THE HIDDEN COST OF MOBILITY: PUBLIC TRANSIT POLLUTION AND ACADEMIC ACHIEVEMENT*

DIEGO A. MARTIN‡, DARIO SALCEDO†, AND DARIO A. ROMERO∓

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Abstract. Developing transportation infrastructure may impose hidden welfare costs due to pollution exposure. However, evidence regarding the effects of public transportation on academic achievement in developing countries is limited. Bus Rapid Transit (BRT) systems that rely heavily on pollutant fuels can influence educational outcomes by negatively affecting students' health and daily routines. We assess the impact of BRT-related pollution from Bogotá's BRT system, TransMilenio, on student academic performance by leveraging exogenous variation in wind direction and route intensity. Our findings indicate that a one-unit increase in particulate matter (PM2.5) reduces math scores by 0.014 standard deviations, with more pronounced effects on female students and those from higher-income families. Additionally, we show that the increases in the risk of respiratory diseases might explain these negative effects of pollution on education outcomes. Our results show the negative externalities of transportation infrastructure and its impacts on human capital development and public health, emphasizing the need for policy interventions to mitigate the environmental impact of mass transit systems in developing cities.

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‡Harvard University, Harvard Business School. Cambridge, MA 02138. E-mail: dimartin@hbs.edu.
†Indiana University Bloomington, School of Public and Environmental Affairs, 107 S Indiana Ave, Bloomington, IN 47405. E-mail: djsalced@iu.edu.
∓ New York University - Abu Dhabi, Social Science Division, Bldg A5-142 P.O. Box 129188, Abu Dhabi, UAE. E-mail: drf312@nyu.edu.

1. Introduction

Investment in public transportation is essential for promoting economic growth and improving urban mobility, particularly in developing countries that experience some of the highest congestion levels worldwide (Tsekeris and Geroliminis, 2013). However, when public transportation relies on highly polluting fossil fuels, it can become a significant source of air contamination, sometimes emitting more pollutants than private vehicles (Morales Betancourt, 2022). In this case, developing this type of infrastructure imposes some negative externalities that policymakers need to address to evaluate and design strategies to curb the possible welfare losses induced by public transportation. In particular, we are interested in measuring the adverse effects that transportation systems might induce on education outcomes through exposure to their pollutants.

Efficient public transit systems can reduce travel time and enhance access to economic opportunities (Barreca et al., 2021), yet instead of mitigating environmental challenges, such transit systems may worsen air quality, leading to adverse effects on public health and economic productivity (Kelly and Zhu, 2016). For example, pollution can hinder economic growth by reducing worker productivity, increasing healthcare costs, and disrupting student learning (Aguilar-Gomez et al., 2022; Deryugina et al., 2019; Hanna and Oliva, 2015). In this paper, we examine the impact of exposure to pollution from Bogotá's Bus Rapid Transit (BRT) system, TransMilenio, on the academic performance of schoolchildren in the city.

We examine the case of Bogotá, a city where air pollution levels still exceed the World Health Organization's (WHO) recommended annual concentration but are not among the worst in the world (IQAir, 2023), with vehicle emissions being the primary source of pollution.[1]. We assess the effects of the city's public transportation pollution on

[1]The WHO states that the annual average concentration of PM2.5 should remain below five $\mu g/m^3$ (World Health Organization, 2021). As of 2024, Bogotá's PM2.5 concentration is 1.4 times higher than the WHO's annual air quality guideline value, compared to 3.6 times in Mexico City, 2.4 in New York City, and 1.2 in Los Angeles.

high school education achievements, finding a negative relationship between exposure to pollutants and math scores.

We measure student outcomes by compiling nationally standardized test scores for approximately 500,000 students per year, covering all final-year high school students (comparable to the SAT in the U.S.) from 2014 to 2018. We use each school's georeferencing of latitude and longitude data to match students' pollution exposure using pollution data recorded at the hour level for monitoring stations in Bogotá since 2000 and to calculate the distance from each school to the nearest BRT route. We find a negative effect on math scores while no impact on language scores. Additionally, we complement the school performance analysis by examining pollution's effects on school-age children's health outcomes. We use three waves (2011, 2014, and 2017) of a georeferenced household survey at the block level to assess the impact of BRT-induced pollution on health outcomes. We find a positive effect of exposure to pollution and the development of respiratory diseases.

To address potential endogeneity concerns, that is, that pollution is not exogenously assigned, school locations are not random and that student selection varies across different types of institutions, we employ an instrumental variable strategy. We exploit variation in school proximity to BRT lines and wind direction to estimate exogenous exposure to pollutions unrelated to student characteristics and their sorting in different schools in the city. We instrument the air quality measure as the average exposure to PM2.5 particles from the nearest rapid transit highway within a 45-degree angle of a ray extending from the pollution source (major bus lanes) to the school. Schools with higher downwind frequency from BRT corridors are exposed to greater PM2.5 concentrations. Our identification strategy builds on methodologies such as Anderson (2020), which analyzes wind patterns near highways in Los Angeles to examine pollution's impact on adult mortality. More relevant to our approach, Heissel et al. (2022) compare students in Florida who attend schools downwind and upwind of highways to evaluate pollution's effect on academic performance. However, our study is the first to exploit the variation in the context of a developing country and to use the public transportation system as a pollution source, highlighting the negative consequences of massive transportation system infrastructures.

Our results provide strong evidence that pollution negatively impacts academic performance. The IV estimates indicate that increased exposure to PM2.5 corresponds to a significant decline in test scores, with an additional microgram per cubic meter of PM2.5 reducing math scores by 0.014 standard deviations and global scores by 0.012 standard deviations. The OLS estimates, while smaller in magnitude, show the same negative trend, further supporting the adverse relationship between pollution and academic performance. The reduced form results affirm a strong connection between wind direction and PM2.5 concentrations, reinforcing the validity of the instrument. The first-stage regression reveals a significant and positive relationship between wind share and particulate matter, and the F-statistic (exceeding 63) confirms that wind direction is a strong instrument for pollution exposure. Furthermore, we observe that the negative effects are more pronounced for schools located closer to pollution sources, while downwind frequency during nighttime—when students are not in school—does not affect test scores.

Before 2019, the BRT system predominantly used diesel engines, exposing people to Nitrogen Oxides (NOx) and PM10, two pollutants closely linked to poor air quality. Increased levels of PM10 and NOx are associated with declines in math scores of 0.02 and 0.01 standard deviations, respectively, reinforcing the broader link between pollution and student outcomes.

The heterogeneous effects by demographic groups show that girls aged 15-18 experience the strongest negative effects of pollution, scoring 0.03 and 0.02 standard deviations lower than boys in math and overall test scores, respectively. Socioeconomic differences also contribute, as students from higher-income households experience greater declines in performance compared to their peers in lower-income groups. This pattern aligns with the notion that disadvantaged students may already face higher baseline pollution levels, potentially making additional exposure to PM2.5 less disruptive in relative terms (Heissel et al., 2022).

We extend our analysis to explore potential mechanisms by examining how pollution exposure impacts health outcomes using the georeferenced Multipurpose Survey. The results indicate that higher levels of PM2.5 increase the likelihood of developing respiratory diseases, while the effects on other conditions, such as allergies, emergency department visits, and routine check-ups, are less pronounced. Moreover, the findings suggest that these respiratory effects do not differ significantly by gender or socioeconomic status.

We conduct several robustness tests to validate our findings. First, we examine the relevance of our instrumental variable by using wind frequency at night, when traffic is lower and students are not in school. As expected, pollution exposure during these hours shows no impact on test scores, and the instrument loses strength, reinforcing the assumption that daytime pollution is the primary driver of the observed effects. We also demonstrate that the negative effect of PM2.5 on academic performance disappears for schools far from BRT highways, confirming that proximity to pollution sources plays a crucial role. Furthermore, we assess the impact of wildfire-related pollution and find no significant effects, suggesting that long-term exposure to transportation emissions, rather than temporary pollution spikes, is the main factor affecting student outcomes.

Furthermore, we eliminate potential biases linked to student sorting, alternative pollution sources, and spurious correlations. Wind frequency does not systematically affect student demographics, indicating that sorting into schools is not influencing our results. Older test-takers, who face less school-related pollution, do not experience negative effects, highlighting the significance of exposure during school hours.[2] Finally, pollution from non-BRT highways does not significantly impact test scores, and analyzing exposure by month shows that cumulative pollution levels throughout the academic year are more predictive of academic performance than short-term exposure fluctuations.[3] These robustness checks confirm that the observed negative effects are driven by sustained exposure to PM2.5 from BRT corridors rather than alternative explanations.

This study contributes to the extensive literature on the effect of transportation systems on air pollution. This relationship has been broadly studied across cities in developed countries (Gendron-Carrier et al., 2022). Public transport has a heterogeneous impact on surrounding air pollution exposure (Lalive et al., 2018). Implementing a BRT system in Mexico City reduced emissions of carbon monoxide, nitrogen oxides, and particulate matter (PM10). On the contrary, the BRT increased the population, such as aerosol particles in some sides of Bogotá (Behrentz, 2009; Bonilla and Carriazo, 2018; Morales et al., 2017). We show that BRT increased PM2.5 exposure in Bogotá.

Our research expands on understanding the effect of air pollution on school performance. Other studies have demonstrated the impact of air pollution on education and school test results in the developed world (Heissel et al., 2022; Lu et al., 2021; Persico and Venator, 2019). The broadest body of work used US data. For example, Marcotte (2017) analyzed differences in air quality across test days and determined that children who took exams on days with higher levels of pollen and fine particulate matter performed worse. Outside the US, Ebenstein et al. (2016) identified that air pollution reduced students' scores on high school exit exams in Israel. Our study shows that the increase of PM2.5 from the BRT resulted in a decline in global scores driven by math scores but did not affect language scores.

[2]For a placebo test, we randomly assign PM2.5 levels and find no significant impact on test scores, further supporting the validity of our findings estimates.

[3]Excluding the bus intensity from our models weakens the statistical significance of the results, emphasizing the importance of high-traffic BRT corridors in pollution exposure.

This paper expands the scarce literature on the effect of pollution in the developing world. Balakrishnan and Tsaneva (2021) found that higher pollution levels in rural India significantly decreased score outcomes. Zhang et al. (2018) found that air contamination statistically affected verbal and math tests. Our research contributes to this body of work by estimating the causal effects on math, language, and global school scores in a Latin American city that saw a plausibly exogenous change in pollution levels with the introduction of its BRT.

The literature has also examined the negative effects of development on long-term human capital accumulation in developing countries due to exposure to pollution (Chen, 2025). However, we provide evidence of the mechanism that explains these adverse effects, we demonstrate that the effects on health outcomes and daily routines are likely explanations for the negative impact of air pollution on learning. In contrast to Chen (2025), we focus on local variation and exploit within-city exposure to pollution. Furthermore, we show that the negative effects associated with pollutant exposure are not limited to early childhood but also extend to later learning stages, reducing academic achievement.

The effects of pollution are also relevant to broader discussions in the economic analysis of gender. The evidence shows a more significant decline in test scores for men than women in Israel and China (see Ebenstein et al. (2016) and Zhang et al. (2018), respectively). Our paper adds to the debate by showing that girls are more affected than men in the biggest Colombian city, similar to what Balakrishnan and Tsaneva (2021) found in rural India.

Finally, this paper contributes to the growing literature analyzing the relationship between air pollution and development outcomes. Some articles showed a decline in worker productivity (Fu et al., 2021; He et al., 2019; Lichter et al., 2017) and a rise in crime (Aguilar-Gomez et al., 2022; Herrnstadt et al., 2021) related to air contamination. Other articles study the effect of pollution on school performance (Duque and Gilraine, 2022; Gilraine, 2023; Heissel et al., 2022). However, to our knowledge, our paper is the first to address the question in a developing city such as Bogotá and to use the exogenous variation of building a public transportation system.

The rest of the paper is organized as follows: Section 2 presents background information from the school system in Colombia, the history of BRT – TransMilenio, and the socio-demographic characteristics of Bogotá, the capital of Colombia. Section 3 presents the data to measure school performance and air population. Section 4 shows the empirical strategy using the instrumental variables. Section 5 presents the results, and Section 6 shows the robustness tests. Section 7 discusses the implications of these results and concludes.

2. Background

2.1. **School system in Bogotá.** The Colombian school system follows a structure of 11 years of education. Primary education consists of five years, and secondary education is six years. Children typically start at age six and graduate from high school at 16 (Barrera-Osorio et al., 2020). Every child in the country must take an exit exam in the last year of secondary (Posso et al., 2023). This exam is one of the variables in the application to access higher education at universities or technical institutions (similar to the SAT in the US) (Balyo et al., 2017).

As of 2023, the population of Bogotá is estimated to be around eight million people. This makes Latin America's fifth most populated metropolitan area, after Sao Paulo, Mexico City, Buenos Aires, and Rio de Janeiro (Statista Research Department, 2024). In 2023, Bogotá had 1,141,573 children between 5 and 16 years old and a net enrollment rate, measuring age-appropriate enrollment focusing on students within the target age, of 86.97% for primary education and 86.48% for secondary education. The gross enrollment rate, including students outside the target age and providing a broader picture of educational demand, was close to 97.91% for primary and 100% for secondary. These rates have been stable during the last 13 years (Ministerio de Educación Nacional de Colombia, 2024).

2.2. **Bus Rapid Transportation (BRT) – The TransMilenio case in Bogotá.** TransMilenio (TM) is a public transit system with exclusive highways for high capacity-low-cost bi-articulated buses (Echeverry et al., 2005). The construction of TM began in 1998, and the first phase of the system was inaugurated two years later. Before the TM, Bogotá had a competition between public buses and a lack of exclusive bus lines (Cracknell, 2003). The TM has undergone several expansion phases, including new corridors and connecting previously underserved areas. Between 2003 and 2006, Phase II expanded the network, adding new routes to connect more city areas. Phase III, launched in 2012, focused on extending service to the city's western and southern regions. Figure 1 shows the current version of the TM network, which has been the same since late 2013. Despite the expansion, the system is overcrowded and cannot meet the high demand for transportation (Guzman and Oviedo, 2018; Hidalgo et al., 2013; Tsivanidis, 2022).

TM buses account for 30% to 50% of the sources of PM2.5 in Bogotá, since the buses mainly used diesel before 2019 (Belalcazar-Cerón et al., 2021). Depending on the corridor, TM produces PM2.5 between 0.8 ug/min and 3.7 ug/min doses. The TM produces exposure to PM2.5 higher than pure electric public transportation (Castillo-Camacho et al., 2020). In July 2019, the fleet of buses that ran on diesel (Euro-II and Euro-III) and had been in operation since the early 2000s started to be replaced with new Euro-VI compressed natural gas and filter-equipped Euro-V buses. These upgrades led to a significant reduction in air pollution, as PM2.5 concentrations inside the buses and stations decreased by 45% and 76% in 2019 and 2020 respectively, considering the 2017 baseline measures (Morales Betancourt, 2022). Given these important technological changes in 2019, our period of interest covers the years 2014 through 2018[4].

3. Data

3.1. **Air pollution.** We have access to air pollution data per hour from the 11 air monitor stations spread around Bogotá (see Figure 1 for the location of the stations). Bogotá's Secretary of the Environment is responsible for collecting these data and maintaining the stations.[5] We kept the data from 2014 to 2018 and collapsed them into monthly average concentrations starting in the last week of January until the day the students take the *Saber 11* test. The exact date varies by year, but it is always in the fourth quarter. We created a four-kilometer radius around the air monitor stations and assigned each school to the nearest station, assigning them the pollution value divided by the distance to the station. This method to assign contamination comes from environmental science research such as (Diao et al., 2019; Duque and Gilraine, 2022; Gilraine and Zheng, 2022).[6]

On average, and following the standard set by the WHO in 2005, PM2.5 levels in Bogotá during our study period were more than twice the recommended guidelines. As evidenced in Panel A of Figure 2, the average for the city is 20.4 while the WHO target was equal to 10. Using the updated air quality guidelines (World Health Organization, 2021), the situation worsens, as the new recommendation is 5 micrograms per cubic meter (μg/m^3), four times less than what is observed in the sample of this study. Pollution also changes between daytime and nighttime, as seen in Panel B. While the

[4]We don't explore the implications of cleaner TransMilenio alternatives after 2019 given the COVID-19 pandemic declaration in 2020, which notably affected test scores and kids' mental health through a number of factors — such as school closures, social isolation, economic and health disruptions (Jack and Oster, 2023) — that can confound the effects of lower PM2.5 levels.

[5]Table A-1 shows the names of the stations, their locations, and the year when the stations were opened. Five stations started to work in 2000, two in 2004, another two in 2005, one in 2006, and the newest one in 2010.

[6]We selected a four-kilometer radius to avoid one school having a contamination report from two different stations.

distribution for acceptable levels of particulate matter are similar, during the day (6am-6pm) the concentration of unhealthy levels is noticeably larger than during the night, which matters for the sample of students who spend most of the day at school and are exposed to noxious chemicals for a longer time.

PM2.5, or fine particulate matter, refers to tiny particles in the air that can negatively impact human health when inhaled. Exposure to high levels of PM2.5 has been linked to respiratory problems, cardiovascular disease, and premature death.

Research has also suggested that exposure to high levels of PM2.5 can negatively impact academic achievement, particularly among school-aged children. Studies have found that exposure to high levels of PM2.5 is associated with lower test scores and poorer academic performance in areas such as reading, math, and science.

Given the potential negative impacts of PM2.5 on academic achievement, policy-makers need to take steps to reduce air pollution levels in schools and surrounding communities. This may include investing in clean energy sources, implementing regulations to limit emissions from industry and transportation, and encouraging public transportation and active transportation options such as walking and cycling. Take for instance Figure A-1, which shows average levels of particulate matter against the distances (in Km) to the nearest TransMilenio bus routes. As expected, moving further away from the main routes means lower pollution concentrations. TransMilenio is a system used by millions of people, and those living or studying closer to its main trunk routes are exposed to higher levels of fine particulate matter than those living further away. This creates an opportunity and incentive to invest in new buses to keep a valid public system option. Additionally, schools can take steps to improve indoor air quality by using air filters and ensuring that ventilation systems work properly.

3.2. **Test scores.** School performance comes from standardized math, language, and global test scores at the individual level for the mandatory and national exam (called *Saber 11*) taken by students about to graduate from high school and which is a requisite to apply to higher education. The ICFES (*Instituto Colombiano para la Evaluación de la Educación*) is responsible for evaluating the quality of education in Colombia.

The data is available and comparable between 2014 and 2018. We observe students' scores, demographic characteristics (e.g., gender, age, mother's education, etc.), and the school where they study. Then, we geo-referenced the school using Google Maps and obtained latitude and longitude for each school. On average, students score 54 out of 100 in math and 55 out of 100 in language. Figure A-2 shows the evolution by year for girls and boys, and the averages fluctuated about 54 out of 100 points in math and 55 out of 100 in language. The median is 50 points for both exams. Men scored about four more points than women in math (see Panel A) and one point in language (see Panel B). Table 1 shows that most students were 17 years old when they took the exam, studied in public schools (52%), lived in families with four members, and half were women. About 37% of students have mothers with lower completed tertiary education, 29% completed tertiary education and 23% with completed high school or lower. Close to half of the students live in low-income families (50%), 40% are middle class, and 8% are high-income.

3.3. **Multipurpose Survey (EM).** The EM captures health, economic, and environmental information about households and residents in Bogotá and its surrounding region. The data are available for 2011, 2014, 2017, and 2021. We excluded the last year because of COVID-19 and the multiple effects on child performance. Using Google Maps, we georeference each household at the neighborhood level.

4. Empirical Strategy

To estimate the effects of fine particulate matter on test scores, we first propose the following baseline OLS specification:

$$y_{ist} = \alpha + \beta \text{PM2.5}_{st} + \mathrm{X}_{it}'\delta + \gamma_s + \gamma_t + \varepsilon_{ist} \tag{4.1}$$

where y_{ist} is the test score (math, language, or global) for student i, in school s and year t. Access to detailed microdata at the student level allows us to control for several individual characteristics included in X_{it}, such as age, sex, parental education level, socioeconomic stratum, household size, whether students have access to a computer and whether they go to an official school or not[7]. We also include school (γ_s) and year (γ_t) fixed effects, to absorb any unobserved heterogeneity explained by the educational institutions or time-varying shocks that are shared by the schools in different periods, respectively. Standard errors are clustered at the school × year level.

There are three main dependent variables. These are the standardized test scores for math, language, and the global results of the Saber 11 exam, taken by the students between July and August of each year. PM2.5 is the average concentration of fine particulate matter between the last week of January and the date the exam is taken each year. It's important to mention that we are capturing the cumulative exposure to pollution throughout the year for students right until they take the test, however, not all of them take it in the same school, as some kids might be assigned to go to a different location on that particular day.

Additional pollutants of interest include the average concentration of PM10 (larger particles with a diameter of 10 microns) and NOx, nitrogen oxides that are emitted from electric power plants and industrial boilers, incinerators, cement manufacture, glass manufacture and automobiles plus other sources that burn fuel, among others, that can also affect the lungs and exacerbate respiratory diseases (EPA, 1999).

4.1. **IV Strategy.** There are several concerns with the model shown in equation 4.1. The main one is that pollution is not exogenously assigned, so certain neighborhoods might be more likely to experience higher levels of PM2.5 than others because of industrial activities in the area, for instance. Second, the levels of PM2.5 are likely to be measured with error, given the sparse distribution of pollution monitors across

[7]Official schools are public institutions. Nearly 55% of our sample is enrolled in these types of schools.

the city, which could lead to measurement error and an attenuation bias (Deryugina et al., 2019; Gilraine and Zheng, 2022). Therefore, and in the spirit of Heissel et al. (2020) and Anderson (2020), we implement an instrumental variables strategy using the downwind frequency of wind from the main TransMilenio highways to schools as an instrument for PM2.5 exposure. The first and second stages are as follows:

$$PM2.5_{st} = \alpha + \eta \text{Wind Share}_{st} + \mathrm{X}'_{it}\delta + \gamma_s + \gamma_t + \epsilon_{ist} \tag{4.2}$$

$$y_{ist} = \alpha + \beta \widehat{\mathrm{PM2.5}}_{st} + \mathrm{X}'_{it}\delta + \gamma_s + \gamma_t + \varepsilon_{ist} \tag{4.3}$$

In equation 4.2, the exogenous regressor $WindShare$ is the percentage of time a day that the wind direction blows from the bus routes towards the school at one mph or less[8] interacted with bus intensity, a measure at the route level that captures the heterogeneous amount of TM traffic that services the city. Wind share is operationalized as the wind direction within 45 degrees of a ray running from the nearest point on the trunk route to the school. The advantage of this exogenous variation relies on the fact that wind blowing at lower speeds allows for pollution to be transported to nearby neighborhoods with concentrations that create a higher exposure for most of the day, while wind blowing at higher speeds might take pollution further away without really affecting anyone on its way.

To measure downwind frequency by school and year, we first compute the angle and distance between each school in the sample to the nearest point on a highway segment used by the rapid transit system. The angle is the same as the orientation, which tells us whether the school "faces" the highway. Next, we compute the frequency of downwind at the monitor level and then we assign each school to a pollution monitor and assign them the PM2.5 levels of that station. The distance to these monitors ranges between

[8]Taking advantage of the granularity of the pollution data, we define a day as the hours between 6:00 am and 5:00 pm.

600 meters and 6 kilometers, with a mean of 2 Km. Since the pollution concentrations of a school near a station might be larger compared to schools further away, we use the inverse of the distance to the pollution stations as weights (Currie and Neidell, 2005; Hanna and Oliva, 2015). The idea of the downwind frequency interacted with the intensity of TransMilenio buses as IV is that schools receiving winds directly from the primary traffic way receive a larger amount of pollutants versus schools located on the other side of the road, this results in different concentrations of particles at the school level due to wind patterns.

Take for example Figure 3, which depicts a group of schools (black markers) on both sides of a segment of the Caracas trunk route. If the wind blows with a higher frequency from west to east, as the arrows point, then schools on the right-hand side of the highway will experience a higher intensity of particulate matter than schools right to the left of the trafficway. To further explore this relationship, Figure 4 shows the results of a binned regression of PM2.5 on downwind frequency interacted with bus intensity between 2014 and 2018. The plot can be seen as graphical evidence of the first stage and it suggests that larger values of downwind frequency by station in a day are positively correlated with increases in pollution, while lower frequencies show less exposure to pollutants.

5. Results

Table 2 shows the main OLS results estimated from equation 4.1. The overall OLS estimates in Panel B suggest a negative effect of pollution on test scores. Column 2 indicates that one additional microgram per cubic meter ($\mu g/m^3$) of PM2.5 throughout the academic year decreases math scores by 0.0040 standard deviations, this is equivalent to 6% of the mean. Column 3 shows a decrease in language scores of 0.0015 standard deviations, although the coefficient is not statistically significant at conventional values. Column 4 shows the global score, and in line with column 2, it suggests a negative and significant effect of 0.0028 standard deviations. All specifications include student and household covariates plus school and year fixed effects.

The discussion about the endogeneity concerns of particulate matter concentrations moves us to the analysis of panel A of Table 2. This panel shows the reduced form specification, in which the three exam scores are regressed against wind share (downwind frequency) interacted with bus intensity. Column 1 reports the result of the first stage, with a significant and positive association between wind frequency and particulate matter. Following the same direction as in panel B, columns 2 and 4 indicate negative and significant effects on the math and global scores respectively, while there are no effects on language scores. The same negative correlations by gender can be seen in appendix Figure A-3, where all panels show an inverse association between downwind frequency and test scores. The IV estimates are presented in panel C. Columns 2 and 4 suggest that the exposure to an additional microgram per cubic meter of PM2.5 is associated with a 0.014 standard deviation decrease in math and a 0.012 decrease in global scores, respectively. The F-stat indicates that wind share blowing to schools is a relevant instrument, with a value greater than 63.

5.1. **Heterogeneous effects.** The main pollutant we study in this paper is PM2.5, however, other particles are directly correlated with the sources of poor air quality, especially diesel engines (like the ones used by the TransMilenio fleet before 2019) like Nitrogen Oxides (NOx) and PM10. Panels B and C of Table 3 report the second stage of the IV strategy, using as the main pollutants PM10 and NOx, respectively - Panel A reports the main PM2.5 estimates as in Table 2 for comparison. The statistically significant results indicate that high concentrations of emissions in areas with high bus traffic lead to worse academic performance for both types of chemical compounds, with decreases in math test scores of 0.02 and 0.01 standard deviations.

The estimates in Table 4 break the PM2.5 coefficient by gender, to show that girls 15-18 years are the most negatively affected by pollution, as boys perform on average

0.03 and 0.02 standard deviations higher in both math and the global score. In Table 5 we further explore the differences in performance by socioeconomic stratum, using the six strata under which every household is classified in Colombia[9]. Interestingly, students who are classified as non-poor, those in strata 5 and 6, score worse than those in the middle or bottom segment of the SES classification. This goes in line with the idea that more disadvantaged kids may already be exposed to other pollution sources or even higher levels of PM2.5 in comparison to those less disadvantaged (Heissel et al., 2022).

5.2. **Health outcomes.** One of the main mechanisms that could explain these negative results is the detrimental effect of pollution on children's health. Particularly in a major city like Bogotá, the bulk of emissions and pollutants come from large buses and cars, which constitute nearly 80% of the total contribution to the poor air quality (CONPES, 2018). Previous research has demonstrated the negative externalities of traffic and the air pollution that comes with it on respiratory health. From the effects of particulate matter on inadequate lung growth and asthma symptoms (Simeonova et al., 2019), to prematurity and low birth weight (Currie and Walker, 2011) and the association between traffic levels, carbon monoxide, and infant mortality (Knittel et al., 2016). Motivated by the evidence on air toxics and the exacerbation of several respiratory diseases, such as coughing, wheezing, bronchitis and pneumonia (Beatty and Shimshack, 2011; Peden, 2002), we present some suggestive plots that show the correlation between PM2.5 and health outcomes for children under 14 years old in Bogotá.[10]

[9]Categories closer to 6 imply a higher socioeconomic stratum. In our study sample, 55% fall in the first two strata, 34% are moderately poor, and 9% fall in the highest 2 points of the scale

[10]The main caveat of this exercise, which is also why we don't use the IV approach for health status, is that the city's Department of Health collected the different variables by surveying a sample of parents and the responses were aggregated at the locality-year level, and this gives us roughly 100 observations for the plots.

Panels A-C of the correlation Figure 5 were created by matching the centroid of each locality to the nearest pollution station, and then running a binned specification over time for each outcome.[11] Panel A shows a positive association between PM2.5 concentrations and school absences related directly to respiratory illnesses for both boys and girls. Areas with a higher level of poor air quality experience more school absenteeism. Panels B and C directly reflect a noticeable positive correlation between particulate matter and coughing and wheezing (acute sound when breathing). Both plots imply that areas with low PM2.5 levels exhibit lower rates of coughing and wheezing, and as fine particles increase, the prevalence of respiratory conditions for children ages 14 and younger sees an escalation as well, especially for girls. Taken together, although suggestive, these figures support the idea that pollution exposure might exacerbate kids' respiratory ailments that lead to worse health status and eventually, to lower human capital accumulation.

Using the Multipurpose Survey, which has georeferenced households, we can refine the study of potential mechanisms by estimating the first and second stages on a sample of children under 18 years old, but now we focus on health outcomes and assign the pollution levels of each air monitor to the nearest households. The estimates reported in Table A-2 indicate that those under 18 years of age are effectively more likely to develop respiratory diseases as a result of the exposure to PM2.5, over other conditions such as allergies, emergency department visits and check-ups. Table A-3 shows that these respiratory effects are not significantly different between males and females or by socioeconomic stratum. In Table A-4 the sample is restricted to children in primary school (approximately under 11 years of age) and we find no health effects on them, even though the first stage is still robust. This suggests that children might not be affected to a great extent by pollution in their households, as they spend a considerable amount of time during the day at school.

[11] Bogotá is divided into 20 localities, which are large groups of neighborhoods.

6. Robustness Tests

We now evaluate the robustness of the main results by implementing a series of tests focused on wind frequency at night, exposure to wildfires, sorting into schools based on wind direction, and the composition of the sample of students taking the test each year.

Wind frequency at night. The main results presented so far point to a negative effect of pollution on test scores, supported by the OLS and IV estimates. The instrument, however, is restricted to downwind frequency during the day, as we believe that traffic between 7:00 am and 6:00 pm is the one that matters for pollution levels, both because more buses are circulating and, more importantly, because most young students go to school during the daytime. For this reason, we estimate equation 4.3 again, but this time using downwind frequency at night as an instrument for two different time frames. Panel A of Table A-5 uses wind frequency between 7:00 pm and 11:00 pm as an instrument. During these hours, the TransMilenio system still works, but is less likely that young students are in schools. Panel B again uses wind frequency as an IV, but now measured after the mass transportation system shuts down its services, at midnight, and until 6:00 am. Both sets of estimates confirm that PM2.5 levels instrumented with the frequency of wind direction at night do not affect test scores, and it is not even a relevant IV, displaying an F-stat of less than 2.0.

Distance to the sources of pollution. The estimates in Tables 2 through 5 restrict the sample to schools within 2 kilometers of the nearest BRT trunk route. This is done considering that schools closer to the pollution source should in principle be exposed to more pollutants. The right-hand side of Table 3, columns 4-6, uses the sample of schools that are further away from the main highways, above 1.86 kilometers (third quartile of the distribution). We find null results of PM2.5 on academic performance, which is expected as these schools do not face the full effect of worst air quality originating in a nearby major traffic-way.

Wildfires. Bogotá is not exempt from experiencing wildfires, especially during sustained periods of scarce rain and over-the-average heat. When this happens, the city, or some parts of it, can be exposed to high levels of pollutants for several days. However, these events occur with a very low frequency, potentially making their negative effects much less significant for students. To explore this possibility, we estimate the main IV specification and present the results in Table 6 but using the concentration of pollution coming from burns during our study period. As evidenced in panels A through C, there are no significant effects of these substances on test scores, whether for those living outside a 6.5 kilometers radius or within this limit[12]. The lack of significant effects suggests that infrequent wildfires do not affect students as much as being continuously exposed to other sources of particulate matter, such as buses and cars passing by their schools daily.

Sorting into schools by wind frequency. A potential concern comes from the idea that wind frequency might systematically determine student's demographic characteristics and therefore, lead to a potential sorting into schools. Table A-6 addresses this concern by regressing several household and student-level characteristics, such as age, sex, parental education, socioeconomic stratum, and household size, on the instrument. We find no effects of the percentage of time wind blows from TransMilenio to the schools during the day (Panel A) or at night (Panel B) on household or children's attributes.

Older test-takers. The sample of interest corresponds to students who are between 15 and 18 years old. First, they are the ones who massively take the ICFES test each year (as they are near their high school graduation) and second, they spend most of their time at school. The test, nonetheless, can be taken by anyone who wishes to

[12]We set this threshold to ensure that the wind is strong enough to transport pollutants from the wildfire location to the city, specifically, above a light breeze, or 6 km per hour. We selected areas that could be affected by pollutant dispersion, considering the distance wildfire emissions are in particulate places where the pollution can reach after one hour, that is above 6.5 kilometers

access higher education programs in Colombia and by people who want to get their high school degree, regardless of age. Since these individuals, who are considerably older than the main sample, do not spend as much time in educational institutions, they should not be affected by particulate matter in the same way, specifically when it comes to academic performance. Even though the sample is reduced, Table A-7 shows that indeed, older test-takers, those between 19 and 70 years old, are not negatively affected by continued exposure to PM2.5, either during the day, as shown in Panel A, or during the night, as seen in Panel B.

Randomized pollution levels. To rule out that the main estimates might be derived from spurious relationships, we implement a series of placebo tests, in which we randomly assign particulate matter levels at the station level — effectively modifying PM2.5 at the school level as well — and then run again the main OLS specifications. Panels A through C of Figure A-4 indicate that after randomly assigning pollution in 500 iterations, the main OLS estimates for math, language and global test scores are far from the randomized versions, which are essentially equal to zero, making the placebo effects statistically insignificant.

Pollution without bus intensity. As discussed previously, not every TransMilenio route carries the same volume of traffic. For example, sections such as Caracas Avenue or Carrera Décima (near the downtown area) sustain a significantly higher burden of buses than other parts of the city, and this might change the level of PM2.5 that reaches the surrounding areas. To test this, we estimate the main OLS and IV specifications, but without interacting the pollution measures with bus intensity. Table A-8 indicates that the statistical significance of the reduced form and the second stage is reduced when we do not consider the number of buses that use exclusive lanes, suggesting that indeed the frequency and number of TransMilenio buses circulating on the busiest traffic-ways matter for the amount of particulate matter that students receive during the school day.

Wind frequency from non-TransMilenio routes. The exposure to pollution we study comes mainly from the TransMilenio network that covers most of Bogotá. There are, however, other large traffic ways where TransMilenio does not work but still have schools located near them. We explore the association between pollution from these highways and test scores in Table A-9. We re-run the primary specifications, but now the IV is the wind frequency blowing from the nearest route without any TransMilenio stop. To avoid the case in which the same school is close to both types of highways (with and without the mass transportation system), we keep the ones that are within 1.86 Km, as in Table 2, but impose a distance of over 1.16 Km from the traffic ways with a TransMilenio stop. As Panel A shows, there is a weak first stage between wind and PM2.5, while Panel C reports no statistically significant effects of pollution on test scores once the endogenous variable has been instrumented.

Wind share by months. All documented effects consider the average pollution levels throughout the year from January until students take the *Saber 11* exam, which is usually between August and September. This is key given that they are exposed to poor air quality for most of the academic year. Table A-10 shows that this cumulative measure is important, by regressing different versions of PM2.5 for different months prior to the exam on the instrument. Two results stand out. First, the estimate of interest is highly significant and then loses explanatory power as pollution is measured closer to the *Saber 11* date. Second, the coefficient also decreases in magnitude, suggesting that the average yearly wind share explains less of PM2.5 concentrations measured during shorter time frames.

7. Conclusions

This paper sheds light on an essential and often overlooked aspect of urban development: the impact of air pollution on educational outcomes in the developing world.

Analyzing a comprehensive dataset, employing an exogenous variation from wind direction, and using as the source of poor air quality a mass traffic system, this article demonstrates a link between increased air pollution and reduced school performance among urban students.

Ultimately, the findings presented in this paper underscore the need for concerted efforts to reduce air pollution in urban areas, not only for public health but also for the educational outcomes of the younger generation. By recognizing and addressing the adverse effects of air pollution on math scores, we can strive for more equitable and inclusive educational systems that empower all students, regardless of their environmental circumstances.

The findings of this research have significant implications for policymakers, educators, and urban planners. As air pollution continues to be a pressing issue in many cities worldwide, understanding its detrimental effects on academic performance is crucial for designing effective interventions and mitigating its negative consequences. By prioritizing policies that reduce air pollution and improve air quality, decision-makers can create healthier and more conducive learning environments for students.

The relationship between air pollution and academic achievement is complex, influenced by multiple factors such as socioeconomic status, school quality, and individual characteristics. Future research should delve deeper into these underlying mechanisms to gain a more comprehensive understanding of the issue and identify potential avenues for intervention.

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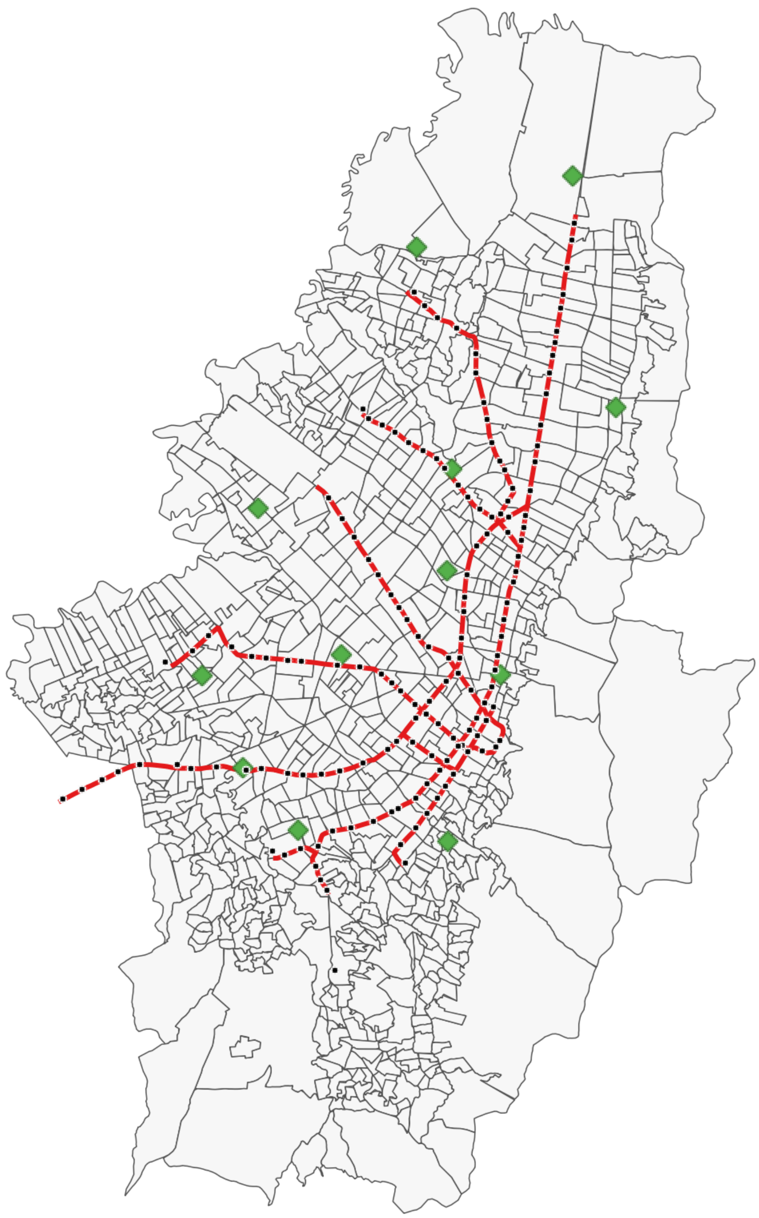
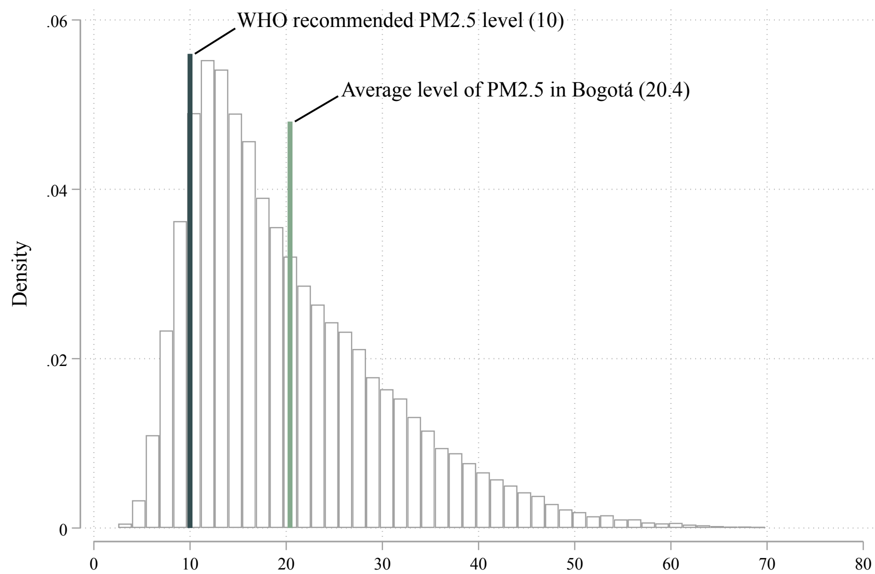
Tables and Figures

Figure 1. TransMilenio and Air Quality Monitors

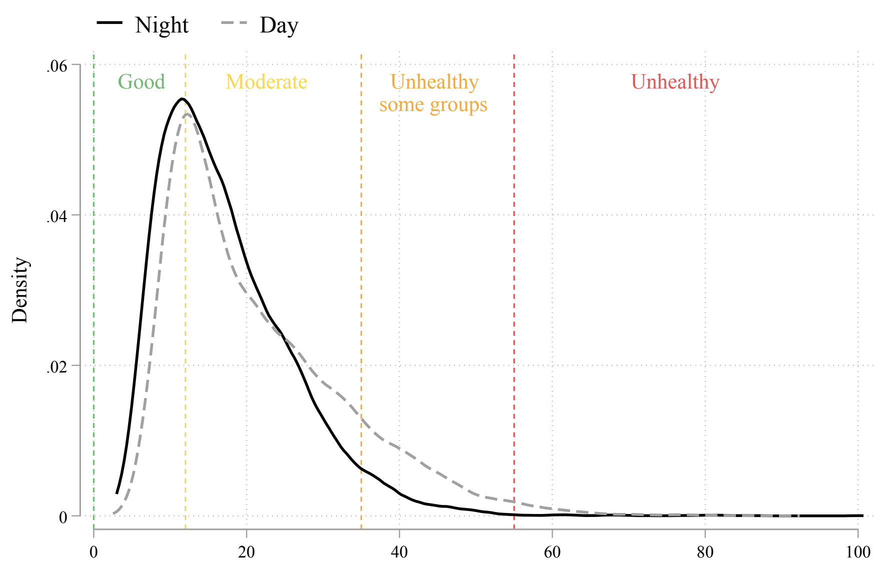


Notes: The figure shows transport and air quality monitoring network in Bogotá. The lines represent the TransMilenio network. The dots over the lines indicate TransMilenio stations where buses stop. The diamond markers represent stations in the Bogotá Air Quality Monitoring Network.

FIGURE 2. PM2.5 Density in Bogotá



A. General



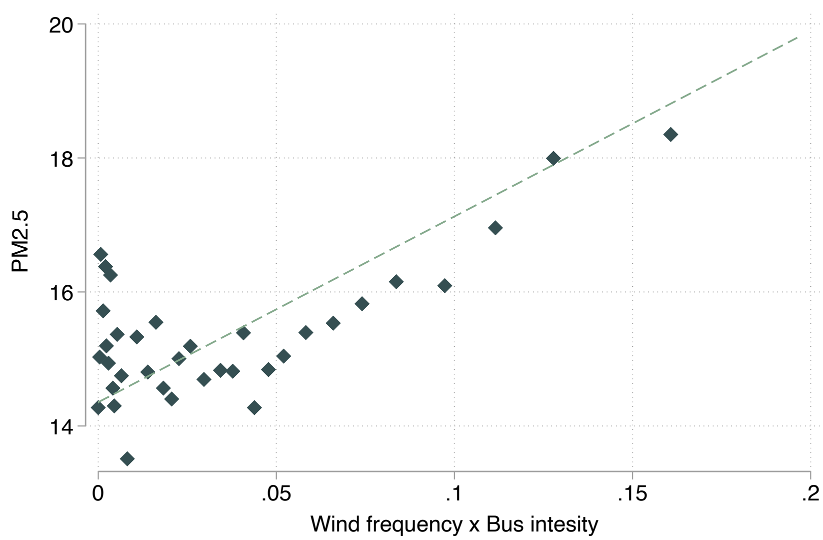
B. By time of Day

Notes: The figures show the distribution of PM2.5 levels in Bogotá from 2014 to 2018. Panel A shows the distribution of all values during all hours. Panel B shows the distribution separately for daylight hours (6 AM to 6 PM) and night hours (midnight to 6 AM).

Figure 3. Schools and Wind Direction

Notes: The figure shows a group of schools (black markers) near a segment of the Caracas trunk route (bright pink line). The arrows depict the frequency of downwind conditions from west to east.

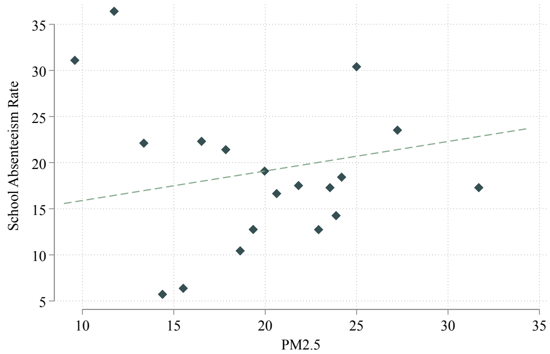
Figure 4. PM2.5 and Downwind Frequency



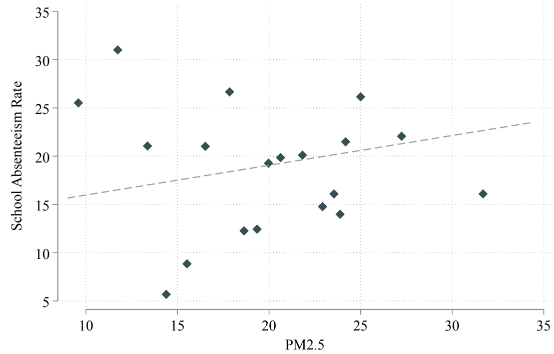
Notes: The figures illustrate the relationship between PM2.5 levels and wind frequency during daylight hours, with wind blowing from the TransMilenio route to the school. This relationship is derived from a binned regression of daily PM2.5 levels on the percentage of time that pollution stations are downwind.

Figure 5. PM2.5 School absenteeism and respiratory health

Panel A: School absenteeism rate

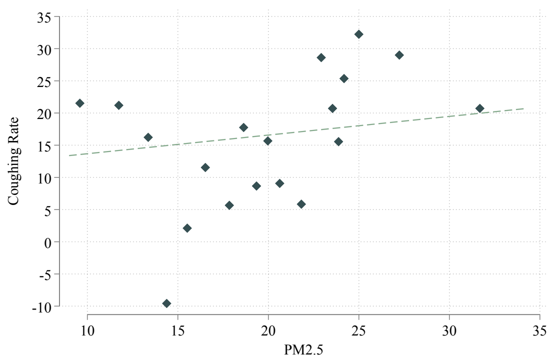


A. Men

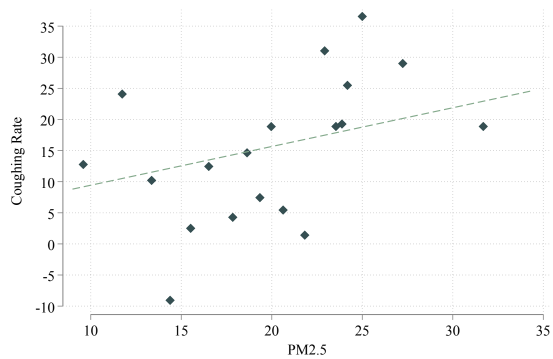


B. Women

Panel B: Coughing Rate

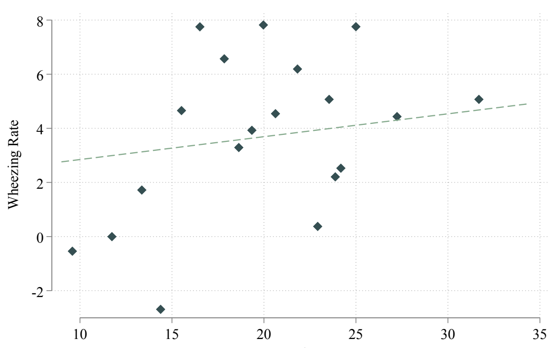


C. Men

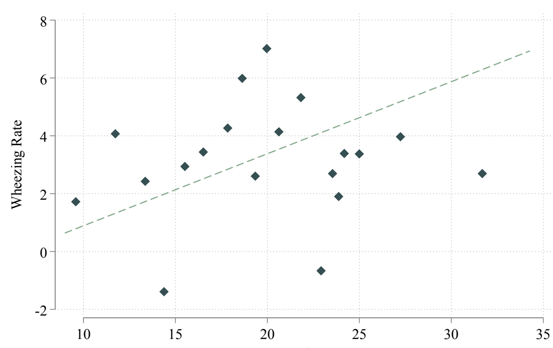


D. Women

Panel C: Wheezing Rate



E. Men



F. Women

Notes: The figure show the relationship between PM2.5 levels and various health outcomes for children under 14 for boys and girls. Panel A shows the absenteeism rate, Panel B shows the coughing rate, and Panel C shows the wheezing rate. These relationships are derived from a binned regression of the rates on PM2.5 levels at the locality level. The rates are based on surveys conducted by Bogotá's Department of Health, which collected information about the health status of their children from a sample of parents.

Table 1. Descriptive statistics

	Distance to closest TransMilenio route					
	< 1.86 km			> 1.86 km		
	Mean	Stdv.	Obs	Mean	Stdv.	Obs
	Panel A: *Academic achievements outcomes*					
Math score	0.08	0.93	285320	0.00	0.96	96904
Language score	0.09	0.95	285320	−0.01	0.97	96904
Global score	0.09	0.93	285320	−0.02	0.97	96904
	Panel B: *Pollution ($\mu g/m3$)*					
PM2.5	21.69	6.38	271716	21.49	7.04	92525
PM10	50.74	17.23	285320	51.43	17.44	96904
NOx	37.45	14.71	206647	36.49	14.20	66796
	Panel C: *Controls*					
Age	16.97	0.71	285320	16.99	0.70	96904
Female	0.54	0.50	285320	0.55	0.50	96904
Gender (No info)	0.00	0.03	285320	0.00	0.02	96904
Mother education						
Lower completed primary school	0.08	0.26	285320	0.12	0.32	96904
Lower completed high school	0.23	0.42	285320	0.29	0.45	96904
Lower completed tertiary education	0.37	0.48	285320	0.34	0.47	96904
Completed tertiary education	0.29	0.46	285320	0.23	0.42	96904
No info	0.03	0.17	285320	0.02	0.16	96904
Family stratum						
Lower	0.50	0.50	285320	0.70	0.46	96904
Medium	0.40	0.49	285320	0.18	0.39	96904
High	0.08	0.28	285320	0.10	0.30	96904
No info	0.02	0.12	285320	0.02	0.12	96904
Household Size	4.55	1.66	285320	4.67	1.68	96904
Household Size (No info)	0.01	0.09	285320	0.01	0.09	96904
Household has computer	0.87	0.34	285320	0.82	0.38	96904
Household has computer (No info)	0.01	0.08	285320	0.01	0.08	96904
	Panel D: *School characteristics*					
Public school	0.52	0.50	285320	0.63	0.48	96904
School type						
Academic	0.83	0.37	285320	0.91	0.28	96904
Academic-Technical	0.13	0.33	285320	0.06	0.24	96904
Technical	0.02	0.15	285320	0.01	0.12	96904
Other	0.00	0.06	285320	0.00	0.05	96904
No info	0.01	0.11	285320	0.00	0.07	96904

Notes: Sample students aged 15 to 18 from 2014-2018, Schedule A, who presented the exam in the second half of the year. The first three columns show summary statistics for students whose schools are within 1.86 km of the TransMilenio route. The last three columns show summary statistics for students whose schools are more than 1.86 km from the TransMilenio route.

TABLE 2. Main results: Effect PM2.5 day pollution and exam scores Wind share blowing to the school at sunlight hours x bus intesity

	PM25 (1)	Math (2)	Lang. (3)	Global (4)
	Panel A: *First-stage and reduced-form estimates*			
Wind share	14.3264***	−0.1972**	−0.0746	−0.1660**
	(1.7925)	(0.0934)	(0.0773)	(0.0808)
R2	0.9961	0.3161	0.2365	0.3575
Observations	271555	271555	271555	271555
	Panel B: *OLS estimates*			
PM2.5	- -	−0.0040***	−0.0015	−0.0028**
		(0.0010)	(0.0012)	(0.0011)
R2		0.3162	0.2365	0.3575)
Observations		271555	271555	271555
	Panel C: *IV estimates*			
PM2.5	- -	−0.0138**	−0.0052	−0.0116**
		(0.0066)	(0.0055)	(0.0057)
R2		0.0687	0.0304	0.0631)
Observations		271555	271555	271555
Kleibergen-Paap F		63.88	63.88	63.88
Controls	✓	✓	✓	✓
School FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. The wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the school at sunlight hours. In Panel C, the wind share is used as an instrument for a student's yearly average PM2.5 exposure. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Table 3. Main results: Effect day pollution and exam scores
Wind share blowing to the school at sunlight hours

	< 1.86 km			> 1.86 km		
	Math	Lang.	Global	Math	Lang.	Global
	(1)	(2)	(3)	(4)	(5)	(6)
			Panel A: *PM 2.5*			
Pollution	−0.0138**	−0.0052	−0.0116**	−0.0665	−0.0573	−0.0554
	(0.0066)	(0.0055)	(0.0057)	(0.0487)	(0.0407)	(0.0452)
R2	0.0687	0.0304	0.0631	0.0705	0.0292	0.0632
Observations	271555	271555	271555	92476	92476	92476
Kleibergen-Paap F	63.88	63.88	63.88	4.06	4.06	4.06
			Panel B: *PM 10*			
Pollution	−0.0181**	−0.0057	−0.0160**	0.1069	0.1044	0.0804
	(0.0091)	(0.0065)	(0.0081)	(0.1359)	(0.1343)	(0.1108)
R2	0.0450	0.0280	0.0431	-0.0063	-0.0321	0.0162
Observations	285156	285156	285156	96853	96853	96853
Kleibergen-Paap F	7.91	7.91	7.91	0.74	0.74	0.74
			Panel C: *NOx*			
Pollution	−0.0077***	−0.0038	−0.0071***	−0.0110	0.0081	−0.0061
	(0.0029)	(0.0024)	(0.0025)	(0.0118)	(0.0080)	(0.0089)
R2	0.0668	0.0296	0.0607	0.0725	0.0294	0.0641
Observations	206515	206515	206515	66756	66756	66756
Kleibergen-Paap F	44.59	44.59	44.59	27.89	27.89	27.89
Controls	✓	✓	✓	✓	✓	✓
School FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. In each panel, the yearly average exposure to each pollutant is instrumented with the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the school during sunlight hours, interacted with bus intensity. Columns 1, 2, and 3 use the sample of students whose schools are within 1.86 km of the TransMilenio route. Columns 4, 5, and 6 use the sample of students whose schools are more than 1.86 km from the TransMilenio route. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Table 4. Effect PM2.5 day pollution and exam scores by gender
Wind share blowing to the school at sunlight hours

	Math (1)	Lang. (2)	Global (3)
PM2.5	-0.0250^{***}	-0.0083	-0.0193^{***}
	(0.0068)	(0.0055)	(0.0058)
PM2.5 x Male	0.0264^{***}	0.0066^{***}	0.0186^{***}
	(0.0011)	(0.0006)	(0.0009)
R2	-0.1058	0.0203	-0.0290
Observations	271555	271555	271555
Kleibergen-Paap F	29.98	29.98	29.98
Controls	✓	✓	✓
School FE	✓	✓	✓
Year FE	✓	✓	✓
Municipality FE	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. We estimate the differential effect according to students' gender. The instruments are the wind share interacted with the dummy indicators and bus intensity, representing the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the school during sunlight hours. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

TABLE 5. Effect PM2.5 day pollution and exam scores by family stratum Wind share blowing to the school at sunlight hours

	Math (1)	Lang. (2)	Global (3)
PM2.5	-0.0228^{***}	-0.0085	-0.0183^{***}
	(0.0082)	(0.0063)	(0.0069)
PM2.5 x Medium	0.0071^{***}	0.0042^{***}	0.0062^{***}
	(0.0020)	(0.0014)	(0.0017)
PM2.5 x Poor	0.0082^{***}	0.0021	0.0055^{***}
	(0.0022)	(0.0016)	(0.0019)
PM2.5 x Missing	0.0001	0.0003	-0.0068^{**}
	(0.0030)	(0.0028)	(0.0027)
R2	0.0661	0.0296	0.0591
Observations	271555	271555	271555
Kleibergen-Paap F	16.29	16.29	16.29
Controls	✓	✓	✓
School FE	✓	✓	✓
Year FE	✓	✓	✓
Municipality FE	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. We estimate the differential effect according to students' gender. The instruments are the wind share interacted with the dummy indicators and bus intensity, representing the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the school during sunlight hours. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

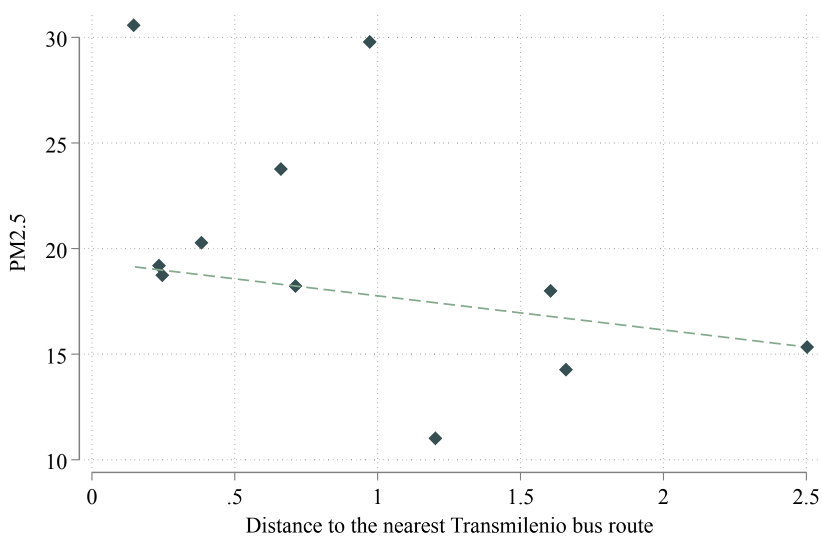
Table 6. Effect day pollution during burns and exam scores
Wind share blowing to the school at day hours

	> 6.5 km			< 6.5 km		
	Math	Lang.	Global	Math	Lang.	Global
	(1)	(2)	(3)	(4)	(5)	(6)
			Panel A: *PM 2.5*			
Pollution	0.0004	0.0002	−0.0034	0.0338	0.0548	0.0259
	(0.0064)	(0.0058)	(0.0058)	(0.0617)	(0.0594)	(0.0538)
R2	0.0692	0.0299	0.0628	0.0755	0.0330	0.0698
Observations	325211	325211	325211	36436	36436	36436
Kleibergen-Paap F	28.83	28.83	28.83	11.78	11.78	11.78
			Panel B: *PM 10*			
Pollution	−0.0007	0.0012	−0.0019	0.0021	0.0035	0.0016
	(0.0029)	(0.0026)	(0.0030)	(0.0039)	(0.0038)	(0.0034)
R2	0.0691	0.0296	0.0616	0.0759	0.0337	0.0700
Observations	342981	342981	342981	36644	36644	36644
Kleibergen-Paap F	1.71	1.71	1.71	43.49	43.49	43.49
			Panel C: *NOx*			
Pollution	0.0003	0.0013	0.0002	−0.0249	0.0094	0.0673
	(0.0011)	(0.0009)	(0.0009)	(0.0554)	(0.0667)	(0.0688)
R2	0.0713	0.0302	0.0643	0.0770	0.0340	0.0723
Observations	229249	229249	229249	19601	19601	19601
Kleibergen-Paap F	40.59	40.59	40.59	8.05	8.05	8.05
Controls	✓	✓	✓	✓	✓	✓
School FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. In each panel, the yearly average exposure to each pollutant is instrumented with the percentage of time during the year when wind speeds are above 6 mph, blowing from Transmilenio to the school during night hours. Columns 1, 2, and 3 use the sample of students whose schools are on average more than 6.5 km of the burns. Columns 4, 5, and 6 use the sample of students whose schools are on average withn 6.5 km from the burns. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Appendix

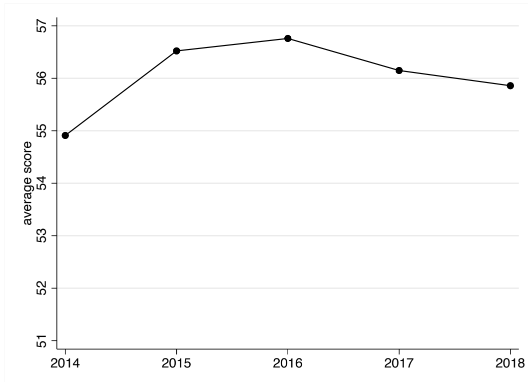
Figure A-1. PM2.5 and Distance to Bus Stations



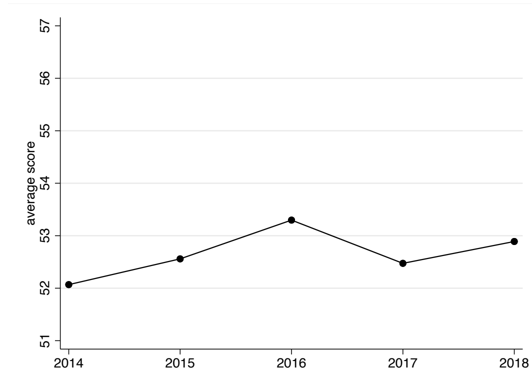
Notes: The figure illustrates the relationship between PM2.5 levels and the distance to the nearest Transmilenio bus route. This relationship is derived from a binned regression of daily PM2.5 levels on the distance to the routes.

FIGURE A-2. Average Scores in Bogotá

Panel A: Math scores

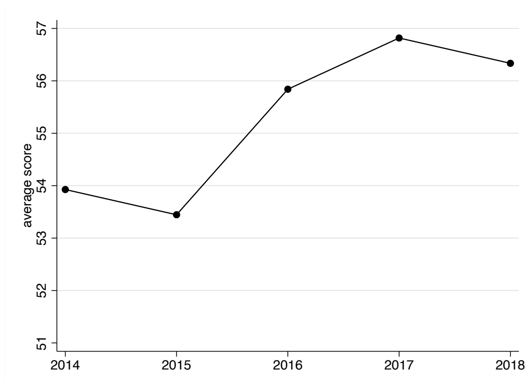


A. Men

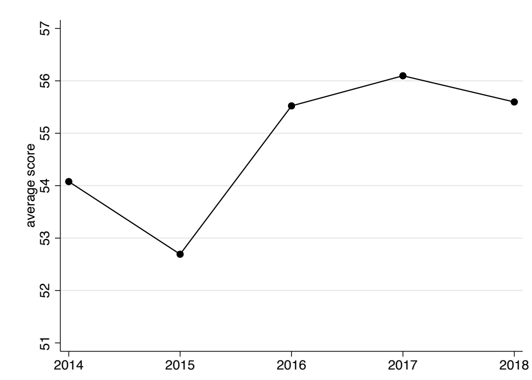


B. Women

Panel B: Languages scores



C. Men

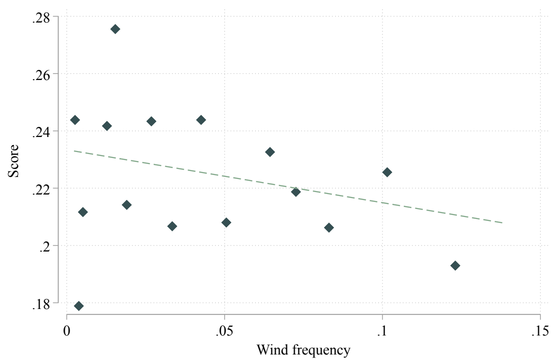


D. Women

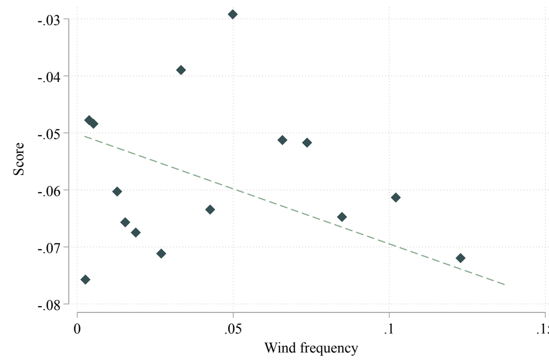
Notes: The figures show the relationship between wind frequency blowing to the school and various test scores. Panel A shows the math scores, Panel B shows the language scores, and Panel C shows the global scores. These relationships are derived from a binned regression of the rates on PM2.5 levels at the locality level.

Figure A-3. Wind frequency and test scores

Panel A: Math scores

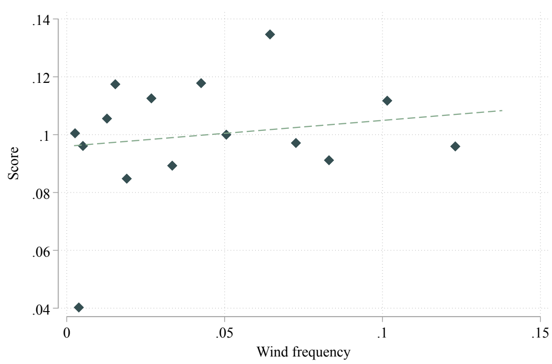


A. Men

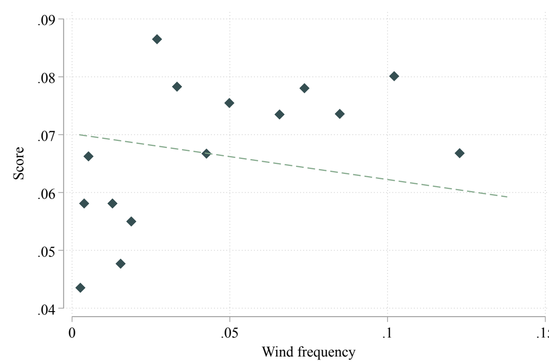


B. Women

Panel B: Languages scores

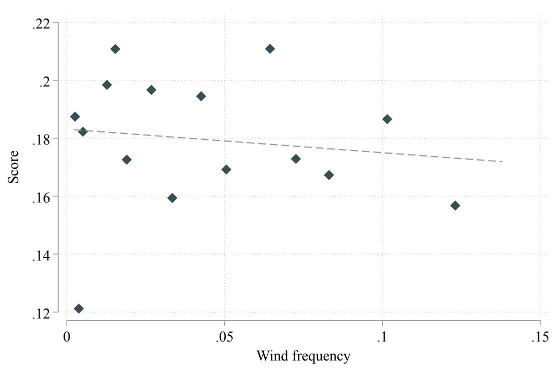


C. Men

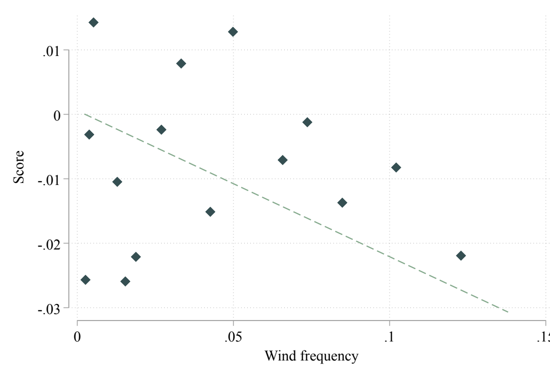


D. Women

Panel C: Global scores



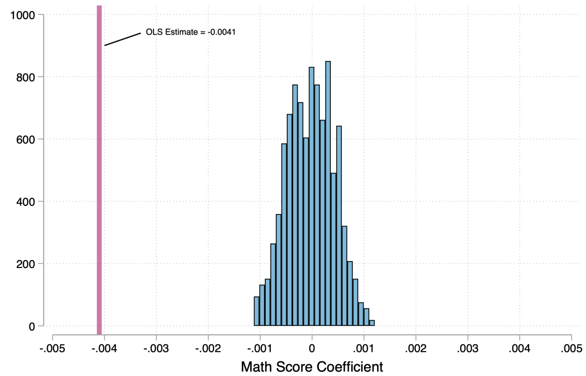
E. Men



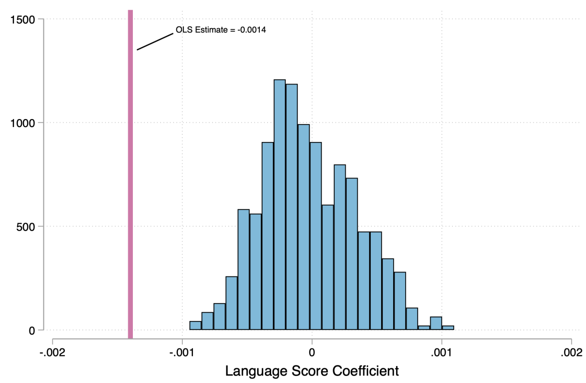
F. Women

Notes: The figures show the relationship between wind frequency blowing to the school and various test scores. Panel A shows the math scores, Panel B shows the language scores, and Panel C shows the global scores. These relationships are derived from a binned regression of the rates on PM2.5 levels at the locality level.

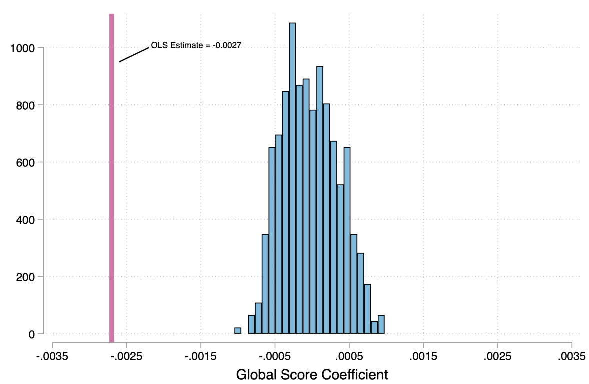
Figure A-4. Randomized pollution levels by station



A. Math Scores



B. Language Scores



C. Global Scores

Notes: The figures show the result of randomizing the pollution levels across stations and estimating the OLS specification for each test score. The distribution in blue represents the estimates after 500 iterations and the red vertical line corresponds to the baseline OLS coefficients reported in Table 2.

Table A-1. Air monitoring stations

Station name	Latitude	Longitude	Zone	Open year
Guaymaral	4.7837501	-74.044144	Sub urbana	2005
Usaquen	4.71035	-74.030418	Urbana	2000
Suba	4.76125	-74.09346	Sub urbana	2000
Las Ferias	4.6907001	-74.082481	Urbana	2004
Centro de alto rendimiento	4.6584702	-74.083969	Urbana	2004
MinAmbiente	4.6254902	-74.066978	Urbana	2000
Puente Aranda	4.6317701	-74.117477	Urbana	2000
Kennedy	4.6250501	-74.161331	Urbana	2005
Carvajal-Sevillana	4.59583	-74.148499	Urbana	2000
Tunal	4.57623	-74.130959	Urbana	2006
San Cristobal	4.5725498	-74.083809	Urbana	2010

TABLE A-2. Main results: Effect PM2.5 day pollution and health outcomes
Wind share blowing to the house during the sunlight hours

	PM25 (1)	Respiratory disease (2)	Allergy (3)	Any disease (4)	Emergency visit (5)	Stop routine (6)
	Panel A: *First-stage and reduced-form estimates*					
Wind share	9.6164***	0.1488*	0.0110	−0.0933	−0.1223	−0.0256
	(2.1925)	(0.0809)	(0.0656)	(0.0950)	(0.0812)	(0.0856)
R2	0.9420	0.1972	0.1959	0.1838	0.1675	0.1737
Observations	14720	14720	14720	14720	14720	14720
	Panel B: *OLS estimates*					
PM2.5	- -	−0.0003	0.0002	−0.0001	0.0002	−0.0000
		(0.0003)	(0.0003)	(0.0002)	(0.0003)	(0.0001)
R2		0.1969	0.1959	0.1837)	0.1673	0.1737)
Observations		14720	14720	14720	14720	14720
	Panel C: *IV estimates*					
PM2.5	- -	0.0155*	0.0011	−0.0097	−0.0127	−0.0027
		(0.0093)	(0.0068)	(0.0102)	(0.0091)	(0.0089)
R2		-0.1887	0.0066	-0.0451)	-0.0741	-0.0009)
Observations		14720	14720	14720	14720	14720
Kleibergen-Paap F		19.24	19.24	19.24	19.24	19.24
Controls	✓	✓	✓	✓	✓	✓
Sector FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓	✓

Notes: The sample consists of students attending secondary education below 18 years old who live within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, household head education, family stratum, household size, presence of the mother and the father at home, the presence of a computer in the house, dummy of no residency change in the previous years and school schedule interacted by year. The wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from Transmilenio to the house at sunlight hours. In Panel C, the wind share is used as an instrument for a student's yearly average PM2.5 exposure. The outcome in column 2 is the report of having a diagnosis of any respiratory disease. In column 3, the outcome is the diagnosis of an allergy. In column 4, the outcome is equal to one if they report the diagnosis of any disease in the previous 30 months. In column 5, the outcome is equal to one if they report a visit to the emergency room. In column 6, the outcome is equal to one if they report stopping their routine due to an illness. Standard errors are clustered at the building-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Table A-3. Effect PM2.5 day pollution and health outcomes Heterogeneous effects

	Respiratory disease (1)	Allergy (2)	Any disease (3)	Emergency visit (4)	Stop routine (5)
Panel A: *Gender*					
PM2.5	0.0158*	0.0007	−0.0095	−0.0116	−0.0024
	(0.0092)	(0.0067)	(0.0099)	(0.0090)	(0.0086)
PM2.5 x Male	−0.0002	0.0005	−0.0002	−0.0011**	−0.0003
	(0.0004)	(0.0004)	(0.0006)	(0.0005)	(0.0005)
R2	-0.1910	0.0068	-0.0422	-0.0722	0.0009
Observations	14714	14714	14714	14714	14714
Kleibergen-Paap F	9.80	9.80	9.80	9.80	9.80
Panel B: *Family stratum*					
PM2.5	0.0253*	−0.0027	−0.0236	−0.0224	−0.0115
	(0.0150)	(0.0109)	(0.0172)	(0.0157)	(0.0148)
PM2.5 x Medium	−0.0053	0.0052	0.0124**	0.0067	0.0084*
	(0.0045)	(0.0036)	(0.0055)	(0.0057)	(0.0043)
PM2.5 x Poor	−0.0104	0.0037	0.0162*	0.0111	0.0099
	(0.0070)	(0.0056)	(0.0087)	(0.0084)	(0.0072)
R2	-0.2555	0.0033	-0.0641	-0.0951	-0.0098
Observations	14714	14714	14714	14714	14714
Kleibergen-Paap F	4.62	4.62	4.62	4.62	4.62
Controls	✓	✓	✓	✓	✓
Sector FE	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓

Notes: The sample consists of students attending secondary education below 18 years old who live within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, household head education, family stratum, household size, presence of the mother and the father at home, the presence of a computer in the house, dummy of no residency change in the previous years and school schedule interacted by year. The wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from Transmilenio to the house at sunlight hours. In Panel A, we estimate the differential effect according to students' gender, and in Panel B, we estimate the differential effect according to the students' family stratum. The outcome in column 1 is the report of having a diagnosis of any respiratory disease. In column 2, the outcome is the diagnosis of an allergy. In column 3, the outcome is equal to one if they report the diagnosis of any disease in the previous 30 months. In column 4, the outcome is equal to one if they report a visit to the emergency room. In column 5, the outcome is equal to one if they report stopping their routine due to an illness. Standard errors are clustered at the building-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Table A-4. Main results: Effect PM2.5 day pollution and health outcomes
Wind share blowing to the house during sunlight hours - Primary school

	PM25 (1)	Respiratory disease (2)	Allergy (3)	Any disease (4)	Emergency visit (5)	Stop routine (6)
	Panel A: *First-stage and reduced-form estimates*					
Wind share	9.1553***	−0.0450	−0.1030	0.1607	−0.1141	0.1248
	(2.3429)	(0.0692)	(0.0706)	(0.1139)	(0.1073)	(0.0761)
R2	0.9323	0.2527	0.2612	0.2485	0.2233	0.2278
Observations	11346	11346	11346	11346	11346	11346
	Panel B: *OLS estimates*					
PM2.5	- -	−0.0000	−0.0000	−0.0003	0.0003	−0.0002
		(0.0003)	(0.0001)	(0.0002)	(0.0004)	(0.0002)
R2		0.2527	0.2610	0.2482)	0.2233	0.2276)
Observations		11346	11346	11346	11346	11346
	Panel C: *IV estimates*					
PM2.5	- -	−0.0049	−0.0113	0.0175	−0.0125	0.0136
		(0.0077)	(0.0082)	(0.0134)	(0.0123)	(0.0090)
R2		-0.0110	-0.1096	-0.1729)	-0.0635	-0.1465)
Observations		11346	11346	11346	11346	11346
Kleibergen-Paap F		15.27	15.27	15.27	15.27	15.27
Controls	✓	✓	✓	✓	✓	✓
Sector FE	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓	✓

Notes: The sample consists of students attending secondary education below 18 years old who live within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, household head education, family stratum, household size, presence of the mother and the father at home, the presence of a computer in the house, dummy of no residency change in the previous years and school schedule interacted by year. The wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from Transmilenio to the house at sunlight hours. In Panel A, we estimate the differential effect according to students' gender, and in Panel B, we estimate the differential effect according to the students' family stratum. The outcome in column 1 is the report of having a diagnosis of any respiratory disease. In column 2, the outcome is the diagnosis of an allergy. In column 3, the outcome is equal to one if they report the diagnosis of any disease in the previous 30 months. In column 4, the outcome is equal to one if they report a visit to the emergency room. In column 5, the outcome is equal to one if they report stopping their routine due to an illness. Standard errors are clustered at the building-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

TABLE A-5. Effect PM2.5 night pollution and exam scores
Wind share blowing to the school at night hours

	(1) PM2.5	(2) Math	(3) Lang.	(4) Global
	Panel A: *First-stage wind share 6:00pm - 11:00pm*			
Wind share	-1.435	-0.264*	-0.045	-0.191
	(1.100)	(0.160)	(0.120)	(0.140)
R2	0.9962	0.3293	0.2432	0.3699
Observations	199699	199699	199699	199699
	Panel B: *IV Wind share 6:00pm - 11:00pm*			
PM2.5	–	0.184	0.031	0.133
		(0.200)	(0.090)	(0.150)
R2		-0.0877	0.0216	-0.0295
Observations		199699	199699	199699
Kleibergen-Paap F		1.69	1.69	1.69
	Panel C: *First-stage wind share 12:00am - 5:00am*			
Wind share	-4.133***	-0.238	-0.060	-0.169
	(1.160)	(0.150)	(0.130)	(0.130)
R2	0.9910	0.3293	0.2432	0.3699
Observations	199699	199699	199699	199699
	Panel D: *IV Wind share 12:00am - 5:00am*			
PM2.5	–	0.058	0.015	0.041
		(0.040)	(0.030)	(0.030)
R2		0.0451	0.0245	0.0461
Observations		199699	199699	199699
Kleibergen-Paap F		12.64	12.64	12.64
Controls	✓	✓	✓	✓
School FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓

Notes: The sample consists of test-takers aged 15 to 18 from 2014-2018, who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. In Panels An and B, the wind share used as an instrument is the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the schools between 6:00pm and 11:00pm. In Panels C and D, the wind share blowing from TransMilenio to the schools used as an instrument is measured between 12:00am and 5:00am. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Table A-6. Wind share and demographic characteristics

	(1) Age	(2) Female	(3) Educ. Father	(4) Educ. Mother	(5) Stratum ≤ 3	(6) HH Size	(7) HH Computer
				Panel A: *Wind share - Day*			
Wind share	0.015	0.017	-0.039	-0.059	0.021	-0.173	0.040
	(0.060)	(0.040)	(0.030)	(0.040)	(0.020)	(0.120)	(0.030)
R2	0.0847	0.1107	0.2986	0.1780	0.4134	0.0908	0.1177
Observations	271555	271555	255142	267470	271555	271555	271555
				Panel B: *Wind share - Night*			
Wind share	0.041	0.008	-0.011	0.033	0.055	-0.088	0.075
	(0.090)	(0.060)	(0.050)	(0.060)	(0.040)	(0.210)	(0.050)
R2	0.0847	0.1107	0.2986	0.1780	0.4134	0.0908	0.1177
Observations	271555	271555	255142	267470	271555	271555	271555
School FE	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓	✓	✓

Notes: The sample consists of test-takers aged 15 to 18 from 2014-2018, who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The outcomes in each column are children's and houshold's socioeconomic characteristics such as age, female, indicators for parents education above high school, economic stratum below 3, household size above 4 members, and presence of a computer in the house. All specifications include the whole set of demographic characteristics as controls, except when that variable is the outcome. In Panel A, the wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the schools at sunlight hours. In Panel B, the wind share is computed at night. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

TABLE A-7. Effect PM2.5 day pollution and older test-takers

	(1) Math	(2) Lang.	(3) Global
	Panel A: *IV Wind share - Day*		
PM2.5	0.003	0.015*	0.012
	(0.010)	(0.010)	(0.010)
R2	0.1058	0.0524	0.0938
Observations	38997	38997	38997
Kleibergen-Paap F	39.98	39.98	39.98
	Panel B: *IV Wind share - Night*		
PM2.5	0.022	0.041	0.078
	(0.070)	(0.090)	(0.080)
R2	0.1033	0.0470	0.0615
Observations	38997	38997	38997
Kleibergen-Paap F	3.21	3.21	3.21
Controls	✓	✓	✓
School FE	✓	✓	✓
Year FE	✓	✓	✓
Municipality FE	✓	✓	✓

Notes: The sample consists of test-takers aged 19 to 70 from 2014-2018, who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. In Panel A, the wind share used as an instrument is the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the schools between 7:00am and 6:00pm. In Panel B, the wind share blowing from TransMilenio to the schools used as an instrument is measured between 7:00pm and 11:00pm. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

TABLE A-8. Effect PM2.5 day pollution and exam scores
Wind share blowing to the school at sunlight hours without bus intensity

	PM25 (1)	Math (2)	Lang. (3)	Global (4)
	Panel A: *First-stage and reduced-form estimates*			
Wind share	64.3070***	−0.6124*	−0.2571	−0.4839
	(6.3737)	(0.3370)	(0.2977)	(0.2991)
R2	0.9961	0.3161	0.2365	0.3575
Observations	271555	271555	271555	271555
	Panel B: *OLS estimates*			
PM2.5	- -	−0.0040***	−0.0015	−0.0028**
		(0.0010)	(0.0012)	(0.0011)
R2		0.3162	0.2365	0.3575)
Observations		271555	271555	271555
	Panel C: *IV estimates*			
PM2.5	- -	−0.0095*	−0.0040	−0.0075
		(0.0053)	(0.0046)	(0.0047)
R2		0.0689	0.0304	0.0633)
Observations		271555	271555	271555
Kleibergen-Paap F		101.79	101.79	101.79
Controls	✓	✓	✓	✓
School FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. The wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the school at sunlight hours. In Panel C, the wind share is used as an instrument for a student's yearly average PM2.5 exposure. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

Table A-9. PM2.5 pollution and exam scores
Wind share blowing to the school at sunlight hours from routes with no TransMilenio buses

	PM25 (1)	Math (2)	Lang. (3)	Global (4)
	Panel A: *First-stage and reduced-form estimates*			
Wind share	10.3600**	−0.0520	0.1452	−0.1238
	(4.6097)	(0.3874)	(0.3433)	(0.3615)
R2	0.9849	0.3435	0.2509	0.3830
Observations	166378	174842	174842	174842
	Panel B: *OLS estimates*			
PM2.5	- -	−0.0067***	0.0006	−0.0011
		(0.0020)	(0.0022)	(0.0020)
R2		0.3326	0.2452	0.3723)
Observations		166378	166378	166378
	Panel C: *IV estimates*			
PM2.5	- -	0.0082	−0.0013	−0.0024
		(0.0377)	(0.0341)	(0.0354)
R2		0.0723	0.0316	0.0657)
Observations		166378	166378	166378
Kleibergen-Paap F		5.05	5.05	5.05
Controls	✓	✓	✓	✓
School FE	✓	✓	✓	✓
Year FE	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year and whose schools are above 1.16 km from the nearest TransMilenio route and within 1.86 km from the nearest route without TransMilenio. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. The wind share represents the percentage of time during the year when wind speeds are below 1 mph, blowing from TransMilenio to the school at sunlight hours. In Panel C, the wind share is used as an instrument for a student's yearly average PM2.5 exposure. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.

TABLE A-10. Effect wind share blowing to the school at sunlight hours on PM2.5 Pollution

	Year (1)	5.5 Months (2)	5 Months (3)	4.5 Months (4)	4 Months (5)	3.5 Months (6)	3 Months (7)	2.5 Months (8)	2 Months (9)
Wind share	21.2317***	22.5326***	17.7762***	12.8579***	16.0349***	7.9797**	11.2821**	5.8216	−3.2901
	(2.8331)	(4.0107)	(4.0314)	(3.9085)	(3.9986)	(3.4868)	(4.8650)	(3.6106)	(2.3899)
R2	0.9961	0.9936	0.9933	0.9903	0.9911	0.9894	0.9832	0.9868	0.9907
Observations	271555	271555	271555	271555	271555	271555	271555	271555	271555
Controls	✓	✓	✓	✓	✓	✓	✓	✓	✓
School FE	✓	✓	✓	✓	✓	✓	✓	✓	✓
Year FE	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipality FE	✓	✓	✓	✓	✓	✓	✓	✓	✓

Notes: The sample consists of students aged 15 to 18 from 2014-2018 (Schedule A) who took the exam in the second half of the year and whose schools are within 1.86 km far from the TransMilenio route. The analysis controls for student age, gender, mother's education, family stratum, household size, and the presence of a computer in the house. The wind share represents the percentage of time during each interval of time before the exam when wind speeds are below 1 mph, blowing from Transmilenio to the school at sunlight hours. Standard errors are clustered at the school-year level in parentheses. * is significant at the 10% level, ** is significant at the 5% level, *** is significant at the 1% level.