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Can a Low Emission Zone Improve Academic Performance? Evidence from a Natural Experiment in the City of Madrid

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Can a Low Emission Zone Improve Academic Performance? Evidence from a Natural Experiment in the City of Madrid

Abstract: In late 2018, the government of Madrid instituted a low emission zone (LEZ) in the central district of the city, aiming primarily to alleviate traffic-related emissions and enhance air quality. Extensive research has documented the adverse effects of air pollution on academic performance. Consequently, the success of Madrid's LEZ in reducing traffic-related emissions could potentially translate into improved performance among students schooled in the designated area. Through a difference-in-differences design, we demonstrate the policy's effectiveness in improving air quality during the four years following its implementation. Subsequently, we show a noteworthy increase of 0.17 standard deviations in the average EvAU scores (high-stakes examinations for university admittance) of high schools within the LEZ, a crucial advantage for gaining entry into the most competitive university programs. Importantly, our findings reveal positive spillover effects in the surroundings of the LEZ area and a larger effect the longer and earlier the exposure to cleaner air. In sum, our study offers compelling empirical evidence of the beneficial educational impacts resulting from the implementation of a low emission zone successful in improving air quality.

Keywords: Low emission zone; air pollution; academic performance; difference-in-differences.

1 Introduction

Air pollution is a pressing global concern. On the one hand, it is intrinsically linked to the emission of CO_2 and methane, major contributors to global warming. On the other hand, it is associated with a range of individual risks, notably deteriorating the health of people living in highly polluted areas (Juginović et al. 2021; König and Heisig 2023; Sorensen et al. 2022). Beyond health, air pollution has also been connected to other important life-course outcomes (Aguilar-Gomez et al. 2022). In particular, there is growing evidence showing how students exposed to high levels of pollution perform worse at schools (Amanzadeh, Vesal, and Ardestani 2020; Balakrishnan and Tsaneva 2021; Duque and Gilraine 2022; Grineski, Collins, and Adkins 2020; Heissel, Persico, and Simon 2022; Shier et al. 2019).

Consequently, numerous policies have been put in place to curb pollution levels. Traffic restriction plans are particularly popular since air pollution is commonly linked to vehicle-related emissions, especially Nitrogen Dioxide (NO_2).[1] Numerous studies show that traffic is a leading cause of medical conditions such as lung cancer (Hamra et al. 2015) and asthma (Alotaibi et al. 2019). Hence, it is logical to assume local policies aimed at reducing traffic would result in lower pollution levels and, ultimately, improved life-course outcomes.

This article seeks to evaluate whether the implementation of a low emission zone (LEZ) in the city of Madrid (Spain) in 2018 had a positive impact on the academic performance of students schooled in that area. Recent evidence indicates a significant reduction in traffic and pollution levels one year after the introduction of Madrid's LEZ (Lebrusán and Toutouh 2021; Moral-Carcedo 2022; Salas et al. 2021). However, previous research has not investigated the subsequent development of pollution levels nor whether the presumed success of the LEZ in reducing traffic-related emissions enhanced the academic performance of students schooled in that area. To do so, we analyse the students' scores in the EvAU, a high-stakes national exam aimed at ranking students for university admission. While one might reason that the effect of the LEZ might be more evident for academic performance at younger ages (Balakrishnan and Tsaneva 2021; Persico and Venator 2019), prior

[1] For instance, traffic has been used as a proxy to estimate the impact of the implementation of COVID lockdowns on air quality (Cooper et al. 2022; Restrepo 2021).

research has already established a causal link between air pollution and performance in high-stakes examinations similar to the Spanish EvAU (Carneiro, Cole, and Strobl 2021; Ebenstein, Lavy, and Roth 2016; Lavy, Ebenstein, and Roth 2014; Sanders 2012).

Employing a Difference-in-Differences design, we find that Madrid's LEZ caused a sustained decrease in air pollution over the four years following its introduction. As for academic performance, our results reveal that the LEZ increased the average EvAU scores of students schooled in the designated area by 17% of a standard deviation. In practical terms, this translates into a notable improvement of 0.14 points on the 0-10 scale of the EvAU, a significant advantage since admission to certain university programs is often determined by differences of less than one-hundredth of a point. We conducted several checks to confirm the robustness of our findings. Additionally, we report positive spillover effects for schools located 0.5km away from the borders of the LEZ area and a larger effect the farther away from the implementation date (i.e., the longer and earlier the exposure to cleaner air).

In conclusion, Madrid's LEZ not only achieved its stated goal of reducing pollution levels in the area but also produced positive externalities in terms of students' academic achievement. Thus, evaluating the policy solely in terms of its ability to reduce traffic-related emissions overlooks its broader contribution, which may extend to other outcomes such as workplace productivity, car accident rates, or overall well-being.

The remainder of the paper is structured as follows. In the next section, we describe the implementation of Madrid's LEZ and the studies documenting its initial effects. Subsequently, we present evidence on the relationship between air pollution and academic performance, the most likely channel for the hypothesized improvement in academic performance following the introduction of the LEZ. The next section is devoted to the description of the Spanish educational system and, very particularly, the EvAU examination. An overview of our data comes later, followed by our identification strategy. We then present the results and several robustness checks. In the last section, we discuss our findings and summarize the main conclusions of our work.

2 Low emission zones, traffic, and air pollution: the case of Madrid

Reducing traffic-related emissions is at the core of the global political agenda. One popular measure across European cities to reduce air pollution involves the implementation of low emission zones (LEZ), designated urban areas with some kind of mobility restriction for vehicles. These may range from charging entrance to totally banning access, and they might target highly polluting vehicles, vintage vehicles, or all non-resident vehicles. Previous works have documented the overall positive effects of such measures on pollution levels, with varying degrees of effectiveness depending on the specific characteristics of the LEZ (Barahona, Gallego, and Montero 2020; Zhang, Lin Lawell, and Umanskaya 2017).

In the case of Madrid, a LEZ was implemented in late 2018. Madrid is a comparatively large city (3,305,408 inhabitants in 2021)[2], with 5,479.8 inhabitants per km^2 and 1,815,972 registered motorized vehicles. In terms of air pollution, the city notably exceeds recommended levels. For instance, although the World Health Organization recommends a maximum level of 5 $\mu g/m^3$ for fine particulate matter ($PM_{2.5}$), the average level in Madrid in 2021[3] was 9.3 $\mu g/m^3$. Importantly, compared to other major European cities, Madrid ranks highest in the levels of Nitrogen Dioxide (NO_2), which is mostly emitted by cars and contributes to premature mortality (Khomenko et al. 2021). Furthermore, the centre of Madrid has been traditionally the most polluted area in the city, with pollution readings well above recommended levels (Galdon-Sanchez et al. 2023; Lebrusán and Toutouh 2021; Moral-Carcedo 2022; Salas et al. 2021).

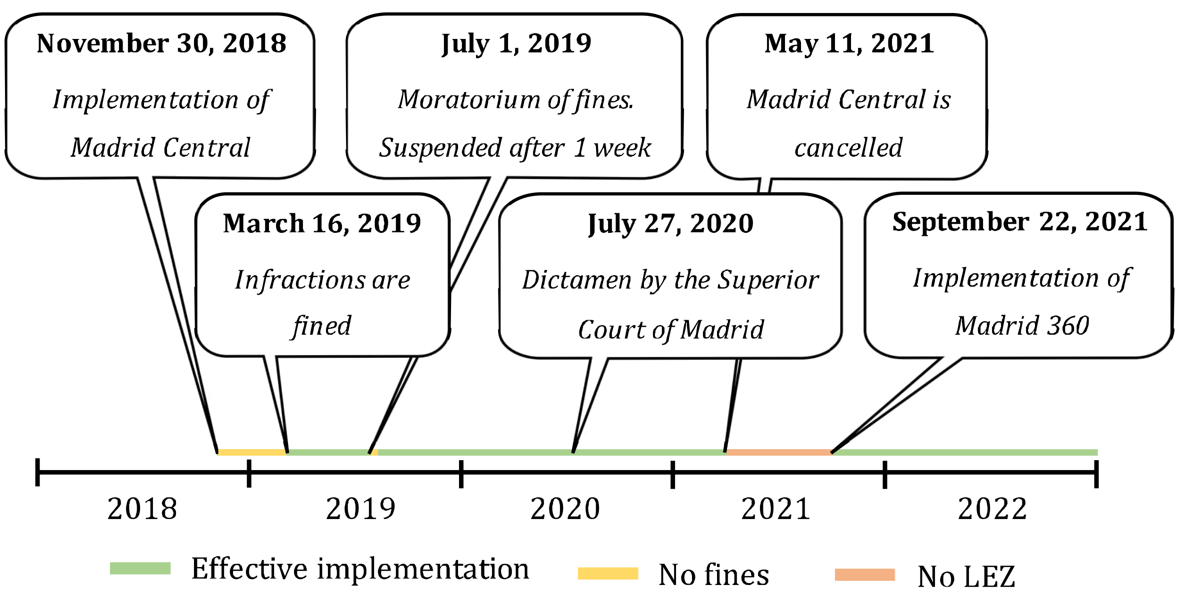
To address this situation, *Madrid Central* was designed as a traffic-restriction plan seeking to eliminate transit traffic, that is, non-resident vehicles whose origin or destination was not the restricted area. Only electric and hybrid cars were allowed to cross it, although all cars could access *Madrid Central* if it was their end destination. The LEZ was confined to *Distrito Centro* (one of the twenty-one districts of the city of Madrid), which comprises five neighbourhoods: *Palacio*, *Embajadores*,

[2] Madrid is the sixth most populated city in Europe after Istanbul, Moscow, London, Saint Petersburg, and Berlin. The data can be consulted at: https://populationdata.org.uk/largest-cities-in-europe/
[3] The data can be consulted at: https://www.eea.europa.eu/themes/air/urban-air-quality/european-city-air-quality-viewer

Cortes, *Justicia*, *Universidad*, and *Sol*. The size of *Madrid Central* was comparatively small, covering an area of 4,72 km^2 (0.7% of the city) with 142,099 inhabitants.

Traffic restrictions began on November 30, 2018 (Figure 1), but it was not until March 16, 2019, that infractions were fined (90 euros). However, on May 26, 2019, a new local government was elected promising the derogation of *Madrid Central*. As a first step, a moratorium on fines was enacted on July 1, although it was quickly suspended by a court after one week. On July 27, 2020, the Superior Court of Madrid dictated that the implementation of Madrid Central failed to carry out essential formalities, leading to the suspension of all traffic restrictions on May 11, 2021. A revised plan was approved on September 22, 2021, under the name of *Madrid360*, including the Low Emission Zone of *Distrito Centro*. Although the new plan was somehow more permissive, the main traffic restrictions were kept in place. The LEZ has been uninterruptedly applied since then.

Figure 1. Timeline of Madrid's low emission zone



Despite the turbulent history of Madrid's LEZ, previous works have reported a positive impact on air quality over the first year of implementation. Moral-Carcedo (2022) and Galdon-Sanchez et al. (2023) reported a statistically significant reduction in traffic following the implementation of *Madrid Central*. As for pollution, Salas et al. (2021) concluded that the introduction of the LEZ led to a decrease of 11 $\mu g/m^3$ in NO_2 levels. Similar conclusions were drawn by Lebrusán and Toutouh (2021) and Galdon-Sanchez et al. (2023), who also reported that NO_2 readings did not bounce back when fines were suspended. Interestingly, Moral-Carcedo (2022) also documented a decrease in the levels of noise within the LEZ area. Meanwhile, Galdon-Sanchez et al. (2023) employed credit card transaction data to report a reduction of retail commerce in the area (partially alleviated by an increase in e-commerce).

Importantly, a spirited political debate was held regarding whether *Madrid Central* would reduce air pollution in the designated area at the cost of increasing pollution readings in the surroundings. Indeed, Moral-Carcedo (2022) documented a slight traffic increase in the bordering areas of *Madrid Central*. However, neither Salas et al. (2021) nor Lebrusán and Toutouh (2021) documented any displacement of pollution. On the contrary, both works reported that monitoring stations in the surroundings of *Madrid Central* also measured slightly lower levels of pollution following the implementation of the LEZ, suggesting a change in transportation habits rather than just a change in routes.

In this work, we extend previous analyses on the effect of *Madrid Central* on air pollution during the first year of implementation to years 2020, 2021, and 2022. The intuition is that if air pollution remained low in *Distrito Centro* for a long enough period, that could have created the conditions for an improvement in academic performance among students schooled in that area.

3 Pollution and academic achievement

Numerous studies have extensively documented the detrimental impact of air pollution on academic performance. While the majority of these works have centred on the United States (Duque and Gilraine 2022; Grineski et al. 2020; Marcotte 2017; Persico and Venator 2019; Sanders 2012; Shier et al. 2019), there is evidence of this negative relationship in countries such as the United Kingdom (Roth 2016), Italy (Bernardi and Conte Keivabu 2023), Israel (Ebenstein et al. 2016; Lavy et al. 2014), Iran (Amanzadeh et al. 2020), India (Balakrishnan and Tsaneva 2021), Australia (Claesen et al. 2021), Brazil (Carneiro et al. 2021), or Chile (Bharadwaj et al. 2017).

Air pollution affects students' academic achievement either impacting their capability to learn or affecting their performance on exam days. Firstly, air pollution hampers brain development, impairing cognitive processing, attention, and memory

(Brockmeyer and D'Angiulli 2016; Castagna et al. 2022). Since school-aged children are particularly vulnerable to the adverse effects of polluted air given their higher breathing rate to body size ratio and less developed natural barriers (Brockmeyer and D'Angiulli 2016),[4] one would expect that being schooled in a highly polluted area decreases cognitive functioning during classes and deteriorates learning.

Secondly, exposure to air pollution might lead to or exacerbate health conditions such as asthma, rhinitis, or allergies (Alotaibi et al. 2019; Garcia et al. 2023), resulting in more frequent health-related school absences (Balakrishnan and Tsaneva 2021; Heissel et al. 2022; Persico and Venator 2019). For instance, Conte Keivabu and Rüttenauer (2022) have recently documented a decrease in the number of school absences in low-SES schools following the implementation of London's Congestion Charge Zone. If students are more likely to miss school days in highly polluted areas, that could cause a learning loss consequential to academic achievement (Mohai et al. 2011; Shier et al. 2019).

Thirdly, several studies have reported that high levels of pollution on exam days lower performance over and above past exposure (Carneiro et al. 2021; Ebenstein et al. 2016; Lavy et al. 2014; Marcotte 2017). Being tested on highly polluted days affects concentration, causes fatigue, and is detrimental to cognitive functioning, which might leave an impact on the results of the assessment.[5] Thus, even if students are not regularly exposed to air pollution, being tested in a polluted environment might affect the evaluation of their academic prowess.

Therefore, if the implementation of Madrid's LEZ was successful and students in that area were indeed schooled under lower levels of pollution, their academic performance should have increased compared with the period before *Madrid Central*.

4 The EvAU: a high-stakes assessment for university admission

In Spain, compulsory education starts at age 6 and spans ten years: six of primary education and four of lower secondary education. After completing tenth grade,

[4] Nonetheless, the adverse effects of pollution on cognitive functioning have also been reported among adults (Clifford et al. 2016; Tonne et al. 2014).

[5] This effect of air pollution on performance on exam days would be comparable to the effect observed for chess players' performance (Künn et al. 2023).

students receive the compulsory education credential, enabling them to enrol in one of the two tracks of upper secondary education: the academic track (*Bachillerato*) or the vocational track. While both programs last two years, only the academic track provides access to university education.

To gain entry into university, graduates from the academic track must undergo the *Evaluación para el Acceso a la Universidad* (EvAU),[6] a high-stakes examination aimed at ranking students for university admission similar to the Scholar Aptitude Tests (SATs) in the United States, the A-levels in the United Kingdom, or the Bagrut in Israel.[7] The EvAU consists of several exams on different subjects taken over three consecutive days after completing the academic track of upper secondary education. Typically, students are supposed to take the EvAU in June of the year they turn eighteen. However, due to grade retention over the educational career, a significant proportion of students sit the exams one or two years later.[8]

The assessment is divided into two phases. The general phase consists of four exams[9] graded from 0 to 10: Spanish, Foreign Language, Spanish History, and one specific subject that depends on the modality of the academic track completed.[10] The score in this phase is calculated as the arithmetic mean of the four exams, and students are considered apt if they score at least a 4. Only apt students are ranked for university admission.

In the specific phase, students take up to four additional exams. This phase is not mandatory, but students need these additional points to gain access to the most competitive programs, so the majority of the students also take the specific phase.

The university admittance score is computed as the weighted mean between the scores in the general phase of the EvAU (40%) and the academic track grades (60%).

[6] Also known in some parts of the country as *Evaluación de Bachillerato para el Acceso a la Universidad* (EvAU), *Prueba de Acceso a la Universidad* (PAU), or, popularly, *Selectividad*.

[7] For a thorough description of the EvAU and its evolution over time, see Cobreros, Gortázar, and Moreno (2023).

[8] According to the Ministry of Universities, 70% of the students that took the EvAU in 2022 were 18, 15% were 19 or 20, and the remaining 15% were 21 and over.

[9] In those regions with a co-official language, students take a fifth exam assessing the domain of this language.

[10] The subjects are Mathematics, Mathematics applied to Social Sciences, Latin, or Fundamentals of Art.

Then, the two best scores from the specific phase are weighted by 0.20 and added to that mean.[11] Consequently, the final admittance score ranges from 0 to 14.

However, we investigate the effect of Madrid's LEZ on EvAU scores rather than the university admission score. While the EVAU assessment is standardized at the regional level (i.e., all students in the region of Madrid undergo the same exam), the distinct grading standards of each school hinder the comparison of the university admittance score. Specifically, we analyse the scores in the general phase of the EvAU since, unlike the specific phase, all students participating in the assessment take these exams. For brevity, we refer to them as EvAU scores throughout the remainder of this work.

5 Data

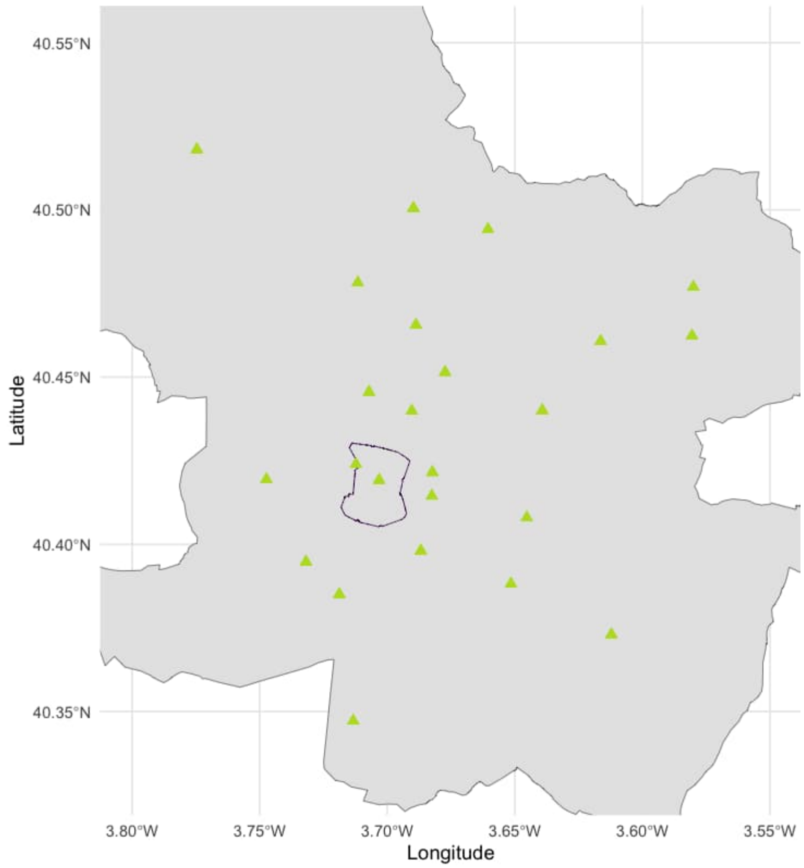
5.1 Pollution data

We leverage air pollution data coming from 24 monitoring stations spread over the city of Madrid (Figure 2). This dataset, sourced from the Open Data repository of the Municipality of Madrid, encompasses daily measurements of various air pollutants such as Benzene, Ozone, Sulphur Dioxide, $PM_{2.5}$, PM_{10}, NO_2 and NO_X. We focus on NO_2, a pollutant closely associated with traffic and commonly employed in similar studies. Furthermore, the dataset provides the most complete data for NO_2, while other pollutants exhibit numerous missing values at certain monitoring stations. The data spans from 2001 and is updated monthly with the latest values. In our analysis, we use daily validated values of NO_2 to compute yearly averages for each monitoring station.

As for the configuration of the treatment and control groups, we follow previous works on the effect of *Madrid Central* (Galdon-Sanchez et al. 2023; Lebrusán and Toutouh 2021; Salas et al. 2021). The single monitoring station within the LEZ area, namely the Plaza de Carmen station, is designated as the treated group. The remaining 23 monitoring stations scattered throughout the city constitute the control group.

[11] The weights oscillate between 0.10 and 0.20 depending on the proximity between the exams undertaken and the university program the student is opting to.

Figure 2. Monitoring stations reading pollution levels in the city of Madrid.



Note: Authors' own elaboration using data of pollution monitoring stations from the Open Data Repository of the Municipality of Madrid. In the figure, we mark the locations of the 24 monitoring stations with triangles, and the Madrid's Low Emission Zone is represented by the purple polygon.

5.2 EvAU data

For the assessment of the effect of Madrid's LEZ on academic performance, we examine the school average scores in the general phase of the EvAU. We retrieve this data from the school search engine publicly accessible on the official website of the *Comunidad de Madrid.* This tool is designed for parents to aid in the choice of their children's school. It offers different types of information, including the average results in the EvAU over the preceding five years (with a one-year lag). Thus, someone consulting the school search engine in 2023 could retrieve the EvAU results for any school in the region of Madrid for the period 2018-2022. We performed this task for all high schools in the city of Madrid that offer the academic track. Subsequently, we merge this data with the publicly available dataset *Panel Data on High Schools in Madrid (2013-2018)* compiled by Espadafor and Martínez (2021). Thus, our analysis covers the period 2015-2022, encompassing four years before (2015-2018) and after (2019-2022) the implementation of *Madrid Central*.

Our initial sample comprised 292 high schools that offered the academic track at some point during the period 2015-2022. However, not all high schools operated through the entire period of analysis. We exclude from the main analysis those schools that stopped operating before the academic year 2021-2022 or started operating after 2014-2015, resulting in an analytical sample of 261 high schools (Table 1). As a robustness check, we rerun the analysis for the extended sample including all high schools.

Table 1. Descriptive information about the sample.

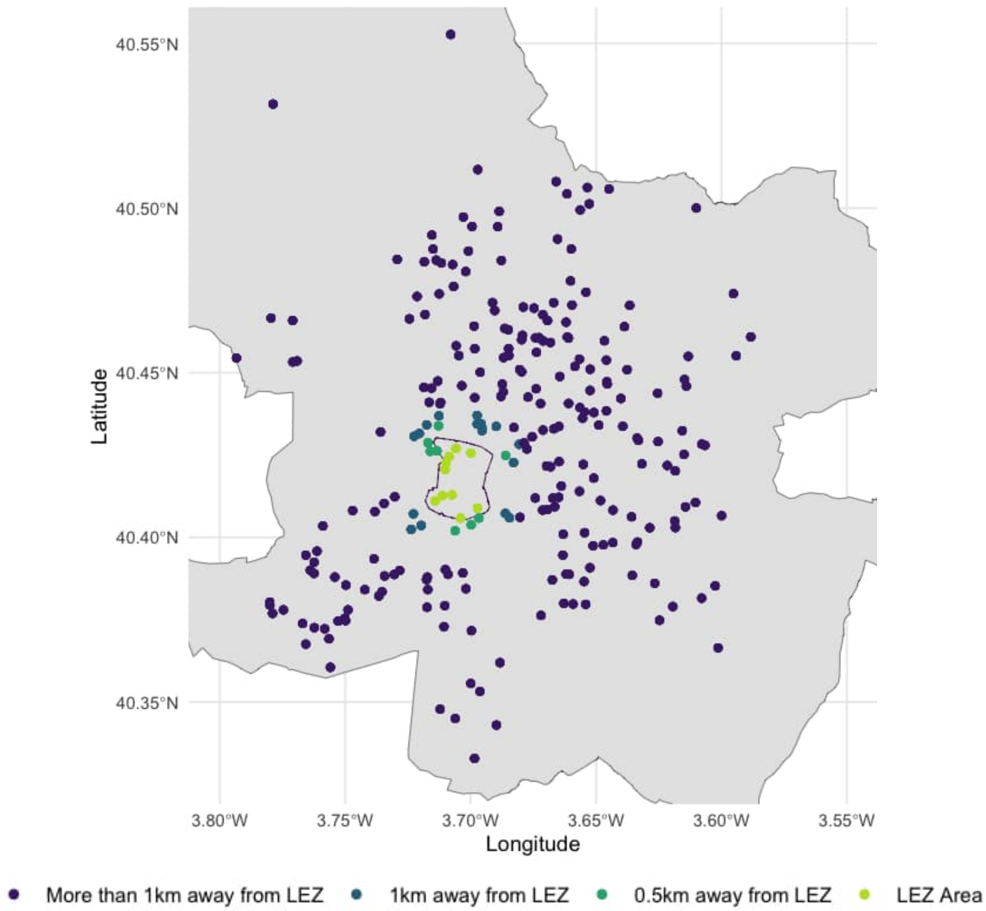
	2015	2016	2017	2018	2019	2020	2021	2022
Initial sample of schools	271	274	281	284	279	281	283	280
Final sample of schools	261	261	261	261	261	261	261	261
Students taking the EvAU	12,597	12,861	12,538	13,374	16,867	18,313	17,197	17,253
Average EvAU score	6.40 (0.67)	6.33 (0.70)	6.33 (0.75)	6.72 (0.54)	6.30 (0.75)	6.59 (0.75)	6.55 (0.76)	6.54 (0.70)

Note: Authors' own elaboration using information of schools offering the academic track in Madrid (2015-2022). The average EvAU score is computed as the weighted mean of school scores using the number of students taking the exam in each school as weights. The standard deviation is reported between parentheses.

Figure 3 illustrates the location of the 261 high schools in our analytical sample. Similar to the map above, the border in purple corresponds to the LEZ. Consequently, the 10 high schools (in green) in that area comprise our treatment group. In our main specification, the control group is formed by the remaining 251 high schools spread throughout the other twenty districts in the city of Madrid (see Table A1 in the Appendix for details). We test for spillover effects by considering high schools 0.5 and 1 km away from the LEZ area.

To ease the interpretation of the results, we standardize the EvAU scores within each year. Thus, the average EvAU score each year is 0 and a value of 1 reflects an EvAU score 1 standard deviation above the mean of that year. We also rerun the analysis for the unstandardized EvAU score as a robustness check.

Figure 3. High schools in the city of Madrid that offered the academic track over the whole period 2015-2022.



Note: Authors' own elaboration. In the figure, we plot the locations of schools on the academic track within Madrid's LEZ. The schools are colour-coded based on their proximity to the Low Emission Zone, which is outlined by a purple polygon.

5.3 Controls

Importantly, we control the results for compositional changes in the population of the different districts of Madrid over the period of analysis. If *Distrito Centro* became more attractive after the implementation of *Madrid Central*, it could have changed the socioeconomic composition of the district, subsequently impacting the average academic performance of the students schooled in that district. To address this concern, we exploit the databank of the city of Madrid to obtain the following three time-varying, district-level variables: the percentage of the population over 25 that attained university education, the percentage of non-native residents, and the number of students attending the academic track (see Tables A2-A4 in the Appendix). All models control for these variables.

6 Method

6.1 Identification strategy

To estimate the effect of Madrid's LEZ on academic performance, we use a Difference-in-Differences (DiD) design. Previous studies have already used this strategy to identify the effect of traffic-restriction policies on academic outcomes (Brehm et al. 2022; Conte Keivabu and Rüttenauer 2022), as well as other similar natural experiments such as closures of industrial sites (Persico and Venator 2019) or coal-fired power plants (Duque and Gilraine 2022). Basically, the DiD model examines the evolution over time of two groups (a treated group and a control group) and compares the difference between them in the pre-treatment and post-treatment years (hence the name, difference in differences). If no other thing happened specifically to the treatment group other than the treatment itself (i.e., all other events affect equally the treatment and control groups), that comparison yields the Average Treatment Effect on the Treated (ATT).

For this logic to hold, however, the parallel trend assumption must be met. It requires that the difference between the treatment and control groups would have remained equal in the post-treatment years had no treatment been implemented. If so, we can attribute any change in that difference to the treatment. Regrettably, we cannot test this assumption directly, but we can provide evidence to make it more plausible. Specifically, if the difference between the treatment and control groups in the pre-treatment years was already constant, it is reasonable to assume that it would have remained constant in the post-treatment years in the absence of the treatment. In other words, the observed trends in both groups before the treatment should be parallel.

We test for parallel trends in Figure 2. In the top panel, we report graphical diagnostics for NO_2 readings. The left-hand graph depicts observed means for the years 2015 to 2022 in the treatment and control groups, showing a relatively constant distance with higher levels of NO_2 in *Distrito Centro*. Notably, within a general decline in pollution readings after the treatment, the reduction seems more pronounced within the LEZ area, which entails suggestive evidence of the efficacy of the LEZ. The right-hand graph reports the results of an augmented linear-trend model,[12] which allows us not only to visually assess whether pre-treatment trends are parallel but also to statistically test whether the slopes of the control and treatment groups in the pre-treatment years are equal. In the graph, pre-treatment trends completely overlap, yielding strong support for the parallel trends assumption. As for the statistical test, we do not reject the null hypothesis of equal trends before the treatment ($F_{(1,23)} = 2.35$; p-value = 0.139).

The bottom panel of Figure 2 reports the same diagnostics for EvAU scores. Observed means follow a similar pattern in the treatment and control groups during the pre-treatment years, although the drop in performance in 2017 is more evident in the treatment group.[13] However, the results from the linear-trend model indicate substantial overlap in pre-treatment trends, and the statistical test fails to reject the null hypothesis of equal trends before the treatment ($F_{(1,20)} = 0.18$; p-value = 0.677).

Consequently, the conditions for the causal interpretation of the DiD estimator for the effect of Madrid's LEZ are met.

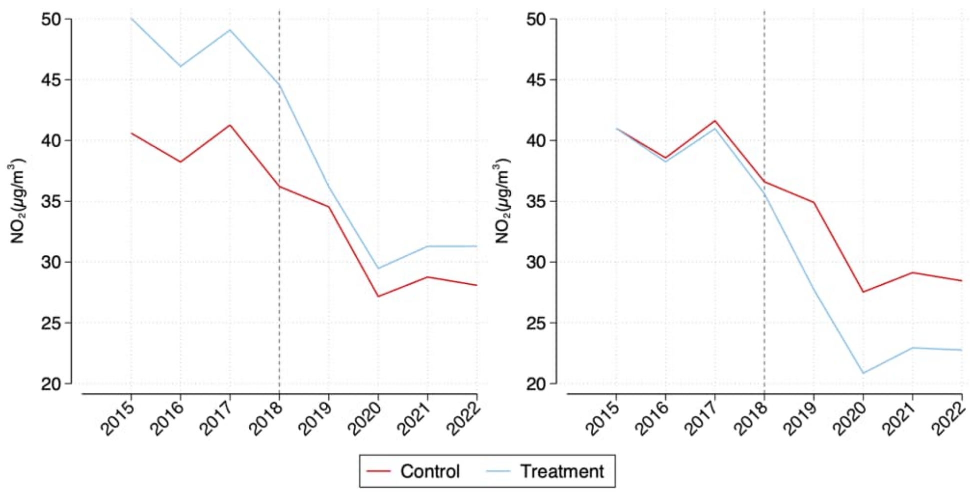
[12] We use the postestimation command *trendplots* for the package *didregress* in *STATA* to produce these results. Basically, the DiD model is augmented considering a binary indicator for pre- and post-treatment years, a binary indicator for treated schools, and the three-way interaction with the time factor. The estimations displayed in Panel B of Figure 2 are the predicted EvAU scores from that augmented model. See the documentation for the *didregress* user-written package for more details.

[13] Year 2017 was a very atypical year as a new regulation for the EvAU was enacted creating notable distortions. This is probably behind the exaggerated drop in the average EvAu scores of the high schools in *Distrito Centro* that year. See Cobreros et al. (2023) for more information.

Figure 2. Graphical diagnostics for parallel trends

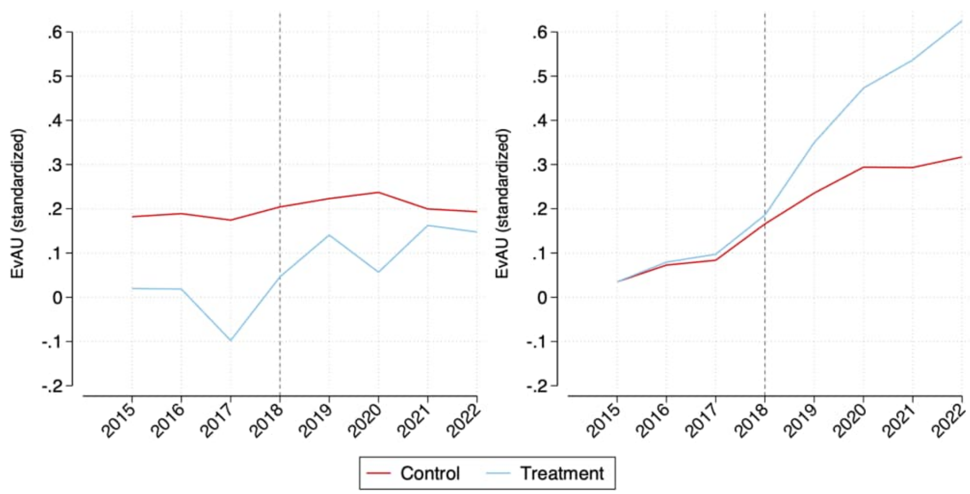
NO_2 readings

(A) Observed means *(B) Linear-trends model*



EvAU scores

(C) Observed means *(D) Linear-trends model*



Note: Authors' own elaboration. In the figure, we show the trends for air pollution within (Treatment) and outside (Control) the Low Emission Zone in Panels A and B. Similarly, we show the EvAU scores in panels C and D.

6.2 The model

To estimate the effect of interest, we employ the following two-way fixed effects (TWFE) model:

$$Y_{it} = \alpha + \gamma_i + \lambda_t + \tau D_{it} + \beta \boldsymbol{Z_{it}} + u_{it} \quad (1)$$

Where i indexes schools and t indexes years, Y_{it} is the dependent variable measuring EvAU scores (or NO_2 readings) over the period 2015-2022, γ_i is the high-school-fixed effect that controls for unobserved heterogeneity across schools, λ_t is the time-fixed effect that controls for unobserved non-variant changes over time, D_{it} is a binary indicator that takes value 1 for schools located in *Distrito Centro* after the implementation of the LEZ and 0 otherwise, and Z is a vector of time-varying, district-level controls. Thus, τ retrieves the ATT, that is, the average effect of the introduction of the LEZ on the academic performance of students schooled in *Distrito Centro* (or pollution readings).

However, the impact of Madrid's LEZ on EvAU scores might be more pronounced the further away from the implementation date. While students taking the EvAU in 2019 enjoyed only one academic year under lower levels of air pollution (twelfth grade), students taking the EvAU in 2022 enjoyed four years of cleaner air (from ninth grade to twelfth grade). Expecting a stronger effect with longer and earlier exposure, we employ a dynamic DiD model where the effect of interest varies across years. Formally:

$$Y_{it} = \alpha + \gamma_i + \lambda_t + \sum_{k=2015}^{2017} \tau_k D_{ik} + \sum_{k=2019}^{2022} \tau_k D_{ik} + \beta \boldsymbol{Z_{it}} + u_{it} \qquad (2)$$

Where D_{ik} is a set of dummies taking value 1 if the school i is in the LEZ area and 0 otherwise in year k. We use the year 2018 as the reference group to compare each of the subsequent post-treatment years (2019-2022) because it is the last year before *Madrid Central* was launched.[14]

Importantly, we weight the analyses by the average number of students taking the EvAU in each school. Since our dependent variable is the school mean, high schools with a lower number of students present more volatile figures due to the significant influence of a few very good or bad students in each cohort. By weighting for the average number of students taking the exam, we give more importance in the estimation of the ATT to schools with less volatile means. Nonetheless, we test the robustness of the conclusions in an unweighted model.

[14] The comparison with the pre-treatment years (2015-2017) serves as a placebo-like test that provides additional evidence to judge the parallel trend assumption.

7 Results

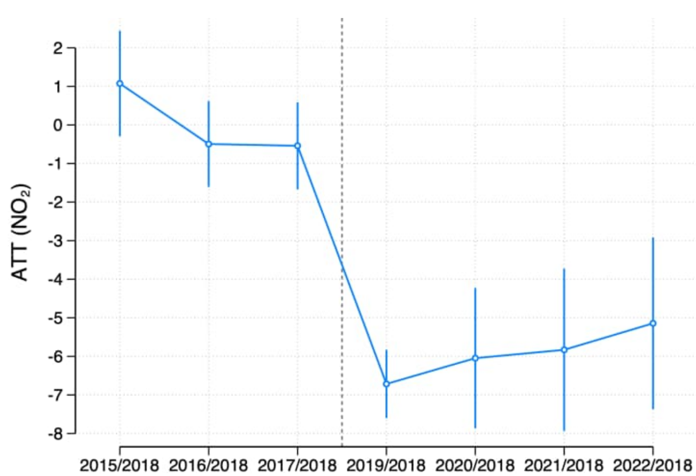
7.1 Madrid's LEZ and air pollution

In a first step, we assess the effectiveness of Madrid's LEZ in reducing air pollution levels. Since air pollution is not our main outcome of interest, however, we directly report in Figure 3 the results of the dynamic DiD model, where pollution readings in post-treatment years are compared with 2018, the last pre-treatment year.

As reported in previous works, there was a significant drop in NO_2 levels one year into *Madrid Central*. NO_2 readings in the LEZ area fell by 6.7 μg/m^3 (p-value = 0.000) more than we would have observed had no treatment been implemented. This is a remarkable effect, accounting for 80% of the difference in pollution readings between the treatment and control groups in the pre-treatment years. The results for the years 2020, 2021, and 2022 also reveal a statistically and economically significant decrease in NO_2 readings compared with 2018. Nonetheless, the effect slightly dilutes over time: by 2022, the ATT diminishes to -5.1 μg/m^3 (p-value = 0.000). Crucially, this decreasing pattern is not the result of worse air quality within the LEZ but the consequence of an improvement in the rest of the city.

Overall, Madrid's LEZ was effective in reducing traffic-related emissions and substantially improved air quality in the designated area during the following four years.

Figure 3. Dynamic difference-in-differences model for the effect of Madrid's LEZ on NO_2 levels.



Note: Authors' own elaboration. The figure presents the results of the dynamic DiD model based on Equation 2 with NO_2 as the outcome. The figure shows the ATT for each year compared with 2018 and reports 95% confidence intervals.

7.2 Madrid's LEZ and academic performance

Now, we assess the impact of Madrid's LEZ on the academic results of students schooled in *Distrito Centro*. In our main specification (first column of Table 2), we report the results of a TWFE model for the standardized EvAU scores, using as weights the average number of students taking the EvAU. We find a positive effect of Madrid's LEZ on the average EvAU scores of schools located in *Distrito Centro*. As of 2019, performance at EvAU increased by 17% of a standard deviation (σ) compared with the schools in the other twenty districts of the city of Madrid (p-value = 0.025).

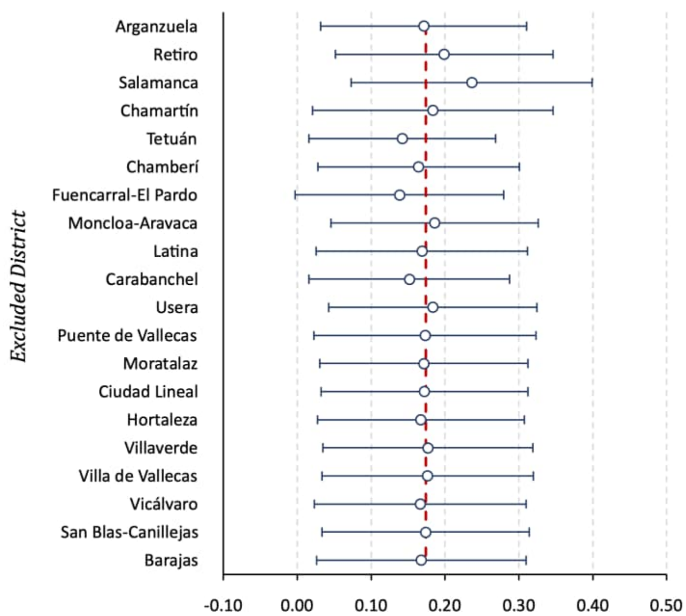
To test the robustness of this finding, we run three additional specifications. First, we include in the analytical sample those schools that did not operate during the whole period of analysis (second column of Table 2). The estimated effect of Madrid's LEZ remains unchanged (ATT = 0.171; p-value = 0.033). Second, we rerun the analysis for the unstandardized EvAU scores, which provides the ATT in the original scale of the EvAU (third column). The LEZ increased the academic performance of students schooled in that area by one-seventh of a point (ATT = 0.147; p-value = 0.030). If we also drop the weights for the average number of students taking the EvAU in each school (fourth column), the effect slightly increases (ATT = 0.160; p-value = 0.012).

Additionally, we examine whether our findings were affected by the COVID-19 pandemic (fifth column), which highly reduced traffic and pollution levels due to the three-month full lockdown in 2020 and greatly conditioned the EvAU assessment that year.[15] If some areas in the city benefited more than others from that reduction in pollution levels or the more accessible EvAU examination, that could affect our identification strategy. Excluding the year 2020, the identified effect of Madrid's LEZ on academic performance is even larger and remains highly statistically significant (ATT = 0.236; p-value = 0.001).

[15] Ancillary analyses revealed a significant rise in the number of students taking the EvAU in 2020, primarily attributed to schools adopting a more lenient approach to ensure students' progression on the academic track despite the difficulties caused by school closures. Conversely, this number saw a substantial correction in 2021, likely a result of retaining students who had advanced to the second grade in 2020 under the lower standards implemented during that year.

Finally, another possible source of bias could arise from the composition of our control group, which includes all districts of Madrid other than *Distrito Centro*. The results could be mainly driven by one district that, for some reason, followed a highly diverging pattern. To test for it, we rerun our main specification excluding one district at a time. As can be observed in Figure 4, there is not much variation in the estimations. All of them are close to the value of 0.17 reported in the first column of Table 2, and all remain highly statistically significant. The most diverging estimate is found excluding *Distrito Salamanca*, one of the richest districts in the city. After dropping schools from that district, the ATT rises to 0.24σ (p-value = 0.011). Nonetheless, we conclude that no district in the control group is heavily driving our main conclusions.

Figure 4. Effect of Madrid's LEZ on EvAU scores excluding one untreated district at a time.



Note: Authors' own elaboration. In the figure, we report the coefficients of the analysis when excluding each of the districts listed in the y-axis. The dashed line represents the coefficient found in the main analysis reported in the first column of Table 2.

Table 2. DiD estimates for the effect of Madrid's LEZ on academic performance

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Model 1	Model 2a	Model 2b	Model 2c	Model 2d	Model 3a	Model 3b
ATT	0.174 (0.072)**	0.171 (0.075)**	0.147 (0.063)**	0.160 (0.058)**	0.236 (0.077)***	0.063 (0.037)*	-0.004 (0.035)
Year-fixed effects	X	X	X	X	X	X	X
School-fixed effects	X	X	X	X	X	X	X
Weighted by number of students taking EvAU	X	X	X		X	X	X
EvAU scores standardized within year	X	X			X	X	X
Only schools with data for the whole period	X		X	X		X	X
Excluding year 2020					X		
Treatment group: 0.5 km away from the LEZ						X	
Treatment group: 1 km away from the LEZ							X

Note: Authors' own elaboration. For all models: *** p-value ≤ 0.01, **p-value ≤ 0.05, *p-value ≤ 0.10. Standard Errors are clustered at the district level and reported between parentheses.

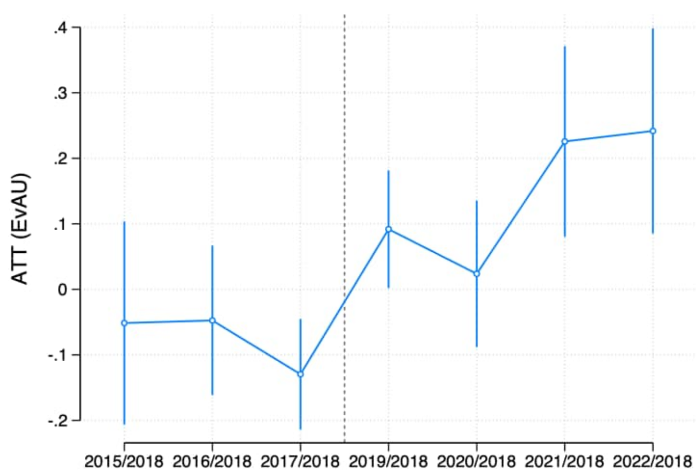
7.2.1 Spillover effects

We test for spillover effects in two additional specifications where we compare schools 0.5 km and 1 km away from the LEZ with the rest of the city (excluding schools within the LEZ area). The results are reported in the sixth and seventh columns of Table 2, respectively. The introduction of the LEZ had a positive impact on the average EVAU scores of schools 0.5km away from the LEZ area (ATT = 0.063; p-value = 0.099), although the effect is smaller than the one identified for schools within the LEZ area (around 40%). In turn, if we extend the buffer zone to 1km away from the LEZ area, the ATT is virtually zero. Put simply, the further away from the borders of Madrid's LEZ, the lower the effect of the LEZ on academic performance, although schools sufficiently close to the designated area still benefited from it.

7.2.2 Dynamic treatment effects

Finally, we test whether the effect of Madrid's LEZ on academic performance increased over time. To assess this, we fit a dynamic DiD model and report the results in Figure 5. Compared with the last pre-treatment year, it seems clear that the effect is larger the further away from the introduction of the LEZ: while it was one-tenth of a standard deviation in 2019, it escalated to almost one-fourth of a standard deviation in 2022. Figure 5 also reports that consistently with our previous results, the ATT is virtually zero for 2020 and then bounced back in 2021 and 2022.

Figure 5. Results from the Dynamic DiD for EvAU scores



Note: Authors' own elaboration. The figure presents the results of the dynamic difference-in-differences model based on Equation 2 with EvAU as the outcome. The figure shows the ATT for each year compared with 2018 and reports 95% confidence intervals.

8 Discussion and Conclusions

Local governments have increasingly adopted low emission zones in the centre of densely populated cities as a strategy to reduce air pollution and align with international air quality guidelines. This study delves into the impact of the implementation in late 2018 of Madrid's LEZ, which banned non-resident vehicles (except hybrid and electric cars) from crossing the *Distrito Centro* unless it was their final destination. Our findings outline four key aspects. Firstly, the LEZ wielded a significant positive effect on air quality during the four years following its implementation. Secondly, it had positive externalities on the academic performance of students schooled within the designated area. Thirdly, there were positive spillover effects for schools located within a 0.5km radius of the LEZ's borders. Lastly, the effect consistently increased over time, implying that prolonged exposure to better air quality yielded cumulative benefits.

Regarding air pollution, previous research had already documented an improvement in air quality within the first year of Madrid's LEZ (Galdon-Sanchez et al. 2023; Lebrusán and Toutouh 2021; Salas et al. 2021). In this work, we demonstrate that Madrid's LEZ effectively and significantly reduced pollution levels in *Distrito Centro* over the four years following its implementation. The improvement in air quality nearly closed the gap between *Distrito Centro* and the rest of the city that existed before the launch of the LEZ.

We argued that this sustained enhancement in air quality within the LEZ created the conditions for an improvement in academic performance for students schooled in that area. However, we are cautious in suggesting that the only (or even the main) mechanism behind the effect of Madrid's LEZ on academic performance is the decrease in air pollution. Indeed, polluted air is detrimental to academic achievement, so cleaner air should be associated with better educational outcomes (Amanzadeh et al. 2020; Balakrishnan and Tsaneva 2021; Duque and Gilraine 2022; Grineski et al. 2020; Heissel et al. 2022; Shier et al. 2019). However, the reduction in traffic might have other positive effects. For instance, traffic-related noise adversely impacts cognitive development (Foraster et al. 2022) and, therefore, could be a factor explaining our results. Similarly, improvements in commuting time resulting from the LEZ (Santos and Bhakar 2006) could have a beneficial effect on students' attendance and test scores (Kaushik et al. 2023; Stein and Grigg 2019). Therefore, by documenting the sustained decrease in pollution following the introduction of Madrid's LEZ, we only show that the conditions for an improvement in academic performance were created, but remain agnostic about the precise mechanisms linking the low emission zone and educational outcomes.

Our results show that following the implementation of Madrid's LEZ, students schooled in *Distrito Centro* improved their performance in the general phase of the EvAU by 17% of a standard deviation. This result is highly consistent with the only other paper examining the effect of the implementation of a low emission zone on academic performance (Brehm et al. 2022), which documented a positive impact on the probability of being allocated into the academic track of lower secondary education in Germany. Furthermore, our findings also align with research on the detrimental effect of air pollution on academic performance, where a one-standard-deviation increase in pollution is generally linked to a decrease in performance of 0.05 to 0.10 standard deviations (Amanzadeh et al. 2020; Bernardi and Conte Keivabu 2023; Carneiro et al. 2021; Ebenstein et al. 2016; Grineski et al. 2020; Marcotte 2017; Roth 2016; Shier et al. 2019).

Considering the EvAU's original scale, the LEZ yielded a notable 0.14-point gain, immensely significant to access the most competitive university programs. To illustrate the relevance of the effect, Table A5 in the Appendix shows the 2023 waiting list[16] for medicine studies at the *Universidad Complutense de Madrid* (UCM), one of the most competitive degrees in the country. A total of 37 students who did not choose Medicine at UCM as their first option were later selected from the waiting list. They are, therefore, the last 37 students who entered Medicine at UCM in 2023. Note that the range of variation in the admittance scores of the whole list is smaller than the 0.14-point improvement attributed to the low emission zone. In other terms, the implementation of Madrid's LEZ greatly enhanced the opportunities not

[16] Applicants for university admission in Spain list several options (Degree + University) ordered according to their preferences. If their admission score is not high enough to secure their first option, they are placed on the waiting list for the second option. Again, if their admission score is not high enough, they enter in a waiting list for their third option, and so on. Due to the absence of publicly available lists in Spain that disclose admission scores for both accepted and non-accepted candidates, we present this waiting list as an indicator of how closely matched the competition is for entry into certain degree programs.

only for gaining access to university education but also for enrolling in the specific program and institution preferred by the student.

Additionally, we report positive spillover effects on schools 0.5km away from the borders of Madrid's LEZ, which marginally increased their average performance at EvAU after the implementation of the low emission zone. This finding is consistent with previous works that documented a reduction in pollution levels in the surrounding of *Madrid Central* (Lebrusán and Toutouh 2021; Salas et al. 2021). Furthermore, the results are in line with the fact that, according to the 2018 Household Mobility Survey conducted by the *Consorcio de Movilidad de Madrid*, the average commuting distance from home to school for students under 18 in the city of Madrid is 503.7 metres. Since we work with the location of the school and not the residence of the student, this positive spillover effect likely captures the impact of the enhancement in air quality among students that live within the LEZ area but are schooled 0.5km away from it.

Finally, we reasoned that the observed effect of Madrid's LEZ on academic performance should increase as we move away from the implementation date. Students taking the EvAU later not only enjoyed the positive effects of Madrid's LEZ for more years (length of exposure) but also from younger ages (timing of exposure), where the effect of air pollution tends to be larger (Balakrishnan and Tsaneva 2021; Persico and Venator 2019). The results of the dynamic DiD model confirm our expectations: while the effect was one-tenth of a standard deviation for students taking the EvAU in 2019, it rose to one-fourth among those sitting the exam in 2022.

In sum, our results reveal a positive and robust effect of Madrid's LEZ on the academic performance of students schooled in that area highly consequential for their educational future. However, our work is not without limitations. Most importantly, we do not have individual-level data, so we cannot assess whether the effect differs by gender or socioeconomic background as documented in previous works (Bernardi and Conte Keivabu 2023; Carneiro et al. 2021; Ebenstein et al. 2016; Lavy et al. 2014; Roth 2016). Similarly, due to lack of data on the location of the children's residence, we are not able to test if the policy was more beneficial for students not only schooled within the LEZ, but also living in that area. Furthermore, we observe the impact of the policy on an aggregate measure of academic performance, so we cannot explore whether the effect is more salient for math scores as reported in other studies about air pollution (Amanzadeh et al. 2020; Bernardi and Conte Keivabu 2023; Duque and Gilraine 2022). Despite those limitations, however, our study offers valuable insights into the positive externalities resulting from the implementation of a low emission zone successful in improving air quality. These benefits might not be solely confined to academic performance but could also extend to other outcomes such as workplace productivity, car accident rates, and overall well-being.

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10 Appendix

Table A1. Number of schools in the final sample by district

District	Number of schools
Centro	10
Arganzuela	4
Retiro	10
Salamanca	15
Chamartín	25
Tetuán	7
Chamberí	16
Fuencarral-El Pardo	22
Moncloa-Aravaca	13
Latina	19
Carabanchel	18
Usera	9
Puente de Vallecas	16
Moratalaz	8
Ciudad Lineal	22
Hortaleza	16
Villaverde	7
Villa de Vallecas	5
Vicálvaro	5
San Blas-Canillejas	11
Barajas	3
Total	261

Table A2. Number of students enrolled in *Bachillerato*, by year and district.

District	2015	2016	2017	2018	2019	2020	2021	2022
Centro	4,211	4,190	3,954	3,686	3,596	3,548	3,136	3,069
Arganzuela	1,097	1,115	1,049	1,001	1,039	1,125	1,158	1,125
Retiro	2,736	2,701	2,664	2,583	2,678	2,627	2,568	2,433
Salamanca	2,806	2,796	2,689	2,584	2,555	2,666	2,568	2,435
Chamartín	5,618	5,370	5,344	5,291	5,196	5,486	5,390	5,192
Tetuán	1,670	1,700	1,593	1,460	1,364	1,272	1,218	1,060
Chamberí	2,120	2,149	2,161	2,258	2,338	2,300	2,366	2,271
Fuencarral-El Pardo	3,288	3,519	3,588	3,673	3,656	3,897	4,005	3,993
Moncloa-Aravaca	2,322	2,338	2,418	2,504	2,522	2,599	2,678	2,478
Latina	2,621	2,641	2,758	2,736	2,672	2,682	2,802	2,725
Carabanchel	3,112	3,189	3,015	2,905	2,807	2,885	2,810	2,784
Usera	1,587	1,614	1,589	1,529	1,502	1,503	1,526	1,454
Puente de Vallecas	3,370	3,415	3,161	3,067	2,961	2,975	2,998	2,935
Moratalaz	1,605	1,616	1,608	1,514	1,452	1,403	1,366	1,300
Ciudad Lineal	2,925	2,930	2,935	3,041	3,031	3,096	3,009	2,969
Hortaleza	2,647	2,581	2,756	2,884	2,960	3,297	3,404	3,391
Villaverde	1,101	1,153	1,152	1,200	1,247	1,302	1,290	1,287
Villa de Vallecas	619	632	677	618	583	737	805	858
Vicálvaro	715	740	747	748	751	769	850	909
San Blas-Canillejas	1,704	1,747	1,770	1,863	1,925	2,033	2,025	2,018
Barajas	577	598	599	597	596	576	600	563

Source: Madrid Databank https://www-s.madrid.es/CSEBD_WBINTER/arbol.html

Table A3. Percentage of the population over 25 that attained university education, by year and district.

District	2015	2016	2017	2018	2019	2020	2021	2022
Centro	42.5	44.2	45.5	46.7	48.4	50.0	50.6	51.5
Arganzuela	41.9	43.1	44.4	45.7	47.0	48.3	49.2	50.1
Retiro	49.6	50.7	51.7	52.9	54.1	55.2	55.9	56.9
Salamanca	52.4	53.6	54.9	56.3	57.5	58.7	59.5	60.4
Chamartín	53.7	54.9	56.0	57.5	58.6	59.6	60.3	61.2
Tetuán	33.3	34.3	35.3	36.6	37.9	39.2	39.7	40.5
Chamberí	52.7	54.2	55.5	56.9	58.1	59.4	60.0	61.1
Fuencarral-El Pardo	41.6	42.5	43.4	44.4	45.4	46.3	47.0	47.7
Moncloa-Aravaca	48.2	49.1	50.1	51.3	52.3	53.1	53.8	54.8
Latina	20.2	20.7	21.2	21.7	22.5	23.3	23.7	24.3
Carabanchel	17.5	18.0	18.4	19.1	19.7	20.5	20.8	21.3
Usera	12.7	13.0	13.2	13.6	14.3	15.0	15.4	16.0
Puente de Vallecas	11.3	11.7	12.0	12.6	13.4	14.0	14.3	14.6
Moratalaz	25.6	26.1	26.7	27.4	28.3	29.1	29.5	30.2
Ciudad Lineal	30.1	30.6	31.3	32.1	33.2	34.3	34.8	35.5
Hortaleza	36.7	37.8	38.9	40.1	41.4	42.6	43.5	44.6
Villaverde	12.5	12.7	13.1	13.3	13.8	14.4	14.9	15.4
Villa de Vallecas	22.4	22.8	23.3	23.7	24.3	25.2	25.8	26.2
Vicálvaro	21.5	21.9	22.1	22.7	23.4	24.0	24.8	26.4
San Blas-Canillejas	23.7	24.3	24.9	25.6	26.5	27.2	27.7	28.4
Barajas	38.6	39.5	40.1	40.7	41.6	42.3	43.0	43.0

Source: Madrid Databank https://www-s.madrid.es/CSEBD_WBINTER/arbol.html

Table A4. Percentage of the population that was born abroad, by year and district.

District	2015	2016	2017	2018	2019	2020	2021	2022
Centro	29.9	29.9	30.2	30.8	31.6	33.1	35.0	36.3
Arganzuela	16.2	16.2	16.0	16.2	16.5	17.2	17.5	17.6
Retiro	11.8	11.9	12.0	12.4	13.1	14.0	14.4	14.9
Salamanca	18.1	18.6	19.0	19.8	20.7	22.1	22.9	23.8
Chamartín	15.2	15.4	15.4	15.7	16.2	16.9	17.2	17.4
Tetuán	26.5	27.2	27.6	28.5	29.5	30.8	31.4	31.6
Chamberí	17.5	17.4	17.3	17.6	18.2	19.1	19.7	20.2
Fuencarral-El Pardo	12.4	12.6	12.9	13.6	14.3	15.1	15.3	15.4
Moncloa-Aravaca	15.8	16.0	15.9	16.1	16.8	17.7	18.2	18.2
Latina	20.8	21.3	21.7	23.0	24.3	26.0	26.9	27.1
Carabanchel	24.9	25.6	26.6	28.1	29.9	32.0	32.8	33.1
Usera	26.6	27.7	28.8	30.5	32.3	34.3	35.1	35.1
Puente de Vallecas	22.2	23.0	23.9	25.4	27.3	29.6	30.6	30.9
Moratalaz	13.6	14.1	14.6	15.2	16.4	17.8	18.2	18.6
Ciudad Lineal	21.2	21.8	22.4	23.5	24.7	26.0	26.5	26.9
Hortaleza	14.4	14.7	15.0	15.6	16.5	17.5	17.9	18.4
Villaverde	25.4	26.0	26.7	28.4	30.1	32.3	33.2	33.6
Villa de Vallecas	16.1	16.1	16.4	17.2	18.5	20.1	20.8	21.5
Vicálvaro	16.4	16.5	16.5	17.1	18.0	19.1	19.6	20.1
San Blas-Canillejas	16.4	16.8	17.4	18.6	20.1	22.0	22.7	23.1
Barajas	14.5	14.5	14.6	15.0	15.6	16.4	16.7	16.9

Source: Madrid Databank https://www-s.madrid.es/CSEBD_WBINTER/arbol.html

Table A5. Students selected from the waiting list for the degree in Medicine at *Universidad Complutense de Madrid* for the academic year 2023/2024.

Student	Admittance score
1	13.315
2	13.309
3	13.309
4	13.309
5	13.302
6	13.301
7	13.300
8	13.300
9	13.296
10	13.295
11	13.294
12	13.290
13	13.290
14	13.289
15	13.289
16	13.286
17	13.284
18	13.280
19	13.279
20	13.278
21	13.277
22	13.275
23	13.275
24	13.275
25	13.275
26	13.273
27	13.271
28	13.271
29	13.268
30	13.267
31	13.266
32	13.264
33	13.262
34	13.260
35	13.257
36	13.257
37	13.257

Source: *Universidad Complutense de Madrid* public waiting lists.