Exposure on Earning Outcomes

	(1) Wages at age 23	(2) Wages at age 24	(3) Wages at age 25	(4) Wages at age 26	(5) Wages at age 27
Panel A: Female					
DID: Lead (kg)	-12***	-14***	-18***	-19***	-22***
	(1)	(2)	(2)	(3)	(4)
N	595042	472549	349142	230866	115813
2SLS: Lead (g/m^3)	-25472**	-33162**	-37156***	-51389***	-87262***
	(10180)	(13081)	(13047)	(17391)	(28878)
N	331499	262628	193306	127240	63206
Panel B: Male					
DID: Lead (kg)	-14***	-15***	-15***	-14***	-13**
	(2)	(2)	(3)	(4)	(6)
N	595747	477680	353941	235477	119655
2SLS: Lead (g/m^3)	-23911**	-27125**	-45239**	-52566**	-25769
	(9575)	(12251)	(19073)	(20713)	(29675)
N	330587	263892	194734	128671	64781

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A16: Heterogeneity Effect of Lead Exposure on Reading Scores

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: White					
DID: Lead (kg)	-0.0005***	-0.0006***	-0.0004***	-0.0005***	-0.0003**
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	420193	413184	405439	402319	314834
2SLS: Lead (g/m^3)	-4.4841***	-3.3218***	-2.7255**	-4.1196***	-3.0131***
	(1.0224)	(0.9808)	(1.1630)	(1.0602)	(0.9136)
N	209870	206393	201937	200068	156630
Panel B: Hispanic					
DID: Lead (kg)	-0.0006***	-0.0004***	-0.0006***	-0.0006***	-0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	524806	505599	516133	509996	386908
2SLS: Lead (g/m^3)	-0.8925**	0.1146	-0.8556**	-0.5733*	-0.5867
	(0.3638)	(0.4611)	(0.3533)	(0.3430)	(0.5721)
N	295421	283088	289808	285592	216264
Panel C: Black					
DID: Lead (kg)	-0.0005***	-0.0004***	-0.0004***	-0.0005***	-0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
N	140366	136806	137789	136903	104881
2SLS: Lead (g/m^3)	-1.8409	-0.8999	-1.9823	-3.2191**	-2.7416*
	(1.3434)	(1.3473)	(1.6190)	(1.4820)	(1.4527)
N	92043	89490	90254	89344	68010

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A17: Heterogeneity Effect of Lead Exposure on Math Scores

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: White					
DID: Lead (kg)	-0.0005***	-0.0007***	-0.0008***	-0.0008***	-0.0007***
	(0.0001)	(0.0001)	(0.0002)	(0.0001)	(0.0001)
N	420193	399762	405439	402319	308201
2SLS: Lead (g/m^3)	-4.7068***	-4.5731***	-5.1236***	-4.8911***	-3.8437***
	(0.9816)	(1.0645)	(1.1872)	(1.1251)	(1.0120)
N	209870	200260	201937	200068	153634
Panel B: Hispanic					
DID: Lead (kg)	-0.0007***	-0.0006***	-0.0007***	-0.0008***	-0.0007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	524806	479466	516133	509996	372818
2SLS: Lead (g/m^3)	-1.0081***	-0.3982	-1.0287***	-1.0163***	-0.5772
	(0.3248)	(0.2974)	(0.2717)	(0.3609)	(0.5860)
N	295421	269423	289808	285592	208947
Panel C: Black					
DID: Lead (kg)	-0.0006***	-0.0006***	-0.0007***	-0.0007***	-0.0007***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0002)
N	140366	124799	137789	136903	99200
2SLS: Lead (g/m^3)	-2.8214**	-1.6442	-2.8364*	-3.3079**	-3.8334**
	(1.4298)	(1.6441)	(1.6227)	(1.4953)	(1.6271)
N	92043	81568	90254	89344	64370

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A18: Heterogeneity Effect of Lead Exposure on Disciplinary Outcomes

	(1) Days absent	(2) Absence%	(3) Any Disci.	(4) Violence	(5) Crime	(6) Suspension	(7) Expul
Panel A: White							
DID: Lead (kg)	0.0570***	0.0647***	0.0101***	0.0007***	0.0005***	0.0095***	0.0007***
	(0.0067)	(0.0065)	(0.0013)	(0.0001)	(0.0001)	(0.0012)	(0.0001)
N	446118	446118	446118	446118	446118	446118	446118
2SLS: Lead (g/m^3)	312.9934***	295.6099***	58.7207***	3.0603**	1.9802**	55.2277***	3.5611***
	(60.6253)	(56.2984)	(11.2631)	(1.1893)	(0.9097)	(10.4676)	(1.3182)
N	222733	222733	222733	222733	222733	222733	222733
Panel B: Hispanic							
DID: Lead (kg)	0.0523***	0.0553***	0.0072***	0.0007***	0.0004***	0.0068***	0.0005***
	(0.0064)	(0.0060)	(0.0010)	(0.0001)	(0.0001)	(0.0009)	(0.0001)
N	552180	552180	552180	552180	552180	552180	552180
2SLS: Lead (g/m^3)	20.6881	26.8249	2.2915	-0.0240	-0.0079	2.1917	0.1215
	(31.2589)	(28.7308)	(4.5782)	(0.4423)	(0.2421)	(4.3589)	(0.2913)
N	309626	309626	309626	309626	309626	309626	309626
Panel C: Black							
DID: Lead (kg)	0.0713***	0.0702***	0.0073***	0.0009***	0.0004***	0.0067***	0.0006***
	(0.0082)	(0.0078)	(0.0017)	(0.0002)	(0.0001)	(0.0016)	(0.0002)
N	151557	151557	151557	151557	151557	151557	151557
2SLS: Lead (g/m^3)	254.6865***	255.9070***	16.9209	1.8665	1.0385	12.9090	4.2957**
	(88.2053)	(82.3572)	(16.2214)	(2.2341)	(1.0238)	(15.1347)	(1.9102)
N	98693	98693	98693	98693	98693	98693	98693

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A19: Heterogeneity Effect of Lead Exposure on Educational Attainment

	(1) Ever HG	(2) Ontime HG	(3) Any Coll.	(4) Ontime Coll.	(5) Ever 4years	(6) Ontime 4years	(7) Ever 2years	(8) Ontime 2years
Panel A: White								
DID: Lead (kg)	-0.0004***	-0.0004***	-0.0003***	-0.0005***	-0.0006***	-0.0005***	-0.0003***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	447124	447124	447124	447124	447124	447124	447124	447124
2SLS: Lead (g/m^3)	-1.2915**	-1.6865***	-2.4646***	-3.2524***	-4.1863***	-3.9504***	-1.3231**	-2.1193***
	(0.5178)	(0.5549)	(0.5688)	(0.6059)	(0.7488)	(0.6643)	(0.5229)	(0.5416)
N	223318	223318	223318	223318	223318	223318	223318	223318
Panel B: Hispanic								
DID: Lead (kg)	-0.0003***	-0.0004***	-0.0004***	-0.0005***	-0.0004***	-0.0003***	-0.0004***	-0.0004***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	552817	552817	552817	552817	552817	552817	552817	552817
2SLS: Lead (g/m^3)	-0.1644	-0.3274	-0.4810*	-0.5261*	-0.3583	-0.2793	-0.4575**	-0.4268*
	(0.1666)	(0.2293)	(0.2780)	(0.3175)	(0.2718)	(0.2038)	(0.2138)	(0.2593)
N	310025	310025	310025	310025	310025	310025	310025	310025
Panel C: Black								
DID: Lead (kg)	-0.0004***	-0.0004***	-0.0004***	-0.0005***	-0.0005***	-0.0004***	-0.0004***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	151877	151877	151877	151877	151877	151877	151877	151877
2SLS: Lead (g/m^3)	-2.1317***	-2.4833***	-3.1573***	-3.1618***	-1.8263***	-1.3787***	-3.0588***	-2.8341***
	(0.6271)	(0.7169)	(0.6835)	(0.6898)	(0.5659)	(0.5336)	(0.7001)	(0.6385)
N	98909	98909	98909	98909	98909	98909	98909	98909

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A20: Heterogeneity Effect of Lead Exposure on Wages

	(1) Wages at age 23	(2) Wages at age 24	(3) Wages at age 25	(4) Wages at age 26	(5) Wages at age 27
Panel A: White					
DID: Lead (kg)	-24***	-28***	-33***	-29***	-38***
	(3)	(3)	(5)	(6)	(8)
N	447088	363587	273513	184088	94872
2SLS: Lead (g/m^3)	-124605***	-132756***	-139577***	-131315***	-223083***
	(32198)	(35886)	(36864)	(37605)	(59936)
N	223304	181578	136205	91542	47039
Panel B: Hispanic					
DID: Lead (kg)	-11***	-11***	-11***	-11***	-9**
	(1)	(2)	(3)	(3)	(4)
N	552765	435301	318204	208450	103337
2SLS: Lead (g/m^3)	-11088*	-11946	-9417	-19869	8599
	(5723)	(7399)	(9955)	(15294)	(21375)
N	309990	243411	177551	115429	56600
Panel C: Black					
DID: Lead (kg)	-10***	-9***	-16***	-17***	-21***
	(3)	(3)	(3)	(5)	(7)
N	151818	120661	89193	59332	29763
2SLS: Lead (g/m^3)	-34177	-29229	-62265**	-46659*	-66144
	(26795)	(27197)	(26914)	(28121)	(52080)
N	98858	78059	57374	37981	18834

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A21: Heterogeneity Effect of Lead Exposure on Test Scores

	(1) G4	(2) G5	(3) G6	(4) G7	(5) G8
Panel A: Reading Scores (Econ Disadv)					
DID: Lead (kg)	-0.0005***	-0.0004***	-0.0004***	-0.0005***	-0.0004***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	633245	611754	622189	615366	468772
2SLS: Lead (g/m^3)	-0.6452*	0.3689	-0.4679	-0.5305	-0.4867
	(0.3802)	(0.3415)	(0.3697)	(0.3391)	(0.4814)
N	348290	334589	341700	336870	255869
Panel B: Reading Scores (Not Econ Disadv)					
DID: Lead (kg)	-0.0007***	-0.0006***	-0.0006***	-0.0007***	-0.0005***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	489179	479803	472495	468704	364587
2SLS: Lead (g/m^3)	-3.7745***	-2.3601*	-2.8805***	-3.2462***	-2.2569***
	(1.1726)	(1.2189)	(1.0666)	(0.8698)	(0.7410)
N	277538	272083	267511	265011	205702
Panel C: Math Scores (Econ Disadv)					
DID: Lead (kg)	-0.0006***	-0.0005***	-0.0006***	-0.0007***	-0.0006***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	633245	574143	622189	615366	449704
2SLS: Lead (g/m^3)	-0.7799*	-0.1300	-0.6889	-0.8530**	-0.3255
	(0.4217)	(0.4400)	(0.4345)	(0.3648)	(0.5084)
N	348290	314754	341700	336870	245965
Panel D: Math Scores (Not Econ Disadv)					
DID: Lead (kg)	-0.0007***	-0.0008***	-0.0010***	-0.0010***	-0.0010***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	489179	465388	472495	468704	356958
2SLS: Lead (g/m^3)	-4.3851***	-3.5469***	-4.4380***	-4.5020***	-4.0821***
	(1.3683)	(1.2723)	(1.3461)	(1.0802)	(0.9935)
N	277538	263908	267511	265011	201462

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A22: Heterogeneity Effect of Lead Exposure on Disciplinary Outcomes

	(1) Days absent	(2) Absence%	(3) Any Disci.	(4) Violence	(5) Crime	(6) Suspension	(7) Expul
Panel A: Econ Disadv							
DID: Lead (kg)	0.0546***	0.0597***	0.0066***	0.0007***	0.0004***	0.0062***	0.0005***
	(0.0061)	(0.0058)	(0.0010)	(0.0001)	(0.0001)	(0.0009)	(0.0001)
N	675004	675004	675004	675004	675004	675004	675004
2SLS: Lead (g/m^3)	39.8404	41.6820	-0.3820	-0.1895	0.1377	-0.6623	0.3061
	(39.2006)	(34.0953)	(4.3275)	(0.5304)	(0.2887)	(3.9907)	(0.4340)
N	369205	369205	369205	369205	369205	369205	369205
Panel B: Not Econ Disadv							
DID: Lead (kg)	0.0541***	0.0523***	0.0102***	0.0008***	0.0004***	0.0096***	0.0006***
	(0.0050)	(0.0045)	(0.0009)	(0.0001)	(0.0001)	(0.0009)	(0.0001)
N	513849	513849	513849	513849	513849	513849	513849
2SLS: Lead (g/m^3)	213.8656***	193.5864***	41.3104***	2.7256***	1.2380**	38.9391***	2.4994***
	(52.8642)	(51.8492)	(10.6145)	(0.9631)	(0.5649)	(10.0704)	(0.7588)
N	291694	291694	291694	291694	291694	291694	291694

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

Table A23: Heterogeneity Effect of Lead Exposure on Educational Attainment

	(1) Ever HG	(2) Ontime HG	(3) Any Coll.	(4) Ontime Coll.	(5) Ever 4years	(6) Ontime 4years	(7) Ever 2years	(8) Ontime 2years
Panel A: Econ Disadv								
DID: Lead (kg)	-0.0003***	-0.0004***	-0.0004***	-0.0005***	-0.0004***	-0.0003***	-0.0004***	-0.0004***
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
N	676006	676006	676006	676006	676006	676006	676006	676006
2SLS: Lead (g/m^3)	-0.3561*	-0.4813*	-0.8267**	-0.8444**	-0.5653**	-0.4342**	-0.7145***	-0.6123**
	(0.2041)	(0.2595)	(0.3419)	(0.3750)	(0.2648)	(0.2114)	(0.2465)	(0.2705)
N	369797	369797	369797	369797	369797	369797	369797	369797
Panel B: Not Econ Disadv								
DID: Lead (kg)	-0.0003***	-0.0004***	-0.0004***	-0.0005***	-0.0006***	-0.0005***	-0.0003***	-0.0004***
	(0.0000)	(0.0000)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
N	514917	514917	514917	514917	514917	514917	514917	514917
2SLS: Lead (g/m^3)	-0.9939**	-1.4543***	-1.8475***	-2.3112***	-2.7647***	-2.5154***	-1.2346**	-1.7226***
	(0.4840)	(0.5515)	(0.6627)	(0.7556)	(0.9534)	(0.7795)	(0.5682)	(0.6381)
N	292379	292379	292379	292379	292379	292379	292379	292379

Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

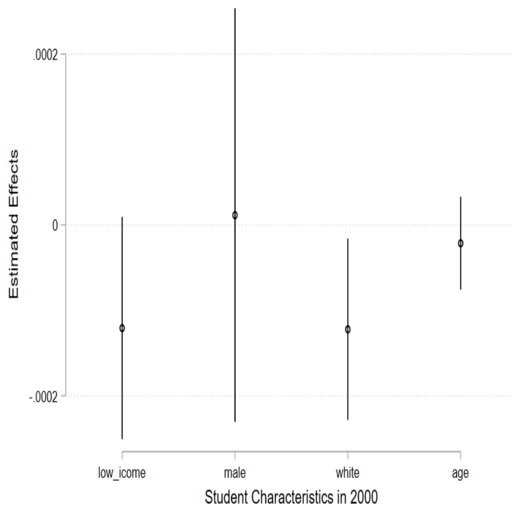
Table A24: Heterogeneity Effect of Lead Exposure on Wages

	(1) Wages at age 23	(2) Wages at age 24	(3) Wages at age 25	(4) Wages at age 26	(5) Wages at age 27
Panel A: Econ Disadv					
DID: Lead (kg)	-11***	-11***	-11***	-10***	-9**
	(1)	(2)	(2)	(3)	(4)
N	675911	537315	394676	259468	130068
2SLS: Lead (g/m^3)	-18484***	-17794**	-20332**	-22777*	-1060
	(6188)	(7669)	(9850)	(12247)	(18348)
N	369731	292514	213942	139536	68966
Panel B: Not Econ Disadv					
DID: Lead (kg)	-18***	-23***	-29***	-30***	-33***
	(2)	(3)	(4)	(5)	(7)
N	514852	412899	308378	206816	105262
2SLS: Lead (g/m^3)	-48771**	-72084**	-94615***	-117420***	-160182***
	(22201)	(28053)	(31713)	(33696)	(58913)
N	292337	233995	174075	116332	58943

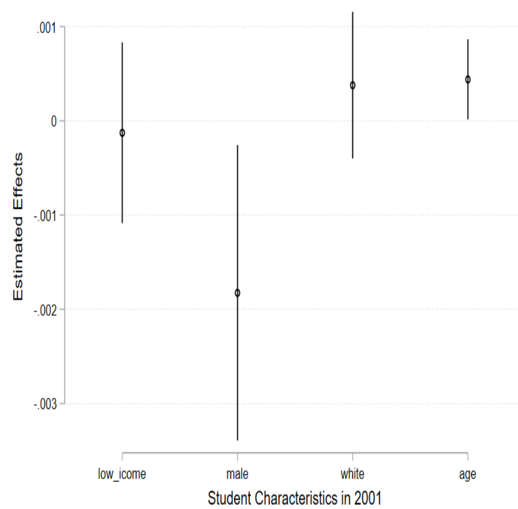
Notes: The sample consists of kindergartners from the 2000 to 2004 cohorts who attended schools within 50 miles of the nearest airport. Student demographics, school, and cohort fixed effects are included in all columns. Standard errors are clustered at the school level in parentheses. * $p < 0.1$, ** $p < .05$, *** $p < .01$.

8.2 Figures

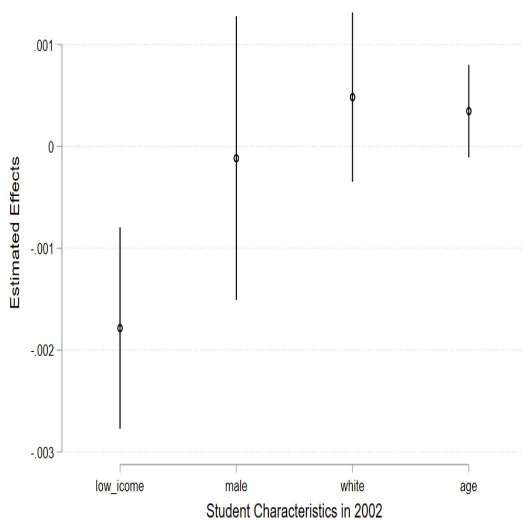
Figure A1: Effect of Cumulative Lead Exposure on Pre-characteristics



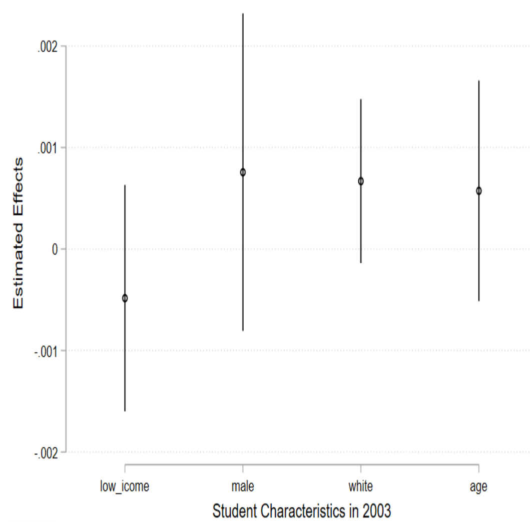
(a) 2000



(b) 2001



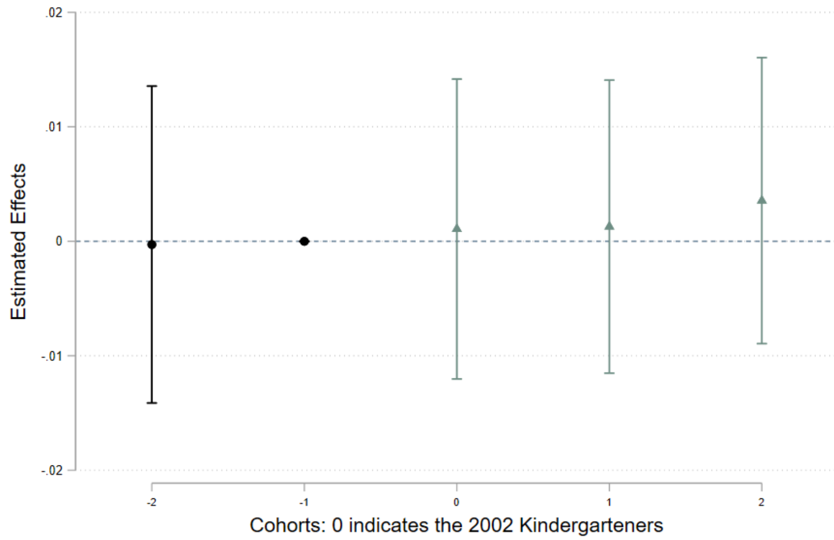
(c) 2002



(d) 2003

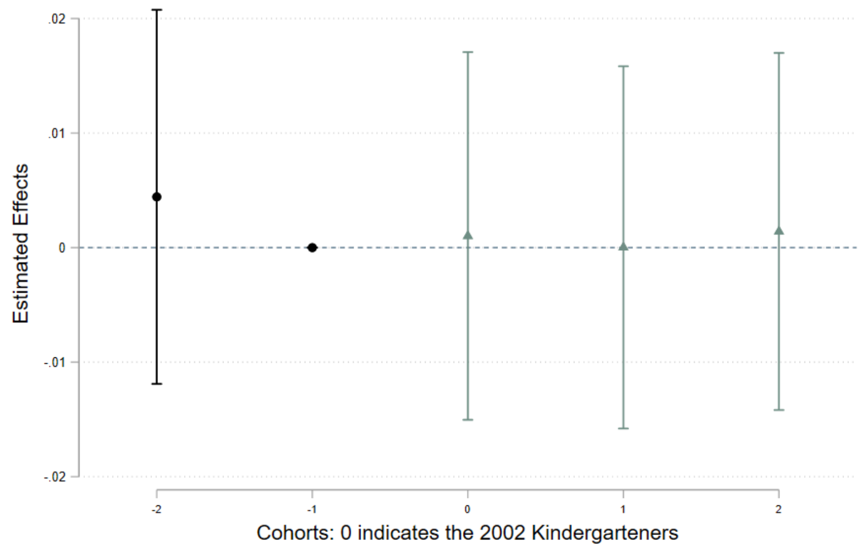
Notes: These figures show the estimates of regressing students' characteristics observed at the beginning of Kindergarten on the cumulative lead exposure between Kindergarten and grade three conditional on school fixed effect

Figure A2: Event Study: High School Graduation



Note: the figure shows the trend of high school graduation for students with the reduction of lead exposure post-2001 above the median compared to those below the median over time. All regressions control for gender, race, economic disadvantage, and district and cohort fixed effects. The sample includes Kindergarteners from 2000 and 2004 who attended schools within five miles of the airport. We use heteroskedasticity-robust standard errors. Standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Figure A3: Event Study: Public University or Community College Enrollment



Note: the figure shows the trend of enrollment in public universities or community colleges for students with the reduction of lead exposure post-2001 above the median compared to those below the median over time. All regressions control for gender, race, economic disadvantage, and district and cohort fixed effects. The sample includes Kindergarteners from 2000 and 2004 who attended schools within five miles of the airport. We use heteroskedasticity-robust standard errors. Standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Figure A4: Effects of PEA Operation on Lead Concentration by Distance

	(1) Lead: 0-50mi	(2) Lead: 0-25mi	(3) Lead: 0-20mi	(4) Lead: 0-15mi	(5) Lead: 0-10mi	(6) Lead: 0-5mi
PEA Operation	0.0338	-0.0864	0.579***	1.081***	2.542	78.76***
(10,000 flights)	(0.0595)	(0.181)	(0.135)	(0.0595)	(1.282)	(10.63)
Year FE	Y	Y	Y	Y	Y	Y
Monitor FE	Y	Y	Y	Y	Y	Y
Cluster	Y	Y	Y	Y	Y	Y
N	1275	507	370	270	144	36
# Airport	48	25	20	16	8	4
# Air Monitor	14	14	14	14	14	6
R^2	0.816	0.803	0.724	0.763	0.744	0.488

Note: The table shows the effects of PEA operation on lead concentration by the distance of the airport to monitors. Standard errors are in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.