From Low Emission Zone to Academic Track: Environmental Policy Effects on Educational Achievement in Elementary School[*]

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Abstract

Low Emission Zones (LEZs) reduce local air pollution by restricting emission-intensive vehicles from accessing designated areas and have been shown to improve population health. Little is known about the effects of driving restriction policies on other areas of life. This paper studies the effects of LEZs on the educational achievements of elementary school students in Germany, measured by secondary-school transition rates. Using school-level data from North-Rhine Westphalia (NRW), Germany's most populous federal state, we exploit the staggered adoption of LEZs since 2008 in a difference-in-differences framework. Our results imply that LEZs increased rates of transition to the academic track by 0.9-1.6 percentage points in NRW. Our findings on the district level for all of Germany confirm the external validity of these findings. Using geo-referenced data from the German Socio-Economic Panel, we provide suggestive evidence that a reduction in the prevalence of respiratory infections is a vital channel through which LEZs affect schooling outcomes.

Keywords: Low Emission Zone, Education, Air Quality, Germany
JEL Codes: I21; J24; Q52; Q53; Q58

[*]We thank Lukas Hörnig for his excellent support and Henri Gruhl and Ronald Bachmann as well as participants of the RWI Brown Bag, DIW internal seminar, and BeNA summer workshop for their comments. The authors gratefully acknowledge the financial support of the German Environmental Agency (UBA) under research reference number 19121040.

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To Do: Robustness checks: - Buffer picture and results - Results excluding any schools which offer Abitur from Gesamt N

1 Introduction

Traffic remains a major source of air pollution in many industrialized countries. Driving restrictions are one way to target air quality in urban areas that several countries have explored. While such measures were often deemed unpopular and ineffective,[1] Germany, along with other European countries, started introducing Low Emission Zones (LEZs) in 2008, restricting vehicle access to designated inner-city areas based on emission intensity thresholds. This policy has indeed proved effective in lowering air pollution in the treated areas (e.g., Wolff, 2014; Sarmiento *et al.*, 2021) and, in doing so, has been shown to improve health outcomes (Klauber *et al.*, 2021; Margaryan, 2021; Pestel and Wozny, 2021). At the same time, LEZs were found to have short-term adverse effects on self-rated life satisfaction (Sarmiento *et al.*, 2021). To comprehensively evaluate the costs and benefits of LEZs, it is essential to consider the policy's externalities on the full spectrum of socio-economic outcomes. To date, to the best of our knowledge, no study has evaluated the effectiveness of specific driving restriction policies, like LEZs, on children's educational outcomes.

Children are particularly susceptible to the adverse health effects of air pollution, ranging from respiratory diseases to infant mortality (e.g., Chay and Greenstone, 2003; Jayachandran, 2009; Luechinger, 2014; Knittel *et al.*, 2016; Coneus and Spiess, 2012). Recent economic literature has shown that poor air quality may also harm the human brain (Aguilar-Gomez *et al.*, 2022), affecting individuals' cognitive performance (Archsmith *et al.*, 2018; Künn *et al.*, forthcoming) and leading to behavioral problems (Mortamais *et al.*, 2019). Given these findings, it is not surprising that air quality can also affect children's test scores (Stafford, 2015; Lavy *et al.*, 2014; Ebenstein *et al.*, 2016; Roth, 2016; Marcotte, 2017; Persico and Venator, 2021; Cho, 2022; Requia *et al.*, 2022) and school absence rates (Currie *et al.*, 2009; Chen *et al.*, 2018). Substantially less is known about the longer-term schooling effects of policies targeting air quality.

This paper studies the causal effect of the implementation of LEZs on the educational achievement of elementary school students in Germany. We focus on the transition rates of children in 4$^{\text{th}}$ grade, the last year of primary education, to a *Gymnasium*, the academic track of the secondary school system. The German school system is characterized by the early tracking (usually at age 10) of students to different secondary school tracks. This practice has been shown to determine a child's educational and professional trajectory in

[1] Davis (2008), evaluating Mexico City's *Hoy no circula* (HNC) policy, points to HNC as being high-cost and largely ineffective, primarily since it incentivized car owners to buy another car to circumvent the restriction with a second license plate.

essential ways: once assigned to a track, upward mobility is rare (Mühlenweg, 2008; **?**; Müller and Schneider, 2013; Dustmann *et al.*, 2017; Matthewes, 2021). Being assigned to the academic track (*Gymnasium*) is highly correlated with enrolling in university education and higher earnings later in life (e.g., Dustmann, 2004). Hence, transition rates to the academic track are an exceptionally well-suited indicator for educational achievement in Germany.

We combine several data sources to comprehensively assess the link between LEZs and school track assignments. Our main analysis relies on geo-referenced administrative school-level data from North Rhine-Westphalia (NRW), Germany's most populous federal state. Knowing the exact location of elementary schools allows us to distinguish whether they lie within or outside a LEZ, and to take school heterogeneity (regarding student and neighbourhood characteristics) into account. We complement this school-specific analysis with district-level data from all of Germany to test the external validity of our results. In addition, we shed light on the underlying channels through which LEZs affect schooling outcomes using geo-referenced data from the German Socio-Economic Panel (SOEP), which allows us to distinguish between children living within or outside a LEZ.

To account for the staggered implementation of LEZs (e.g., Goodman-Bacon, 2021), we opt for two novel approaches to estimate the causal effects of LEZs on track choice besides the standard two-way fixed effects (TWFE) estimation. The first one is the stacked-by event approach (Cengiz *et al.*, 2019; Deshpande and Li, 2019; Baker *et al.*, 2022) and the second one is the two-way fixed effects with heterogeneous treatment effects estimator developed by de Chaisemartin and D'Haultfœuille (2020a). The main advantage of these estimators is that they bypass the vulnerability of two-way fixed effects difference-in-differences to potential heterogeneous time effects of the policy (de Chaisemartin and D'Haultfœuille, 2020a; Goodman-Bacon, 2021). This is important in our setting as the effects between the first and last introduction of LEZ may have changed, e.g., due to the changes in the vehicle fleet.

Our results based on school-level data from the state of NRW imply that the implementation of LEZs increased rates of transition to the academic track by 0.9-1.6 percentage points. Effects take some time to materialize, which is in line with the underlying channels, as the adverse effects of air pollution accumulate over time. Our analysis using the district-level data for all of Germany suggests that the effect is not merely a state-specific phenomenon. In addition, our heterogeneity analysis indicates that boys drive the results. Finally, we find suggestive evidence that a reduction in the prevalence of respiratory infections in the respective age group is a likely channel through which LEZs affect schooling outcomes. This finding is in line with Klauber *et al.* (2021), who find that LEZs lead to a reduction of asthma drug prescriptions for children. The more substantial schooling effect found for boys substantiates this premise since asthma is more prevalent in boys during childhood (e.g., Bjornson and Mitchell, 2000; Postma, 2007). Another potential channel could be a reduction in ADHD, which is also more prevalent in boys (Schlack *et al.*, 2007).

Our study makes several contributions. First, our findings add to our knowledge of the efficacy of LEZs in improving health and socio-economic outcomes. Pestel and Wozny (2021) show that the introduction of LEZs in Germany reduced the number of hospitalizations due to circulatory and respiratory conditions. Margaryan (2021) further suggests that LEZs effectively lower the number of patients with cardiovascular disease by 2–3 percent, with a particularly pronounced effect on elderly patients (7–12.6 percent). Wolff (2014) provides evidence that the health benefits of the policy imply lower health expenditures. Klauber *et al.* (2021) find that newborns exposed to cleaner air needed less medication for respiratory diseases. Gehrsitz (2017) finds minor effects on the number of stillbirths but no impact on infant health. In contrast, looking at self-rated life satisfaction, Sarmiento *et al.* (2021) discover that LEZs can temporarily have adverse effects on the well-being of residents. We extend this literature by focusing on the schooling effects of LEZs.

Second, our analysis contributes to our understanding of how exposure to air pollution affects educational attainment. Thus far, several studies have focused on the immediate (Lavy *et al.*, 2014; Marcotte, 2017; Heissel *et al.*, 2022) and longer-term (Ebenstein *et al.*, 2016) effects of acute short-term variations in pollution exposure. In addition, some authors have examined how exposure to lower air quality during gestation and early life affects human capital formation later in life (Almond *et al.*, 2009; Sanders, 2012; Black *et al.*, 2019; Bharadwaj *et al.*, 2017; Isen *et al.*, 2017; Marcotte, 2017; Persico and Venator, 2021). In contrast, little is known about how continuous exposure to different air quality levels affects educational success in the medium and long run. To our knowledge, Heissel *et al.* (2022) is the only study assessing the long-term effects of medium-term exposure to pollution on student outcomes in middle and high school by exploiting variation in wind patterns for schools within the same distance from major highways in Florida. Finding significant adverse effects of visiting a "downwind" high school on test scores, behavioral instances, and school absences, this study is thus far the only one shedding light on the channels through which pollution affects educational attainment. We add to these findings by focusing on the younger age group of elementary school children and providing both school-level estimates for a specific region and district-level estimates for all of Germany.

Third, our study contributes to the research on the factors determining school tracking choices. Early tracking systems like the one in Germany are generally associated with higher educational inequalities (e.g., Waldinger, 2007). Hence, it is necessary to understand the determinants of tracking decisions and the channels through which they lead to unequal outcomes. Besides the students' ability, various socio-economic factors have been shown to influence the probability of transitioning to the academic track.[2] On the other hand, school factors such as class size (Argaw and Puhani, 2018) and gender of the teacher (Puhani, 2018) do not seem to play a critical role. The link between school tracking and environmental factors has barely been explored in the empirical literature. This paper is the first to study how exposure to different air quality levels affects school tracking decisions.

These contributions feed into broader discussions on the well-being and (non-)cognitive development of school-age children and the role of environmental factors therein. While the adverse long-term effects of health shocks for preschool children (e.g., Almond *et al.*, 2009) are well-researched, less is known about the school-age years (Heissel *et al.*, 2022). The elementary school years are a critical period for determining later educational success (e.g., Dustmann, 2004), as well as for forming motivations and beliefs (e.g., Kosse *et al.*, 2020). In addition, health shocks during childhood have lasting adverse consequences for later-life health and labour market outcomes (e.g., Schiman *et al.*, 2017). Hence, the students in the focus of our study are in a decisive and malleable period of their (non-)cognitive development and are likely sensitive to environmental factors such as air pollution.

The paper proceeds as follows. In Section 2, we provide information on the implementation of LEZs and the education system in Germany. Section 3 provides an overview of the data and descriptive statistics. Section 4 explains the empirical strategy we use to analyze the implementation of LEZs on student attainment. In Section 5, we present the main results, test their robustness, and investigate heterogeneous treatment effects. Section 6 concludes the paper.

[2]For example, boys and younger students have lower chances of entering the highest track (Hendrik and Kerstin, 2011; Mühlenweg and Puhani, 2010). The same is true for children of immigrant ancestry (Hendrik and Kerstin, 2011), even after controlling for the grade point average (Kristen and Dollmann, 2010). While socioeconomic background (Dustmann, 2004) and risk preferences (Wölfel and Heineck, 2012) of parents influence the decision for the highest track, there is no causal effect of parental income (Tamm, 2008) and their employment status (Schildberg-Hoerisch, 2011).

2 Background

2.1 Low Emission Zones in Germany

As more evidence on the health risks of air pollution was brought forward in the early 2000s, the European Commission responded with the Clean Air Directive as an unprecedented attempt to mitigate air pollution caused by fine particles, coarse particle matters (PM_{10}), nitrogen dioxide (NO_2) as well as several other air pollutants. In Germany, cities failing to comply with EU air quality standards must develop "Clean Air Plans" (*Luftreinhaltepläne*). Between 2005 and 2007, this was the case for 65 percent of all large German cities (Sarmiento *et al.*, 2021).[3]

While the Clean Air Plans can consist of various measures, the most drastic has been the introduction of LEZs, which ban emission-intensive vehicles such as older diesel cars from designated areas, typically inner cities. Since vehicle traffic is a significant factor in local air pollution by particulate matter and nitrogen oxides in urban areas, restricting traffic-based pollution in the form of an LEZ was the most critical policy measure to improve air quality. The 2007 Immission Control Act (35th BImSchV) provides the legal basis for LEZs by giving local governments the right to prohibit cars not complying with specific emission standards from entering designated areas. Since the first implementation in 2008, cars must display an appropriately colored windscreen sticker based on EU-wide tailpipe emissions categories. Only vehicles bearing a respective sticker, i.e., those not exceeding predetermined levels of pollution, are allowed to enter.[4] In the first phase, bans were applied to vehicles without a sticker. In a second phase, this was gradually applied to vehicles with a red or yellow sticker (Figure A.1). Nowadays, only cars with green stickers are permitted to enter the zones.[5] The policy is enforced by the police and public order office, and violation leads to fines of EUR 100 for the vehicle driver.

The introduction of LEZs is decided on a regional level involving city administrations, city councils, and local stakeholders. However, state governments can always overrule local authorities. Although the need for a Clean Air Plan and a possible LEZ depends on the previous levels of air pollution, there is idiosyncratic variation in the timing of their

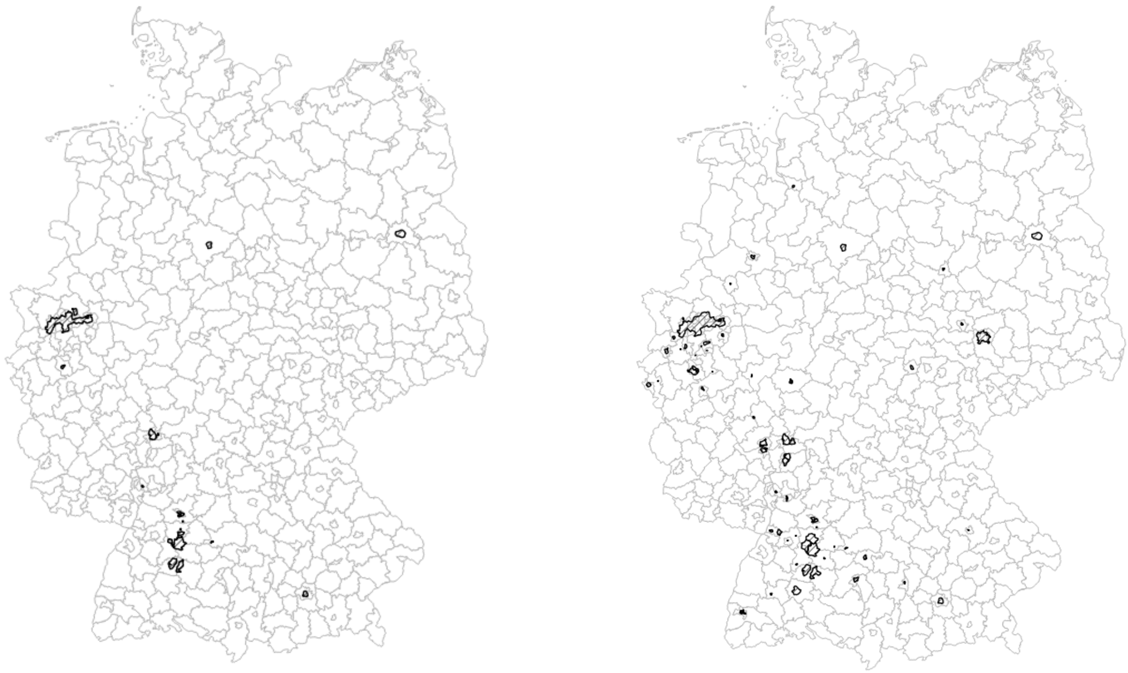
[3] These legally binding standards have been in effect since 2005. Directive 2008/50/EC (EU, 2008) defines the current lawfully binding limits and detailed measurement procedures for all criteria pollutants (NO_2, SO2, PM_{10}, CO, and O3). It is a revised version of Directives 1999/30/EC (EU, 1999), 2000/69/EC (EU, 2000), and Directive 2002/3/EC (EU, 2002).

[4] Stickers are assigned based on the tax class and EURO standard recorded in the car registration book and regulated by the labeling regulation in the 35th Ordinance for the Implementation of the Federal Immission Control Act (35. BImSchV).

[5] One exception is Neu-Ulm, where yellow stickers are still allowed.

Figure 1: Low Emission Zones in Germany, 2008 and 2018

(a) 2008 **(b)** 2018



Notes: Expansion of LEZs in Germany between 2008 and 2018. See Table A.2 for detailed information on the LEZs implementation dates and their stringency levels.
Source: UBA.

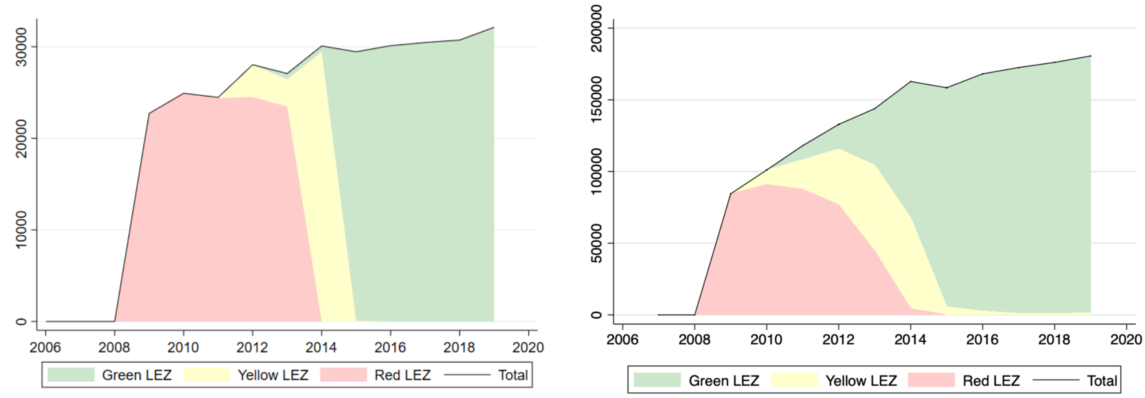
introduction. The decision-making process varies between different regions, depending on conflicting interests. Further, there are several stakeholders that advocate against or in favor of LEZs. For example, lawsuits both in favor of and against the introduction have been initiated by local stakeholders (see Klauber *et al.*, 2021, for a detailed discussion).

The first LEZs were introduced in 2008, predominantly in the largest cities (12 LEZs in 20 cities). As of 2022, this number has increased to 56 (see Table A.2). Figure 2 reflects the first sharp and then more gradual increase of the number of LEZs by showing the evolution of the number of 4th grade elementary school students living inside LEZs of different stringencies over the observation period.[6] Compared to all of Germany, the majority of LEZs in NRW were introduced within the first implementation wave (see Table A.2 for detailed information on the LEZ implementation dates and their stringency levels).

[6]Since we only have school-level administrative data for NRW, the Germany figure depicts the number of elementary students living in districts that contain a LEZ. See section 4 for details.

Figure 2: Elementary school students covered by LEZs in NRW and all of Germany

(a) NRW **(b)** Germany



Notes: Cumulative number of students at schools inside LEZs in NRW (Panel (a)) and in districts which contain a LEZ in Germany (Panel (b)).
Source: UBA and IT.NRW (Panel (a)); UBA and and bildungsmonitoring.de (Panel (b)).

2.2 School system in Germany

Education policy in Germany is decentralized and regulated by the federal states. However, while some aspects of the education system vary across states, the Standing Conference of the Ministers of Education and Cultural Affairs of the Federal States (Kultusministerkonferenz; KMK) harmonizes education policies between states in terms of the general structure and curriculum (KMK, 2014).

Compulsory elementary education starts when children are around six and usually lasts for four years.[7] Based on their performance in third and fourth grade, children are then divided into different tracks. In Western Germany, the secondary school system comprised three vertically ordered tracks: the basic track (*Hauptschule* lasting five years), the middle track (*Realschule* lasting six years), and the academic track (*Gymnasium* lasting eight to nine years). Over time, due to the lack of prospects for graduates of the lowest track (e.g., Helbig and Nikolai, 2015; Matthewes, 2021), many Western German federal states moved from the three-tier to a two-tier system. This system, traditionally common in Eastern Germany, merges the low and middle track while retaining the three different school-leaving certificates. Several federal states, among others NRW, have also adopted different comprehensive secondary schools (*Gesamtschulen)* where children are taught together beyond elementary school.[8] These schools offer different educational tracks at the same school,

[7] In Berlin and Brandenburg, children remain in elementary schools for six years. In Schleswig-Holstein, even though elementary school ends after grade four, the first two years of secondary school are track independent, i.e., the tracking decision also takes place after grade six (KMK, 2014).
[8] In NRW, there are several types of comprehensive schools with minor organizational differences. Besides

allowing students to either leave school with a general degree (*Hauptschulabschluss*) at age 15, a secondary school-leaving certificate (*Mittlere Reife*) at age 16, or to attend upper secondary school and sit the university-qualifying exams (*Abitur*, academic track).[9]

The academic track differs substantially from the non-academic track(s) in terms of curriculum and peer composition. It has the most demanding curriculum and is the only track granting access to university. In the last year of elementary school, the headteacher gives the track recommendation, which is not generally strictly binding. The exact rules again differ by the federal states. In most federal states, except for Bavaria, Brandenburg, Saxony, and Thuringia, the teacher's recommendation is not binding. However, it is usually the case that parents follow the teacher's recommendation (Bos, 2003). Once assigned to a track, mobility across tracks is rare, with upward mobility, i.e., moving from the lower to the higher track, especially difficult (e.g., Dustmann, 2004; **?**; Dustmann *et al.*, 2017). Only 2.2 percent of all students in grades 7 to 9 change track in NRW.[10] Further, only about 5.5 percent of all students entering 11$^{\text{th}}$ grade had been at one of the lower tracks in 10$^{\text{th}}$ grade.[11] Hence, performance in elementary schools and the subsequent tracking have broad implications for a child's educational and professional career.

2.3 School reforms in North-Rhine Westphalia

North Rhine-Westphalia changed the rules regarding secondary school tracking for a short period between 2006 and 2010 from a non-binding to a binding system. During these years, children whose parents disagreed with the recommendation still had the opportunity to attend three-day trial lessons. They had to pass exams in German and mathematics with specific grades to be accepted into a *Gymnasium* against the recommendation of their headteacher (Ministry of Education North Rhine-Westphalia, 2012). While this policy change could well have affected the transition rates during this period, we do not consider this to endanger our identification since there is no reason to believe this rule affected our treatment and control groups differently.

In addition, in 2006, the state government decided to reform the education system in

Gesamtschulen, these schools can be called *Gemeinschaftsschulen*, *Sekundarschulen*, and *Primusschulen*.

[9]In NRW, there are several types of comprehensive schools, which differ mainly in terms of the timing of the tracking. For example, integrated secondary schools (*Integrierte Sekundarschule*), introduced in 2011, teach all students together for two more years after elementary school and offer separate educational programs starting in grade seven. *Primusschulen* offer elementary and secondary school together.

[10]See Landesdatenbank NRW 21111-123is Allgemeinbildende Schulen (D12.3): Schulformwechsel in den Jahrgängen 7 bis 9 nach Geschlecht, Nationalität, Schulform und Schulform der Zielschule - Gemeinden - Schuljahr, 2021/2022

[11]See Landesdatenbank NRW: Allgemeinbildende Schulen (D12.3): Schulformwechsel in den Jahrgängen 7 bis 9 nach Geschlecht, Nationalität, Schulform und Schulform der Zielschule - Gemeinden - Schuljahr

two important ways: first, to abolish catchment areas in all municipalities in NRW as of the 2008/09 school year, and second, to decrease the number of elementary schools (Makles and Schneider, 2012). Allocation to elementary school was traditionally organized through catchment areas, making the geographical distance to the children's homes the primary determinant of school choice at the elementary school level. The dissolution of the school districts was justified, on the one hand, by the introduction of competitive elements between the schools and, on the other hand, by the desire to take parental preferences in the choice of a suitable school more into account. This was also expected to provide support for the decisions on school closures. Schools that were not in demand could be closed without major resistance.

Makles and Schneider (2012) study the determinants of school choice in the light of the 2008/09 reform in the city of Wuppertal and find that when given more freedom in school choice, students tend to favor schools that are close to their homes and that have higher transition rates to the academic track. Hence, the reform may have led to students sorting into schools with higher transition rates to *Gymnasium* and schools with lower rates to have a higher likelihood of being closed. Figure D.2 indeed shows an increasing trend in transition rates to the academic track after 2007 for both treatment and control group.

In a separate analysis for all of NRW, however, Makles and Schneider (2011) show that the reform has not affected segregation measures in schools.[12] This may be seen as an indication that the reform did not lead to a concentration of children with high socio-economic status (SES) – with higher average transition rates to the academic track – in certain areas, which could potentially correlate with the location of LEZs and could endanger our identification. To further test this premise, we analyze whether, during our observation period, districts with LEZs were differently affected by school closure rates than districts with no driving restrictions. Figure B.1 provides evidence that the introduction of LEZs is not associated with the rate of school closures due to the 2006 reform.

[12] However, evidence on that matter is mixed. Some analyses focusing on more narrow regional developments point in a different direction. For example, a mixed-method study for the city of Mühlheim, Ramos Lobato and Groos (2019) finds an increase in segregation as a result of the reform.

3 Data and Descriptive Statistics

3.1 Administrative school-level data

The administrative school-level data is provided by the North Rhine Westphalian state statistics office (IT.NRW) and contains information on the number of students transitioning from elementary school (after grade 4) to the different secondary school tracks. For our main analysis we To avoid potential biases in data due to the Covid-19 pandemic, which may have affected school transitions, we restrict our analysis to the school years from 2005/06 to 2018/19. In 2005/06, there were 3,425 elementary schools in the data set, while the number was reduced to 2,720 in the school year 2018/19.[13] The data contains the total number of students graduating from each elementary school after 4$^{\text{th}}$ grade at the end of the school year (July) and which school type they are transitioning to. Those school types comprise the *Gymansium*, which is the standard academic track option, schools which also offer the academic track[14], and schools that do not offer an academic track [15]. The data further comprises public as well as private schools.[16] Moreover, the number of students can be disaggregated by sex and nationality.[17] Table A.3 depicts the descriptive statistics for different school types inside and outside LEZs. We focus on the transition rate to the academic track (*Gymnasium*). This school type is the central one leading to the *Abitur*, which is the entrance requirement for universities.[18] Figure 3 depicts the transition rate to the academic track for schools which lie inside a (future) LEZ and schools outside. The average transition rate to the academic track is 43.4 percent for schools outside LEZs, while it is 38.9 percent for schools inside (future) LEZs. Moreover, as Figure 3 shows, the average transition rates tend to increase over time.

[13] See 2.3 for details on the reforms leading to the closure of elementary schools in NRW.

[14] *Gesamtschulen, Sekundarschulen, PRIMUS-Schulen* and *Gemeinschaftsschulen*

[15] *Realschulen* and *Hauptschulen*

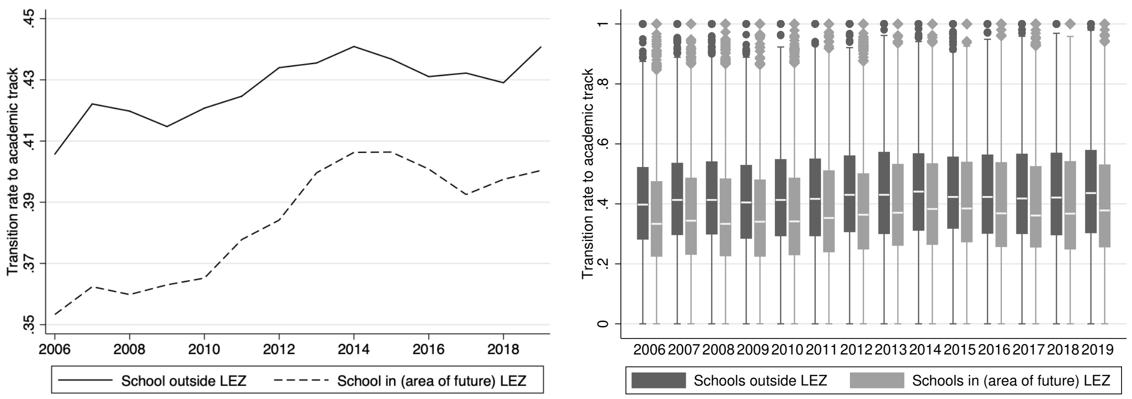
[16] We restrict the empirical analysis to public schools since the catchment area of private schools will be larger than the neighborhood of the school. While the private school sector is growing especially in Eastern Germany, it still does not play a significant role at the primary school level (e.g., Helbig, Marcel, Schmitz, Laura and Weinhardt, Felix, 2022).

[17] Nationality is coded as German nationality and non-German nationality. This data should be interpreted cautiously as the numbers of non-Germans are low, and since there have been changes to the nationality rules in Germany, identification by nationality is challenging.

[18] See Section 2.2 for the institutional background.

Figure 3: School level transition rates to Gymnasium in NRW by LEZ status, 2006 – 2019

(a) Mean **(b)** Distribution



Notes: The left panel displays the average transition rates to the academic track for schools outside of LEZs and for schools, which at any point between 2005-2018 are inside a LEZ. In the right panel, the distribution of school-level transition rates is displayed for both types of schools via boxplots. The transition rates are weighted by the number of students. The comparison group comprises large cities with $>$ 100,000 inhabitants.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

We match the school IDs to school address lists to determine whether a school lies within a LEZ.[19] We then proceed to identify schools inside LEZs, considering the temporal and spatial dynamics of LEZs. The black dots in Figure 4 represent elementary schools in NRW and their location.

3.2 Administrative district-level data

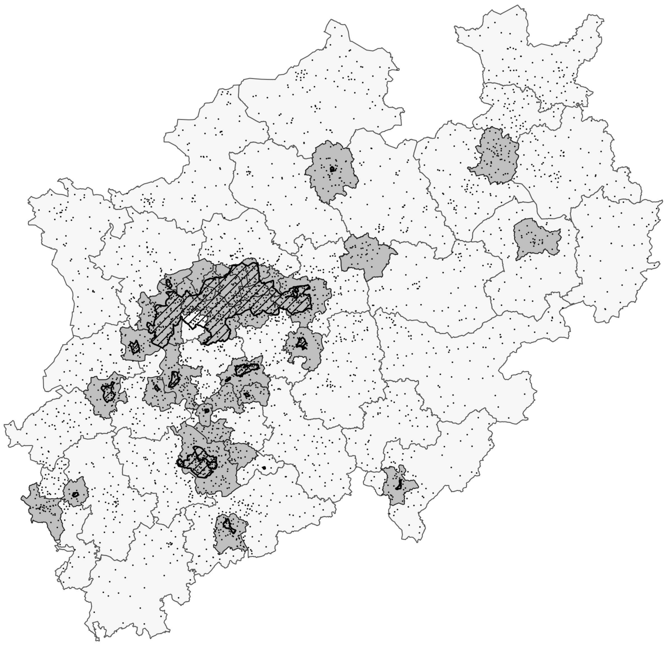
In addition, we use aggregated district-level data for all of Germany (except for Saarland) for an additional analysis checking the external validity of the results found for NRW (Section 5.4). This data was provided by the respective statistical offices and is collected online.[20]

3.3 Low Emission Zones data

Data on the history of implementation, stringency (ban of Euro 1-3 vehicles), and geographic coverage is provided by the Germany Environmental Agency (UBA, Umweltbundesamt).[21] In our analysis, the main treatment variable is a binary indicator for whether a school is located inside an active LEZ area. As the implementation dates of LEZs do

[19]School addresses of schools that were not matched were added manually.
[20]The data can be retrieved from bildungsmonitoring.de.
[21]Table A.2 in the Appendix lists the introduction date and stringency of all LEZs in Germany.

Figure 4: School locations, LEZs and comparison sample in NRW, 2018



Notes: Each dot represents the location of an elementary school in NRW. The main comparison sample (large cities with > 100,000 inhabitants) is shaded in grey. The dashed area represents the extent of LEZs in NRW in 2018.
Source: UBA and IT.NRW.

not necessarily coincide with the start of the school year (starting typically in August or September and lasting until June or July of the following calendar year), the LEZ treatment variable is one if at least half of the school year is treated by an active LEZ. For example, for a given school in the school year in calendar years $t/t+1$, the LEZ variable takes the value of one if the respective LEZ was introduced between 1 July and 31 December of year t and zero if it was only introduced between 1 January and 30 June of year $t+1$. Note that in the following, we refer to school years by the latter calendar year ($t+1$) when the transition from elementary to secondary school takes place.

In terms of spatial identification, the school-level and district-level analyses differ. While we can geo-reference each elementary school and thus identify schools inside LEZs for the administrative school-level data in the state of NRW (see Section 3.2), the aggregated district-level data for all of Germany does not allow such a granular identification. We define "treated" districts as those districts which contain an LEZ. In case the LEZ does not cover the entire surface of the district, this should give us lower-bound estimates as areas that have not experienced air quality improvements due to the introduction of the LEZ are included.

3.4 Pollution data

Data on air pollution levels is provided by the air pollution monitoring system of the German Federal Environment Agency. We use data on all stations measuring the concentration of nitrogen dioxide (NO_2) and particulate matter (PM_{10}) between 2003 and 2018. We first match the station IDs to data on the exact location of the stations and merge this data with our low emission zones data via geo-coding to determine whether a school lies within a LEZ. The variables of interest are the yearly averages of pollutants.[22] Table 1 gives an overview of air pollution levels for stations inside and outside of LEZs. More than 800 stations measure pollution within LEZs for NO_2 and PM_{10}. The pollution levels are significantly higher within LEZs than outside LEZs.

Table 1: Comparison of pollution levels within and outside LEZ, Germany and NRW

	unit	(Future) LEZ	No LEZ	Difference
		Germany		
Nitrogen Oxide (NO_2)	µg/m3	41.51	26.89	-14.62***
Particulate matter (PM_{10})	µg/m3	24.37	22.31	-2.05***
Number of stations		915	5548	6463
		NRW		
Nitrogen Oxide (NO_2)	µg/m3	40.32	31.07	-9.26***
Particulate matter (PM_{10})	µg/m3	25.26	24.39	-0.87*
Number of stations		296	605	901

Notes: The table shows differences of average NO_2 and PM_{10} levels for stations outside and within LEZs for Germany and NRW.
Source: UBA, years 2003-2018.

3.5 RWI-GEO-GRID data

We use the RWI-GEO-GRID data (Breidenbach and Eilers, 2018) for further information on the neighborhood of each elementary school. This data set covers aggregate information for all of Germany on the 1km×1km grid cell level. The definition of grid cells follows the European INSPIRE regulation. The RWI-GEO-GRID data comprises information on the composition of the residential population regarding age, gender, nationality, and migration background. Further, there is information on the aggregated available income, the share of households with credit failure risk, the unemployment rate, average household

[22] Another possibility to check the impact of LEZ on the exposure of elementary school children to pollution is to exclude the summer vacation months from the analysis. A robustness check excluding the month of August yields very similar results (available upon request.

sizes, and the number and type of buildings. Finally, there is information on car density and the composition of cars regarding size and brand. The RWI-GEO-GRID data spans from 2005 to 2021, except for 2006 to 2008. We linearly interpolate those years to have a balanced data set. Table 2 depicts some descriptive statistics for key socio-economic characteristics of the grids where the elementary schools are located. The purchasing power per capita is lower, while the unemployment rate and the share of foreigners are higher at the grids inside a (future) LEZ. In sum, the neighborhoods of elementary schools outside LEZs tend to be economically better off.

Table 2: Comparison of grid characteristics between treatment and comparison group, NRW

	unit	(Future) LEZ	No lez	Difference
Purchasing Power per capita	€	19512.71	22354.96	2842.24***
Share of foreign nationals	%	15.95	10.89	-5.05***
Unemployment rate	%	12.44	7.93	-4.51***
Share of households with children	%	24.41	30.20	5.78***
Number of schools		8329	9612	17941

Notes: Tables depicts the comparison of the average grid value of schools inside a (future) LEZ vs. grid values of schools outside LEZs for the sample of large cities (> 100,000 inhabitants).
Source: UBA, IT.NRW, and RWI-GEO-GRID.

3.6 SOEP

We use geo-referenced data from the German Socio-economic Panel (SOEP) to examine the underlying channels of the effect of the introduction of LEZs on track choice. The SOEP is an annual, nationally representative survey covering information on demographics, household composition, educational outcomes, and labor market characteristics of nearly 13,000 households and 30,000 individuals (Goebel *et al.*, 2019). With the anonymized regional information on the places of residence of SOEP respondents, regional indicators can be linked to the SOEP data through matching by municipality or zip codes. For all years since 2000, it is possible to trace respondents' places of residence back to the street-block coordinates. This information allows us to precisely identify children residing within LEZ, and to build a control group similar to our main specification.[23] We consider a child as treated when they have lived within a LEZ starting from age 7.[24] For our outcome vari-

[23] As in our school-level analysis, we limit our sample to individuals residing in urban areas (municipalities with at least 100,000 inhabitants). In addition, we exclude special surveys, such as the M1 and M2 Migration samples and the M3 Refugee sample.
[24] Individuals who move between ages 7 and 9 are excluded from the analysis.

ables, we use information from the mother-and-child questionnaire asking parents questions on their child's health, schooling, and well-being at age 9-10, i.e., shortly before they transition to secondary school. Hence, we observe the outcomes when the children in the treatment group have had at least two years of exposure to LEZ.

4 Empirical Strategy

We evaluate the changes in school-level transfer rates to the academic track following the implementation of LEZs using the difference-in-difference methodology. Until recently, using a two-way fixed effects (TWFE) model with the following form was the norm for recovering the difference-in-differences estimates of the average treatment on the treated (ATT):

$$Y_{i,t} = \beta^{TWFE} LEZ_{i,t} + \gamma X_{i,t} + \lambda_i + \phi_t + \varepsilon_{i,t}, \quad (1)$$

where $Y_{i,t}$ is the transition rate for school i in year t and is regressed on the treatment variable LEZ_{it}, school fixed effects (λ_i), year fixed effects (ϕ_t), $X_{i,t}$ a set of time-varying GRID characteristics [25] and standard errors clustered at the district level $\varepsilon_{i,t}$.[26]

The difference-in-differences coefficient is generally thought of as the coefficient β^{TWFE}. Recent contributions have, however, highlighted potential issues with this interpretation (de Chaisemartin and D'Haultfœuille, 2020a; Callaway and Sant'Anna, 2021; Goodman-Bacon, 2021; Wooldridge, 2021). In other words, when there are many periods and the treatment implementation is staggered, the β^{TWFE} may represent a biased approximation of the true underlying ATT. A weighted average of all 2×2 comparisons of "switchers" and "non-switchers" is estimated when there is variability in the treatment effects over time or between groups. These comparisons include potentially problematic comparisons such as comparing later treated to earlier treated units and "clean" comparisons between treated and not-yet-treated units (Goodman-Bacon, 2021). This may lead to negative weights in the weighted average, which may result in a downward bias or even a negative coefficient, even when all underlying ATTs are positive (de Chaisemartin and D'Haultfœuille, 2020b). These problems are more likely to occur as treatment outcomes differ between treatment groups or over time. Since the vehicle fleet's makeup changed between the first and last in-

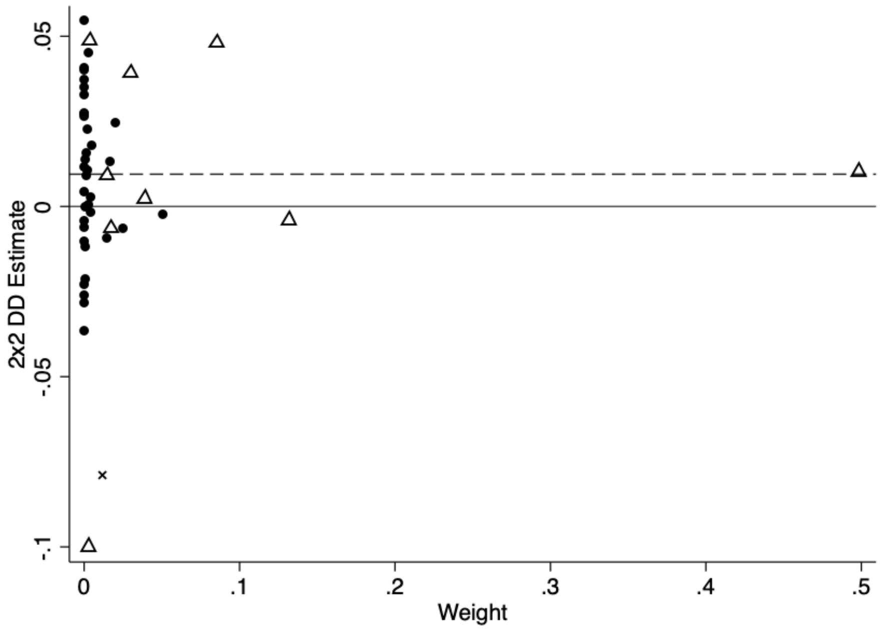
[25] In our case these time-varying characteristics include purchasing power per capita, unemployment rate, share of foreigners, and share of households with children.

[26] We conservatively cluster at the district level since the decision on whether a LEZ is implemented is taken at the administrative district (*Regierungsbezirk*) level in collaboration with the district/city.

troduction, the staggered adoption of LEZ in our situation may have caused time-varying treatment effects.

We evaluate the extent to which our analysis may suffer from this bias by performing a Goodman-Bacon decomposition (Goodman-Bacon *et al.*, 2019). The command produces a scatterplot of the 2×2 difference-in-differences estimations and their corresponding weights (Figure 5). By far, the largest weight is assigned to the 2×2 comparison of the first-wave early treated vs. the never treated group. Overall, the treated vs. never treated group receives a weight of 0.83, and the early vs. late and late vs. early groups have a weight of 0.16. The estimates by the latter (0.004) are substantially smaller than those estimated by the former (0.012), albeit not negative, indicating that our TWFE estimates may be slightly downward biased. The third group, labeled "within", tells us how much time-varying controls drive our estimates. Although this group gets the smallest weight in the Goodman-Bacon decomposition, the corresponding beta is negative, implying that controlling for the yearly grid-level covariates is important.

Figure 5: Bacon decomposition



	Components	Beta	Weight
•	Early vs. Late & Late vs. Early	0.0040	0.1626
△	Treated vs. Never Treated (C)	0.0118	0.8254
×	Within	-0.0792	0.01203

Notes: This figure implements the Goodman-Bacon (2021) decomposition using the large sample and the purchasing power per capita, the unemployment rate, the share of foreigners and families (all variables at the grid cell level) as time-varying control variables. The command is run on a balanced panel.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

In recent years, numerous proposals of alternative difference-in-differences estimators that are robust to heterogeneous treatment effects across time and/or cohorts have been made (Callaway and Sant'Anna, 2021; de Chaisemartin and D'Haultfœuille, 2020a; Sun and Abraham, 2021; Borusyak *et al.*, 2021). All these estimators have in common that they only use the never-treated and the not-yet-treated as comparison groups.

In this study, we make use of a stacked event-by-event design (SD) (Cengiz *et al.*, 2019; Deshpande and Li, 2019; Baker *et al.*, 2022) as well as the estimator suggested by de Chaisemartin and D'Haultfœuille (2020a) (dC&D'H). We opt for this combination of estimators because the SD is the simplest and most transparent way to solve the negative weight problem. While many of the new estimators are quite restrictive in the use of fixed effects, linear trends or the inclusion of time-varying control variables, the stacked design allows for such flexibility. In this approach, we develop event-specific data sets that include the outcome variable, controls for the treated state, and controls for any other "clean controls" that do not introduce LEZs within the 9-year observation period (t = -2 to t = 6). Then, using a single set of treatment indicators, we stack these event-specific data sets in relation to time to get the average effect across all events. The dC&D'H estimator is arguably the most flexible and comprehensive approach, yielding time-specific ATTs for each time period after treatment, averaging across numerous cohorts that get treated at various intervals. An important reason for us to prefer this method over similar ones is that it allows for time-varying covariate controls, which may play a key role in our setting, as indicated by Figure 5. An additional advantage is that it offers the option to include non-parametric time trends for different groups.

Identification in the difference-in-differences framework relies on a number of identifying assumptions. First, we need to make the canonical difference-in-differences framework's identifying assumption – that the prospective outcomes for the untreated and treated follow parallel trends. The effect is identified even if there are shocks affecting the potential outcome, as long the severity of the shock is not correlated with the location of LEZs. Evidence that there are no substantial pre-trends may be inferred from the analysis of event study estimates (see Figure 6). In addition, we run balancing tests to investigate possible compositional changes which could have happened due to the introduction of the LEZs. For this, we take the control variables purchasing power per capita, unemployment rate, the share of foreigners, and the share of households with children in the respective grid cells as the dependent variables (Table B.2). The results suggest that most of these variables were not affected by the introduction of LEZs. One exception is the share of foreigners, which increased by 0.3 to 0.5 percentage points in neighborhoods within LEZs. This finding could be related to the fact that the share of foreigners in Germany generally increased in the last decade, e.g., due to the increased intake of refugees after 2015. Since students of immigrant ancestry are less likely to transition to the academic track (e.g., Hendrik and Kerstin, 2011), this result would, if anything, suggest an underestimation of the true effect of LEZ on transition rates.

To justify the identifying assumptions, we select a comparison group of schools that are not treated (i.e., which don't lie inside a LEZ) and are likely to be similar to the treatment group in (un)observable characteristics. In our main specification, we restrict the sample to large cities with more than 100,000 inhabitants, which excludes rural and less densely populated areas (see Figure 4). Table 2 depicts the differences between the characteristics of the treatment and the control group (never treated). While Table 2 indicates some baseline differences, identification relies on comparing trends and shocks that may be related to the treatment; hence differences in levels do not represent a problem. We further include school and administrative region-by-year fixed effects.[27] Finally, we add time-varying control variables on the 1km$\times$1km grid cell level (see Section 3.5) to account for changes in the socio-economic status (SES) composition on the neighborhood level, which may influence the evolution of the transition rates to the academic track. Specifically, we include the unemployment rate, purchasing power per capita, foreign inhabitants share, and households with children (families) within the grid cells (see Table **??**).

5 Results

5.1 LEZ effects on air quality

Since the effectiveness of LEZs in reducing air pollution has been demonstrated widely by previous studies (e.g., Wolff, 2014; Gehrsitz, 2017; Pestel and Wozny, 2021; Sarmiento *et al.*, 2021), we only briefly touch on this issue. We report reductions in nitrogen dioxide (NO_2) and coarse particulate matter (PM_{10}) since data coverage is the largest for these two pollutants, and they are the most relevant regarding traffic emissions and health outcomes (see Pestel and Wozny 2021 for an overview). Table 3 provides an overview of TWFE and

[27] Administrative regions (in German *Regierungsbezirke*) for NRW are the regional administrative entities between districts and the state. This entity also serves as the upper-level supervisory school authority, which motivates its usage as a fixed effect to account for different trends across the administrative regions. We refrain from accounting for district $\times$ time trends since the LEZ of Herne spans the entire district, resulting in this district being entirely absorbed.

dC&d'H estimates of the reduction of NO_2 and PM_{10} levels in Germany and NRW.

Our findings for all of Germany suggest that the introduction of LEZs decreases NO_2 levels by 1.6-2.1 micrograms per cubic meter ($\mu g/m^3$) or 6.5-7.5 percent of the mean. The average PM_{10} levels are reduced by 0.8-1.3 $\mu g/m^3$ or 3.7-5.7 percent of the mean, similar to the findings of Pestel and Wozny (2021). Our estimates for NRW are less precisely estimated because of the much smaller sample and large gaps in the data. For the NRW sample, only the reduction in NO_2 is statistically significant both using a TWFE design and the dC&D'H estimator, pointing to a reduction of 1.6-1.7 $\mu g/m^3$, which corresponds to 4.8-5.7 percent of the NRW mean. This marks a medium to large effect compared to similar driving restriction policies in other countries.[28] It is plausible that NO_2 is most strongly affected by the driving restriction policy since motor vehicle exhaust accounts for up to 80 percent of NO_2 pollution (Environmental Protection Agency, 2016). Because of its significant impacts on human health (Vitousek *et al.*, 1997; Schneider *et al.*, 2018) and particularly respiratory infections in children (Kampa and Castanas, 2008; Janke, 2014), we assume that any reduction in NO_2 pollution can affect educational outcomes.

Table 3: Impact of LEZs on air pollution in Germany

	Germany			NRW		
			NO_2			
Low Emission Zones	-1.5752***	-1.5986***	-2.1654***	-1.7114**	-1.8303**	-1.9394***
	(0.4846)	(0.2840)	(0.4125)	(0.6886)	(0.7555)	(0.6065)
Observations	4968	15501	4968	655	1178	655
			PM_{10}			
Low Emission Zone	-0.8286**	-0.7110***	-1.3116***	-0.5230	-0.1350	-0.2464
	(0.3606)	(0.2708)	(0.4305)	(0.7027)	(0.8067)	(0.7222)
Observations	4642	13987	4642	695	1191	695
TWFE	✓	-	-	✓	-	-
Stacked	-	✓	-	-	✓	-
dC & D'H	-	-	✓	-	-	✓
Grid controls	✓	✓	✓	✓	✓	✓

Notes: This table displays the results for the effect of Low Emission Zones on nitrogen dioxide (NO_2) and coarse particulate matter (PM_{10}). Each coefficient is the result of a separate regression controlling for monitor station and year fixed effects as well as time-varying grid-level controls.
*** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: UBA.

[28] For example, Ellison *et al.* (2013) find that concentrations of particulate matter within the low emission zone in London dropped by 2.46–3.07 percent. Larger effects are reported for areas with higher baseline pollution like China. Viard and Fu (2015) show that alternate-day driving restrictions in Beijing reduce particulate matter by 22 percent during every-other-day and 15 percent during one-day-per-week restrictions.

5.2 LEZ effects on transitions to the academic track

Table 4 presents the results of the stacked TWFE estimation of the ATT of LEZs on academic-track transition in NRW.[29] Following Cengiz *et al.* (2019), specifications include event time $\times$ wave FEs and group $\times$ wave FEs to account for the stacking procedure. Gradually, we add more restrictive fixed effects, time-varying controls, and linear district trends. We find a positive and statistically significant effect of the introduction of LEZs on transition rates to the academic track ranging between 0.9 and 1.2 percentage points. To put this into perspective, the average transition rate of all schools in the sample is 42.6 percent. The effect estimate thus indicates a 2.0 to 2.8 percent increase in the transition rate due to the introduction of the LEZ. The estimated effects are smaller than effects observed regarding school entry age (Mühlenweg, 2008) or parental risk attitudes (Wölfel and Heineck, 2012). However, the observed effect indicates a large and economically meaningful effect due to the indirect relationship.

For the dC&D'H estimation, we include the same time-varying control variables, school linear trends, and administrative district-by-school-year non-parametric trends. Figure 6 depicts the event study graph of the evolution of transition rates to the academic track followed by the staggered introduction of LEZs. The effect becomes statistically significant in the third year and reaches a peak in the fifth year after introduction, after which it levels out at around two percentage points. Overall, the statistically significant average treatment effect on the treated (ATT) is estimated at 1.6 percentage points. This result is consistent with the findings of the TWFE analysis in Table E.1 and the Goodman-Bacon decomposition in Figure 5: since TWFE appears to slightly underestimate the true effects of LEZs on track choice, it ranges around 1.6 rather than 1 percentage points.

An increase in the transition rate to the academic track implies changes to the transition rates to other school types. Given the heterogeneous school system in Germany and NRW (see Section 2.3), we aggregate the transition rates to three types of schools: first, the academic track (*Gymnasium*) as discussed, second, other schools which offer the option of graduating with the *Abitur*[30] and third, schools which do not offer this option.[31] Table 5 displays the results of the impact of the introduction of LEZs on the transition rate to the second (Panel A) and the third group (Panel B). The results indicate that while the in-

[29] Table E.1 in the Appendix displays the results for the canonical TWFE. The results are qualitatively very similar, with coefficients between 0.009 and 0.012.

[30] Schools with "option academic track" include *Gesamtschulen, Sekundarschulen, PRIMUS-Schulen* and *Gemeinschaftsschulen*.

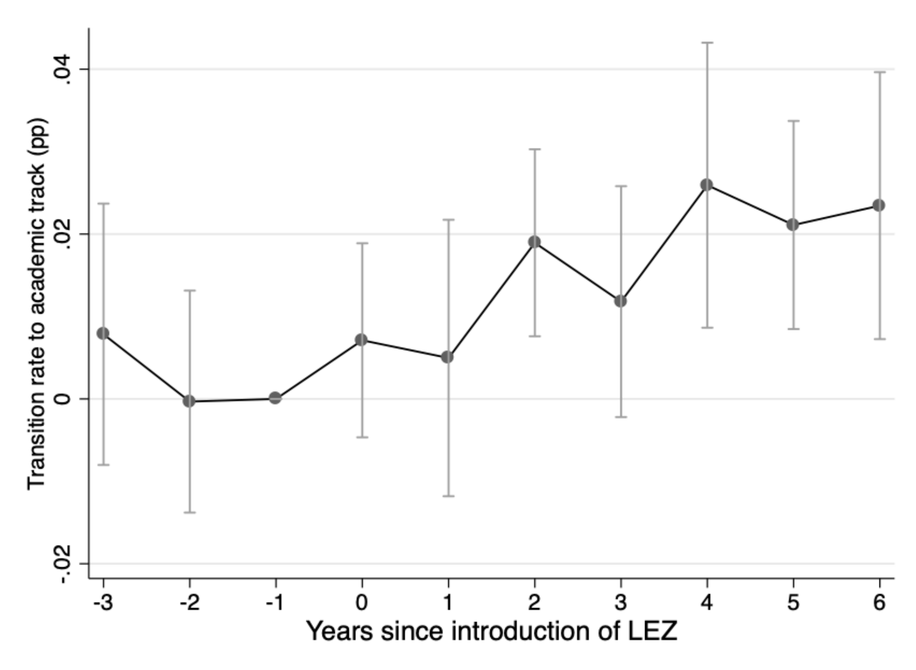
[31] Schools which do not provide an option to the academic track in NRW are *Hauptschulen* and *Realschulen*. We exclude all other schools since it is a heterogeneous group and account for less than 1 percent

Table 4: Impact of LEZs transition rates to the academic track, stacked TWFE

	Transition rate to academic track				
Low emission zone	0.0134***	0.0102**	0.0091**	0.0119***	0.0091**
	(0.0041)	(0.0043)	(0.0044)	(0.0045)	(0.0046)
Number of observations	47,806	47,806	47,806	47,806	47,806
Event time x Wave FEs	✓	✓	✓	✓	✓
Group x Wave FEs	✓	✓	✓	✓	✓
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district x Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓

Notes: Sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate, and the share of households with families. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Figure 6: Event study of LEZs transition rates to the academic track



Notes: Sample: large cities(> 100,000 inhabitants). This figure depicts the dynamic difference-in-differences estimates for the effect of the introduction of LEZs on school-level transition rates to the academic track using the estimator proposed by de Chaisemartin and D'Haultfœuille (2020a) and implemented with the *did_multiplegt* Stata package. The estimation includes school linear trends and admin. district × year non-parametric trends as well as time-varying grid controls (purchasing power per capita, unemployment rate, share of foreigners, share of households with children). The plotted confidence intervals (95%) are computed using 100 bootstrap replications and are clustered at the district level. The corresponding ATT is .0164 with a standard error of 0.0060.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

troduction of LEZs did not significantly impact the transition rates to the comprehensive schools with academic track option, they negatively affected the share of students transitioning to the track with no option to obtain the *Abitur* (Panel B, columns 4 and 5). In addition, we amend the control group by excluding schools which also offer the option of graduating with the academic track (see Section 3.2). Table E.6 displays the results, which confirm our main analysis. In sum, the results indicate that the positive impact of LEZs on choosing the highest track is accompanied by a decrease in the ratio of students choosing the lowest track.

Table 5: Impact of LEZs on transition rates to different school types except for pure academic track, stacked TWFE

Panel A: Track with *Abitur* option					
Low emission zone	-0.0020	-0.0006	-0.0011	0.0061	0.0089*
	(0.0044)	(0.0047)	(0.0047)	(0.0044)	(0.0047)
Number of observations	47,806	47,806	47,806	47,806	47,806
Panel B: Track without *Abitur* option					
Low emission zone	-0.0093	-0.0089	-0.0073	-0.0172***	-0.0171***
	(0.0061)	(0.0063)	(0.0063)	(0.0062)	(0.0059)
Number of observations	47,806	47,806	47,806	47,806	47,806
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district × Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓
Event time × Wave FEs	✓	✓	✓	✓	✓
Group × Wave FEs	✓	✓	✓	✓	✓

Notes: Schools which "Track with *Abitur* option" include *Gesamtschulen, Sekundarschulen, PRIMUS-Schulen* and *Gemeinschaftsschulen*. Schools without the *Abitur* option are *Hauptschulen* and *Realschulen*. Comparison sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate, and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

5.3 Effects by gender, neighborhood and school characteristics

With respect to student characteristics, our data only allows for distinguishing between girls and boys. Table 6 shows that the school track choice of girls and boys are differently affected by the introduction of LEZs and that the positive effect found in our principal analysis seems to be driven by boys. While for our preferred specification (columns 4 and 5), the coefficient for girls is close to and not statistically different from zero, the estimates for males are larger than the overall effect (1.7 and 1.5 percentage points increase in transition rates to the academic track) and statistically significant at the 1 and 5 percent level, respectively. In other words, the better air quality due to the introduction of LEZs seems to have a more substantial positive effect on male students than on their female peers. One way to interpret this finding is that boys react more strongly to the improvements in air quality. This could for example be the case because boys are more likely to suffer from respiratory diseases during childhood (e.g., Bjornson and Mitchell, 2000). Another reason for the stronger effect on boys could be that they tend to spend more time outside than girls of the same age, e.g. running or playing outside during the school break (Cherney and London, 2006).

Table 6: The impact of LEZs on the school-level transition rates to the academic track, stacked TWFE, by sex

Panel A: Female	Transition rate to academic track				
Low emission zone	0.0118**	0.0080	0.0064	0.0098	0.0060
	(0.0058)	(0.0061)	(0.0061)	(0.0061)	(0.0063)
Number of observations	47,803	47,803	47,803	47,803	47,803

Panel B: Male	Transition rate to academic track				
Low emission zone	0.0179***	0.0158**	0.0151**	0.0168***	0.0152**
	(0.0059)	(0.0066)	(0.0067)	(0.0061)	(0.0068)
Number of observations	47,801	47,801	47,801	47,801	47,801
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district × Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓
Event time × Wave FEs	✓	✓	✓	✓	✓
Group × Wave FEs	✓	✓	✓	✓	✓

Notes: Comparison sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

To explore further potential effect heterogeneities with respect to socioeconomic characteristics, we proxy individual with neighborhood characteristics. We find no clear heterogeneity patterns when we distinguish between above and below-median levels of grid-level characteristics (Table C.1). The estimated effect is slightly higher for socio-economically disadvantaged areas, i.e., neighborhoods with below-median purchasing power, above-median shares of unemployed and foreigners. This could be due to the fact that (baseline) air pollution tends to be higher in economically deprived regions (Lipfert, 2004). Although these differences are small and not statistically significant, we do expect out results to have implications for educational inequality. Since LEZs in Germany are located in rather deprived areas with higher baseline pollution (Table 1) and lower socio-economic status (Table ??) – positive average improvements in schooling outcomes in these areas imply an overall decrease in educational inequality.

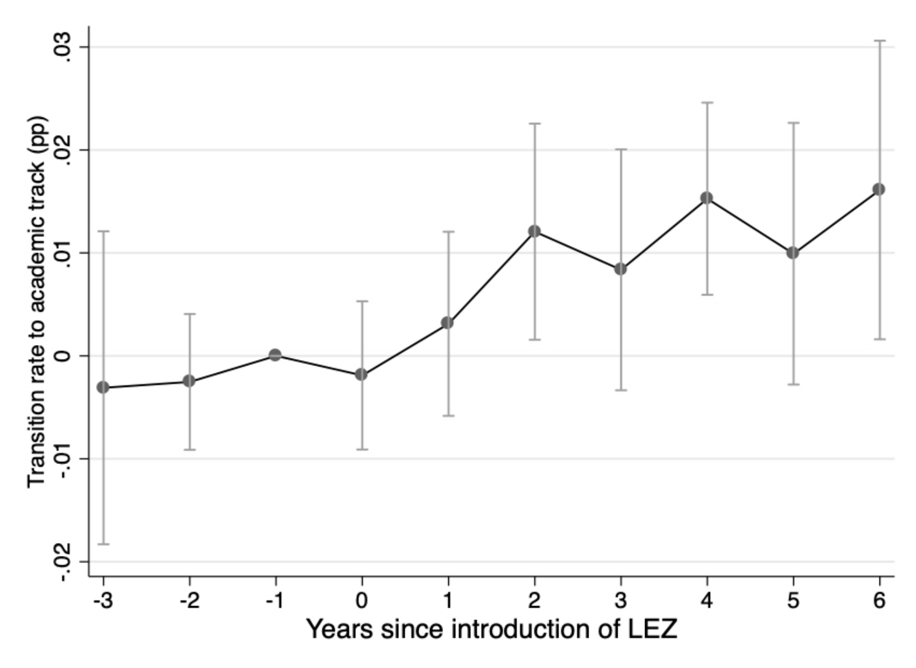
Third, we check whether the estimated effects differ between schools that offer after-school care and those which do not. Following a large investment program in 2003 (BMBF, 2009), a rapidly increasing share of primary schools started offering afternoon programs in NRW (KMK, 2021). Since participating in after-school care implies that the children spend more time in school – usually until 3-4 pm rather than 1 pm – this could theoretically imply a stronger treatment intensity for children whose schools are located in LEZs while their homes are not. In practice, however, whether or not a school offers after-school care is unlikely to affect our results, since we expect most of the children who visit elementary schools in LEZs to also live within the same zones. In addition, more than 90 percent of all primary schools offer after-school care in NRW (KMK, 2021), and all of these schools do this in a non-integrated way, i.e., participation is voluntary. Hence, the fact that a school offers after-school care is not necessarily a strong indicator for more time spent within a LEZ. Indeed, we do not find evidence for a stronger effect of LEZ on academic-track transition rates for schools that offer after-school care (Table C.2).

5.4 District-level analysis

To investigate whether the results have external validity beyond North-Rhine-Westphalia, the most populous federal state (about 22 percent of all German residents live in NRW), we contrast the findings to Germany-wide district-level data as no administrative school-level data exists for all of Germany. We thus rely on aggregated district-level data where we define districts as treated once they contain a LEZ (see Section 3.2). We chose district-free cities as the comparison sample in this analysis as most LEZs were introduced in district-free cities, making them a suitable comparison group. The results of the district-level analysis can be found in Appendix D. The dC&d'H estimator provides an average treatment effect of 0.88 percentage points which is statistically significant at the 5 percent level (see Figure 7). In other words, the introduction of LEZs in Germany increased the transition rate to the academic track by 0.88 percentage points. Given the treatment definition of the district-level analysis, the smaller size of the district-level coefficients is not surprising since they include areas not covered by a LEZ, which will downward bias the coefficients. It should be noted, however, that the coefficient of the district-level stacked design (0.52

percentage points) remains statistically insignificant in the most restrictive stacked specification (see Table D.3). This missing statistical significance may be the result of the small number of observations (106 districts, of which 39 were "treated" districts in 2016).

Figure 7: District-level event study



Notes: Comparison sample: district-free cities. The estimation includes district linear trends, as well as state-by-year non-parametric trends (to account for the educational sovereignty of the states), as well as time-varying district controls (share of foreigners, gross earnings, net migration, unemployment rate). Standard errors are computed using 100 bootstrap replications and are clustered at the district level. The ATT is 0.0088 with a standard error of 0.0040.
Source: UBA and bildungsmonitoring.de.

5.5 Channels

There are several channels through which a reduction in emissions as a result of LEZs could affect the educational achievement of elementary school children. First, children exposed to lower levels of air pollution may experience fewer health problems (e.g., asthma, see for example Knittel *et al.* 2016), leading to fewer missed school days. Second, the lower exposure to air pollution could have an effect on the students' brains, affecting the cognition of students (e.g., Graff Zivin and Neidell, 2012; Künn *et al.*, forthcoming). Lastly, air pollutions' impact on the brain can result in mental stress and attention deficit hyperactivity disorder (ADHD) (e.g., Chen *et al.*, 2018; Mortamais *et al.*, 2019).

We use geo-referenced SOEP data representative for all of Germany to explore potential links between living within a LEZ and various schooling and health outcomes at age 10, i.e., at the age of the tracking decision. Since we observe the outcome variables only once per child for the relevant age group 9-10 (towards the end of elementary school) [32], we cannot apply a TWFE approach. Table 7 shows the results of an OLS regression controlling for district and survey year fixed effects. Respiratory diseases are the only outcome showing a statistically significant (at the 5 percent level) link to LEZ. This result implies that a reduction of respiratory infections such as asthma in LEZ – and potentially a reduction in missed school days – seems to play a role in the positive effects of LEZs on transition rates to the academic track.

Table 7: LEZ and individual student outcomes, pooled OLS

	Transition	Math grade	German gr.	Goal *Abitur*
Low emission zone	0.052	0.107	0.151	0.058
	(0.055)	(0.148)	(0.104)	(0.052)
Number of observations	1879	1270	1268	1390
	Good health	**Resp. disease**	**Concentration**	**Enjoys school**
Low emission zone	0.018	-0.126**	-0.084	0.046
	(0.036)	(0.055)	(0.225)	(0.099)
Number of observations	1430	1312	1307	1428

Notes: OLS regression controlling for district and survey year fixed effects, and individual control variables (parental education and employment status, number of children in the household, migration background, log income, social transfer receiving household). Standard errors are clustered on the district level. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.
Source: SOEP v35 and UBA.

Due to the data limitations, we do not claim causality for this result. However, it should be taken as further suggestive evidence that the level of air pollution is directly related to children's health, affecting their school success. This is in line with previous findings in related studies, e.g., that children are particularly susceptible to adverse health effects of pollution (Coneus and Spiess, 2012; Stafford, 2015), and that improved air quality as a result of LEZs leads to a reduction in asthma medicine prescriptions (Klauber *et al.*, 2021). The finding of the overall effect of LEZs on transition rates to be driven by boys presented in Section 5.3 further strengthens this argument since respiratory diseases such as asthma are more prevalent for boys at that age (e.g., Bjornson and Mitchell, 2000; Postma, 2007).[33]

[32] Some of the outcome variables, e.g. respiratory disease are surveyed multiple times per child, i.e., at age 5/6, 7/8 and 9/10. However, the question is posed as "Has your child ever been diagnosed with one of the following diseases or disorders during a medical examination?", i.e., the variable cannot decrease over time. Hence, improvements in respiratory diseases as a result of LEZ could not be detected in a TWFE analysis.

[33] Testing the hypothesis of a stronger reduction in respiratory diseases for boys in response to LEZ with the SOEP data, we do not find a statistically significant gender effect (Table F.1. However, this could be due to the SOEP analysis being underpowered.

5.6 Robustness checks

We run several sensitivity checks to test the robustness of our results. First, the expectation that the district-level estimates underestimate the true effect is further corroborated by Table 8, which displays the results for NRW using both the administrative school-level data as well as the district data. To make the two data sets more comparable, we use district-free cities as the comparison sample. We note that first, the district-level coefficients are smaller than the school-level coefficients, and second, the TWFE estimations are smaller than the stacked estimations, which are in turn smaller when applying the dC&d'H estimator, both accounting for the staggered treatment timing and heterogeneous treatment effects.

Table 8: Comparison school-level to district estimations NRW

	Transition rate to academic track		
School analysis	**TWFE**	**Stacked**	**dC & d'H**
Low emission zone	0.0103*	.0119***	0.0163**
	(0.0054)	(0.0042)	(0.0062)
Number of observations	16,118	40,055	16,118
District analysis	**TWFE**	**Stacked**	**dC & d'H**
Low emission zone	0.0047*	0.0067**	0.0111***
	(0.0026)	(0.0028)	(0.0036)
Number of observations	345	478	345
Unit FEs	✓	✓	✓
School year FEs	✓	✓	✓
Time-varying controls	✓	✓	✓
Method specific FEs	–	✓	✓

Notes: Comparison sample: district-free cities. All district-free cities in NRW have more than 100,000 residents. Only 7 large cities are not district-free cities. School analysis includes district-level time-varying controls: purchasing power per capita, the share of foreigners, and the unemployment rate. Method-specific fixed effects include event time× wave and group × wave FEs in the stacked design, and unit linear trends and admin. district/state-by-year non-parametric trends in the school and district analysis, respectively. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, bildungsmonitoring.de, INKAR (BBSR), and RWI-GEO-GRID.

Second, we amend the way we define the comparison sample by using an alternative comparison group for our analysis. We chose cities that introduced Clean Air Plans (*Luftreinhaltepläne*) but did not implement a LEZ, which is one possible measure to improve air quality. Clean Air Plans were introduced in cities crossing traffic exhaust-related pollutants thresholds. Consequently, the sample should be comparable in terms of air quality. Table 9 displays the results using this comparison sample as a robustness check. The results are very close to the sample of large cities with more than 100,000 inhabitants.

Third, the time-varying control variables in the main results are defined at the 1km×1km grid of where the elementary school is located. We test the robustness of our results by us-

Table 9: Stacked TWFE, cities with Clean Air Plans

	Transition rate to academic track				
Low emission zone	0.0122***	0.0088**	0.0079*	0.0112**	0.0082*
	(0.0042)	(0.0043)	(0.0044)	(0.0046)	(0.0046)
Number of observations	50,960	50,960	50,960	50,960	50,960
Event time x Wave FEs	✓	✓	✓	✓	✓
Group x Wave FEs	✓	✓	✓	✓	✓
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district x Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓

Notes: Comparison sample: cities that implemented a Clean Air Plan (CAP) at some point in time. Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate, and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

ing a broader definition of the school's neighborhood. Table E.2 re-runs the stacked specification from Table 4 using control variables aggregated at the zip code level. The results stay exactly the same, indicating that they are not driven by the granularity of the control variables used in the analysis.

Fourth, to avoid the negative weighting problem while sticking to a simple difference-in-differences setting, we include only the first wave of LEZs (introduced in 2008/09) in the treatment group and compare them to the group of never treated schools (Table E.3). In this setting, the coefficient is similar to the one estimated by stacking our sample but not significant in the most restrictive specification. This is likely due to the smaller number of observations.

Moreover, given that the number of schools was reduced considerably during the study period, we run the analysis on a balanced comparison sample for schools that existed for the entire period. Table E.4 displays the results. The coefficients are very similar to the unbalanced sample. In conjunction with the finding that the introduction of LEZs did not impact the likelihood of school closures (Table B.1) finding indicates that the estimations are robust to school closures.

Lastly, spillovers may violate the stable unit treatment values assumption (SUTVA) needed for causal estimates. The air quality around schools that are located just outside a LEZ is likely affected by the policy, as may be the air quality of schools just inside a LEZ (e.g. due to winds carrying air pollution). We thus create different buffers to exclude those schools from our analysis. Table E.5, Panel A displays the results excluding schools within a 500m buffer to both sides of the LEZ border, while Panel B excludes schools in a 1000m buffer outside a LEZ. In line with our expectation of positive spillovers, we find that the size of the estimate increases. This implies that our main results are conservatively estimated.

6 Conclusion

In 2008, several German cities started introducing Low Emission Zones, i.e., emission-intensity-based driving restrictions in urban agglomerations. The policy has been shown to effectively reduce air pollution (e.g., Wolff, 2014; Gehrsitz, 2017) and improving health outcomes (Margaryan, 2021; Pestel and Wozny, 2021) but also to exhibit social costs (Sarmiento *et al.*, 2021). Given the large potential advantages of LEZs and the related costs of limiting mobility, it is vital to assess further spillover effects on broader areas of people's lives. One of these areas are schooling outcomes of children living within LEZs, which might be affected through different channels like better health (e.g., Klauber *et al.*, 2021) or concentration and improved cognitive abilities (Stafford, 2015).

Children are increasingly growing up in urban centers (e.g., Bishop and Corkery, 2017; Javad, 2017), where they are exposed to high pollution levels on a daily basis. Traffic is a primary source of air pollution within cities, which has been shown to have detrimental effects on children's development and health (e.g., Stafford, 2015; Klauber *et al.*, 2021). Therefore, policies restricting air pollution are necessary to ensure cities provide a child-friendly living environment that allows them to grow up healthy and develop their full potential.

In this paper, we study the effects of LEZs on the educational achievements of elementary school children in Germany, measured by the transition rates to the academic track. Germany is known for its rigid early tracking system, which greatly determines a child's later educational and professional trajectory (e.g., Dustmann, 2004). Since only a small fraction of students change tracks during secondary school, the chosen track at age 10 is a meaningful indicator of educational achievement in Germany.

To identify the causal effect of LEZs, we rely on a stacked-by-event design (Cengiz *et al.*, 2019) and the estimator developed by de Chaisemartin and D'Haultfœuille (2020a). Both estimators account for the staggered implementation of LEZs and time-varying treatment effects that potentially downward bias the two-way-fixed effect estimator (Goodman-Bacon, 2021; de Chaisemartin and D'Haultfœuille, 2020b). We use geo-coded administrative school-level data from North Rhine-Westphalia, the most populous German federal state, and district-level data for all of Germany complemented with socio-economic information on the 1×1 km grid neighborhood level and geo-referenced data from the German Socio-Economic Panel (SOEP).

Our findings for the school-level data in NRW point to an increase in transition rates to the academic track by 0.9-1.6 percentage points in response to the introduction of LEZs. Running the analysis on district-level data for all of Germany, we find a slightly weaker but positive effect, suggesting that our findings have validity beyond NRW. In the SOEP analysis, we find suggestive evidence that a reduction in respiratory infections is one channel through which LEZs improve student outcomes. The effects on transition rates are driven by boys, who more often suffer from respiratory diseases during childhood.

Our results indicate a significant and lasting causal effect of even moderate improvements in air quality on educational achievement. The effects are estimated for an industrialized country with already relatively high air quality standards. Hence, the effects in countries with worse air quality could be even more pronounced. These findings also have social equity implications since pollution exposure is not evenly distributed across socioeconomic groups. Children from low-income and migrant families are more likely to live in areas of high pollution (e.g., Jerrett *et al.*, 2001; Barnes *et al.*, 2019). Hence, even though we do not find stronger transition-rate effects of LEZ in more deprived areas (Table C.1), the fact that LEZs in Germany can primarily be found in more deprived areas in the first place – areas that are more polluted (Table 1) and have lower baseline socio-economic characteristics (Table **??**) – implies that the policy has helped to reduce educational inequalities.

From a policy perspective, our findings show that policies that effectively target air quality in cities have wide-ranging effects on urban residents. When evaluating the potential costs and benefits of such measures, it should be considered that they are likely to have positive effects on different fundamental areas of people's lives, such as their health, well-being, and productivity. If inadequate air quality prevents the considerable and growing number of children living in urban areas from reaching their full potential, this has severe implications for human capital.

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Appendix A: LEZ Descriptives

Table A.1: Overview sticker rules and requirements

	Sticker categories			
				
	No sticker	Red	Yellow	Green
Requirements **diesel vehicles**	Euro 1 or worse	Euro 2 or Euro 1 with partcile filter	Euro 3 or Euro 2 with particle filter	Euro 4 or Euro 3 with particle filter
Requirements **gasoline vehicles**	Without 3-way catalytic converter			Euro 1 with regulated catalytic converter or better

Source: UBA.

Table A.2: Low Emission Zones in Germany

State	City	Level 1	Level 2	Level 3
BW	Freiburg	01.01.2010	01.01.2012	01.01.2013
BW	Heidelberg	01.01.2010	01.01.2012	01.01.2013
BW	Heidenheim	01.01.2012	01.01.2012	01.01.2013
BW	Heilbronn	01.01.2009	01.01.2012	01.01.2013
BW	Herrenberg	01.01.2009	01.01.2012	01.01.2013
BW	Ilsfeld	01.03.2008	01.01.2012	01.01.2013
BW	Karlsruhe	01.01.2009	01.01.2012	01.01.2013
BW	Leonberg / Hemmingen and surroundings	02.12.2013	02.12.2013	02.12.2013
BW	Ludwigsburg and surroundings	01.01.2013	01.01.2013	01.01.2013
BW	Mühlacker	01.01.2009	01.01.2012	01.01.2013
BW	Mannheim	01.03.2008	01.01.2012	01.01.2013
BW	Pfinztal	01.01.2010	01.01.2012	01.01.2013
BW	Pforzheim	01.01.2009	01.01.2012	01.01.2013
BW	Reutlingen	01.03.2008	01.01.2012	01.01.2013
BW	Schramberg	01.07.2013	01.07.2013	01.01.2015
BW	Schwäbisch Gmünd	01.03.2008	01.01.2012	01.01.2013
BW	Stuttgart	01.03.2008	01.07.2010	01.01.2012
BW	Tübingen	01.03.2008	01.01.2012	01.01.2013
BW	Ulm	01.01.2009	01.01.2012	01.01.2013
BW	Urbach	01.01.2012	01.01.2012	01.01.2013
BW	Wendlingen	02.04.2013	02.04.2013	02.04.2013
BY	Augsburg	01.07.2009	01.01.2011	01.06.2016
BY	München	01.10.2008	01.10.2010	01.10.2012
BY	Neu-Ulm	01.11.2009	05.11.2012	NA
BY	Regensburg	15.01.2018	15.01.2018	15.01.2018
BE	Berlin	01.01.2008	01.01.2010	01.01.2010
HB	Hessen	01.01.2009	01.01.2010	01.07.2011
HE	Darmstadt	01.11.2015	01.11.2015	01.11.2015
HE	Frankfurt a.M.	01.10.2008	01.01.2010	01.01.2012
HE	Limburg an der Lahn	31.01.2018	31.01.2018	31.01.2018
HE	Marburg	01.04.2016	01.04.2016	01.04.2016
HE	Offenbach	01.01.2015	01.01.2015	01.01.2015
HE	Wiesbaden	01.02.2013	01.02.2013	01.02.2013
NI	Hannover	01.01.2008	01.01.2009	01.01.2010
NI	Osnabrück	04.01.2010	03.01.2011	03.01.2012
NW	Aachen	01.02.2016	01.02.2016	01.02.2016
NW	Bonn	01.01.2010	01.07.2012	01.07.2014
NW	Düsseldorf	15.02.2009	01.03.2011	01.07.2014
NW	Dinslaken	01.07.2011	01.07.2011	01.10.2012
NW	Eschweiler	01.06.2016	01.06.2016	01.06.2016
NW	Hagen	01.01.2012	01.01.2013	01.07.2014
NW	Köln	01.01.2008	01.01.2013	01.07.2014
NW	Krefeld	01.01.2011	01.01.2011	01.07.2012
NW	Langenfeld	01.01.2013	01.01.2013	01.07.2014
NW	Mönchengladbach	01.01.2013	01.01.2013	01.07.2014
NW	Münster	01.01.2010	01.01.2010	01.01.2015
NW	Neuss	15.02.2010	01.03.2011	01.07.2014
NW	Overath	01.10.2017	01.10.2017	01.10.2017
NW	Remscheid	01.01.2013	01.01.2013	01.07.2014
NW	Ruhrgebiet	01.01.2012	01.01.2013	01.07.2014
NW	Siegen	01.01.2015	01.01.2015	01.01.2015
NW	Wuppertal	15.02.2009	01.03.2011	01.07.2014
RP	Mainz	01.02.2013	01.02.2013	01.02.2013
SN	Leipzig	01.03.2011	01.03.2011	01.03.2011
ST	Halle (Saale)	01.09.2011	01.09.2011	01.01.2013
ST	Magdeburg	01.09.2011	01.09.2011	01.01.2013

Notes: The LEZ "Ruhrgebiet" consists of LEZs in Bochum, Bottrop, Dortmund, Duisburg, Essen, Gelsenkirchen, Mülheim, Oberhausen, and Recklinghausen and was introduced 01.01.2008. The LEZ was merged and enlargened further, including Castrop-Rauxel, Gladbeck, Herten, and Herne on 01.01.2012.
Source: UBA.

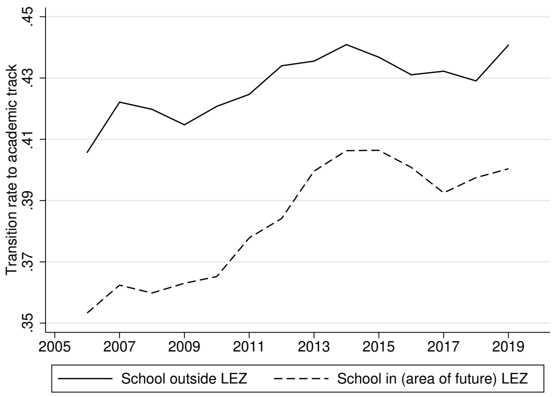
Table A.3: Comparison of the number of students of schools inside and outside of (future) LEZs, NRW

	Schools outside LEZ					Schools inside (future) LEZ				
	count	mean	sd	min	max	count	mean	sd	min	max
Total graduating students	8645	54.0	20.2	1	155	6786	55.0	18.5	2	148
Gymnasium	8645	22.9	13.7	0	98	6786	21.4	13.6	0	128
Realschule	8645	13.0	8.06	0	52	6786	12.4	7.33	0	67
Hauptschule	8645	4.51	5.15	0	45	6786	4.50	5.19	0	46
Gesamtschule	8645	8.21	9.02	0	70	6786	9.65	10.6	0	72
PRIMUS Schule	3303	11.5	9.88	0	73	2935	13.7	11.1	0	58
Gemeinschaftsschule	4530	0.91	2.90	0	46	3903	0.84	2.81	0	34
Sekundarschule	3903	0.36	1.83	0	32	3420	0.41	2.03	0	31
Sonstige	8645	0.33	0.75	0	11	6786	0.44	0.91	0	11

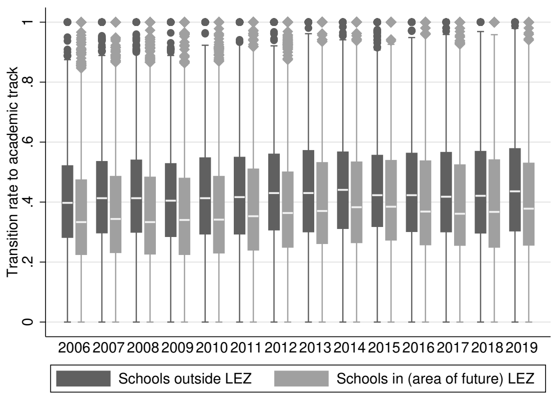
Source: UBA and IT.NRW.

Figure A.1: School level transition rates to Gymnasium in NRW by LEZ status, 2005 – 2018, district-free cities

(a) Panel A



(b) Panel B



Notes: Panel A displays the average transition rates to Gymnasium for schools outside of LEZs and for schools, which at any point in time between 2005 – 2018 are inside a LEZ. In Panel B the school-level transition rates are displayed for both types of schools. Student-weighted rate.
Source: UBA and IT.NRW.

Appendix B: Balancing Tests

Table B.1: Impact of LEZ on school closures after NRW reforms

	School closures (in percent)		
Low emission zone	0.0334	0.0076	0.0330
	(0.0260)	(0.0190)	(0.0217)
Number of observations	17,941	17,941	17,941
Admin. district x Year FE	✓	✓	✓
District FE	-	✓	✓
Time-varying grid-level controls	-	-	✓

Notes: The table depicts the effect of LEZ on the share of school closures, measured on the zip code level. Since the outcome is not measured at the school level, instead of school and year fixed effects (TWFE) we include administrative district by year FE (column 1), district FE (column2), and time-varying grid-level controls (column 3). Comparison sample: large cities (> 100,000 inhabitants). Standard errors clustered at the district level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Table B.2: Grid controls as outcomes to investigate possible compositional changes, stacked TWFE

Purchasing power		
Low emission zone	129.6040	163.2953
	(117.4125)	(108.8304)
Number of observations	177,515	177,515
Unemployment rate		
Low emission zone	-0.1224	-0.0052
	(0.0857)	(0.0858)
Number of observations	177,515	177,515
Share of foreigners		
Low emission zone	0.3872***	0.3083*
	(0.1454)	(0.1648)
Number of observations	177,515	177,515
Share of families		
Low emission zone	0.0140	-1.0896
	(0.4289)	(0.6624)
Number of observations	177,515	177,515
Grid FEs	✓	✓
Year FEs	✓	–
GRID controls (1x1km)	✓	✓
Admin. district × Year FEs	–	✓
Linear district trends	✓	–
Event time × Wave FEs	✓	✓
Group × Wave FEs	✓	✓

Notes: This table shows the results of separate regressions using the time-varying grid control variables as outcomes. The remaining grid variables are used as controls in each regression. Comparison sample: large cities (> 100,000 inhabitants). Standard errors clustered at the district level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Appendix C: Heterogeneities

Table C.1: Treatment effect heterogeneity, stacked TWFE

	Transition rate to academic track	
Purchasing power	**Low**	**High**
Low emission zone	0.0093*	0.0069*
	(0.0042)	(0.0055)
Number of observations	47,806	47,806
Unemployment rate	**Low**	**High**
Low emission zone	0.090*	0.0095*
	(0.0050)	(0.0049)
Number of observations	47,806	47,806
Share of foreigners	**Low**	**High**
Low emission zone	0.0082	0.0090**
	(0.0055)	(0.0045)
Number of observations	47,806	47,806
Share of families	**Low**	**High**
Low emission zone	0.0082*	0.0102**
	(0.0050)	(0.0051)
Number of observations	47,806	47,806
School FEs	✓	✓
School year FEs	✓	✓
GRID controls (1x1km)	✓	✓
Admin. district × Year FEs	✓	✓
Linear district trends	✓	✓
Event time × Wave FEs	✓	✓
Group × Wave FEs	✓	✓

Notes: To determine the effect heterogeneities, we first identify treated schools by LEZ implementation wave and consequently determine their median split of the variable in the year prior to the implementation of the LEZ. The control units in each wave are categorized as "low" or "high" based on the median value of the variable of the treated schools. This procedure is performed for each wave before stacking. Comparison sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate, and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

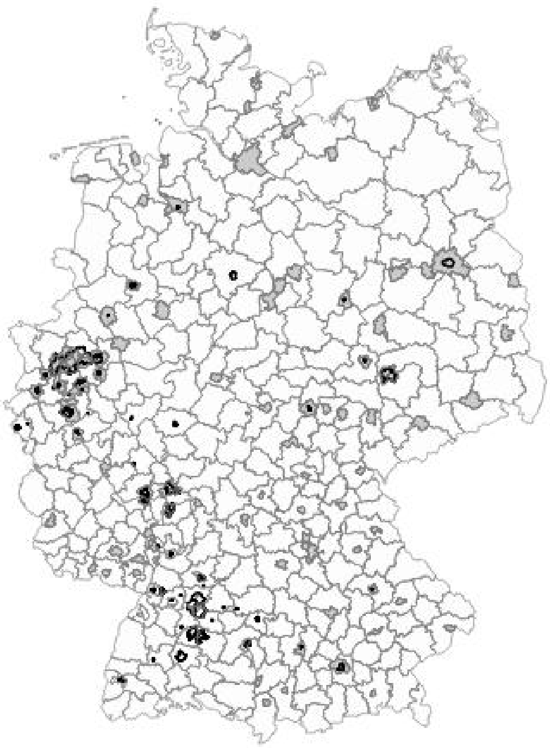
Table C.2: The role of after-school care

	Transition rate to academic track				
Low emission zone	0.0217**	0.0183**	0.0168*	0.0199*	0.0171*
	(0.0091)	(0.0090)	(0.0090)	(0.0106)	(0.0101)
After-school care	-0.0026	-0.0018	-0.0018	-0.0024	-0.0027
	(0.0024)	(0.0025)	(0.0025)	(0.0025)	(0.0025)
LEZ*after-school care	-0.0095	-0.0093	-0.0089	-0.0091	-0.0091
	(0.0095)	(0.0096)	(0.0096)	(0.0104)	(0.0102)
Number of observations	47806	47806	47806	47806	47806
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	✓	✓	✓	✓
GRID controls (1x1km)	-	✓	✓	✓	✓
Admin. district × Year FEs	-	-	✓	–	✓
District linear trends	-	-	-	✓	✓

Notes: Comparison sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate, and the share of households with children. Standard errors clustered at the district level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Appendix D: District-level analysis

Figure D.1: Districts considered for the empirical analysis



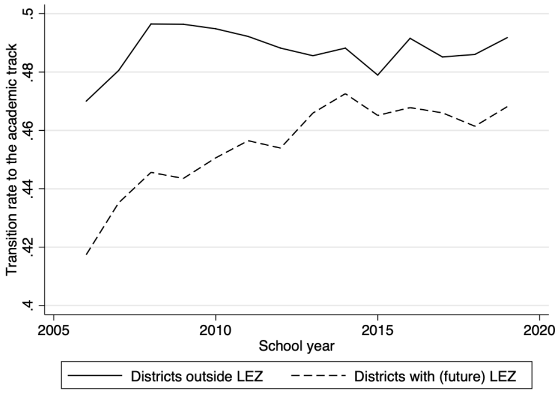
Notes: Comparison sample consists of district-free cities only. Those with a LEZ are considered treated, and those without a LEZ comparison group.
Source: UBA.

Table D.1: Comparison of district-free cities with and without LEZs

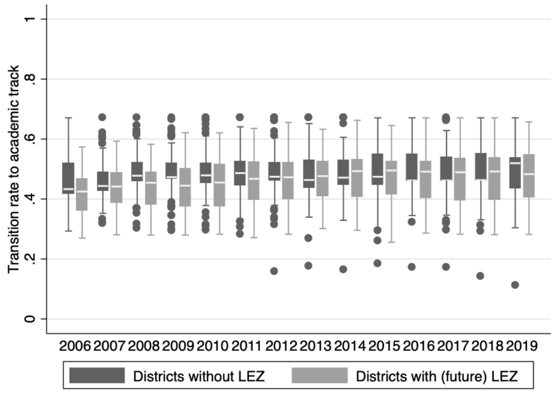
	District-free cities without LEZ					District-free cities with LEZ				
	count	mean	sd	min	max	count	mean	sd	min	max
Age (mean)	900	43.8	1.76	40.3	50.5	547	42.6	1.39	39.7	45.7
Unemployment rate	900	8.26	3.10	2.94	19.4	547	8.94	3.06	3.19	20.1
Gross income	900	2590.9	495.9	1697.0	5196.7	547	2779.8	451.4	1857.7	4274.9
BIP per inhabitant in €	900	45.8	20.6	18.4	188.3	547	46.1	18.1	16.6	96.0
Migration balance	900	5.57	7.20	-40.6	59.3	547	5.87	6.41	-20.8	39.9
Foreigners (%)	900	10.5	4.55	1.39	27.0	547	15.6	5.77	3.06	36.6

Notes: Table shows the two groups' averages between 2005 – 2018.
Source: UBA and bildungsmonitoring.de.

Figure D.2: District-level transition rates to the academic track for districts with and without a LEZ



(a) Panel A



(b) Panel B

Notes: Panel A displays the average transition rates to *Gymnasium* for districts that contain no LEZs and for districts, which at any point in time between 2005 – 2018, contain a LEZ. In Panel B, boxplots of the district-level transition rates are displayed. Students' weights applied.
Source: UBA and bildungsmonitoring.de.

Table D.2: District transition rates to the academic track (TWFE)

	Transition rate to academic track			
Low emission zone	-0.0091	0.0090*	0.0050	0.0042
	(0.0155)	(0.0050)	(0.0039)	(0.0032)
Number of observations	1438	1438	1400	1400
District FEs	-	✓	✓	✓
School year FEs	-	✓	-	-
State × Year FEs	-	-	✓	✓
District control variables	-	-	-	✓

Notes: Comparison sample: district-free cities. Time-varying district controls include district share of foreigners, district-level gross earnings, district net migration, as well as the district unemployment rate. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, bildungsmonitoring.de, and INKAR (BBSR).

Table D.3: District transition rates to the academic track, stacked TWFE

	Transition rate to academic track		
Low emission zone	0.0157***	0.0090	0.0052
	(0.0053)	(0.0077)	(0.0071)
Number of observations	4303	4303	4301
District FEs	✓	✓	✓
Year FEs	✓	–	–
Time-varying controls	✓	✓	✓
State × Year FEs	–	✓	✓
Linear district trends	–	✓	✓
Event time × Wave FEs	✓	✓	✓
Group × Wave FEs	✓	✓	✓

Notes: Comparison sample: district-free cities. Time-varying district controls include district share of foreigners, district-level gross earnings, district net migration, as well as the district unemployment rate. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, bildungsmonitoring.de, and INKAR (BBSR).

Appendix E: Further robustness checks

Table E.1: Impact of LEZs transition rates to the academic track, TWFE

	Transition rate to academic track				
Low emission zone	0.0111**	0.0102**	0.0089*	0.0105*	0.0083
	(0.0046)	(0.0047)	(0.0052)	(0.0057)	(0.0056)
Number of observations	17,859	17,859	17,859	17,859	17,859
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	✓	✓	✓	✓
GRID controls (1x1km)	-	✓	✓	✓	✓
Admin. district × Year FEs	-	-	✓	–	✓
District linear trends	-	-	-	✓	✓

Notes: Comparsion sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Table E.2: Impact of LEZs transition rates to the academic track, stacked TWFE

	Transition rate to academic track				
Low emission zone	0.0134***	0.0102**	0.0090**	0.0119***	0.0091*
	(0.0041)	(0.0043)	(0.0044)	(0.0045)	(0.0046)
Number of observations	47,806	47,806	47,806	47,806	47,806
Event time x Wave FEs	✓	✓	✓	✓	✓
Group x Wave FEs	✓	✓	✓	✓	✓
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (zip code)	–	–	✓	✓	✓
Admin. district x Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓

Notes: Comparison sample: large cities (> 100,000 inhabitants). Grid control variables at the zip code level variables purchasing power per capita, the share of foreigners, the unemployment rate, and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Table E.3: TWFE, only first implementation wave (2008/09)

	Transition rate to academic track				
Low emission zone	0.0148**	0.0136**	0.0121	0.0124	0.0101
	(0.0061)	(0.0064)	(0.0073)	(0.0080)	(0.0083)
Number of observations	15,968	15,968	15,968	15,968	15,968
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	✓	✓	✓	✓
GRID controls (1x1km)	-	✓	✓	✓	✓
Admin. district × Year FEs	-	-	✓	–	✓
District linear trends	-	-	-	✓	✓

Notes: Comparison sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Table E.4: Balanced comparison sample, stacked TWFE

	Transition rate to academic track				
Low emission zone	0.0121***	0.0107**	0.0094**	0.0112**	0.0092**
	(0.0042)	(0.0043)	(0.0043)	(0.0044)	(0.0044)
Number of observations	44575	44575	44575	44575	44575
Event time x Wave FEs	✓	✓	✓	✓	✓
Group x Wave FEs	✓	✓	✓	✓	✓
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district x Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓

Notes: Comparison sample: large cities (> 100,000 inhabitants). Only schools which existed for the entire period under investigation were included. Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Table E.5: Excluding schools in buffers around LEZ, stacked TWFE

Panel A: Excluding schools within a 1000m buffer from LEZ (500m both sides)

	Transition rate to academic track				
Low emission zone	0.0149***	0.0117**	0.0104**	0.0133***	0.0104**
	(0.0051)	(0.0053)	(0.0052)	(0.0049)	(0.0051)
Number of observations	42,757	42,757	42,757	42,757	42,757

Panel B: Excluding schools within a 1000m buffer to the outside border of LEZ

	Transition rate to academic track				
Low emission zone	0.0148***	0.0121***	0.0108**	0.0143***	0.0117**
	(0.0041)	(0.0045)	(0.0045)	(0.0044)	(0.0047)
Number of observations	39,061	39,061	39,061	39,061	39,061
Event time x Wave FEs	✓	✓	✓	✓	✓
Group x Wave FEs	✓	✓	✓	✓	✓
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district x Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓

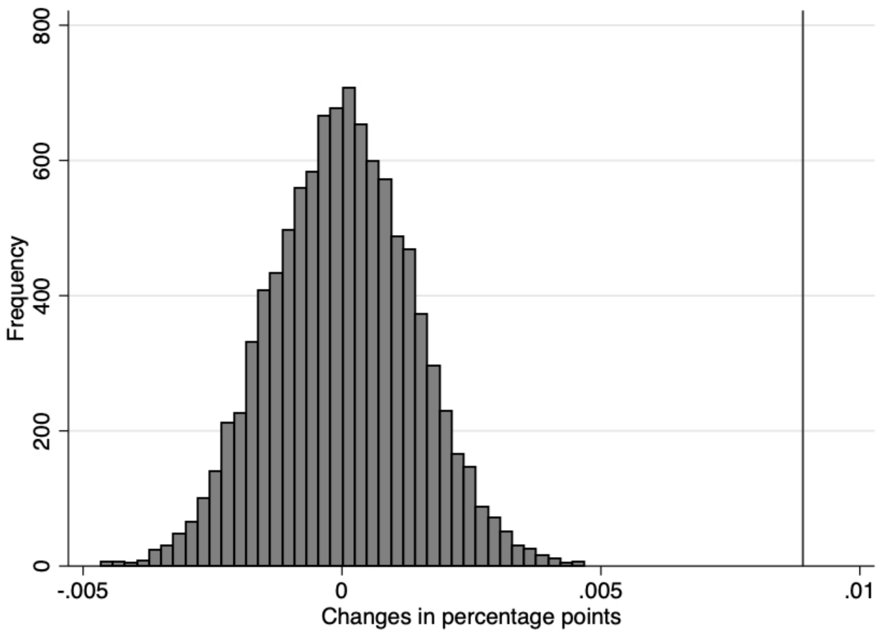
Notes: Stacked TWFE. Comparison sample: large cities (> 100,000 inhabitants). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate and the share of households with children. Standard errors clustered at the district level. *** p<0.01, ** p<0.05, * p<0.1.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Table E.6: Excluding comprehensive schools, stacked TWFE

	Transition rate to academic track				
Low emission zone	0.0169***	0.0141**	0.0121*	0.0206***	0.0199***
	(0.0064)	(0.0069)	(0.0069)	(0.0074)	(0.0073)
Number of observations	47,785	47,785	47,785	47,785	47,785
Event time x Wave FEs	✓	✓	✓	✓	✓
Group x Wave FEs	✓	✓	✓	✓	✓
School FEs	✓	✓	✓	✓	✓
School year FEs	✓	–	–	✓	–
GRID controls (1x1km)	–	–	✓	✓	✓
Admin. district x Year FEs	–	✓	✓	–	✓
Linear district trends	–	–	–	✓	✓

Notes: Comparison sample: large cities (> 100,000 inhabitants). Here, we compare the transition rate to the *Gymnasium* to transition rates to the *Realschule* and *Hauptschule*, thus excluding comprehensive schools (*Gesamtschulen*) which also offer the option of graduating in the academic track (see Section 3.2). Grid control variables include purchasing power per capita, the share of foreigners, the unemployment rate and the share of households with children. Standard errors clustered at the district level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Figure E.1: Permutation Test



Notes: The figure displays the distribution of 10,000 placebo estimates of the TWFE regression in Column 3 in Table E.1. Sample: large cities (> 100,000 inhabitants). Grid control variables Standard errors clustered at the district level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: UBA, IT.NRW, and RWI-GEO-GRID.

Appendix F: Channels

Table F.1: The impact of LEZ on asthma prevalence at age 9-10

	Respiratory disease	
Low Emission Zone	-0.126**	-0.100*
	(0.055)	(0.051)
Male		0.045
		(0.038)
LEZ $\times$ male		-0.049
		(0.058)
Number of observations	1293	1293

Notes: Pooled OLS regression controlling for district and survey year fixed effects, and individual control variables (parental education and employment status, number of children in the household, migration background, log income, social transfer receiving household). Standard errors are clustered on the district level. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.
Source: SOEP v35 and UBA.