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Abstract

Air pollution has a major detrimental impact on population health but little is known about the effectiveness of policy measures targeting pollution. I exploit the staggered implementation of low emission zones in large cities in Germany as a natural experiment to asses their health impact. Using outpatient and inpatient health care data, I demonstrate that low emission zones reduce the number of patients with cardiovascular diagnoses by 2-3 percent. This effect is particularly pronounced for the elderly above 65. The findings suggest that this kind of policies can be an efficient way to reduce air pollution and improve health.

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Introduction

Traffic contributes to more than one quarter of ambient air pollution in urban areas (Umweltbundesamt, 2018). Various solutions such as direct user charges, congestion pricing, license plate based restrictions, and low emission zones have become popular tools to reduce trafficinduced pollution (Davis, 2008, Simeonova et al., 2019, Wolff, 2014). The policies aiming to improve air quality primarily target population health: pollutants such as particulate matter, nitrogen oxides and ozone can exacerbate already existing medical conditions and in some cases even cause them. Despite the considerable attention paid to traffic and pollution effects of such regulations, little is known about the extent of health effects they entail.

This paper studies the effects of one particular regulatory instrument, namely low emission zones (LEZs) on air pollution and cardiovascular health. LEZs are designated areas that restrict cars' access based on their emission class. Since 2007, multiple cities in Europe and particularly in Germany enacted such zones. Across countries and cities LEZs vary in their operating hours and vehicle exclusion restrictiveness. LEZs in Germany are among the tightest, as they impose a permanent ban over all week days and hours, and the restrictions apply to all vehicles, with few exemptions. The roll-out started in 2008 as a response to most major cities not complying with the EU Air Quality Standards. The zones were introduced in three phases, and each phase excluded an additional emission class of vehicles. The rich temporal and spatial variation in LEZs implementation combined with their restrictiveness provides a compelling setting to study the impact of LEZs on ambient air pollution and population health in the German context.

I exploit the across-space and over time variation in the introduction of LEZs across Germany in a difference-in-differences design as a quasi-experiment to study the impact of LEZs on air pollution and cardiovascular health. I use air pollution measurements from the German Environmental Agency covering the period 2004-2016. I focus on two criteria pollutants: particulate matter of aerodynamic diameter below ten (PM_{10}) and nitrogen dioxide (NO_2), since vehicle exhaust is a dominant source of their emission.[1] To evaluate the impact on health, I use a novel data that covers all outpatient statutory health insurance

[1] Vehicle exhaust is a major contributor of carbon monoxide (CO) emissions as well. However, there are fewer CO monitors and CO concentrations are significantly below the limit values across the country.

claims in Germany in the period 2009-2017. I complement the outpatient data with administrative records from hospital admissions for the years 2004-2014.

I find that LEZs reduce monthly PM_{10} concentrations by 2-3%. The reductions in monthly NO_2 concentrations are smaller in magnitude and often imprecisely estimated. These effects corroborate the findings from previous evaluations of LEZs in terms of their effect on air pollution (Wolff, 2014, Gehrsitz, 2017, Malina and Scheffler, 2015). The findings regarding population health from outpatient data suggest a reduction in cardiovascular disease in the magnitude of 2-3%. The reductions are particularly strong for cerebrovascular disease (7-12.6%) and for the elderly. The analysis of the hospital admission data suggests a reduction in the number of people admitted with a cardiovascular disease as well, however the point estimates are imprecisely estimated.

This paper focuses on cardiovascular disease as the outcome for two reasons. First, this disease group generates the highest costs in the German health care system and is the leading cause of death worldwide.[2] Second, series of epidemiologic studies show the adverse effects of air pollution on cardiovascular health (Pope C A, 2000, Brook et al., 2004, Peters et al., 1999, Tsai et al., 2003). The adverse relationship can be observed even at levels below commonly targeted concentrations (Mills et al., 2009). The toxicity of PM_{10} depends on its size and its chemical composition: many of the individual components of atmospheric PM are not especially toxic at ambient levels, whereas combustion-derived particles carry hazardous compounds on their surface (Mills et al., 2009). Particles have two major pathways that trigger the health impact: they can cause a systemic inflammation and can translocate directly into the circulation. Regardless of the pathway, the inhaled particles trigger a range of biological responses, such as elevated heart rate, blood pressure and heart variability, which onset cardiovascular disease.[3] The burden of cardiovascular risk from pollution exposure mainly falls on the elderly and individuals with pre-existing chronic medical conditions (Brook et al., 2010, Wellenius et al., 2005, Hong et al., 2002).

This paper adds to the existing literature in several ways. It builds on the large literature linking air pollution and health, by providing evidence on the effectiveness of low emission zones as a policy instrument. Despite the rich evidence available on the direct link between

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[2] According to the German Federal Statistical Office, 13.7% of health care costs in 2017 were generated by cardiovascular disease (Statistisches Bundesamt, 2017). [3]For a detailed discussion please see Mills et al. (2009).

pollution and health, little is known about the general health effect of policy instruments targeting air pollution. In a previous evaluation of LEZs, Gehrsitz (2017) finds no effect on infant health. The absence of effects on infants, however, does not rule out health improvement for other population groups. Quantifying the general health impact is important since the main argument for enacting LEZs is population health. A recent working paper by Pestel and Wozny (2019) analyses the effects of LEZs in Germany as well, however the authors only use hospital quality report data where they cannot identify the place of residence of the patient.

Second, most of the existing literature focuses on infant and children respiratory health, while only a few papers also examine the effect on the elderly.[3] Two studies using policyinduced variation look at infant health by exploiting electronic toll collection in New Jersey and Pennsylvania (Currie and Walker, 2011) and childhood asthma by exploiting congestion pricing in Stockholm (Simeonova et al., 2019). This paper adds to the literature by providing evidence for cardiovascular disease for the entire population and the elderly. The elderly are of particular interest here, because of their susceptibility and the commonness of circulatory system illnesses.

Third, most studies evaluating the effect of air pollution on health use temporal variations in pollution levels over a short period of time (typically a day or a week), which allows to estimate the impact of immediate exposure, but provides little guidance in terms of longterm exposure effects.[4] This paper adds to the small number of papers analysing the effects of long term marginal reductions in pollution in a setting with relatively low pollution levels (Gehrsitz, 2017, Simeonova et al., 2019, Alexander and Schwandt, 2019). The nature of the present quasi-experiment and the availability of the rich and novel data over a long period enables to evaluate health effects up to eight years after the policy introduction. Furthermore, the national annual average level of PM_{10} in Germany was around 23 $\mu g/m^3$ in 2007–before the roll-out of LEZs. Typical background concentrations of PM_{10} range between 20 and 50 $\mu g/m^3$ in developed countries and increase to between 100 and 250 $\mu g/m^3$ in developing countries (Mills et al., 2009).

[3] See (Chay and Greenstone, 2003, Currie and Neidell, 2005, Currie et al., 2009, Coneus and Spiess, 2012, Neidell, 2004, 2009, Lleras-Muney, 2010, Beatty and Shimshack, 2011, Janke, 2014, Simeonova et al., 2019, Alexander and Schwandt, 2019) for papers on infant and children health, and (Beatty and Shimshack, 2011, Schlenker and Walker, 2016, Deryugina et al., 2016) for adult health.

[4] See for example Schlenker and Walker (2016), Neidell (2009), Deryugina et al. (2016).

The remainder of the paper is organized as follows: the next section provides the background on LEZs in Germany and section three describes the data. Section four discusses the results for air pollution. Section five presents the main results, alongside with robustness checks. Finally, section six concludes.

Low Emission Zones

The EU Clean Air Directives are among the strictest air quality standards worldwide. The first attempt to regulate the air quality in EU member states has been the directive 96/62/EC of the Council of the European Union, establishing the legal framework for ambient air quality regulation in all member states "to avoid, prevent or reduce harmful effects on human health and the environment as a whole". The directive defines how air quality should be assessed, specifies the pollutants for which alert thresholds and limit values should be introduced, and lists the measures member states should take to improve air quality. The daughter Directive 1999/30/EC establishes numerical limit values and alert thresholds for criteria pollutants. It divides the PM_{10} regulations into two phases: 2005-2009 and 2010 onwards with the aim to tighten PM_{10} regulations in 2010. Effective January 1 2005, the daily average of PM_{10} concentrations must not exceed 50 $\mu g/m^3$, and the yearly average should not exceed 40 $\mu g/m^3$. For the daily threshold 35 transgressions days are permitted. For NO_2, the daily average concentrations are limited to 200 $\mu g/m^3$, with 18 transgression days and the yearly average should not exceed 40 $\mu g/m^3$. The stricter regulations have not been phased-in as most EU members struggled to meet the 2005 regulations.[5] Table 1 summarizes these regulations.

Between 2005 and 2007, 79 cities in Germany violated the daily threshold for PM_{10} and among them 12 violated the yearly threshold as well according to estimations in Wolff and Perry (2010). The EU can impose significant financial penalties and even start infringement proceedings in case of non-compliance. Hence the German government mandates that cities where even one pollution monitoring station violates the thresholds must develop a clean air action plan. Clean Air Action plans include four main elements: expanding public transportation, utilising ring roads, improving traffic flow and most importantly

[5] Instead EU introduced new regulations for $PM_{2.5}$ in 2008 (directive 2008/50/EC).

implementing LEZs (Wolff, 2014).[6] LEZs are designated areas that ban cars from accessing the zone based on their emission class.

LEZs are phased-in with increasingly stricter restrictions. Vehicle restrictions are motivated by EU-wide tailpipe emission categories that correspond to four emission classes. Each car receives a windscreen badge of the respective colour. Phase 1 bans access only to vehicles with no stickers (Euro 1 or lower). Subsequently, Phase 2 additionally bans red sticker vehicles (Euro 2), and Phase 3 further restricts access of yellow sticker vehicles (Euro 3).[7] Figure 1 plots the timing of the three phases.[8] The fine for violation is 40 Euro and a driving penalty point.[9]

There is a vast temporal and spatial variation in the introduction of zones. The first zones were enacted in 2008. Among early introducers are Berlin, Hannover and Cologne, as well as cities in the Ruhr area, which in January 2012 united into a common LEZ for the Ruhr area, covering 869 km^2 and including 2.5 million residents. Not all LEZ-cities are non-attainment cities and vice versa: a number of non-attainment cities refrained from implementing LEZs.[10] Figure 2 illustrates the sample composition as well as spatial and temporal variation that I exploit in the empirical design. White perimeters represent the large cities which by 2017 have had no LEZ. The colour-coded perimeters represent the large cities that introduced an LEZ in the observation period. Each colour represents a group that enacted the zone in the given year. Towns and rural areas, shaded by grey, are excluded from the sample.

Table A.2 in the Appendix presents the detailed list of the LEZ cities, with the enactment date, the areal coverage, and the attainment status of treated cities. Since each city is responsible for designing, enacting, and enforcing the LEZs, there is large variation in the proportional size of LEZs: the coverage ranges from as little as 1% of the city area to just below 100% covering the entire city. The perimeters are not randomly drawn–they mainly cover (potential) non-attainment areas of cities. Additionally, factors such as composition of the local fleet, urban layout, and social justice matter for designing the zones.

[6] Wolff (2014) shows that the other elements of APs in general do not have a significant effect on PM_{10}.

[7] Table A.1 in the Appendix present details on tailpipe emission regulations.

[8] Some cities that introduced LEZs in 2011 or later, enacted zones already as phase two or three.

[9] The drivers lose their license after accumulating 18 points. However the fine for LEZ violation was replaced with 80 Euro and no penalty points in May 2014.

[10] Attainment and non-attainment in this context mean cities that comply with air pollution regulations and cities that do not.

Previous evaluations of LEZs in Germany all suggest that the zones reduce PM_{10} concentrations in treated cities. The first evidence comes from Wolff (2014), who analyses the short-term effects of LEZs until October 2008. He finds around a 7-9% drop in daily PM_{10} levels. Further evaluations support these initial findings, despite differences in time span and in composition of treatment and control units (Malina and Scheffler (2015), Morfeld et al. (2014), Jiang et al. (2017), Gehrsitz (2017)). In the most recent evaluation Gehrsitz (2017) finds around a 4-8% reduction in daily PM_{10} levels, and around a 3.4% decrease in daily nitrogen dioxide (NO_2) levels. Gehrsitz (2017) additionally analyses potential effects on infant health, measured by birth weight, the incidence of low birth weight, and still birth.

He finds virtually no effect.

Data

To study the effect of LEZs on air pollution I combine data from multiple sources. I obtain daily PM_{10} and NO_2 measurements from the German Environmental Agency for the period 2004 to 2016. The sample consists of 264 PM_{10} monitoring stations and 261 NO_2 monitoring stations in 69 cities. Using the precise geographic coordinates of each station I locate whether it is inside or outside an LEZ.[11] To account for weather-pollution interaction, I additionally collect weather data from the German Weather Service (Deutscher Wetterdienst, DWD). The data contain information on daily temperature, wind speed, precipitation, cloud cover, vapour, air pressure, and relative humidity. I match each air quality monitoring station to its geographically closest weather station and aggregate the daily measurements at the monitoring station-month level.

To study the health impact of LEZs, I draw on outpatient health data from the Central Research Institute of Ambulatory Health Care (Zi). These data comprise nationwide ambulatory care claims for patients of all statutory health insurance funds in Germany. The data are yearly and cover the period 2009-2017. This is a novel data source, which contains information on patients' postal code of residence. Because of data protection laws, it is not possible to obtain data on the postal code level directly. Instead, I obtain the number of patients with the diagnosis of interest, aggregated separately for control cities and by the

[11] The geographic coordinates are provided by the German Environment Agency. To classify the stations I rely on open source polygons of Low Emission Zones from OpenStreetMap.

areas inside and outside a low emission zone for treated cities. The diagnoses are coded according to the 10th revision of International Classification of Disease (ICD10). Figure 3 illustrates the observation level with the example of Berlin. The grey shaded area covers the Berlin LEZ. Hence for Berlin, I obtain yearly aggregated data for the grey and white shaded areas separately. The advantage of this breakdown is that the treatment status can be defined very precisely. For cities that have no LEZ, I obtain the aggregated number of patients for the city as a whole.

My main outcome is the number of patients with cardiovascular disease (I00-I99). The data also allow to separately analyse heart disease (I20-I49) and cerebrovascular disease, including stroke (I60-I66), and to zoom into certain age groups. Of central interest are elderly over 65, however I also show results for the age groups 15-29 and 30-64. The data for younger patients is unreliable: the data confidentiality requires to censor all cells with less than 30 observations, which for patients under 15 results in a large number of missing values.

I complement the main analysis with additional data from the Hospital Diagnosis Statistics of the Federal Statistical Office. The inpatient administrative register comprises 70% random sample of all hospital admissions between 2004-2014, including emergency room admissions without overnight stay. The data provide information on a patient's date of admission and discharge, primary diagnosis, city of residence, as well as age and gender. However, it has two major caveats: first, identifying whether the patient lives inside or outside an LEZ is not possible. Consequentially, I define the treatment status by city of residence. Second, hospital admission is a severe outcome, particularly so in Germany, where hospitals are obliged to justify that an outpatient treatment is insufficient.

Panel A of Table 2 shows the means of PM_{10}, NO_2 and inpatient health outcomes in 2007 and reports the two sided p-value of the null hypothesis that the levels of these variables were the same in treated and untreated cities. I choose 2007 as it is the last year before the first roll-out of LEZs. For proxying the baseline differences in health outcomes I use inpatient data, as the outpatient data is available only starting in 2009. Since LEZs are mainly measures employed in urban areas, I restrict the sample to cities with more than 100,000 residents to increase comparability between treated and untreated units. In this sample, the treated units are the cities that have introduced an LEZ during the observation period, and control units are cities that have not introduced an LEZ by the end of the observation period.[12]

The annual average levels of PM_{10} and NO_2 in 2007 are, as expected, different between treated and untreated cities. LEZ cities have on average higher PM_{10} and NO_2 concentrations in 2007, and these differences are statistically significant. Note however, that even in non-attainment cities the annual concentrations of both pollutants are relatively low. Hence results should be interpreted in the context of reductions against already low reference levels. In contrast to pollution, the prevalence of cardiovascular disease, measured as the number of hospital admissions with the given diagnosis per 10,000 inhabitants, appears to be statistically indistinguishable between treated and untreated cities.

It is straightforward to control for baseline differences, as long as the main identifying assumption holds. That is, that the trends between LEZ and non-LEZ cities do not differ systematically for reasons other than the implementation of zones. To provide a suggestive evidence towards this assumption, Panel B of Table 2 reports the *p*-values from a test of the null hypothesis that the year-on-year changes in all outcomes are different from zero. The results show that in the majority of cases the yearly changes in outcomes are not statistically different between treated and untreated cities before 2008.

The Effect of LEZs on Air Pollution

I first investigate how LEZs affect air pollution, and then turn to health outcomes. As before I restrict the sample to cities with more than 100,000 residents. To evaluate the effect of LEZs on pollution, I estimate the following equation:

$$y_{ict} = \alpha + \beta LEZ_{ict} + M_t + S_i + W_{ict} + \epsilon_{ict} \quad (1)$$

where y_{ict} is the monthly average concentration of PM_{10} or NO_2 at station i at time t in city c. LEZ_{ict} indicates whether a station i is located inside an LEZ at time t in city c. M_t and S_i are year-month and monitoring station fixed effects. Including station fixed effects accounts for

[12] Note that the introduction of the zones continues and by 2019 many of the control units have enacted their LEZs as well.

time-invariant differences in the level of pollution between the stations (and, hence, also between the cities as the stations are nested in cities) and ensures that identification comes from within-station variation over time. Year-by-month fixed effects net out time shocks that commonly influence pollution in the cities. Furthermore, the vector W_{ict} includes a set of controls for weather, in particular, average temperature, its quadratic, maximum and minimum temperature, average humidity and its quadratic, an interaction term between average temperature and humidity, average air pressure, average precipitation and its quadratic, average wind speed, a dummy variable indicating rainfall, and an interaction term between average wind speed and average temperature. $_{ict}$ is the error term. I cluster standard errors at the city level to allow for serial correlation within cities over time.

I estimate a variant of equation (1) excluding all pollution monitoring stations located in a treated city but outside a low emission zone. These stations might be subject to negative spillover if drivers take longer tours to avoid LEZs or positive pollution spillovers if the introduction of zones leads to a change in fleet composition or a drop in car usage in general.[13]

Table 3 reports the results for PM_{10} in columns (1)-(3) and for NO_2 in columns (4)-(6). The results suggest that LEZs reduce monthly PM_{10} concentrations by 0.6-0.9 $\mu g/m^3$. The coefficients are larger in magnitude in the subsample without the monitoring stations located outside LEZs. The estimated coefficient is 0.9 $\mu g/m^3$ in column (3) which translates into a 3% decline in monthly PM_{10} relative to the average concentration levels in pre-LEZ period at treated stations. The findings for NO_2 suggest a small, if any, reductions in monthly concentration. After controlling for weather covariates, the effect becomes statistically insignificant. Importantly, the findings for PM_{10}, being comparable in column (2) and (3) suggest negligible spillovers in either direction.

To capture the dynamic effect of LEZs on pollution, I estimate an event-study model:

$$y_{ict} = \alpha + \sum_{k=-5,k\neq-1}^{5} \beta^k LEZ_{ik} + M_t + S_i + W_{ict} + \epsilon_{ict} \tag{2}$$

[13] In fact, Wolff (2014) shows that the adoption of “green sticker” cars increases in untreated cities that are geographically closer to a city that has an LEZ.

where the dummy variables LEZ_{ik} indicate yearly lags and leads of up to five years before and after the introduction of LEZs. The reference category is the period -1, hence the effects are relative to the year immediately before the enactment. The rest of the controls are as specified in equation (1). Figure 4 presents the coefficients from the event study. The graph also provides suggestive evidence for the common-trend assumption if the coefficients in the periods before the introduction of LEZs are zero. The event study plots suggest that common trend assumption is likely to hold, as all coefficients before-LEZ are close to zero and statistically insignificant. The event plots also suggest that the reduction in pollution levels were stronger from the third year onward, compared to the year just before the enactment of the zones.

These results are broadly in line with previous findings (Wolff, 2014, Malina and Scheffler, 2015, Gehrsitz, 2017). For comparison, Wolff (2014) finds a reduction of 9% in PM_{10}, and Gehrsitz (2017) find a reduction of 2.5% on average.

The Effect of LEZs on Cardiovascular Health

This section presents the main findings of the paper. To analyse the outpatient data I estimate the following regression specification:

$$log(y_{ict}) = \alpha + \beta LEZ_{ict} + transition_{ict} + T_t + D_i + \epsilon_{ict}, \quad (3)$$

where the outcome is the number of patients with the given diagnose in logarithms in area i in year t. LEZ_{ict} indicates whether the area i in city c has LEZ in January of year t. While most cities enact their LEZs at the beginning of the year, some introduce theirs later. Thus I separate those periods by including the dummy *transition* that is one for all years when the zone was active for less than 12 months. T_t and D_i are year and area fixed effects. Including area fixed effects accounts for time-invariant differences and ensures that identifying variation comes from within-area variation over time. It also takes into account general differences in size of the areas. Year fixed effects net out common time shocks and trends that affect all
areas similarly.

As section 3 discusses, the main caveat of outpatient data is the unavailability of the data before 2009, while the roll-out of LEZs started already in 2008. This data restriction is particularly meaningful if the effect of LEZs on health is time-varying. Goodman-Bacon (2018) shows in a recent working paper that in difference-in-differences framework (DiD) with timing variation every unit acts as a control unit at some point. Hence, treatment effects that pick up over time in the post-treatment period will lead to a downward bias in the DiD coefficient. Therefore, I also present the results based on the sample that excludes previously treated cities from the estimation. Subsection 5.2 shows the event dynamics of the coefficents and implements the proposed decomposition in Goodman-Bacon (2018).

Main Results

Table 4 presents the main results for cardiovascular disease. Columns with odd numbers draw no restrictions on the sample, while columns with even numbers restrict observations to cities that introduce LEZs after 2009, thus excluding all previously treated cities from the estimation. Panel A presents the effect of LEZ on all cardiovascular disease. Column (1) suggests a reduction in the number of patients with cardiovascular diagnoses by 1.9%. Column (2) suggests an almost two times larger reduction in the restricted sample (–3.3%) for patients of all ages. This reduction translates into 1.4 less patients yearly per 10000 people. Columns (3) and (4) present the effect for elderly over 65. Again the point estimates suggest a 2-3% reduction in the number of patients. This translates into approximately 10 less patients yearly per 10000 elderly.

In Panel B and C, I further slice the cardiovascular diagnoses into two subgroups: heart disease and cerebrovascular disease. The estimates suggest that a reduction in heart disease is statistically significant only in the restricted sample. Here the effects are pronounced for elderly above 65. The effect on cerebrovascular disease follows a similar pattern, suggesting a strong reduction of 7-12% both for the overall population and the elderly.

To compare the effect of LEZs across age groups Figure 5 plots the coefficient from the restricted sample for age groups 15-29 and 30-64, juxtaposing these coefficients to the effect for population over 65. The figure shows that the number of all cardiovascular diagnoses decrease for all age groups, however the largest reductions are indeed observed for the elderly patients. The pattern is different when separating the diagnosis group into heart disease and cerebrovascular disease. The estimates suggest that heart disease improves only for the elderly, while cerebrovascular disease improves for middle aged adults as well.

The analysis in this section suggests that the LEZ-induced reductions in air pollution lead to a lower number of patients with cardiovascular disease, particularly among the elderly. The size of the effect appears reasonable. For example, it is roughly comparable to the excess cardiovascular risk of smoking one cigarette a day, which is around 4% (Law et al., 1997). A different reference point provides the recent paper by Simeonova et al. (2019). The authors estimate that the Stockholm congestion tax zone reduced PM_{10} and NO_2 by 5-15% and asthma diagnoses for children by 30%. Assuming linearity, this implies a 2-6% reduction in asthma diagnoses for each percent decrease in pollution. The estimates in this paper are comparable to the lower bound of the effects in Simeonova et al. (2019).

Event study and Goodman-Bacon decomposition

The estimated coefficients in the Tables 4 report the effect of LEZ averaged over the entire study period. However, the LEZ-induced pollution reductions may have a lagged effect on health that may also change over time. Hence, I estimate an event-study model as follows:

$$log(y_{ict}) = \alpha + \sum_{k=-3,k\neq-1}^{4} \beta^k LEZ_{ik} + T_t + D_i + \epsilon_{ict} \tag{4}$$

Figure 6 presents the event study graphs for all cardiovascular diagnoses for the entire population and elderly over 65.[14] Each figure presents the coefficients and their 95% confidence intervals from the entire sample (red line) and after restricting the sample to cities treated after 2009 (blue line). The left panel plots the results for the entire population, and the right panel–for the elderly. Both graphs shows that the trends in cardiovascular disease between treated and untreated cities display no clear trend before the implementation of LEZs. Upon LEZs' enactment, the number of patients falls in treated cities at a faster rate than in untreated cities. Both graphs also show that the treatment effects are not time-constant: their absolute magnitude tends to become larger the longer are LEZs in place.

Time-varying treatment effects might bias the DiD estimate away from the true effect, as discussed in Goodman-Bacon (2018). The author shows that in difference-in-differences designs with timing variation the DiD regression coefficient is a weighted average of all

[14] Figure A.1 in the appendix presents the event study graphs for outpatient data.

possible DiD coefficients of two-group two-period (2x2) comparisons, where the weights depend on the sample share and the treatment variance in each pair. It is possible to decompose and visualize each of these 2x2 DiD estimates against their weight. The decomposition illustrates how average DiDs vary across types of comparisons and which comparisons matter most.

To illustrate the proposed decomposition, Figure 7 plots the DiD estimates for cardiovascular health for the present setting. The graphs refer to all cardiovascular diagnoses from the entire sample for the overall population and the elderly. The vertical axis plots the 2x2 estimate for each pair and the horizontal axis plots the weight each of these pairs receive. The horizontal line shows the DiD estimate. The figure highlights the influential role of the pair "treatment versus never treated". In both figures 68% of the variation comes from this comparison. This is not coincidental, as the variation share reflects the sample shares and the treatment variance, which are identical for both outcomes. The pure timing group comparisons get very small weights (2.5% for "earlier group treatment versus later group control", and 6.4% for "later group treatment vs earlier group control").

The figures also illustrate that the regression DiD coefficients might be smaller in magnitude due to time-varying effects. As the hollow circles show, the treatment versus already treated comparison mostly generates positive DiD coefficients with non-negligible weight (23.6%). It is possible to take out the bias from time-varying effects by subtracting the weighted average of all 2x2 DiD comparisons where the controls are the already treated units.

This provides insight into why the DiD coefficients in Table 4 become larger in magnitude after excluding cities, which introduce LEZs before 2010. This empirical exercise supports the main findings and motivates the latter specification as the preferred specification.

Additional results: Inpatient hospital data

I supplement the evidence from outpatient data with inpatient data from the hospital admission records. The inpatient data offers the advantage of encompassing a longer time period before the roll-out of the zones. To construct the outcome variable I count the number of episodes with cardiovascular diagnosis for each calendar year for the entire population and for elderly above 65 separately. To evaluate th effect of LEZs on health using hospital data I estimate a variant of equation (3), where the outcome is the number of hospital admissions with the given diagnosis per 10,000 population in logarithms in city *c* in year *t*. I add further time-varying controls at the city level, namely GDP per capita, unemployment rate, average age of the population and the number of deceased. Table 5 presents the results. All estimates point to reductions in hospital admissions with cardiovascular disease. However, none of the estimates are precisely estimated at the 95% significance level. Two shortcomings of hospital data might explain this imprecision. First, the data contains no information on whether the person lives inside or outside an LEZ. Second, the inpatient data includes the cases that end up in a hospital, hence while it is ideal for studying severe cases, it is less suited for studying all cases that can be handled by outpatient care.

Additional results: Change in Car Fleet Composition

It is important to note that the bite of LEZs has changed since their early implementation as the composition of the car fleet adapted. Figure 8 illustrates this development. I draw the data from the German Federal Motor Transport Authority (Kraftfahrtsbundesamt Flensburg). It includes the yearly total number of passenger vehicle registrations by Euro-class for large cities between 2007 to 2017 reported on January 1 of each year. Although the assigned emission group also depends on the tax class of the car and the existence of a particle filter, it is still mainly determined by the Euro class of the car.[15] In 2007, the share of Euro

1 cars was close to 20% of the entire passenger car fleet, while in 2017 this share was below 2%. In the meantime, the share of Euro-4 and higher class cars has increased rapidly. The rapid adaptation of the fleet reduces the practical effectiveness of the policy.

Robustness checks

One concern is that the implementation of LEZs might be correlated with simultaneous socioeconomic changes that affect pollution and health outcomes. To test for such violations, I run balancing regressions that use socioeconomic characteristics of cities as dependent variables (Pei et al., 2018, Alexander and Schwandt, 2019). I collect data on unemployment rate, GDP per capita, industrial output, output of health and other services and population

[15] It is likely that the share of the Euro-1 cars in the graph is the upper bound.

density for the years 2004-2016 from the Federal Statistical Office. Table 6 shows corresponding results. I regress the outcome variables (in the heading) on the low emission zone indicator, along with city and year fixed effects. Reassuringly, the coefficients on the LEZ indicator are insignificant in all regressions.

Table 7 performs several sensitivity checks to test the robustness of the main findings.[16]As Table 2 shows, treated cities had a higher level of pollution in 2007, compared to untreated cities. This raises worries about policy endogeneity. To mitigate these concerns Panel R1 tests the sensitivity of the coefficients to the sample composition. Namely, it restricts the estimation sample to treated cities, meaning that the variation comes solely from the timing of the policies. Reassuringly, the point estimates remain similar.

A further issue might be the implementation of anti-pollution measures other than LEZs. As discussed in Section 2 LEZs are not the only instruments that cities enacted as a part of Clean Air Action Plans. If these measures are successful in reducing pollution in untreated cities, the DiD estimates will be downwardly biased. Thus in Panel R2, I add a contemporaneous indicator variable for Clean Air Action Plans in untreated cities. The results in Panel R2 show that the point estimates remain similar to the baseline results. Wolff (2014) also shows that there is little indication that other elements of Clean Air Action Plans have been effective.

Next I address the sensitivity of results with respect to the definition of the outcome. In Panel R3 of Tables 7 I use the number of patient-cases as the outcome instead of the number of patients as in the main specification. This definition of the outcome should capture the intensive margin of the treatment effect as it also counts the multiple visits by the same patient. The results suggest that there is little difference between the intensive and extensive margin of the treatment effect. In Panel R4 I modify the definition of the outcome in a different way. Here I calculate prevalence rates by dividing the number of patients with a given cardiovascular diagnoses by the number of all patients with any diagnoses in the respective age group. This definition is also useful as the total number of patients is likely to approximate the population numbers, which are not available at the observation level of the health data. As the panel R4 shows, the results remain comparable in magnitude to the main estimates.

[16] Table A.3 in the appendix presents the sensitivity checks of air pollution results.

In Panel R5, I generate the timing of the LEZ enactment randomly for all treated cities and drop all the observations after the true treatment date. Reassuringly, the placebo timing has no effect on health outcomes.

In Panels R6-R8 I aggregate the outpatient data at the city level. The aggregation helps to examine whether the cardiovascular health improvements exist at the level of a treated city or only within the boundaries of LEZs. This aggregation also allows to adjust the outcome by population size. Panel R6 presents the results from a specification equivalent to the main regression, where the outcomes are aggregated at the city level. The point estimates are very small and statistically insignificant both for the entire population and the elderly. This emphasizes the importance of treatment definition precision. To examine the issue further, Panel R7 replaces the binary LEZ indicator with the size of the zone, calculated as a percentage of the entire area of the city, ranging between 0 and 1. The point estimate suggest that when the relative size of the zone increases by 10 percentage points, the number of patients with cardiovascular disease in a city decreases by 5% for the entire population and by 8% for elderly over 65. Panel R8 further adjusts the outcome by the population numbers in the respective age group by calculating the number of patients per 10.000 inhabitants in the respective age group. The estimates suggest an around 7% reduction in cardiovascular diagnoses per 10.000 inhabitants for a 10 percentage points increase in the relative size of the zone.

Conclusion

This paper examines the effect of low emission zones in Germany on population health. Despite the well-established understanding that pollution is detrimental to human health, little empirical evidence exists that evaluates the existing policies. I use the across space and over time variation in implementation of low emission zones to estimate their impact on population health.

First I demonstrate that LEZs reduce monthly PM_{10} concentrations by 0.9 $\mu g/m^3$, which translates into a 3% decline. The findings for NO_2 suggest a small and statistically insignificant reductions. Next, using a novel outpatient health care data, I show that the zones improve cardiovascular health outcomes: they reduce the number of patients with cardiovascular diagnoses by 2-3%. The effect is particularly strong for the elderly over 65. These results are robust to a range of robustness checks.

The empirical findings in the paper have strong policy implications. They demonstrate that low emission zones are a helpful tool to reduce air pollution in large urban areas and to improve health outcomes commonly related to air pollution. However, the costs of the policy are not as clear. Since the policy mainly targets highly emitting cars, which tend to be old and cheap cars, the practical burden of LEZs falls mainly on families from low socioeconomic background and small businesses. In the meantime, the car fleet has changed dramatically since the early introduction date of the LEZs. The share of cars that receive a green sticker in 2019 is above 90%. This makes the policy somewhat obsolete, and if the cities aim at reducing the air pollution further, stricter policy measures are necessary.

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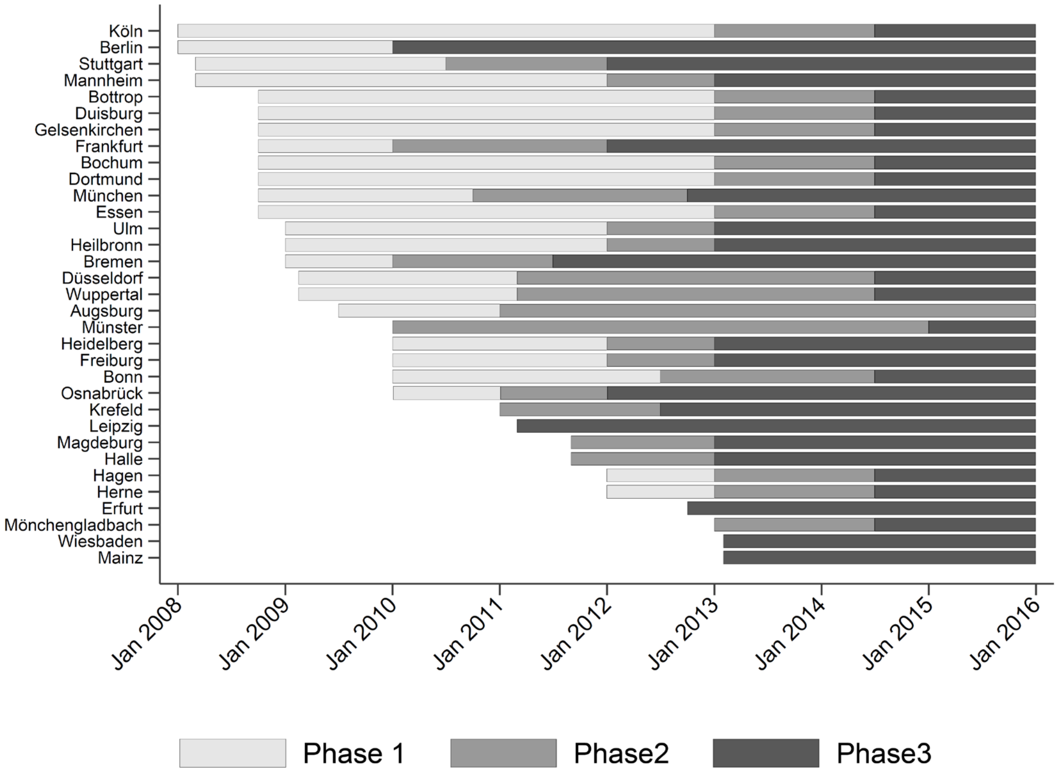


Figure 1: LEZ introduction and phases

The zones are introduced in three phases. Phase 1 restricts access to cars that receive no windshield sticker. Phase 2 restricts access additionally to cars with red windshield stickers, and Phase 3–additionally to yellow sticker cars. The colour-coded stickers are given based on emission classes.

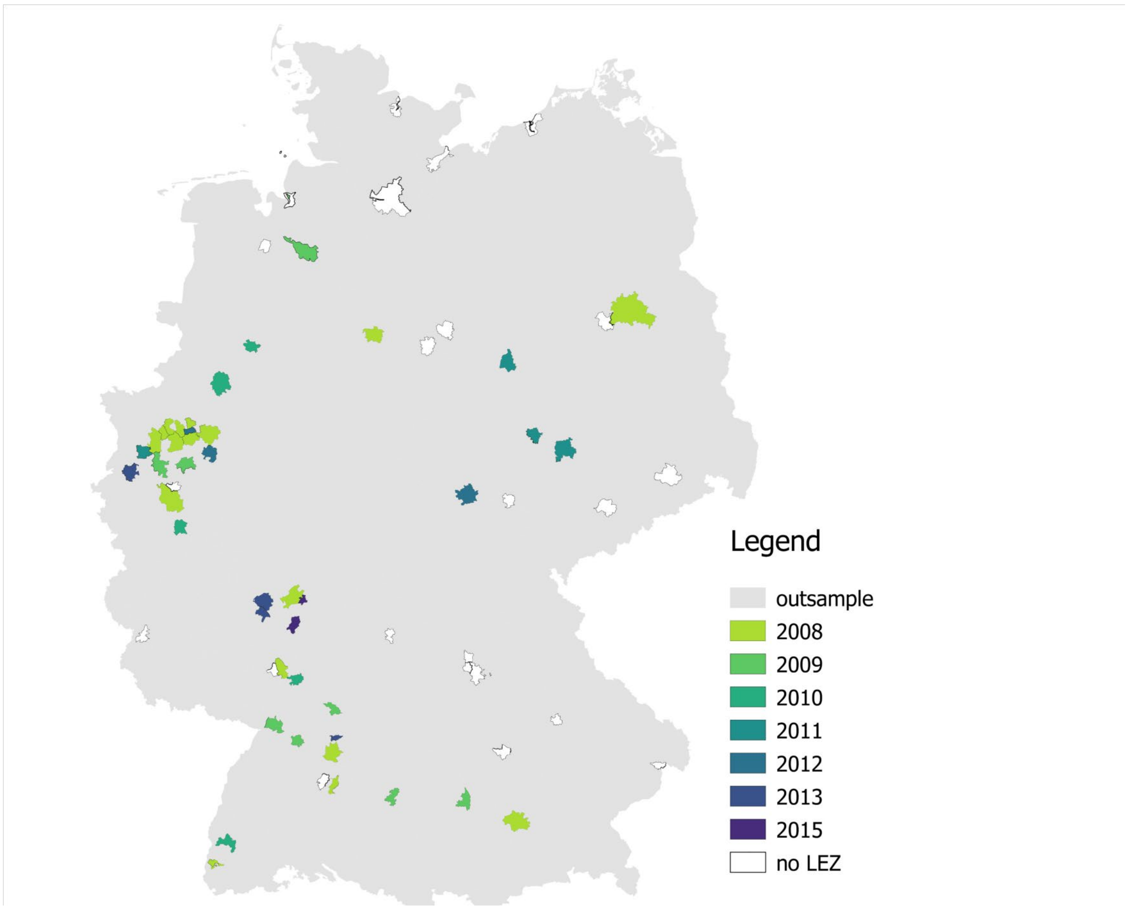


Figure 2: The variation in enactment of LEZ in major German cities

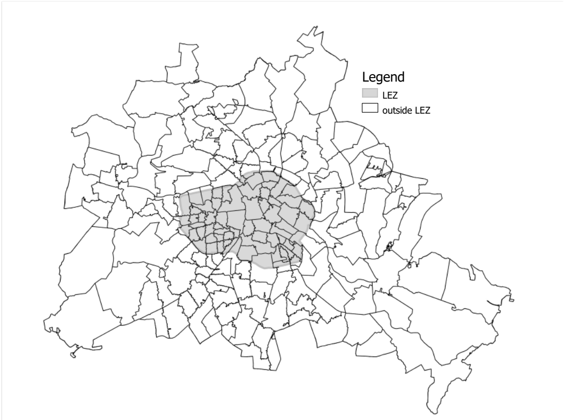
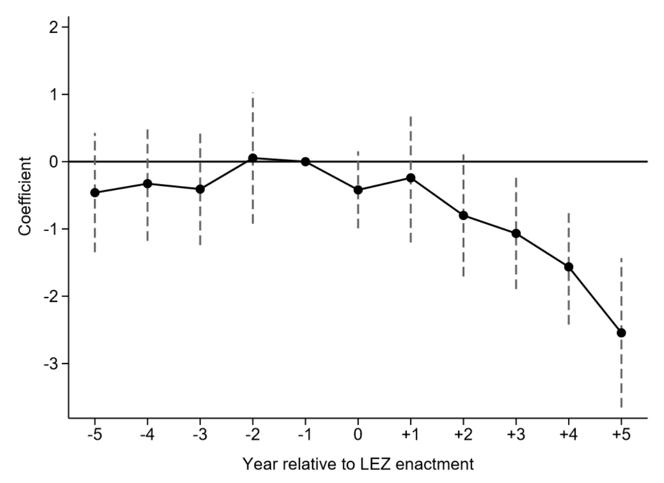


Figure 3: Berlin LEZ

The grey shaded area captures the coverage of the zone. The map illustrates data aggregation inside and outside LEZs.



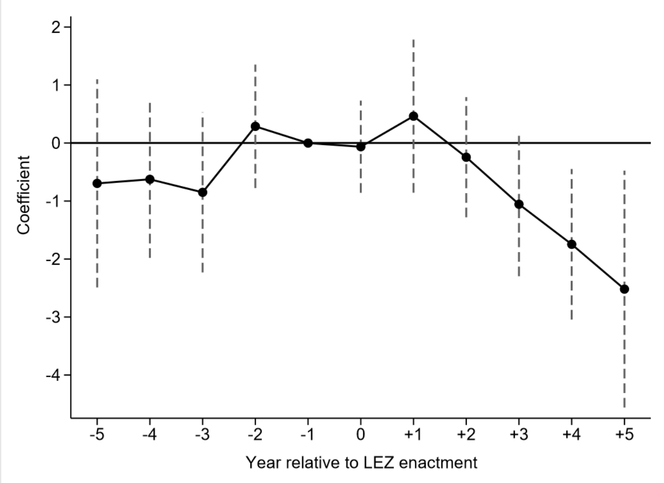


Figure 4: Event study of annual concentrations of PM_{10} and NO_2

The outcome variable is the yearly average concentration of PM_{10} and NO_2. Coefficients and 95% CIs. Standard errors are clustered at the city level.

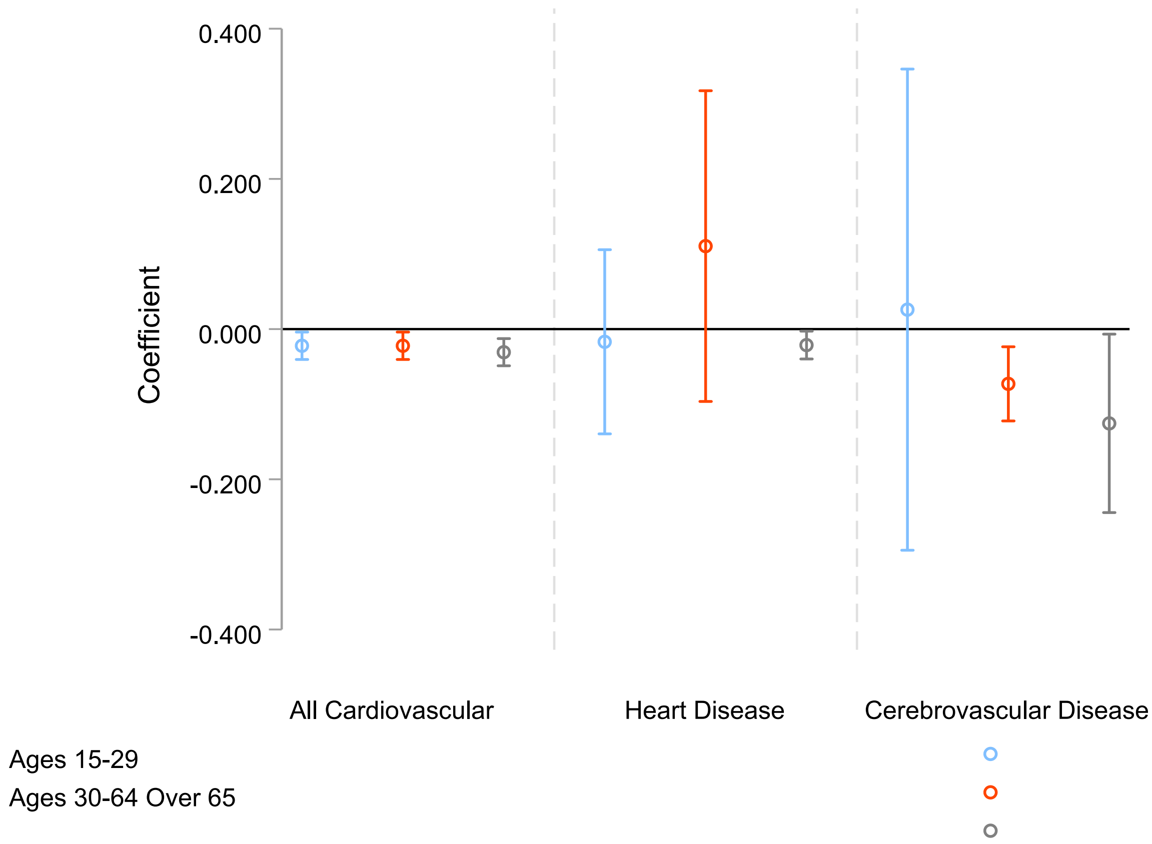
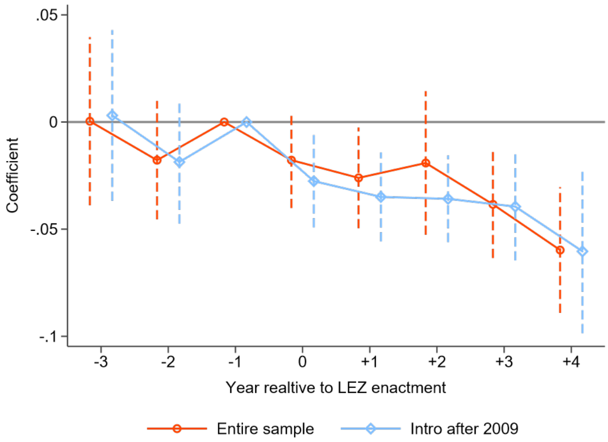

0.400
0.200
0.000
-0.200
-0.400
Coefficient
All Cardiovascular
Heart Disease
Cerebrovascular Disease
Ages 15-29
Ages 30-64 Over 65

Figure 5: Estimated impact of LEZ on cardiovascular health, by sub-diagnoses and age groups. The model specification is the same as in Column (4) of Table 4.



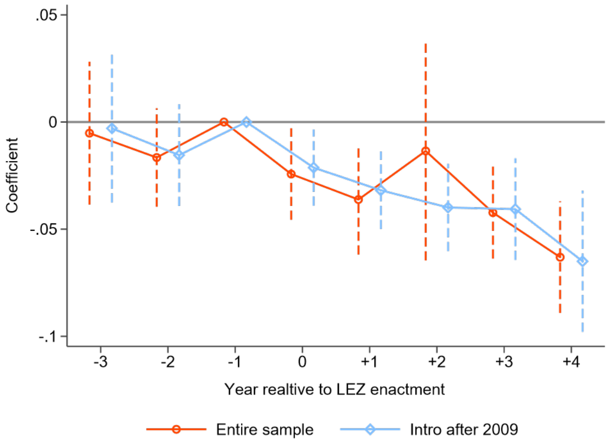


Figure 6: Event study of cardiovascular disease

The outcome variable is the logarithm of the number of patients with cardiovascular disease. The red line reports the coefficients from a regression on the entire sample. The blue line restricts the sample to cities that have introduced an LEZ after 2009. Coefficients and 95% CIs. Standard errors are clustered at the city level.

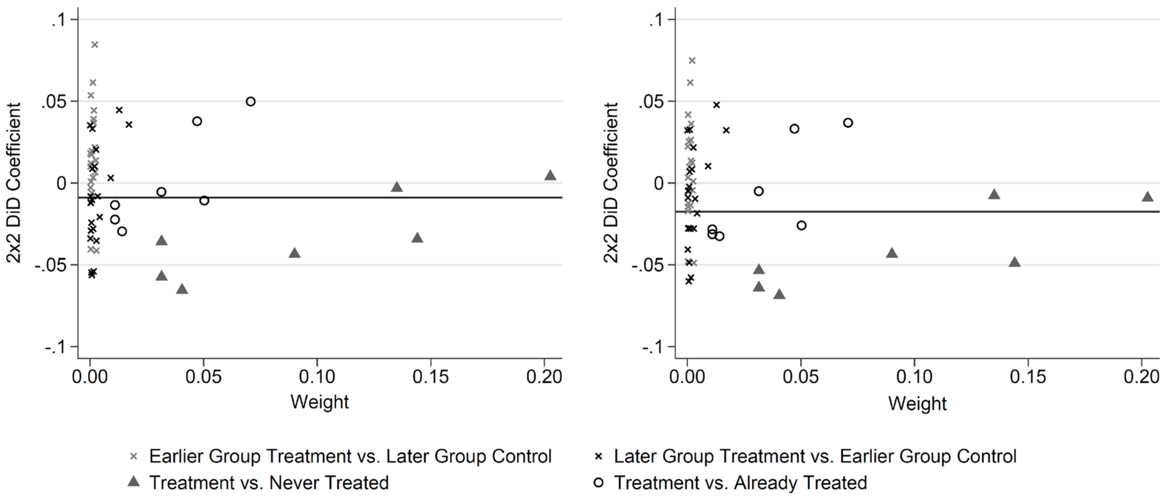


Figure 7: Difference-in-differences decomposition for cardiovascular health

The figures plot each 2x2 DiD components from the Goodman-Bacon (2018) decomposition theorem. The red line signifies the average DiD estimate, and equals the sum of y-axis values weighted by x-axis values.

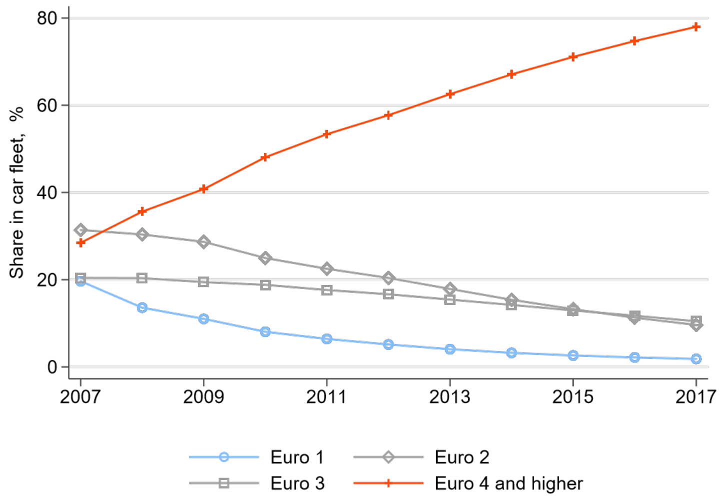


Figure 8: The development of different emission classes in large German cities, by Euro-class classification 2007-2017

Table 1: Limit Values for PM_{10} and NO_2 as defined by Council Directive 1999/30/EC

		Thresholds	Deadline
PM_{10}			
	Yearly average limit	$40\mu g/m^3$	
	Daily average limit	$50\mu g/m^3$	1 January 2005
	Allowed number of transgression days	35	
NO_2			
	Yearly average limit	$40\mu g/m^3$	
	Daily average limit	$200\mu g/m^3$	
	Allowed number of transgression days	18	1 January 2010

Notes: Source: Council Directive 1999/30/EC Annexes II, III

Table 2: Means and Pre-trends of air quality and health outcomes

	PM_{10}	NO_2	Cardiovascular
	(1)	(2)	(3)
	Panel A: Average levels in 2007		
Untreated	23.4	34.08	9.51
Treated	27.02	42.23	9.31
p-value	0.00	0.00	0.87
	Panel B: p-value on difference in pre-trends		
2005-2004	0.91	0.57	0.89
2006-2005	0.01	0.07	0.01
2007-2006	0.27	0.13	0.22

Notes: Variable names in headings. PM_{10} and NO_2 are measured in $\mu g/m^3$. Cardiovascular disease is measured as the number of admissions per 10,000 inhabitants. Panel B presents the p-value on the difference in changes between treated and untreated cities.

Table 3: The effect of LEZ on monthly PM_{10} and NO_2 concentrations

	Monthly PM_{10}			Monthly NO_2		
	(1)	(2)	(3)	(4)	(5)	(6)
In LEZ	−0.872**	−0.622*	−0.869**	−0.818*	−0.748	−0.557
	(0.357)	(0.327)	(0.329)	(0.466)	(0.492)	(0.565)
Pre-LEZ mean	27.88	27.88	27.88	45.05	45.05	45.05
Change in percent	3.12	2.23	3.12	1.82	1.66	1.24
Observations	26,523	25,874	17,974	27,637	26,945	19,224
R-squared	0.808	0.837	0.846	0.918	0.921	0.921
Station fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes	Yes	Yes
Weather controls	No	Yes	Yes	No	Yes	Yes
Station restrictions	No	No	Yes	No	No	Yes

Notes: The outcome is the monthly concentration of either PM_{10} or NO_2. Pre-LEZ mean refers to average concentrations of the respective pollutant at stations inside an LEZ before the enactment of the zone. Columns (1)-(2) and (4)-(5) include all stations. Columns (3) and (6) exclude stations in treated cities that are not inside an LEZ. Robust standard errors, clustered at the city level, are in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 4: The effect of LEZ on cardiovascular disease. Outpatient health care

	Entire population		Elderly over 65	
	(1)	(2)	(3)	(4)
Panel A: All cardiovascular disease				
LEZ	−0.019*	−0.033***	−0.021**	−0.031***
	(0.010)	(0.009)	(0.009)	(0.009)
Observations	954	585	954	585
Panel B: Heart disease				
LEZ	−0.006	−0.012	−0.016	−0.021**
	(0.010)	(0.009)	(0.011)	(0.009)
Observations	954	585	954	585
Panel C: Cerebrovascular disease				
LEZ	−0.072**	−0.126**	−0.071*	−0.126**
	(0.036)	(0.059)	(0.036)	(0.059)
Observations	954	585	954	585
City-by-LEZ FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Intro after 2009	No	Yes	No	Yes

Notes: The outcome is number of patients with the given diagnosis in logarithms. City-by-LEZ FE refers to fixed effect for each district over which the numbers are aggregated. The restriction "Intro after 2009" refers to dropping all treated cities that introduced an LEZ after 2009. Robust standard errors, clustered at the city level, in parentheses. *** $p<0.01$, ** $p<0.05$, * $p<0.1$.

Table 5: The effect of LEZ on cardiovascular disease. Inpatient health care.

	Entire population (1)	Elderly over 65 (2)
	Panel A: All cardiovascular disease	
LEZ	−0.037	−0.030
	(0.031)	(0.034)
Observations	726	726
	Panel B: Heard disease	
LEZ	−0.048	−0.046
	(0.035)	(0.036)
Observations	726	726
	Panel C: Cerebrovascular disease	
LEZ	−0.050	−0.042
	(0.052)	(0.058)
Observations	726	726
City FE	Yes	Yes
Year FE	Yes	Yes
Additional controls	Yes	Yes

Notes: The outcome is the number of patients with the given diagnosis per 10,000 population in logarithms. The additional controls are GDP per capita, unemployment rate, average age of the population and the number of deceased. Robust standard errors, clustered at the city level, in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

Table 6: City characteristics balancing regressions

Dep. var	Industrial output per capita	Unemployment rate	GDP per capita	Health and services per capita	population density
	(1)	(2)	(3)	(4)	(5)
LEZ	0.215	0.001	−447.2	−0.027	8.184
	(0.243)	(0.029)	(311.6)	(0.108)	(13.62)
City FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Observations	897	897	897	897	897
R-squared	0.994	0.999	0.996	0.987	0.994

Notes: LEZ refers to an indicator whether a city has a low emission zone at a given time. The data covers the time period 2004-2016 and comes from the Federal Statistical Office of Germany. Observations are at the city-year level. Standard errors are clustered at the city level.

A Appendix A

Table 7: Robustness Checks

	Entire Population (1)	Elderly over 65 (2)
R1. LEZ cities only		
LEZ	−0.024*	−0.030**
	(0.012)	(0.012)
Observations	360	360
R2. Clean Air Action Plans		
LEZ	−0.036***	−0.043***
	(0.008)	(0.009)
Observations	585	585
R3. Patient-cases		
LEZ	−0.033***	−0.041***
	(0.009)	(0.009)
Observations	585	585
R4: Prevalence rates		
LEZ	−0.033***	−0.015
	(0.012)	(0.012)
Observations	585	585
R5. Placebo timing		
LEZ	0.000	−0.004
	(0.012)	(0.011)
Observations	333	333
R6. Aggregation at the city level		
LEZ	−0.009	−0.013
	(0.014)	(0.015)
Observations	396	396
R7. Size of the LEZs		
LEZ size	−0.049***	−0.054***
	(0.015)	(0.017)
Observations	396	396
R8. Adjustment for population	**size at the city level**	
LEZ size	−0.077***	−0.050**
	(0.014)	(0.022)
Observations	396	396
City-by-lez FE	Yes	Yes

Year fixed effects	Yes	Yes
Intro after 2009	Yes	Yes

Notes: Panel R1 excludes all cities with no LEZ by 2017. Panel R2 additionally controls for Clean Air Action Plans with an indicator variable. The outcome in Panel R3 is the overall number of patient-cases in logs. The outcome in Panel R4 is the number of patients per 10,000 patients with any diagnoses, in logs. Panel R5 replaces the actual LEZ indicator with a randomly generated fake indicator. In Panels R6-R8 the data is aggregated at the city level. The size of the LEZ refers to the size relative to the entire city area. Robust standard error, clustered at the city level, in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

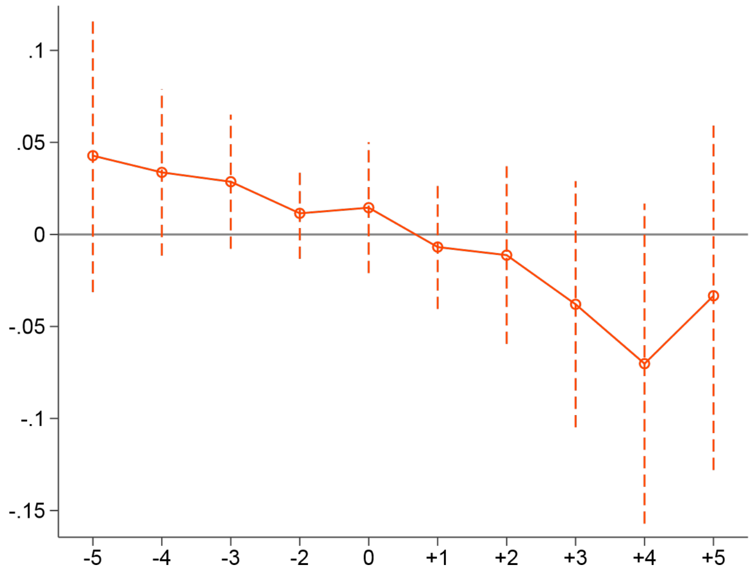


Figure A.1: Event study of cardiovascular diseases. Outpatient care data.

The outcome variable is the logarithm of the number of patients with cardiovascular disease per 10,000 population. Coefficients and 95% CIs. Standard errors are clustered at the city level.

Table A.1: Emission classes, colour codes and phase restrictions

Emission class	**Colour code**	**Banned in**	**Description**
Euro 4	Green	None	Petrol: CO: 1.00g/km HC: 0.10g/km NOx: 0.08g/km Diesel: CO: 0.50g/km HC + NOx: 0.3g/km PM: 0.025g/km
Euro 3	Yellow	Phase 3	Petrol: CO: 2.30g/km HC: 0.20g/km NOx: 0.15g/km Diesel: CO: 0.64g/km HC: 0.56g/km NOx: 0.50g/km PM: 0.05g/km
Euro 2	Red	Phase 2	Petrol: CO: 2.20g/km HC + NOx: 0.50g/km Diesel: CO: 1.00g/km HC + NOx: 0.70g/km PM: 0.08g/km
Euro 1	None	Phase 1	Petrol CO: 2.72g/km HC + NOx: 0.97g/km Diesel: CO: 2.72g/km HC + NOx: 0.97g/km PM: 0.14g/km

Table A.2: Introduction date and the areal coverage of LEZs

City	Introduction	Coverage in %	Attainment Status
Augsburg	July 2009	3.95	non-attainment
Berlin	January 2008	9.88	non-attainment
Bochum[1]	October 2008	39.85	
Bonn	January 2010	6.38	attainment
Bottrop[1]	October 2008	24.85	non-attainment
Bremen	January 2009	2.18	
Cologne	January 2008	7.42	attainment
Darmstadt	November 2015	87.64	non-attainment
Dortmund[1]	October 2008	6.77	non-attainment
Duisburg[1]	October 2008	18.47	non-attainment
Dusseldorf	February 2009	19.78	
Erfurt	October 2012	5.86	non-attainment
Essen[1]	October 2008	66.56	non-attainment
Frankfurt	October 2008	44.3	non-attainment
Freiburg	January 2010	16.18	non-attainment
Gelsenkirchen[1]	October 2008	19.06	non-attainment
Hagen	January 2012	5.39	non-attainment
Halle	October 2011	5.1	non-attainment
Hannover	January 2008	21.05	non-attainment
Heidelberg	January 2010	9.29	attainment
Heilbronn	January 2009	38.34	non-attainment
Herne[1]	January 2012	100	
Karlsruhe	January 2009	6.52	non-attainment
Krefeld	January 2011	23.2	non-attainment
Leipzig	March 2011	61.35	non-attainment
Ludwigsburg	January 2013	100	non-attainment
Magdeburg	October 2011	3.33	non-attainment
Mainz	February 2013	34.95	non-attainment
Mannheim	March 2008	4.67	non-attainment
M¨onchengladbach	January 2013	12.38	attainment
Mu¨lheim[1]	October 2008		attainment
Munich	October 2008	14.16	
Mu¨nster	January 2010	0.47	attainment
Oberhausen[1]	October 2008	30.87	
Offenbach	January 2015	85.77	
Osnabru¨ck	January 2010	14.11	attainment
Pforzheim	January 2009	1.99	non-attainment
Recklinghausen[1]	October 2008	30.08	
Reutlingen	March 2008	100	non-attainment
Stuttgart	March 2008	98.44	non-attainment

Ulm	January 2009	23.07	non-attainment
Wiesbaden	February 2013	31.12	attainment
Wuppertal	February 2009	14.61	non-attainment

Notes: Dates of introduction of the zones come from the *Umweltbundesamt*. The coverage refers to the relative size of LEZ in relation to the area of the city. The size of LEZ has been calculated based on shapefiles from *OpenStreetMap*. [1] The cities in Ruhr area united into a common LEZ in January 2012.

Table A.3: The effect of LEZ on monthly PM_{10} and NO_2 concentrations. Robustness checks

	Monthly PM_{10}		Monthly NO_2	
	(1)	(2)	(3)	(4)
	Panel A: Only LEZ Cities			
LEZ	−0.635**	−0.656*	−0.581	−1.014***
	(0.273)	(0.360)	(0.371)	(0.348)
Observations	13014	13014	13012	13012
	Panel B: Restricted Observation Period			
	B.1: Excluding 2004 and 2005			
LEZ	−0.796***	−0.749**	−0.562*	−1.053**
	(0.260)	(0.301)	(0.304)	(0.437)
Observations	16477	16477	17293	17293
	B.2:Excluding 2013 and 2014			
LEZ	−0.693**	−0.859**	−0.389	−0.795**
	(0.322)	(0.328)	(0.368)	(0.354)
Observations	16357	18099	17039	17039
	B.3: Excluding 2004-2005 and 2013-2014			
LEZ	−0.705**	−0.823**	−0.778**	−1.259***
	(0.308)	(0.340)	(0.296)	(0.345)
Observations	13025	13025	13528	13528
	Panel C: Placebo Timing			
LEZ	0.363	0.132	0.327	0.406
	(0.372)	(0.381)	(0.601)	(0.696)
Observations	13562	13562	14542	14542
Station fixed effects	Yes	Yes	Yes	Yes
Year-month fixed effects	Yes	Yes	Yes	Yes
Weather controls	Yes	Yes	Yes	Yes
Station restrictions	No	Yes	No	Yes

Notes: The outcome is the monthly concentration of PM_{10} and NO_2. Panel A restricts the sample to treated cities only. Panel B restricts the observation period. Panel C regressed the outcome on a randomly generated LEZ introduction date. Robust standard errors, clustered at the city level, are in parentheses. *** p<0.01, ** p<0.05, * p<0.1.

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