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Low Emission Zones for Better Health: Evidence from German Hospitals

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Low Emission Zones for Better Health: Evidence from German Hospitals

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Low Emission Zones for Better Health: Evidence from German Hospitals‡

Abstract

This paper studies health effects from restricting the access of high-emission vehicles to inner cities by implementing Low Emission Zones. For identification, we exploit variation in the timing and the spatial distribution of the introduction of new Low Emission Zones across cities in Germany. We use detailed hospitalization data combined with geo-coded information on the coverage of Low Emission Zones. We find that Low Emission Zones significantly reduce levels of air pollution in urban areas and that these improvements in air quality translate into population health benefits. The number of diagnoses related to air pollution is significantly reduced for hospitals located within or in close proximity to a Low Emission Zone after it becomes effective. The results are mainly driven by reductions in chronic cardiovascular and respiratory diseases.

Keywords: *Low Emission Zone, air pollution, health, Germany*

JEL classification: *I18; Q52; Q53*

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‡ ***Corresponding author:*** *Florian Wozny, Institute of Labor Economics (IZA), Schaumburg-Lippe-Str. 5–9, 53113 Bonn, Germany, Tel.: +49 228 3894–139.* ***Acknowledgments:*** *We thank Felix Holub, Ingo Isphording, Steffen Künn, Andreas Lichter, Juan Palacios, Jonas Radbruch, Ulrich Wagner, Hendrik Wolff and Nicolas Ziebarth as well as seminar and workshop participants at IZA Bonn for helpful comments and suggestions. The usual disclaimer applies.*

1 Introduction

Air pollution is a major concern for human health and well-being across the globe. According to the World Health Organization, about seven million premature deaths per year as well as a wide range of health hazards, in particular respiratory and cardiovascular diseases, can be attributed to poor air quality (WHO, 2018).[1] While adverse health effects of air pollution may be more severe in the developing world, many places in high-income countries are also faced with serious violations of air quality standards. This creates large economic costs through hampered human capital formation (Graff Zivin and Neidell, 2013), increasing defensive medical spending (Deschênes et al., 2017) and reductions in workers' labor supply and productivity on the job (Graff Zivin and Neidell, 2018).

Emissions from traffic are a major source of ambient air pollution in densely populated urban areas (Karagulian et al., 2015). Automobile exhaust is particularly harmful to human health because it is mostly emitted close to the ground. Thus, reducing air pollution from traffic is of great importance for environmental policy-making. In the European Union, a key policy measure to reduce ambient air pollution in inner-cities is the implementation of Low Emission Zones, signposted areas where access of vehicles is regulated, typically banning high-emitting vehicles from entering the zone altogether. While access regulations impose costs on local residents and businesses, benefits may accrue in form of improved health, worker productivity and human capital. However, there is relatively little evidence about potential health benefits from policy interventions aiming at improving air quality in inner-cities. This is remarkable since policy measures, such as Low Emission Zones, are typically justified by improvements in population health.

In this paper, we study whether the implementation of Low Emission Zones affect population health through improvements of air quality by evaluating the staggered introduction of this policy measure across German cities since 2007.[2] For causal identification of the health impact of Low Emission Zones, we exploit variation in the timing as well as the exact geographic coverage of Low Emission Zones across Germany in a difference-in-differences framework. The policy treatment of introducing a Low Emission Zone is triggered by local violations of European Union air quality standards. The decision to implement a Low Emission Zone is then forced upon cities by state governments who are responsible for compliance with air quality legislation. We exploit policy variation in the extent to which inner-city areas, usually the city center, are covered by Low Emission Zones across time as well as between and within cities.

We combine information on the geographic coverage of Low Emission Zones with rich panel data on the universe of German hospitals over the period from 2006 to 2016 with precise information on hospital locations and the annual frequency of detailed diagnoses based on international stan-

[1] Air pollution is also the main cause of more than 440,000 deaths per year in Europe and 62,000 deaths in Germany alone (European Environmental Agency, 2018; Landrigan et al., 2017).

[2] Germany is currently the country which has established most Low Emission Zones based on relatively strict European Union legislation requiring legal actions against air quality standard violations. Low Emission Zones have been implemented in other European countries and will become more frequent in the near future. As of 2018, more than 200 Low Emission Zones have been established in European cities and this number will increase to more than 300 until 2025 (see Figure A.1).

dard classification (ICD-10). We mainly focus on cardiovascular and respiratory diseases, which have been shown to be affected by key target pollutants like particulate matter and nitrogen oxides (Graff Zivin and Neidell, 2013). Additionally, we complement the analysis by looking at further outcomes related to infant health (low birth weight) as well as to outcomes potentially affected by reduced traffic within Low Emission Zones (injuries and stress). While it is straightforward to determine the distance of hospital locations to Low Emission Zones, the hospital data do not contain information on patients' residential locations which would allow us to assign the treatment to a hospital's potential pool of patients.[3] That is why we employ several approaches to construct hospitals' catchment areas, i.e., geographic areas in the surrounding of hospital locations from where admissions are likely to be from. Overlaying hospitals' catchment areas with Low Emission Zone coverage allows us to compute the share of hospital catchment areas treated by the policy. This means that we estimate reduced-form and intention-to-treat effects of Low Emission Zone introductions on hospital admissions. In order to establish that our estimates of Low Emission Zones' health impacts can indeed be attributed to improvements in local air quality ("first stage"), we additionally use data from Germany's official air pollution monitoring system and assign monitor locations to Low Emission Zones and test whether air pollution is affected by the coverage of a Low Emission Zone.

Our results show that Low Emission Zone introductions benefit population health. In a first step, we confirm that Low Emission Zones improve air quality, mainly by decreasing the frequency of exceeding regulatory thresholds. We do not find effects on traffic volume in- or outside the Low Emission Zone. In a second step, we show that these improvements in air quality translate into lower prevalence of several air pollution-related diagnoses, especially diseases of the circulatory and the respiratory system, among hospitals whose catchment areas are covered more by a Low Emission Zone. These results appear to be mainly driven by reductions in diagnoses of non-emergency diagnoses of chronic diseases and not so much by emergency cases. Low Emission Zones do not reduce the incidence of low birth weight significantly. Furthermore, we do not find significant effects on injuries or diagnoses of stress potentially related to changes in traffic volume.

The analysis presented in this paper contributes to the literature in several ways. First, we add to the large literature on the causal impacts of air pollution on human health in both epidemioloy (Pope III, 2000; Pope III and Dockery, 2006) as well as in economics (Graff Zivin and Neidell, 2013). Second, we contribute to a smaller number of studies in the economics literature evaluating the direct impact of Low Emission Zones on local air pollution. The two papers that are closest to ours are Wolff (2014) and Gehrsitz (2017) who both document significant drops in ambient air pollution after Low Emission Zone introductions in treated cities in Germany. A related literature in transportation research documents similar findings (Morfeld et al., 2014; Malina and Scheffler, 2015; Jiang et al., 2017). Wolff (2014) further shows that reductions in air pollution are driven by an improvement of the vehicle fleet in terms of emission standards. Our contribution is an extension of the analysis including the most recent Low Emission Zone implementations in Germany at a higher spatial accuracy using

[3] In Germany, access to individual-level administrative data on hospitalization with precise residential information is unfortunately not available.

within-city variation. Third, the findings of our paper contribute to our understanding of the health benefits associated with policy measures regulating traffic in urban areas. Gehrsitz (2017) evaluates the effects of Low Emission Zones on infant health outcomes in Germany. However, the results do not indicate substantial reductions in the prevalence of low birth weight or the number of stillbirths in Germany following a ban of high-emission vehicles. Simeonova et al. (2018) study the health effect of another policy measure to improve inner-city air quality, showing that implementing a congestion tax in central Stockholm reduced ambient air pollution and significantly decreased the rate of acute asthma attacks among young children. While children, especially newborns, are particularly vulnerable to detrimental environmental conditions (Almond and Currie, 2013), the elderly as well as the working-age population are also negatively affected by air pollution (Schlenker and Walker, 2016; Deschênes et al., 2017; Karlsson and Ziebarth, 2018). In this paper, we are able to study the full range of diseases potentially affected by ambient air pollution among all age groups. Salvo et al. (2018) show that removing Diesel trucks from passing through the inner-city of São Paulo by inaugurating a beltway had positive effects on congestion, pollution, health and mortality benefiting the megacity's population. The results of our paper indicate that potential improvements in population health from reductions in traffic emissions are not restricted to locations starting from extremely high levels of air pollution but that health improvements can be achieved also for medium-sized cities with ex ante moderate levels of air pollution.

The remainder of this paper is structured as follows. In section 2, we provide background information about German Low Emission Zones, targeted pollutants and show the effect of Low Emission Zones on air pollution. Section 3 describes the empirical analysis. Section 4 concludes.

2 Institutional Background and Data

2.1 Low Emission Zones in Germany

Air quality standards in Germany are determined by European Union (EU) legislation. Since the mid-1990s, the EU has established a legal framework in order to aspire levels of air quality that do not give rise to significant negative impacts on and risks to human health and the environment. The EU Directives 2008/50/EC and 1999/30/EC regulate measures to improve ambient air quality in all EU member states. The EU's legal framework has to be adopted by national law. It defines measurement procedures, limit values and alert thresholds for various target air pollutants in ambient air, among others nitrogen dioxide and particulate matter (see Table A.1 for an overview). Violations of air quality standards require member states to adopt action plans with appropriate measures to reduce air pollution. Ultimately, non-compliance may result in penalty charges.[4]

[4] If a member state fails to adopt measures that are sufficient to reach the limit values in reasonable time, the EU can start an infringement procedures. In May 2018, there were 16 infringement cases pending against member states (Belgium, Bulgaria, the Czech Republic, Germany, Greece, Spain, France, Hungary, Italy, Latvia, Portugal, Poland, Romania, Sweden, Slovakia, and Slovenia, see European Commission, 2018).

In Germany, the 16 federal states are responsible for compliance with the EU air quality standards. In case of violations, state governments are obliged to develop city-specific Clean Air Plans (*Luftreinhaltepläne*), defining a bundle of measures aiming at lasting improvements of air quality in compliance with the EU standards. Usually, the respective city administrations as well as other stakeholders (e.g., business or environmental protection associations) are involved in the decision-making process. However, state governments ultimately decide on the Clean Air Plans and may overrule the views of local decision-makers and enforce the implementation or strictness of certain measures to be defined if they are deemed to be necessary to achieve compliance with the air quality standards. The implementation of a Low Emission Zone is the most tangible measure from the Clean Air Plan tool box to reduce traffic emissions in urban areas.[5]

Low Emission Zone implementations are controversially debated on the local level when they are announced for a given city. On the one hand, Low Emission Zones are unpopular as they impose restrictions on car owners and may create costs for local businesses. On the other hand, national environmental protection associations have filed a number of lawsuits aiming at implementing stricter measures to enhance compliance with the EU air quality standards more quickly, usually speeding up the adoption of Low Emission Zones or enforcing stricter regulations.[6] This means that, after there have been violations of air quality standards within a city area, Low Emission Zone policies are exogenously enforced upon cities either by the responsible state governments or court rulings based on EU air quality legislation.

A Low Emission Zone is a signposted area where entry by vehicles is regulated, usually by prohibiting vehicles with higher emissions from entering the area altogether. Access regulation is based on the six emission standards based on EU legislation. The emission standard of a vehicle is categorized by color-coded windscreen stickers with no sticker for the highest emission level Euro 1 and red, yellow and green stickers for “cleaner” emission standards Euro 2–4 (see Table A.2 for details). Typically, Low Emission Zones are introduced in phases. In phase one, only the dirtiest Euro 1 vehicles were banned. Subsequently, the Low Emission Zones became stricter, banning Euro 2 and Euro 3 classes in the second phase and finally allowing only green sticker (Euro 4) vehicles in the third phase. As of 2018, there are 58 Low Emission Zones in Germany with only one being accessible by vehicles displaying a yellow sticker, whereas all remaining Low Emission Zones allow access only to vehicles with a green sticker (see Table A.2 for an overview).[7]

We use data on all Low Emission Zones in Germany from the Federal Environment Agency (*Umweltbundesamt, UBA*) on the history of implementation by stage (ban of Euro 1–3 vehicles) as well as the precise geographic coverage of each zone at all stages.[8] Figures 1 and 2 show the

[5]Other Clean Air Plan measures typically aim at enhancing the use of public transportation, bicycles or electric powered vehicles and are much less specific.

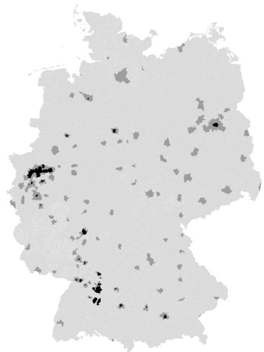
[6]As a result of court decisions, as of 2019 access to certain Low Emission Zones or other specific city areas (e.g., in Stuttgart) requires a minimum emission standard of Euro 5 by diesel-fueled vehicles.

[7]In 2018, the penalty for violation is 80 Euros. The Low Emission Zone policies are enforced by the police and by local public order authorities. Two-wheeled vehicles, vintage cars, police, fire brigade and emergency vehicles and farm machinery are exempt from the scheme.

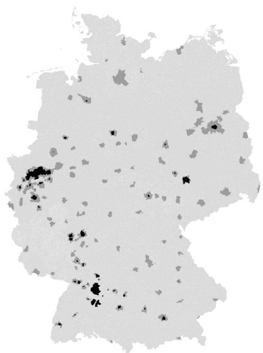
[8]We use open source polygons of Low Emission Zones in German cities from OpenStreetMap.org. As an example,

spatial diffusion as well as the number of implemented Clean Air Plans and Low Emission Zones over the period from 2007 to 2018. The first Clean Air Plans were established in 2007, the number increased to more than 80 by 2018. In 2008, eleven Low Emission Zones were established at stage one (only banning Euro 1 vehicles) followed by a gradual increase of new Low Emission Zones across the country. The earliest second stage (banning Euro 1–2) was introduced in 2009, while over the course of 2010 all Low Emission Zones switched at least to the second stage, some already introduced the third stage (ban on Euro 1–3). From 2013 onwards, the third stage dominated. As of 2018, there are 58 active Low Emission Zones in Germany. Whereas in 2018 Clean Air Plans are rather equally distributed across Germany, most Low Emission Zones are located in urban areas in the West or South-West of Germany.

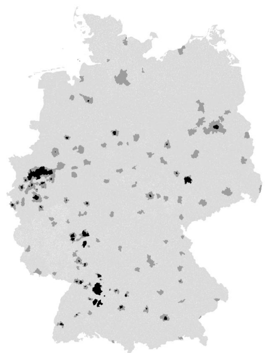
(a) 2007



(b) 2010



(c) 2013



(d) 2016

Figure 1: Clean Air Plans (grey) and Low Emission Zones (black) over time

Figure A.3 shows the high congruency with official documentation for the largest Low Emission Zone in the Ruhr area.

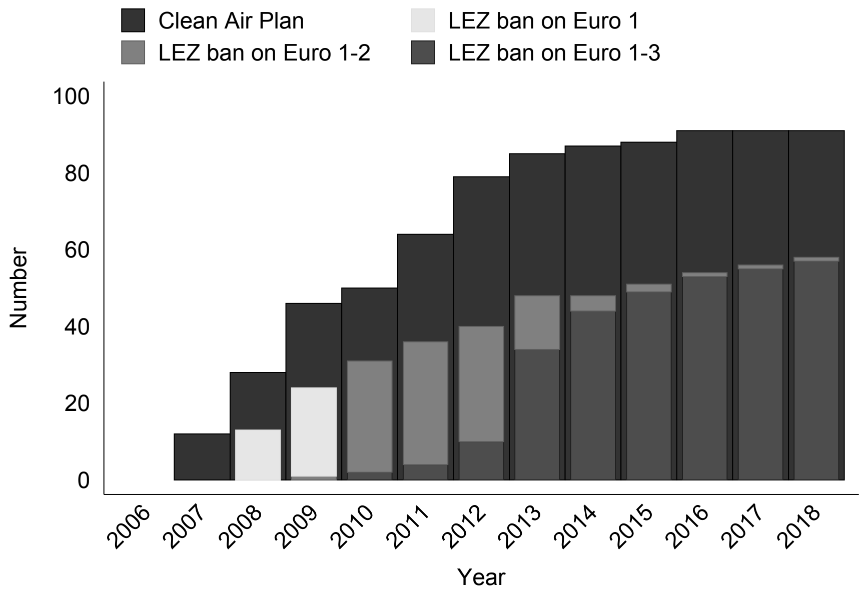


Figure 2: Clean Air Plans and Low Emission Zones by emission standard over time

2.2 Air pollution: Risks to human health and measurement

The purpose of Low Emission Zones is to improve air quality in urban areas by reducing the emission of harmful air pollutants from traffic.[9] The main target air pollutants emitted from traffic are particulate matter (PM) and nitrogen dioxide (NO2).[10] In the following, we explain how these air pollutants are generated and how they may affect human health.

Particulate matter (PM) measures the concentration of small airborne particles including dust, dirt, soot, smoke and liquid droplets which are emitted to ambient air from a variety of sources. Natural sources are bush fires, dust storms, pollens and sea spray while anthropogenic sources include motor vehicle emissions and industrial processes. Small particulates may enter the lungs, the smallest particles may even enter the blood stream and overcome the blood-brain barrier causing inflammation. We focus on PM10, i.e., the concentration of particles that are smaller than 10 μm in

[9]This may be achieved by reducing traffic volume, by decreasing the vehicle fleet's share of high-emission cars or a combination of both. Wolff (2014) shows that Low Emission Zone introductions in German cities encouraged a shift to a less emitting car stock. Additionally, Figure A.4 shows that in Germany the vehicle fleet has become substantially cleaner in terms of average PM10 and NO2 emissions since the mid-1990s. In particular, average emissions of trucks decreased by more than 80 percent. NO2 emissions of cars decreased since 2007 but remained rather constant while PM10 emissions further decreased.

[10]These specific air pollutants are usually used as markers for the cocktail of combustion related pollutants emitted by road traffic. They are highly correlated with each other and associated with other combustion products, such as ultrafine particles, nitrous oxide (NO) or benzene (WHO, 2006). In addition, traffic contributes to the emission of greenhouse gases which are harmful to the climate.

diameter, which has been comprehensively measured since 2000 in Germany.[11] Particulate matter is linked to a number of respiratory and cardiovascular diseases, among others ischemic heart diseases (which may lead to heart attacks), cerebrovascular diseases (e.g. strokes), chronic and acute lower respiratory diseases as well as low birth weight among newborns (Kampa and Castanas, 2008; Block and Calderon-Garciduenas, 2009).[12]

Nitrogen dioxide (NO2) results from burning fossil fuels like coal, oil and gas. In cities, the major source of nitrogen dioxide is motor vehicle exhaust (up to 80 percent, see Environmental Protection Agency, 2016). Nitrogen dioxide contributes to the formation of photochemical smog, which can have significant impacts on human health (Vitousek et al., 1997). Nitrogen oxides are often linked to nose and throat irritation, and increase sensitivity to respiratory infections (Kampa and Castanas, 2008). Exposure to elevated NO2 concentration in ambient air especially causes respiratory problems by inflaming the lining of the lungs.[13] Based on a systematic literature review Schneider et al. (2018) identified possible NO2 cause-specific hospital admissions: cardiovascular and respiratory morbidity, hypertension, ischemic heart diseases and low birth weight.

Data on air pollution comes from the air pollution monitoring system of the German Federal Environment Agency. We use data on all geo-coded monitors measuring the concentration of particulate matter (PM10) or nitrogen dioxide (NO2) between 2006 and 2016. The main variables of interest are the yearly averages of pollutants as well as yearly number of monitor-specific limit-exceedances and violations according to the EU air quality standards (see Table A.1).

Overall, we have 4,290 and 5,237 monitor-by-year observations for PM10 and NO2 respectively. Panels A of Tables 1 and 2 show that, on average, the yearly mean levels of PM10 and NO2 pollution are well below the limit values of 40 micrograms per cubic meter ($\mu g/m^3$). The yearly mean of PM10 is 22 $\mu g/m^3$ and 31 $\mu g/m^3$ for NO2. However, there is sizable variation between monitors within years as well as within monitors by year which leads to violations of the EU air quality standards by exceeding the maximum number of days or hours with higher concentrations. For example, in about eight percent of monitor-year observations there are more than 35 days with a daily mean PM10 concentration of 50 $\mu g/m^3$ and 30 percent of observations exceed the annual mean NO2 limit.[14]

Combined with the data on Low Emission Zones, we are able to assign whether a monitor is located inside or outside of a Low Emission Zone area and, if outside, to compute the distance to the closest Low Emission Zone boundary.[15] Panels B of Tables 1 and 2 show that between 2006 and 2016, more than half of pollution monitor observations are covered by an active Clean Air Plan.

[11] The concentration of fine particles smaller than 2.5 μm (PM2.5) has been regulated by the EU only since 2015.

[12] Particulate pollution from any source has negative impacts on health. However, anthropogenic sources, especially those emitted by traffic, like rubber abrasion, brake dust or exhaust emissions are more harmful (WHO, 2006).

[13] Janke (2014) showed that a one percent increase in NO2 lead to roughly 0.1 percent increase in emergency respiratory hospitalizations for children.

[14] Figure A.5 shows how pollution levels and violations evolved over time.

[15] Figure A.6a shows that the location of pollution monitors across Germany largely reflects more densely populated urban areas, which are also typically covered by Clean Air Plans and Low Emission Zones (see Figure 1).

The share of observations covered by a Low Emission Zone banning at least Euro 1 vehicles (red sticker) is 14–18 percent, the share is 9–12 percent for Low Emission Zones banning at least Euro 1–2 (yellow sticker) and 7–10 percent for Low Emission Zones banning Euro 1–3 (green sticker).

Further control variables for the sample of pollution monitors are shown in Panels C and D of Tables 1 and 2. Since weather conditions are important environmental confounders we further supplement our dataset with a rich set of weather controls. The data are provided by the German Meteorological Service (*Deutscher Wetterdienst*) and contain information on temperature, precipitation and wind speed. We retrieve the yearly averages at the closest weather station for each pollution monitor to control for confounding effects. Finally, we control for a number of population characteristics provided by the Federal Statistical Office at the level of the municipality of the pollution monitor location.

Table 1: Descriptive statistics: Sample of PM10 monitors (2006–2016)

	Mean	SD	Min	Max	N
A. Pollution outcomes					
Yearly mean PM10 ($\mu g/m^3$)	21.94	5.68	7.00	55.00	4290
Yearly days PM10 > 50 $\mu g/m^3$	15.41	14.18	0.00	175.00	4290
Violation (Yearly mean PM10 > 40 $\mu g/m^3$)	0.00	0.06	0	1	4290
Violation (Days PM10 > 50 $\mu g/m^3$)	0.08	0.28	0	1	4290
B. Treatment characteristics					
In active Clean Air Plan	0.54	0.49	0	1	4290
In LEZ ban on Euro 1	0.14	0.33	0	1	4290
In LEZ ban on Euro 1-2	0.09	0.28	0	1	4290
In LEZ ban on Euro 1-3	0.07	0.25	0	1	4290
C. Weather characteristics					
Mean temperature (° C)	9.70	1.44	2.75	12.78	4290
Mean precipitation (mm/m^2)	2.05	0.61	0.54	5.82	4290
Mean Wind speed (m/ss)	3.46	0.98	1.66	11.19	4290
D. Municipality characteristics					
Inhabitants/1000	151.06	453.30	0.04	3574.83	4290
Employed/1000	65.76	182.65	0.00	1367.68	4290
Share male < 30 years	0.32	0.03	0.23	0.41	4290
Share male 30 - 64 years	0.50	0.02	0.43	0.55	4290
Share male > 64 years	0.18	0.02	0.13	0.27	4290
Share female < 30 years	0.29	0.03	0.20	0.39	4290
Share female 30 - 64 years	0.47	0.02	0.41	0.52	4290
Share female > 64 years	0.24	0.03	0.17	0.34	4290

Notes: This table displays the descriptive statistics for the most important variables. The data underlying the statistics in Panel C are measured at the nearest measuring station to the pollution monitor. Panel D is based on the municipality a monitor is located at.

Table 2: Descriptive statistics: Sample of NO2 monitors (2006–2016)

	Mean	SD	Min	Max	N
A. Pollution outcomes					
Yearly mean NO2 ($\mu g/m^3$)	30.86	21.98	0.00	121.35	5237
Yearly hours NO2 > 200 $\mu g/m^3$	2.07	24.73	0.00	853.00	4365
Violation (Yearly mean NO2 > 40) $\mu g/m^3$)	0.30	0.46	0	1	5237
Violation (Hours NO2 > 200 $\mu g/m^3$)	0.02	0.13	0	1	4365
B. Treatment characteristics					
In active Clean Air Plan	0.59	0.49	0	1	5237
In LEZ ban on Euro 1	0.18	0.37	0	1	5237
In LEZ ban on Euro 1-2	0.12	0.31	0	1	5237
In LEZ ban on Euro 1-3	0.10	0.29	0	1	5237
C. Weather characteristics					
Mean temperature ($^\circ$ C)	9.71	1.47	0.48	12.78	5237
Mean precipitation (mm/m^2)	2.09	0.63	0.54	7.52	5237
Mean Wind speed (m/ss)	3.47	1.01	1.44	11.25	5237
D. Municipality characteristics					
Inhabitants/1000	158.24	443.57	0.04	3574.83	5237
Employed/1000	69.09	179.61	0.00	1367.68	5237
Share male < 30 years	0.32	0.03	0.23	0.41	5237
Share male 30 - 64 years	0.50	0.02	0.43	0.55	5237
Share male > 64 years	0.18	0.02	0.13	0.27	5237
Share female < 30 years	0.29	0.03	0.20	0.39	5237
Share female 30 - 64 years	0.47	0.02	0.41	0.52	5237
Share female > 64 years	0.24	0.03	0.17	0.34	5237

Notes: This table displays the descriptive statistics for the most important variables. The data underlying the statistics in Panel C are measured at the nearest measuring station to the pollution monitor. Panel D is based on the municipality a monitor is located at.

2.3 Diagnoses from the universe of German hospitals

For our analysis of health effects from Low Emission Zones we use a panel dataset of the universe of hospitals in Germany reporting the annual number of detailed diagnoses for inpatient cases.[16] German hospitals are obliged by law to publish structured quality reports since 2006, every second year until 2012 and annually from 2012 onwards. The structure and content of these reports are specified legally and misreporting leads to financial penalties. The reported data provide information on structure and performance of a hospital at the hospital department level. The quality reporting was implemented to demonstrate hospitals' performance in a transparent manner to enable a well-informed choice of hospitals by patients and to guide and support referring physicians as well as sickness funds.[17]

[16] Admissions to a hospital are usually due to more severe health issues. Therefore, hospitalization data does not cover milder medical conditions which are reflected in doctor visits (if at all). Inpatient cases are even more severe because hospitals are obliged to justify that an outpatient treatment is not sufficient. Otherwise, they jeopardize the full reimbursement by health insurances. However, hospital discharge rates in Germany are relatively high, also due to the fact that Germany is among the countries with the highest hospital density (Kumar and Schoenstein, 2013).

[17] See Appendix B.1 for a detailed description of the data.

Hospital quality report data comprise hospital characteristics like number of beds and ownership structure but also yearly number of inpatient cases and diagnoses based on the full International Statistical Classification of Diseases and Related Health Problems (ICD-10). Given that the data's intention is to increase transparency, every hospital is non-anonymously identified, allowing us to assign the treatment of coverage by a Low Emission Zone at the exact address location.[18] The full dataset includes more than 2,000 hospitals over the period from 2006 to 2016 (see Figure B.1). We exclude hospitals that do not meet the criteria of hospitals of primary care in Germany (*Krankenhäuser der Regelversorgung*), i.e., having a unit for surgery and internal medicine (Ethikrat, 2016). Hence, we focus on **general hospitals** and exclude specialized hospitals like hospices, wellness clinics, rehabilitation centers, sanatoriums etc., resulting in a sample of around 1,100 hospitals per year and 8,828 hospital-year observations. This reduces measurement error because the excluded hospitals perform an over-proportional amount of planned treatments where spatial proximity is less crucial and often do not treat air pollution related diseases (Klauber et al., 2015).[19]

Panel A of Table 3 shows substantial variation in the characteristics of general hospitals. The mean number of beds ranges from only four to 2,917, revealing that the definition of a hospital is independent of its size but rather a legal concept based on permanent availability and equipment. Inpatients per year range from 77 to 198,452 with a mean of 15,669. Non-profit and public general hospitals account for 43 and 40 percent in our dataset. About 17 percent of the general hospitals in our dataset are private. However, private general hospitals in Germany are obliged to provide the same health services to the same conditions as non-private.[20]

The total number of diagnoses according to the ICD-10 classification (indicated in brackets) are shown in Panel B of Table 3. The average number of annual diagnoses of diseases is 10,506. We mainly focus on the overall number of diagnosed diseases of the circulatory system, making up 22 percent of all diseases, and the respiratory system (about nine percent), which are also broken down to more detailed ICD-10 subcategories. In addition, we will look at low birth weight as an outcome (Gehrsitz, 2017) as well as stress-related diagnoses and to overall number of injuries potentially reflecting changes in the number of traffic accidents due to potentially lower traffic volume caused by Low Emission Zone restrictions of vehicle entry to the area.

Hospital catchment areas are assigned based on hospitals' locations since, unlike other data sources, the hospital quality report data do not provide information on the residence of patients. There is a free choice of hospitals in Germany. However, there is a strong correlation between hospital location and patients' residences (Friedrich and Beivers, 2008). Individuals do prefer hos-

[18] We use the HERE navigation API to convert full addresses into geocodes.

[19] The robustness checks includes an analysis of the specialized hospitals as well as specifications where we only include hospitals located in cities that ever adopted a Clean Air Plan to make the control group more comparable to the treatment group.

[20] Three types of hospital ownership are defined by German Law: Public: Owned by the state, a federal state or a municipality; Non-profit: Owned by non-profit organizations like the Red Cross or institutions of the churches; Private: Contrary to public and non-profit ownership, private hospitals primarily aim at making a profit by individuals or legal entities (Wissenschaftliche Dienste, 2014).

pitals close to their residential address (Klauber et al., 2015). Furthermore, resident doctors are legally obliged to refer patients to one of the two closest hospitals based on the residence of the patient. Knowing the location of the hospital is even more advantageous when analyzing more severe emergency cases where admission is based on the patient's current position which is not necessarily equal to the place of residence (Klauber et al., 2008). In 2016, 45 percent of hospital admissions were emergency cases (Statistisches Bundesamt, 2017a).[21] According to the directive for ambulance transport (*Krankentransport-Richtlinie*), emergencies should be transported directly to the nearest hospital.

For our main analysis, we use the Open Source Routing Machine (OSRM) with the OpenStreetMap road network of 2016 to define mutually exclusive hospital catchment areas based on driving time. This means that for every hospital in our dataset, we create adjacent polygons around the hospital location corresponding to regions comprising all points that have a shorter driving time to the hospital than to any other hospital in the surrounding. These regions are the catchment areas. Hence, each point on a border between two catchment areas has the exact same driving time to the two corresponding hospital locations.[22] As these catchment areas do not perfectly map into administrative geographic areas we do not have information on their population. In a robustness check, we account for heterogeneity in population size by weighting with approximated population density from high resolution satellite data, which is only available for two years over the period of investigation.

Hospitals' treatment by Low Emission Zones is assigned by overlaying the Low Emission Zone areas with the hospital locations and catchment areas. Panel C of Table 3 shows that one third of hospital-year observations are located in a municipality with an active Clean Air Plan and ten percent of the observations in Low Emission Zones that ban at least Euro 1 vehicles, seven percent banning at least Euro 1–2 and six percent banning Euro 1–3. Further, we calculate the proportion of a hospital catchment area that is covered by an active Low Emission Zone. At the extensive margin, 16 percent of all general hospital observations have a catchment area that is at least partly covered by an active Low Emission Zone. The overall share of catchment areas that is covered by Low Emission Zones is six percent. In section 3.4 we provide a series of robustness checks where we use different treatment specifications to account for measurement error.

Figure B.4 reveals a constant increase of hospitals which are located in Low Emission Zones over time. Whereas in 2006 no hospital was located in a Low Emission Zone this share increased to 13 percent in 2016. Hospitals whose catchment areas overlap with Low Emission Zones account for almost 22 percent of all hospitals. This trend is partly driven by a trend of urbanization of hospital supply (Klauber et al., 2015).

[21] The statistics do not allow to distinguish self-referral from referral by emergency services

[22] Mutually exclusive driving time polygons are a well established technique to define hospital catchment areas (McLafferty, 2003) and has been validated for such approaches (Schuurman et al., 2006). Figures B.2 and B.3 shows the location of hospitals and their catchment areas for across Germany and zoomed in for the city Bonn in West Germany.

Table 3: Descriptive statistics of hospital characteristics

	Mean	(SD)	min	max	N
A. Hospital characteristics					
Non-profit	0.43	0.50	0	1	8828
Public	0.40	0.49	0	1	8828
Private	0.17	0.38	0	1	8828
Number of Beds	375.49	312.82	4	2917	8828
Base rate in €	2990.23	260.91	871	14238	8828
Inpatients	15669.04	14263.88	77	198452	8828
Catchment area in km^2	503.51	559.65	0	4671	8828
Population in catchment area	75859.64	54525.85	282	447094	8820
B. Diagnoses					
All diseases (A00-N99)	10506.28	10257.91	32	155406	8828
Diseases of the circulatory system (I00-I99)	2294.15	2579.06	0	55735	8828
Hypertension (I10-I15)	258.84	398.95	0	18855	8828
Ischemic heart diseases (I20-I25)	565.18	867.48	0	17668	8828
Cerebrovascular disease (I60-I69)	277.00	420.80	0	6118	8828
Diseases of the respiratory system (J00-J99)	944.61	989.36	0	15512	8828
Chronic lower respiratory diseases (J40-J47)	203.95	221.67	0	3812	8828
Acute lower respiratory diseases (J20-J22)	103.91	122.82	0	1392	8828
Low birth Weight (P07) [t+1]	46.09	104.92	0	1840	7507
Stress (F40-F48)	74.71	141.68	0	2614	8828
Injuries (S00-S99)	1185.00	1119.20	0	19174	8828
C. Treatment characteristics					
In active Clean Air Plan	0.34	0.47	0.00	1.00	8828
In LEZ ban on Euro 1	0.10	0.30	0.00	1.00	8828
In LEZ ban on Euro 1-2	0.07	0.26	0.00	1.00	8828
In LEZ ban on Euro 1-3	0.06	0.23	0.00	1.00	8828
Catchment areas covered by LEZ	0.16	0.37	0.00	1.00	8828
Overall share of catchment area covered by LEZ	0.06	0.20	0.00	1.00	8828
Overall share of population covered by LEZ	0.07	0.22	0.00	1.00	8828
D. Weather characteristics					
Mean temperature in ° C	9.63	1.43	-5.27	12.64	8828
Mean precipitation in mm/m^2	2.05	0.58	0.80	5.89	8828
Mean Wind speed (m/ss)	3.42	0.98	1.18	11.19	8828
E. Municipality characteristics					
Inhabitants/1000	263.36	634.02	0.40	3574.83	8828
Employed/1000	113.82	249.37	0.00	1367.68	8828
Share male < 30 years	0.32	0.03	0.23	0.41	8828
Share male 30 - 64 years	0.50	0.02	0.43	0.55	8828
Share male > 64 years	0.18	0.02	0.13	0.27	8828
Share female < 30 years	0.29	0.03	0.20	0.39	8828
Share female 30 - 64 years	0.47	0.02	0.41	0.53	8828
Share female > 64 years	0.23	0.03	0.16	0.34	8828

Notes:This table displays the descriptive statistics for the most important variables. The data underlying the statistics in Panel D are measured at the nearest measuring station to the hospital. Panel E is based on the municipality a hospital is located in.

3 Empirical Analysis

3.1 Regression Model

Our aim is to estimate the causal impact of the introduction of a Low Emission Zone (LEZ) on population health via improvements in air quality. The staggered introduction of Low Emission Zones across cities in Germany motivates a difference-in-differences estimation strategy with the following empirical model, which we apply to both the sample of air pollution monitors and the sample of hospitals in Germany over the period 2006–2016. The basic model reads:

$$y_{ict} = \alpha + \beta \, LEZ_{it} + \boldsymbol{X'_{ict}}\gamma + \delta_i + \delta_{ts(c)} + \varepsilon_{ict}, \qquad (1)$$

where y_{ict} indicates the outcome – a measure of air pollution or the number of diagnoses – in year t measured at observation unit i – a pollution monitor or a hospital – located in city c. The main variable of interest is LEZ_{it} and captures the treatment of unit i in year t by a Low Emission Zone, which differs depending on the sample. For the sample of air pollution monitors, LEZ_{it} is simply a binary indicator with a value of one for monitor i being located within the boundaries of an active Low Emission Zone at any strictness level in year t and zero otherwise.[23] For the sample of hospitals, we equate LEZ_{it} with the share of hospital i's catchment area covered by a Low Emission Zone, ranging between zero and one.

The vector $\boldsymbol{X_{ict}}$ controls for a number of time-varying characteristics at the level of monitors and hospitals as well as for city population characteristics. In both samples, we include the set of weather controls measured at the closest weather monitor to the pollution monitor or hospital respectively. Further, we include population size, employment as well as the city population's composition by age groups and gender (see Tables 1–3 for details). For the sample of hospitals, we further control for time-varying hospital characteristics, the number of hospital beds, ownership and the baserate.[24] Finally, unit fixed effects δ_i capture any time-invariant monitor or hospital characteristics while state-year fixed effects $\delta_{ts(c)}$ control for any time-specific effects that are uniform across all observation units within a state s. To capture urbanization processes we also include city-specific linear time trends. The error term ε_{ict} is clustered at the county level.[25]

In order to capture dynamic effects of Low Emission Zone introductions, we conduct event studies where we test whether Low Emission Zone effects differ over the post-treatment periods. In addition, this allows to test whether the identifying assumption of common pre-trends is violated.

[23] In the Appendix, we show that the reductions in pollution are rather mixed across Low Emission Zone strictness levels. Further, most Low Emission Zones were introduced on January 1. If not, we multiply LEZ_{it} by 0.5 if the Low Emission Zone was established not later than June 30 in the introduction year t and set LEZ_{it} to zero if the Low Emission Zone was introduced later than June 30.

[24] The number of beds per hospital are determined annually at the regional level by hospitals, insurance associations and regional administrations to ensure sufficient supply based on population. The baserate reflects the historic cost level and determine hospital specific reimbursement prices.

[25] In Germany, larger cities are identical to a county (*Kreisfreie Stadt*), while more rural counties (*Landkreise*) comprise multiple smaller cities.

The introduction of a Low Emission Zone should not have any impact in pre-treatment periods. The extended model is:

$$y_{ict} = \alpha + \sum_{k=-4,k\neq-1}^{+5} \beta^k \ LEZ_{ik} + \boldsymbol{X'_{ict}}\gamma + \delta_i + \delta_{ts(c)} + \varepsilon_{ict}, \tag{2}$$

where the dummy variables LEZ_{ik} indicate yearly leads and lags of up to four years before and five years after the enactment of a Low Emission Zone. The reference category is $k = -1$, hence the post treatment effects are relative to the year immediately before the policy change and are interpreted as the effect of Low Emission Zones k periods before or after their introduction. We use the same controls as before.[26]

3.2 The impact of Low Emission Zones on air quality

In a first step, we document how the implementation of Low Emission Zones affects local air pollution by regulating the entry of vehicles based on their emission exhaust. Table 4 shows the main results for the effect of introducing a Low Emission Zone on annual average levels, limit exceedances and violations for PM10 and NO2. Each entry represents an estimate for β according to equation (1) from a separate regression of the respective outcome on the Low Emission Zone indicator, i.e., for a monitor being located within the boundaries of an active Low Emission Zone.

The results in Panel A of Table 4 show a negative impact on pollution levels for both PM10 and NO2 concentrations in all three specifications where we start with a fixed effect regression and gradually add time-variant control variables. Controlling for weather characteristics does not change the estimates. By adding additional controls for municipality characteristics effect sizes for most coefficients slightly decrease in absolute terms by capturing different changes in demographic compositions between areas. This is why we prefer the specification in columns (3) and (6) in the following analysis. The introduction of a ban of at least Euro 1 emission classes decreases PM10 by 1.3 $\mu g/m^3$ or six percent of the mean. The average NO2 levels are reduced by 1.6 $\mu g/m^3$ or five percent of the mean. Both effects are statistically significant at the one percent level.

In Panel B, we show results on outcomes related to limit exceedances according to the air quality standards. Introducing a Low Emission Zone reduces the annual number of days with PM10 levels above the regulatory threshold of 50 $\mu g/m^3$ by 7.7 days or almost 50 percent of the mean. In Panel C, we do not find any effect on the incidence of the yearly PM10 mean being above 40 $\mu g/m^3$, which is an extremely rare event to begin with (see Table 1). Although negative, we do not find statistically significant effects on limit exceedances for yearly hours of NO2 > 200 $\mu g/m^3$. Again, the incidence of violating this threshold is relatively rare (Table 2). However, we do find a significant decrease of yearly mean NO2 levels above 40 $\mu g/m^3$ of about four percentage points, which corresponds to a sizable reduction of about 25 percent compared to the mean. Hence, the policy of introducing a

[26]We bin up event dummies at the endpoints of the event window (i.e., $k = -4$ and $k = 5$). Hence, these dummies account for Low Emission Zone effects four or more years before and five or more years after the introduction

Low Emission Zone appears to be very effective in significantly decreasing local air pollution and reducing the incidence of air quality standard violations. Introducing Low Emission Zones effectively reduces the incidence of short-time spikes in PM10 pollution and at the same time reduces the longer-term annual mean concentration of NO2.

These findings are based on the straightforward specifications of equation (1), where we exploit the treatment of any Low Emission Zone irrespective of the strictness levels in terms of the emission exhaust classification.[27] While Low Emission Zone introductions typically begin with banning the dirtiest Euro 1 vehicles from entering the inner-city areas, essentially all Low Emission Zones by now ban Euro 1–3 vehicles. In Table A.4 we show results for interacting the Low Emission Zone treatment with different strictness levels, i.e., banning Euro 2 and Euro 3 additionally. It turns out that all strictness levels contribute to the average effects for most pollution outcomes shown in Table 4. These results also reflect the general improvement of emissions from vehicles and an upgrade of the vehicle fleet towards lower emission cars in cities with Low Emission Zones (Wolff, 2014) since more restrictive Low Emission Zones have been implemented later in time (see Figure A.4). The spatial precision of our dataset allows us to analyze the effect of a Low Emission Zone on pollution in its surroundings. Table A.5 shows that air quality in close proximity to a Low Emission Zone (within a radius of 10 km) is not affected while do some smaller increases for pollution monitors located at a distance of 10–20 km from a Low Emission Zone.

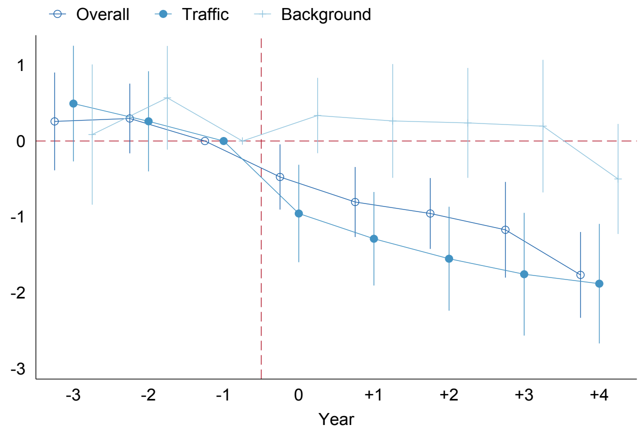
In Figure 3 we present results for the event study specification of equation (2). Focusing on those pollution outcomes with statistically significant effects as shown in Table 4, we use the presence of an active Low Emission Zone at the location of a pollution monitor as treatment independent of its strictness with the reference period $k = -1$, the year before a Low Emission Zone became effective. The event study results do not reveal any pre-trends that could bias our results. Corresponding to the difference-in-differences estimates, we find that air pollution levels as well as the incidence of violating regulatory thresholds for air quality are significantly reduced right after after the introduction of a Low Emission Zone. With the exception of the yearly mean of NO2 being above 40 $\mu g/m^3$ the effects become stronger over time. This could be due to the fact that Low Emission Zones have become stricter over time (see also Table A.4). In addition, Figure 3 shows results for splitting the sample of pollution monitors by whether they are designated as traffic or background monitors. As expected, the reductions in air pollution are strongest for traffic monitors.

[27] In Table A.3 we present results on the effects of introducing a Clean Air Plan, typically preceding Low Emission Zones by a few years, interacted with the introduction of a Low Emission Zone. We find that Clean Air Plans indeed have a negative effect on air pollution but that this is mainly driven by Low Emission Zone introductions. However, we refrain from putting too much emphasis on these findings since Clean Air Plans are very heterogeneous measures with unclear spatial extent.

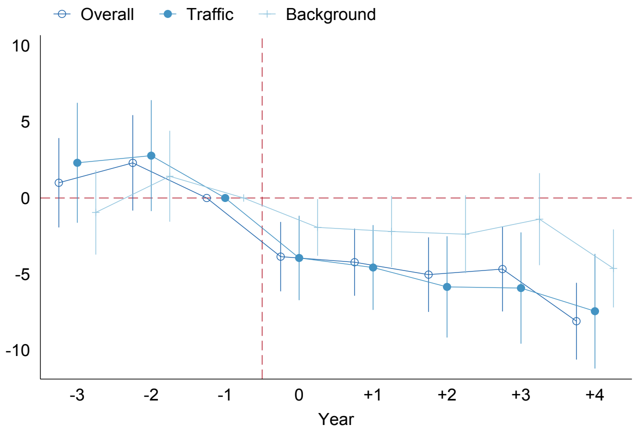
Table 4: The effect of Low Emission Zones on air pollution

	PM10			NO2		
	(1)	(2)	(3)	(4)	(5)	(6)
A. Pollution levels	Yearly mean PM10 ($\mu g/m^3$)			Yearly mean NO2 ($\mu g/m^3$)		
In LEZ	-1.461***	-1.450***	-1.273***	-1.829***	-1.823***	-1.581***
	(0.188)	(0.188)	(0.204)	(0.454)	(0.455)	(0.461)
Adj. R^2	0.93	0.93	0.93	0.74	0.74	0.74
N	4290	4290	4290	5237	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 ($\mu g/m^3$)			Yearly hours NO2 > 200 ($\mu g/m^3$)		
In LEZ	-7.068***	-7.068***	-6.580***	-7.071	-7.061	-5.572
	(0.916)	(0.918)	(0.972)	(4.783)	(4.785)	(3.883)
Adj. R^2	0.81	0.81	0.82	0.48	0.48	0.50
N	4290	4290	4290	4365	4365	4365
C. Violations	Yearly mean PM10 > 40 ($\mu g/m^3$)			Yearly mean NO2 > 40 ($\mu g/m^3$)		
In LEZ	-0.003	-0.003	-0.000	-0.050**	-0.051**	-0.043**
	(0.007)	(0.007)	(0.006)	(0.021)	(0.021)	(0.022)
Adj. R^2	0.16	0.17	0.17	0.86	0.86	0.86
N	4290	4290	4290	5237	5237	5237
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	No	Yes	Yes
Municipality characteristics	No	No	Yes	No	No	Yes

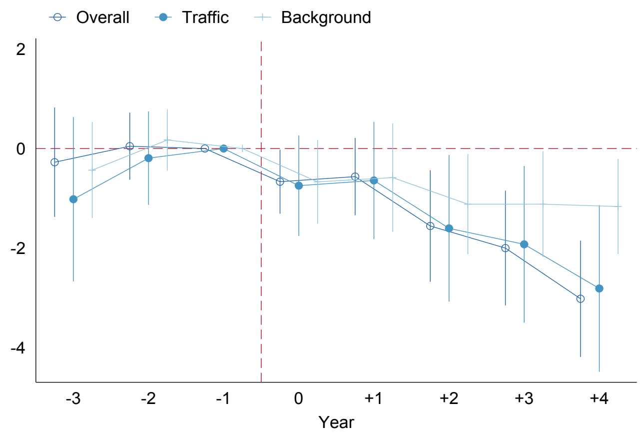
Notes: This table displays the results for the effect of Low Emission Zones on air pollution. Each coefficient is the result of a separate regression of pollution levels listed on the left on an indicator variable for locates in an active Low Emission Zone, while controlling for monitor and year fixed effects as well federal state time trends, weather characteristics characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, work force, age structure (share man(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max). Standard errors are clustered at county level and displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$.



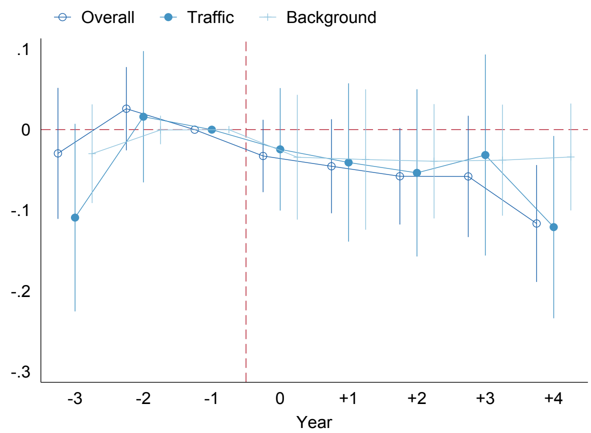
(a) Mean PM10 $\mu g/m^3$



(b) Days PM10 > 50 $\mu g/m^3$



(c) Mean NO2 $\mu g/m^3$



(d) Mean NO2 > 40 $\mu g/m^3$

Figure 3: The effect of Low Emission Zones on air pollution (event study)

Notes: This figure displays an event studies for the effect of Low Emission Zones on air pollution. The reference period is $k = -1$*. Each coefficient is the result of a separate interactions of dummy variables counting the years before and after the introduction of a Low Emission Zone and an indicator variable showing if a monitor is located inside or outside of a Low Emission Zone, while controlling for monitor and year fixed effects as well as weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)). Standard errors are clustered at county level.*

3.3 Health effects of Low Emission Zones

The results presented so far have shown that the introduction of a Low Emission Zone in an inner-city area significantly reduces air pollution and violations of EU air quality standards mainly inside the Low Emission Zone areas. While the EU air quality standards directly target local air pollution one key policy motivation for regulating entry of vehicles to inner-city areas is to improve population health and well-being. After having documented that Low Emission Zones effectively reduce air pollution, we will now turn to the question whether improvements in air quality induced by Low Emission Zones translate into improvements for human health.

In this section, we present the estimation results for the impact of Low Emission Zones on the number of diagnoses per hospital (in logs) as a proxy for general health. Given that the introduction of Low Emission Zones reduced several pollutants at the same time, we are not able to disentangle the effects on diagnoses by pollutant but will focus on hospital diagnoses that are related to PM10 and NO2 (see Section 2). Hence, estimates of the β coefficient measure the total effect of a Low Emission Zone introduction on hospital diagnoses. Therefore, results are reduced-form effects. A higher share of a hospital's catchment area covered by a Low Emission Zone lowers potential exposure to air pollution of people living or working in the catchment area. In addition, β captures the direct physiological impact of air pollution on the human body but may also be partly driven by reductions in traffic noise as well as behavioral responses to air pollution, such as changes in exercise habits or internal migration.

Table 5 reports the main results for the Low Emission Zone effect on hospital diagnoses. Each cell in this table represents an estimate for β from a separate regression of the outcome listed in the left column on the share of the hospital's catchment area covered by a Low Emission Zone based on driving time and the controls listed at the bottom. We look at the total number of all diseases and then separately at diseases of the circulatory and the respiratory system as well as subgroups thereof. In addition, we use the incidence of low birth weight as an outcome.

We begin with a bivariate fixed effect regression and gradually add control variables. Including hospital fixed effects is particularly important because observable characteristics vary considerably between areas with and without Low Emission Zones since Low Emission Zones are primarily located in densely populated urban areas. By using fixed effects we control for time-invariant structural differences. In addition, we control for a number of time-variant hospital and municipality characteristics and eventually include linear municipality-specific time trends to capture the effects of changing population characteristics over time.

Almost all point estimates in columns (1) to (5) of Table 5 are negative irrespective of additional control variables, indicating that the introduction of a Low Emission Zone potentially has a beneficial impact on population health. In columns (2) and (3), once we control for weather and municipality characteristics, coefficient estimates are only slightly affected. Controlling for linear municipality-specific time trends in column (5), capturing differential effects from urbanization, yields to larger point estimates in absolute terms. After including hospital controls in column (5), in particular hospital capacity proxied by the number of beds, most point estimates become larger and more significant. This is not surprising, given that hospitals treated by a Low Emission Zone tend to be located in growing urbanized areas, which increases the number of diagnoses simply because the number of potential patients in the area increases.

Based on the results in column (5), an increase in hospital's catchment area covered by a Low Emission Zone by one standard deviation (corresponding to 20 percentage points, see Table 3) reduces the total number of diagnosed diseases by about 1.4 percent, the estimate being statistically significant at the 0.1 level.[28] Focusing on diagnoses that are closely related to air pollution, we find an effect for diseases of the circulatory system by 2.9 percent, or 67 cases at the mean. Among this broad category of diseases, the corresponding effects are between 3.1 and 5.0 percent. The point estimates suggest that a Low Emission Zone has the largest impact on circulatory diseases like ischemic heart diseases and cerebrovascular diseases, implying a reduction of diagnoses between 29 and 11 cases per year at the respective means. We do find a statistically significant effects for the aggregate category of respiratory diseases in general as well which is 2.16 percent. Chronic diseases of the lower respiratory system are significantly reduced by more than four percent (or 8 cases at the mean) for a one standard deviation increase in the Low Emission Zone coverage of a hospital's catchment area while there is a 3.4 percent reduction for acute lower respiratory diseases.[29] We do not find a statistically significant impact on low birth weight.[30]

In Table 6 we focus on circulatory and respiratory diagnoses that can be described as medical emergencies or non-emergencies. The selection follows Schreyögg et al. (2014) who identify the top 25 of medical emergency and non-emergency hospital diagnoses between 2007 and 2012, based on diagnose characteristics such as the time between admission and treatment. Out of these 25, we select all circulatory and respiratory diagnoses. The results are shown in Table 5. We find that the effect for non-emergency cases is negative and statistically significant while the estimate for emergency cases is much smaller and insignificant. This is in line with our finding that chronic respiratory diagnoses are are more strongly affected than acute diagnoses, indicating that the introduction of Low Emission Zones mainly benefited individuals with a bad health condition who have to be admitted to the hospital less often because of their disease.

In Figure 4 we present the results for the log number of respiratory and circulatory diagnoses in an event study framework.[31] The findings for circulatory diseases in Panel (a) indicate that the effects started to appear already in the first year after the introduction and tend to decrease over time. However, focusing on the sample of Low Emission Zones that were introduced until 2011, we find that the effects are more sustainable over the following years, while statistical significance becomes

[28] As the dependent variable is in logs, the estimates can be interpreted as changes in percentages. For example, in column (5) of Table 5 an increase in the coverage of a catchment area by one standard deviation ($= 0.20$) translates into an effect size of $-0.072 \times 0.20 = 0.014$, i.e., 1.4 percent.

[29] Stronger effect sizes for impacts on the circulatory compared to the respiratory system are in line with findings of a meta study which summarized findings on health effects for traffic related pollutants (Hoek et al., 2013).

[30] We do not observe an effect on stress related diagnoses or injuries, thus not indicating additional health channels but air pollution (Table C.3).

[31] We show event studies for every diagnose in the appendix (see Figure C.1).

less pronounced. Panel (b) shows the event study for respiratory diseases. In the immediate year after the introduction the incidence of respiratory diseases decreases. However, this effect is not sustainable for the overall sample and also less sustainable for Low Emission Zones introduced earlier. This could be due to the fact that since 2012 the majority of the car fleet in Germany reached at least the Euro 4 emission class for the first time, qualifying cars for a green sticker (Kraftfahrt-Bundesamt, 2018). This means that the introduction of Low Emission Zones becomes a less restrictive policy over time as more cars already fulfill the requirements for entering Low Emission Zones, which reduces the potential impact on vehicle emissions.

Table 5: The effect of Low Emission Zones on diagnoses in general hospitals

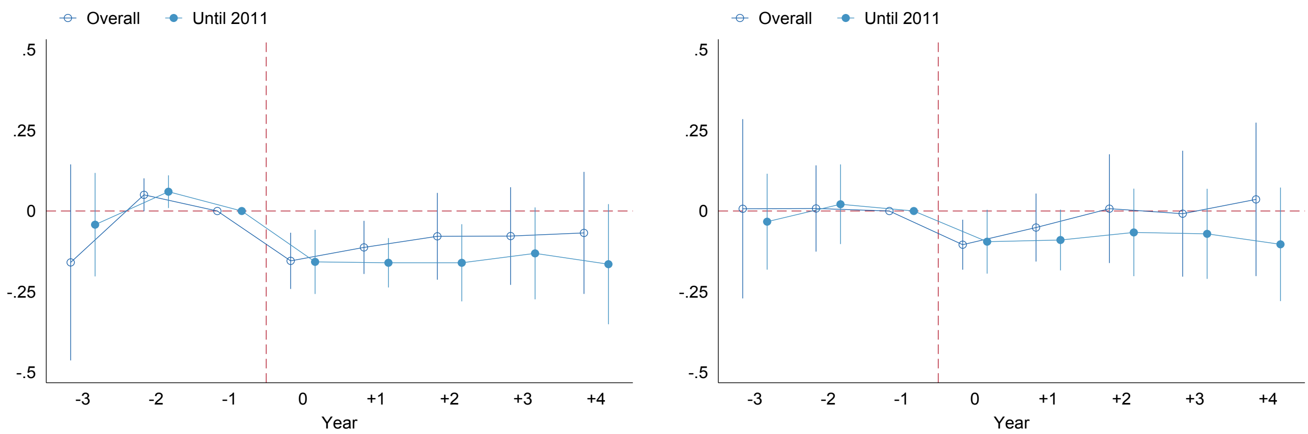
	(1)	(2)	(3)	(4)	(5)
All diseases (A00-N99)	-0.049	-0.050	-0.051	-0.066	-0.072*
	(0.040)	(0.039)	(0.047)	(0.047)	(0.043)
Diseases of the ciculatory system (I00-I99)	-0.105*	-0.105*	-0.109*	-0.144**	-0.145***
	(0.055)	(0.055)	(0.061)	(0.058)	(0.055)
Hypertension (I10-I15)	-0.120*	-0.119*	-0.120	-0.165*	-0.157*
	(0.069)	(0.069)	(0.076)	(0.092)	(0.091)
Ischemic heart diseases (I20-I25)	-0.132	-0.133	-0.174*	-0.258**	-0.263***
	(0.082)	(0.082)	(0.091)	(0.103)	(0.099)
Cerebrovascular disease (I60-I69)	-0.134	-0.133	-0.188*	-0.191*	-0.208**
	(0.099)	(0.099)	(0.103)	(0.106)	(0.102)
Diseases of the respiratory system (J00-J99)	0.009	0.009	-0.007	-0.099	-0.108*
	(0.060)	(0.059)	(0.060)	(0.065)	(0.059)
Acute lower respiratory diseases (J20-J22)	-0.007	-0.006	-0.007	-0.167*	-0.171*
	(0.089)	(0.088)	(0.086)	(0.095)	(0.090)
Chronic lower respiratory diseases (J40-J47)	-0.135**	-0.136**	-0.149**	-0.217***	-0.222***
	(0.063)	(0.063)	(0.067)	(0.079)	(0.077)
Low birth weight (P07) [t+1]	0.027	0.027	0.027	-0.095	-0.091
	(0.077)	(0.077)	(0.082)	(0.111)	(0.112)
N	8828	8828	8828	8828	8828
Controls:					
Hospital FE	Yes	Yes	Yes	Yes	Yes
State $\times$ Year FE	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	Yes	Yes
Municipality characteristics	No	No	Yes	Yes	Yes
Linear municipality time trends	No	No	No	Yes	Yes
Hospital characteristics	No	No	No	No	Yes

Notes:This table displays the results for diagnoses, for general hospitals. The catchment area is calculated by driving time. Each coefficient is the result of a separate regression of diagnose listed on the left on a indicator variable for an active Low Emission Zone (share of catchment area covered by Low Emission Zone), while controlling for hospital and year fixed effects as well as federal state time trends, hospital characteristics (non-profit, public, private, base rate, number of beds, number of beds^2), hospital size (small, medium, large) $\times$ years, municipality characteristics (mean temperature, precipitation and wind speed, population, work force, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)), linear time trends (Municipality $\times$ Years). Standard errors are clustered at county level and displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$. [1])
Based on 7516 observations.

Table 6: The effect of Low Emission Zones on diagnoses: Emergency vs. non-emergency diagnoses

	(1)	(2)	(3)	(4)	(5)
Main Emergency Cardiovascular and Respiratory Diagnoses	-0.017	-0.017	-0.033	-0.063	-0.064
	(0.065)	(0.065)	(0.071)	(0.085)	(0.083)
Main Non-Emergency Cardiovascular and Respiratory Diagnoses	-0.116**	-0.117**	-0.126*	-0.143**	-0.142**
	(0.058)	(0.058)	(0.065)	(0.060)	(0.057)
N	8828	8828	8828	8828	8828
Controls:					
Hospital FE	Yes	Yes	Yes	Yes	Yes
State $\times$ Year FE	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	Yes	Yes
Municipality characteristics	No	No	Yes	Yes	Yes
Linear municipality time trends	No	No	No	Yes	Yes
Hospital characteristics	No	No	No	No	Yes

Notes:This table displays the results for emergency (I100, J180, I200, I214, J209, I63, I181) and non-emergency diagnoses of the Cardiovascular and respiratory system (I208, I251, I501, I481, I702, I839, J342, J189), for general hospitals. The catchment area is calculated by driving time. Each coefficient is the result of a separate regression of diagnose listed on the left on a indicator variable for an active Low Emission Zone (share of catchment area covered by Low Emission Zone), while controlling for hospital and year fixed effects as well as federal state time trends, hospital characteristics (non-profit, public, private, base rate, number of beds, number of beds^2), hospital size (small, medium, large) $\times$ years, municipality characteristics (mean temperature, precipitation and wind speed, population, work force, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)), linear time trends (Municipality $\times$ Years). Standard errors are clustered at county level and displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$. [1])



(a) Circulatory diseases

(b) Respiratory diseases

Figure 4: The effect of Low Emission Zones on diagnoses in general hospitals (event study)

Notes: Figure 4a and 4b display event studies revealing the impact of $\beta\ shareLEZ_{it}$ *on circulatory diseases (I00-I99) and respiratory diseases (J00-J99). The reference period is* $k = -1$. *Each coefficient is the result of a separate interactions of dummy variables counting the years before and after the introduction of a Low Emission Zone and an indicator variable showing if the share of a hospital catchment area covered by an active Low Emission Zone, while controlling for hospital and year fixed effects as well as federal state time trends, hospital characteristics (non-profit, public, private, baserate, number of beds, number of beds*^{2}*), hospital size (small, medium, large)* $\times$ *years, weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)) and linear municipality time trends. Standard errors are clustered at county level*

3.4 Additional Results and Robustness

Definition of hospital sample. Our main results are based on general hospitals, which are hospitals with a unit for surgery and internal medicine and hence excluded more specialized hospitals. The results for this baseline sample selection are shown in column (1) of Table 7, where we standardize diagnoses to mean zero and standard deviation of one to make results comparable across different samples and specifications. Column (2) shows that estimates for the sample of specialized hospitals, which typically do not treat air pollution related diseases, are not affected by the introduction of Low Emission Zones. Column (3) shows estimation results for a subsample of general hospitals that are located in cities that are eventually covered by a Clean Air Plan, which typically precedes the implementation of Low Emission Zones. Hence, hospitals in these cities are more comparable to each other. Focusing on this more homogeneous sample of hospitals reveals similar results as in our main specification, indicating that keeping never adopters in the control group does not increase unobserved heterogeneity.

Assignment of hospital catchment areas. Lacking information on the residential locations of patients, an important potential source of measurement error is the assignment of hospital catchment areas and the extent to which they are covered by Low Emission Zones. We perform a series of robustness checks by applying different alternative definitions of catchment areas. The results in column (4) are based on the share of the population covered by an Low Emission Zone, accounting for heterogeneous population density in a catchment area using high resolution satellite population grids.[32]. The results are very similar to our main specification. This is also true if we apply an alternative approach by defining catchment areas by a ten minutes driving time radius around the hospital, shown in column (5).[33] Using binary indicators for being covered by an active Low Emission Zone in column (6) and (7) tend to increase point estimates. Given that this are rather broad definitions of treatment it not surprising that standard error increase.

Aggregating on municipality and county level. In order to reveal the importance of using high resolution spatial data we aggregate hospital diagnoses at the municipality and county level by year and regress the aggregate number of diagnoses on the share of a county or municipality that is covered by an active Low Emission Zone or on a binary indicator for an active Low Emission Zone. We use similar controls as in the main health regression but use the corresponding controls at the municipality or county level. The results are shown in Table C.1. Columns (1) and (2) show the results on county level for the binary indicator and the share covered by a Low Emission Zone. Columns (3) and (4) show the corresponding results at the municipality level. While most of the

[32]We use the GEOSTAT 2006 and 2011 which are datasets of 1km $\times$ 1km population grids approximate by the building structure in each grid to calculate the population density in Low Emission Zones and in catchment areas. Our treatment is than the share of the population in a catchment area that is covered by a Low Emission Zone

[33]We chose ten minutes because three quarters of the German population reached the next general hospital within ten driving minutes in 2005 (Klauber, 2006).

coefficients are negative only two of them are marginally statistically significant. Furthermore, effect sizes are smaller in most of the cases compared to our main specification with high spatial resolution. This is additional evidence that the health benefits of Low Emission Zones are concentrated very locally for the the population living inside their boundaries.

Accounting for effects on traffic volume. Traffic is a potential additional channel when analyzing the impact of Low Emission Zones on health. If the implementation of Low Emission Zones reduces traffic volumes in addition to the vehicle fleet's emission standards there may be other impacts on public health in the long-term, for example on diseases of the circulatory system due to increased physical activity. Furthermore, less traffic could change the stress level in a city by lowering noise exposure or congestion. Based on a binary treatment indicator Table C.2 shows the effect on traffic volume in and around a Low Emission Zone for all vehicles (columns (1)-(3)) and only passenger cars below 3.5 tonnes (columns (4)-(6)). In general, we control for the same characteristics as in our main specification. However, we now control for labor market region time trends instead of municipality time trends to account for changes in commuting behavior between municipalities. Most of the coefficients in Table C.2 are negative but very small and none is statistically significant. These findings are in line with Wolff (2014) who shows that improvements in air quality are driven by increases in the share of low emitting vehicles in cities with Low Emission Zones.

Other diagnoses related to air pollution and traffic. Table C.3 provides further evidence that health effects are driven by improvements in air quality through reductions in respiratory and cardiovascular diseases. Again, we use the same specification as in our main regression in Table 5 and study the effects on outcomes that may as well be affected by Low Emission Zones. For example, dementia and diabetes are suspected of being caused by air pollution. While we find negative point estimates for dementia, the results are not statistically significant. However, one would expect that improvements in air quality reduce the incidence of dementia only in the long run. We find no affect for diabetes. Additionally, we focus on stress related diagnoses and diagnoses of injuries which would reveal typical diagnoses related to road traffic accidents. Again, the coefficients are not significant which is line with the result that traffic volumes are not affected and suggest that air quality is the main driving factor for health improvements in Low Emission Zones.

Table 7: The effect of Low Emission Zones on diagnoses (alternative specifications)

Catchment area based on		Driving time		Driving time (POP)	10 min radius	Binary(in/out)	Binary(Covered)
Hospital sample	General Hospitals	Special hospitals	General hospitals in CAP	General hospitals	General hospitals	General hospitals	General hospitals
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
All diseases (A00-N99)	-0.014*	-0.011	-0.030*	-0.010	-0.009	-0.015	-0.012
	(0.008)	(0.016)	(0.018)	(0.008)	(0.008)	(0.010)	(0.026)
Diseases of the ciculatory system (I00-I99)	-0.028***	-0.017	-0.087**	-0.022*	-0.022*	-0.030*	-0.026
	(0.011)	(0.042)	(0.043)	(0.012)	(0.011)	(0.017)	(0.044)
Hypertenion (I10-I15)	-0.031*	0.024	-0.044	-0.037*	-0.029*	-0.051***	-0.047
	(0.018)	(0.032)	(0.031)	(0.019)	(0.015)	(0.019)	(0.060)
Ischemic heart diseases (I20-I25)	-0.053***	0.005	-0.078*	-0.047**	-0.028	-0.053*	0.013
	(0.020)	(0.029)	(0.045)	(0.021)	(0.017)	(0.028)	(0.076)
Cerebrovascular disease (I60-I69)	-0.041**	-0.010	-0.075***	-0.034*	-0.040**	-0.033	-0.027
	(0.020)	(0.033)	(0.025)	(0.019)	(0.020)	(0.021)	(0.051)
Diseases of the respiratory system (J00-J99)	-0.021*	-0.022	-0.038	-0.014	-0.019	-0.022	-0.011
	(0.012)	(0.055)	(0.043)	(0.011)	(0.013)	(0.015)	(0.039)
Acute lower respiratory diseases (J20-J22)	-0.034*	-0.023	-0.057	-0.034*	-0.017	-0.048**	-0.117*
	(0.018)	(0.047)	(0.048)	(0.017)	(0.019)	(0.023)	(0.066)
Chronic lower respiratory diseases (J40-J47)	-0.045***	-0.010	-0.050	-0.044***	-0.039***	-0.063***	-0.088*
	(0.015)	(0.030)	(0.039)	(0.016)	(0.014)	(0.021)	(0.050)
Low birth weight (P07)	-0.018	0.015	0.014	-0.014	-0.024	-0.009	0.000
	(0.022)	(0.017)	(0.028)	(0.025)	(0.023)	(0.019)	(0.056)
N	8828	6874	5590	8828	8828	8828	8828
Controls:							
Hospital FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State $\times$ Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear municipality time trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes:This table displays the results for different treatment definitions and samples. Each coefficient is the result of a separate regression of standardized diagnose listed on the left on a indicator variable for an active LEZ, while controlling for hospital and year fixed effects as well as hospital characteristics as well as hospital characteristics (non-profit, public, private, baserate, number of beds, number of beds^2), hospital size (small, medium, large) $\times$ years, municipality characteristics (mean temperature, precipitation and wind speed, population, work force, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)), linear time trends (Municipality $\times$ Years). Standard errors are clustered at county level and displayed in parentheses. Significance levels: $***: p < 0.01, **: p < 0.05, *: p < 0.1.$.

4 Conclusion

In this paper, we show that Low Emission Zones are an effective policy instrument to reduce levels of air pollution in a targeted area, thereby having positive impacts on population health. Exploiting variation in the roll out of Low Emission Zones in Germany, we find that hospitals which catchment areas are covered by a Low Emission Zone diagnose significantly less air pollution related diseases. We find the effect to be stronger before 2012, which is consistent with a general improvement in the vehicle fleet's emission standards. Using precise spatial data on the extension of Low Emission Zones in Germany, our results confirm former results showing that the introduction of Low Emission Zones improved air quality significantly by reducing NO2 and PM10 concentrations. While effect sizes for average pollution levels are equal, our effect sizes for violations of air quality standards are larger compared to previous results (Wolff, 2014; Malina and Scheffler, 2015; Gehrsitz, 2017). This can be explained by our finding of a strong spatial delineation not captured by studies which use between and not within city variation as we do.

We show that the introduction of Low Emission Zones in Germany actually improved population health, in particular by reducing the incidents of chronic diseases of the circulatory and the respiratory system. Our results further suggest that these effects may be driven by reductions in non-emergency diagnoses of chronic diseases rather than emergency cases. We do not find reductions for low birth weight which is in line with Gehrsitz (2017). We further show that traffic volumes and diseases related to traffic (stress, injuries) were not affected by Low Emission Zones.

These findings have strong implications for policy makers. First, in 2015, overall costs for health care in Germany were around 340 billion euros, of which 46 billion euros for diseases of the circulatory system, making it the most expensive type of disease caused by 2.9 million cases (Statistisches Bundesamt, 2017b). Hence, reductions in the incidence of diseases of the circulatory system may directly reduce society's health costs. Besides, improving population health has sizable indirect costs on human capital and growth (Graff Zivin and Neidell, 2013). Second, the results of this study are informative for policy debates about further regulation of emissions from traffic. While the introduction of Low Emission Zones has reduced air pollution there are still numerous violations of EU air quality standards in German cities. As a consequence, as of 2019, vehicles with emission standards below Euro 5 or even Euro 6 (especially Diesel-fueled vehicles) are not allowed to enter designated areas in a number of large German cities (among others Stuttgart, Hamburg, Berlin and Cologne). These Diesel driving bans are currently controversially debated. Opponents question the potential health effects of these policy measures. While our findings show that restricting entry by high-emission vehicles improves population health through better air quality in inner-cities our findings are based on the regulation of emission standards Euro 1–3. Whether further regulation of Euro 5–6 yields further health improvements should be addressed by future research.

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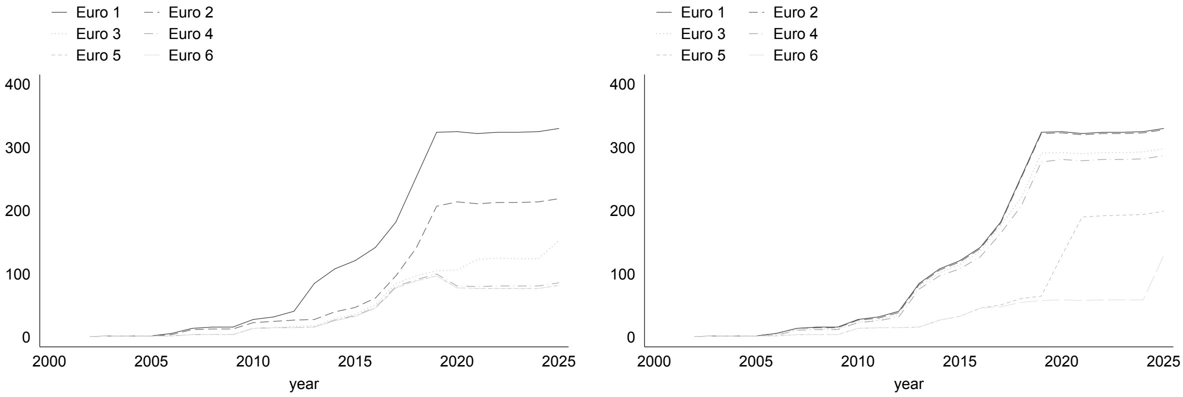
Appendix

A Low Emission Zones and air pollution in Germany



(a) Petrol (b) Diesel

Figure A.1: Low Emission Zones in Europe

Notes: This figure shows the past and future development of Low Emission Zones across the European Union. Euro 2, 3, 4, 5 and 5 are subsets of Euro 1. Panel A.1a shows restrictions on Petrol vehicles and and Panel A.1a on Diesels. Source: urbanaccessregulations.eu.

Table A.1: European Union air quality standards (PM10 and NO2)

(Pollutant)	(Thresholds)	(Deadline)
PM10	Yearly average limit 40$\mu g/m^3$ Daily average limit 50$\mu g/m^3$ Allowed number of transgression: 35	1 January 2005
NO2	Yearly average limit 40$\mu g/m^3$ Hourly average limit 200$\mu g/m^3$ Allowed number of transgression: 18	1 January 2010

Notes: This table displays air quality standards based on the Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphur dioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air. It was repealed by the Directive 2008/50/EC of the European Parliament and of the Council of 21 May 2008.

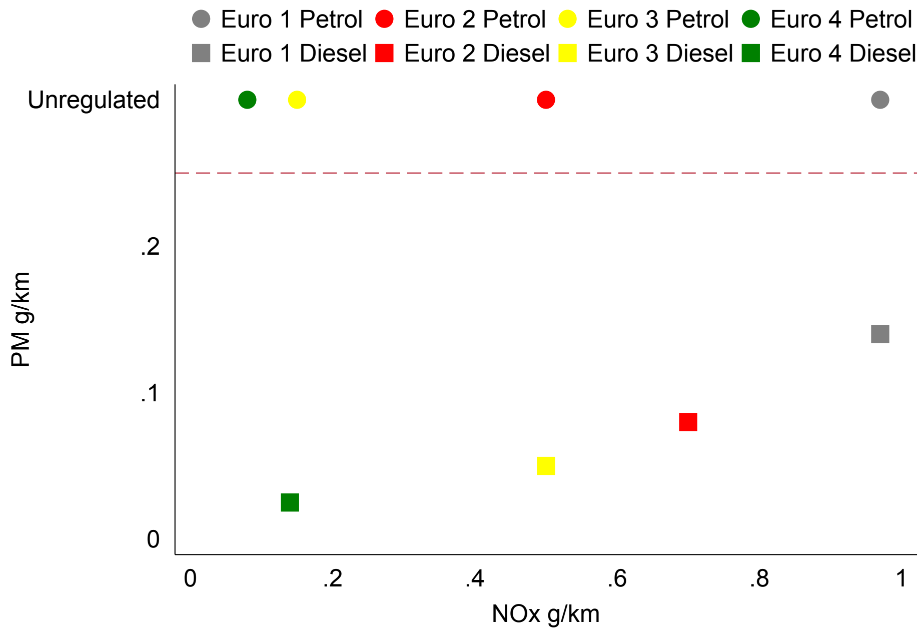


Figure A.2: Vehicle emission standards

Notes: This graph displays European emission standards of acceptable limits for exhaust emissions of new vehicles sold in the European Union and European Economic Area member states. They are defined in a series of European Union directives over time with increasingly stringent standards. Source: Tiwary and Williams (2018)

(a) Official map

(b) Own presentation

Figure A.3: Low Emission Zone of the Ruhr area

Notes:Panel (a) displays the LEZ of the Ruhr area based on official documents while Panel (b) shows the same LEZ based on polygons available at OpenStreetMap.org.

Table A.2: Low Emission Zones in Germany as of 2018

(Low Emission Zone)	(Federal State)	(Sticker)	(Active since)	(Size in Km^2)	(Perimeter in Km)
Balingen	BW	Green	01.04.2017	90 Km^2	50 Km
Freiburg	BW	Green	01.01.2010	25 Km^2	58 Km
Heidelberg	BW	Green	01.01.2010	10 Km^2	34 Km
Heidenheim	BW	Green	01.01.2012	17 Km^2	28 Km
Heilbronn	BW	Green	01.01.2009	38 Km^2	28 Km
Herrenberg	BW	Green	01.01.2009	4 Km^2	9 Km
Ilsfeld	BW	Green	01.03.2008	2 Km^2	5 Km
Karlsruhe	BW	Green	01.01.2009	11 Km^2	16 Km
Leonberg / Hemmingen	BW	Green	02.12.2013	131 Km^2	60 Km
Ludwigsburg	BW	Green	01.01.2013	139 Km^2	58 Km
Möhlacker	BW	Green	01.01.2009	1 Km^2	7 Km
Mannheim	BW	Green	01.03.2008	7 Km^2	16 Km
Pfinztal	BW	Green	01.01.2010	31 Km^2	30 Km
Pforzheim	BW	Green	01.01.2009	2 Km^2	9 Km
Reutlingen	BW	Green	01.01.2008	109 Km^2	91 Km
Schramberg	BW	Green	01.07.2013	4 Km^2	16 Km
Schwäbisch Gmuend	BW	Green	01.03.2008	6 Km^2	17 Km
Stuttgart	BW	Green	01.03.2008	204 Km^2	109 Km
Tübingen	BW	Green	01.03.2008	108 Km^2	73 Km
Ulm	BW	Green	01.01.2009	28 Km^2	26 Km
Urbach	BW	Green	01.01.2012	2 Km^2	8 Km
Wendlingen	BW	Green	02.04.2013	4 Km^2	9 Km
Augsburg	BY	Green	01.07.2009	6 Km^2	12 Km
Müchen	BY	Green	01.10.2008	43 Km^2	28 Km
Neu-Ulm	BY	Yellow	01.11.2009	2 Km^2	21 Km
Regensburg	BY	Green	15.01.2018	1 Km^2	7 Km
Berlin	B	Green	01.01.2008	87 Km^2	38 Km
Bremen	HB	Green	01.01.2009	7 Km^2	13 Km
Darmstadt	HE	Green	01.11.2015	106 Km^2	90 Km
Frankfurt a.M.	HE	Green	01.10.2008	98 Km^2	60 Km
Limburg an der Lahn	HE	Green	31.01.2018	6 Km^2	15 Km
Marburg	HE	Green	01.04.2016	15 Km^2	34 Km
Offenbach	HE	Green	01.01.2015	39 Km^2	35 Km
Wiesbaden	HE	Green	01.02.2013	63 Km^2	78 Km
Hannover	NI	Green	01.01.2008	43 Km^2	30 Km
Osnabrück	NI	Green	04.01.2010	17 Km^2	33 Km
Aachen	NW	Green	01.02.2016	24 Km^2	28 Km
Bonn	NW	Green	01.01.2010	9 Km^2	18 Km
Düsseldorf	NW	Green	15.02.2009	43 Km^2	16 Km
Dinslaken	NW	Green	01.07.2011	4 Km^2	9 Km
Eschweiler	NW	Green	01.06.2016	2 Km^2	7 Km
Hagen	NW	Green	01.01.2012	9 Km^2	19 Km
Köln	NW	Green	01.01.2008	94 Km^2	88 Km
Krefeld	NW	Green	01.01.2011	10 Km^2	16 Km
Langenfeld	NW	Green	01.01.2013	1 Km^2	6 Km
Mönchengladbach	NW	Green	01.01.2013	21 Km^2	26 Km
Münster	NW	Green	01.01.2010	1 Km^2	6 Km
Neuss	NW	Green	15.02.2010	2 Km^2	6 Km
Overath	NW	Green	01.10.2017	1 Km^2	3 Km
Remscheid	NW	Green	01.01.2013	1 Km^2	7 Km
Ruhrgebiet	NW	Green	01.01.2012	868 Km^2	276 Km
Siegen	NW	Green	01.01.2015	3 Km^2	11 Km
Wuppertal	NW	Green	15.02.2009	25 Km^2	48 Km
Mainz	RP	Green	01.02.2013	34 Km^2	35 Km
Leipzig	SN	Green	01.03.2011	182 Km^2	111 Km
Halle (Saale)	SA	Green	01.09.2011	7 Km^2	12 Km
Magdeburg	SA	Green	01.09.2011	7 Km^2	21 Km
Erfurt	TH	Green	01.10.2012	16 Km^2	19 Km
Mean				49.96 Km^2	35.62 Km
Median				12.50 Km^2	21.31 Km
SD				119.39 Km^2	42.28 Km

Notes: This table shows detailed information of all active German Low Emission Zones in 2018. Source: OpenStreetMap.org., Federal Environment Office

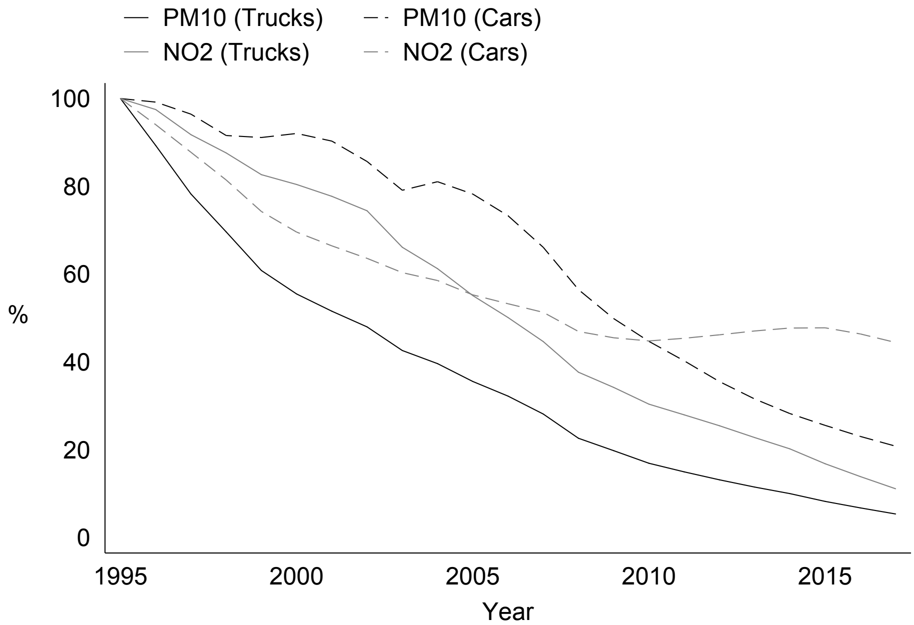
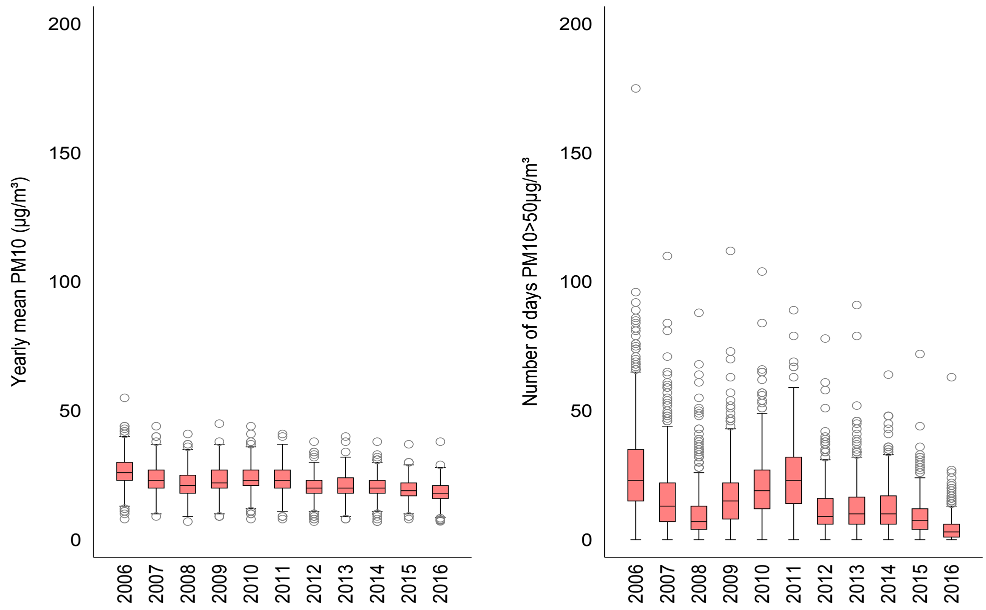
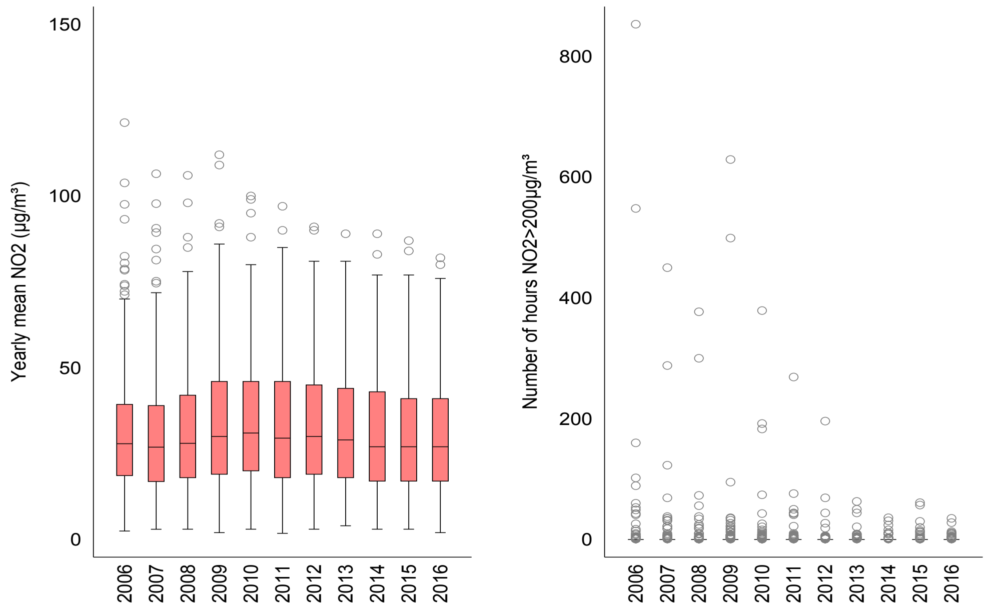


Figure A.4: Average emissions of vehicles in Germany

Source: German Environment Agency (Umweltbundesamt).

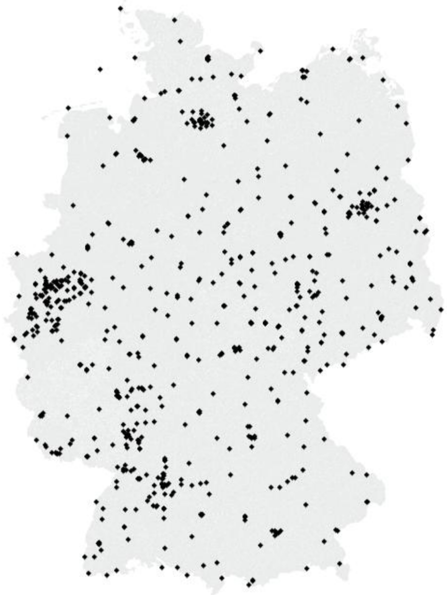


(a) PM10

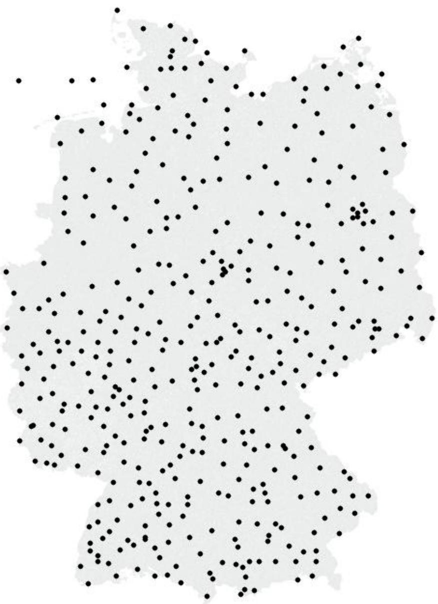


(b) NO2

Figure A.5: Variation of pollutants over time



(a) Pollution monitors



(b) Weather monitors

Figure A.6: Location of pollution and weather monitors

Table A.3: The effect of Clean Air Plans on air pollution

	PM10		NO2	
	(1)	(2)	(3)	(4)
A. Pollution levels	Yearly mean PM10 ($\mu g/m^3$)		Yearly mean NO2 ($\mu g/m^3$)	
Clean Air Plan	-0.598***	-0.315	-0.598***	-0.162
	(0.206)	(0.212)	(0.278)	(0.296)
Clean Air Plan × In LEZ		-2.766***		-2.662***
		(0.546)		(0.546)
Adj. R^2	0.93	0.93	0.74	0.74
N	4290	4290	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 ($\mu g/m^3$)		Yearly hours NO2 > 200 ($\mu g/m^3$)	
Clean Air Plan	-3.502***	-2.193**	4.376	5.501
	(0.824)	(0.859)	(3.175)	(3.813)
Clean Air Plan × In LEZ		-8.088***		-3.268
		(1.948)		(3.868)
Adj. R^2	0.81	0.82	0.50	0.50
N	4290	4290	4357	4357
C. Violations	Yearly mean PM10 > 40 ($\mu g/m^3$)		Yearly mean NO2 > 40 ($\mu g/m^3$)	
Clean Air Plan	0.010*	0.010	-0.008	0.002
	(0.006)	(0.007)	(0.020)	(0.019)
Clean Air Plan × In LEZ		-0.005		-0.027
		(0.005)		(0.049)
Adj. R^2	0.17	0.17	0.86	0.86
N	4290	4290	5237	5237
Controls:				
Station FE	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes

Notes: Each column reports the result from a regression of the pollutant listed at the top on the treatment listed on the left, while controlling for monitor and year fixed effects as well as federal state time trends, weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)). Standard errors are clustered at county level are displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1.$.

Table A.4: The effect of Low Emission Zones on air pollution by emission standard

	PM10			NO2		
	(1)	(2)	(3)	(4)	(5)	(6)
A. Pollution levels	Yearly mean PM10 ($\mu g/m^3$)			Yearly mean NO2 ($\mu g/m^3$)		
In LEZ	-1.273***	-0.728***	-0.837***	-1.581***	0.577	0.056
	(0.204)	(0.210)	(0.207)	(0.460)	(0.522)	(0.466)
In LEZ × Euro 2		-0.831***			-3.116***	
		(0.241)			(0.724)	
In LEZ × Euro 3			-0.810***			-2.874***
			(0.223)			(0.654)
Adj. R^2	0.93	0.93	0.93	0.74	0.74	0.74
N	4290	4290	4290	5237	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 ($\mu g/m^3$)			Yearly hours NO2 > 200 ($\mu g/m^3$)		
In LEZ	-6.580***	-3.934***	-4.031***	-5.572	1.582	-1.443
	(0.970)	(1.165)	(1.068)	(3.878)	(1.366)	(4.125)
In LEZ × Euro 2		-4.032***			-10.098*	
		(1.289)			(5.898)	
In LEZ × Euro 3			-4.735***			-7.147
			(1.114)			(5.357)
Adj. R^2	0.82	0.82	0.82	0.50	0.50	0.50
N	4290	4290	4290	4357	4357	4357
C. Violations	Yearly mean PM10 > 40 ($\mu g/m^3$)			Yearly mean NO2 > 40 ($\mu g/m^3$)		
In LEZ	-0.000	0.009	0.006	-0.043**	0.001	-0.022
	(0.006)	(0.009)	(0.009)	(0.022)	(0.031)	(0.026)
In LEZ × Euro 2		-0.015			-0.064	
		(0.009)			(0.030)	
In LEZ × Euro 3			-0.012			-0.037
			(0.008)			(0.027)
Adj. R^2	0.17	0.18	0.18	0.86	0.86	0.86
N	4290	4290	4290	5237	5237	5237
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Each coefficient is the result of a separate regression of the pollutant listed at the top on the treatment listed on the left while controlling for monitor and year fixed effects as well as federal state time trends, weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)). Standard errors are clustered at county level are displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$. .

Table A.5: The effect of Low Emission Zones on air pollution in surrounding areas

	PM10			NO2		
	(1)	(2)	(3)	(4)	(5)	(6))
A. Pollution levels	Yearly mean PM10 ($\mu g/m^3$)			Yearly mean NO2 ($\mu g/m^3$)		
In LEZ	-1.273***	-1.229***	-1.181***	-1.581***	-1.527***	-1.512***
	(0.204)	(0.202)	(0.197)	(0.460)	(0.457)	(0.458)
10 km around LEZ		0.236	0.292		0.386	0.408
		(0.229)	(0.232)		(0.490)	(0.511)
10-20 km around LEZ			0.805***			0.297
			(0.281)			(0.690)
Adj. R^2	0.93	0.93	0.93	0.74	0.74	0.74
N	4290	4290	4290	5237	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 ($\mu g/m^3$)			Yearly hours NO2 > 200 ($\mu g/m^3$)		
In LEZ	-6.580***	-6.359***	-6.209***	-5.572	-4.832	-4.577
	(0.970)	(0.934)	(0.922)	(3.878)	(3.416)	(3.291)
10 km around LEZ		1.170	1.345		4.333	4.669
		(0.866)	(0.880)		(3.265)	(3.441)
10-20 km around LEZ			2.538**			4.305
			(1.196)			(2.799)
Adj. R^2	0.82	0.82	0.82	0.50	0.50	0.50
N	4290	4290	4290	4357	4357	4357
C. Violations	Yearly mean PM10 > 40 ($\mu g/m^3$)			Yearly mean NO2 > 40 ($\mu g/m^3$)		
In LEZ	-0.000	-0.000	0.000	-0.043**	-0.045**	-0.045**
	(0.006)	(0.006)	(0.005)	(0.022)	(0.022)	(0.022)
10 km around LEZ		0.000	0.001		-0.012	-0.013
		(0.006)	(0.010)		(0.022)	(0.024)
10-20 km around LEZ			0.006*			-0.011
			(0.004)			(0.028)
Adj. R^2	0.17	0.17	0.17	0.86	0.86	0.86
N	4290	4290	4290	5237	5237	5237
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
State $\times$ Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Notes: Each column reports the result from a regression of the pollutant listed at the top on the treatment listed on the left, while controlling for monitor and year fixed effects well as federal state time trends, weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)). Column (2) (4) and (6) report the results from a regression of the pollutant on a full interaction between the active LEZ and mutually exclusive group indicators. Standard errors are clustered at municipality level are displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$.

B Hospital Data

B.1 Hospital quality reports

Hospital quality reports are composed by hospitals and transferred to the Federal Joint Committee (Gemeinsamer Bundesausschuss) which collects and provides reports for the period 2006-2016. The Federal Joint Committee is a supreme decision-making body of the joint self-administration of physicians, dentists, psychotherapists, hospitals, and health care funds in Germany. The Federal Joint Committee, private health insurances, the German Medical Council (Bundesärztekammer) and the representative organizations of nursing professions are responsible for the content and extent of reports (6 § 137 SGB V) (Selbmann, 2004). Starting in 2004, hospitals were obliged to publish quality reports. However, only from 2006 onward reports were standardized and collected by the Federal Joint Committee. Reports are subdivided into hospital locations and hospital departments. The obligation to report refers to hospitals, hospital location, medicine departments that at least operated until 30. September of the reporting year. If closed before, no report is necessary. All provided information refer to the reporting year. Closing date is the 31. December of each year.

It is obligated to provide one report for one hospital location. A hospital location is legally defined in § 2a sec. 1 KHG (Krankenhausfinanzierungsgesetz), emphasizing the spatial and organizational independence. Building complexes with a linear distance not bigger than 2,000 meters can be defined as one location. Thus, if hospitals report several locations within a radius of 2,000 meter around the main location, which we define as the location with the highest initial number of inpatient cases, we merge these hospital locations. This happens 380 times. Otherwise, we would define competing hospital catchment areas for one hospital.

In order to calculate catchment areas, we need the geographic coordinates for each hospital location. We use the full addresses available in the quality reports and convert them using Nokias geocodingHere! API. This involves the input of the hospital address and a street network file provided by navteq for which an iterative comparison of the hospital address to the street network generates geographic coordinates. The calculation is based on interpolation along a street segment for which the geographic coordinates of the beginning and end points are known.

Quality reports are based on inpatient cases which are covered by the following funding schemes: Krankenhausentgeltgesetzes (KHEntgG) and Bundespflegesatzverordnung (BPflV). The BPflV covers a relative narrow scope, mainly treatments in psychological departments. The KHEntgG regulates the G-DRG fixed sum payment system which covers all diseases not covered by the BPflV. In combination, both system cover all inpatient cases. Diagnoses we are using are using for our analysis are based on the (KHEntgG). Under the KHEntgG scheme, one case equals one diagnose in the year of dismissal. Different than under the KHEntgG system, reallocation of patients between medical departments increase the number of inpatient cases under the BPflV scheme. Thus, the number of inpatients can differ from the number of main diagnoses. Readmission does not increase the number of inpatient cases under both funding schemes.

The number of main diagnoses that we use as our identifier for population health is based on the German coding references (ICD-10-GM). The ICD-10-GM is an adaptation of ICD-10-WHO, the World Health Organisation's "International Statistical Classification of Diseases and Related Health Problems". It is translated into German by the German Institute of Medical Documentation and Information (DIMDI). Main diagnoses are provided at 4 digit level. The main diagnose is defined as the disease primarily responsible for in-patient hospitalization. Due to data protection, diagnoses with less than six patients per year equal five.

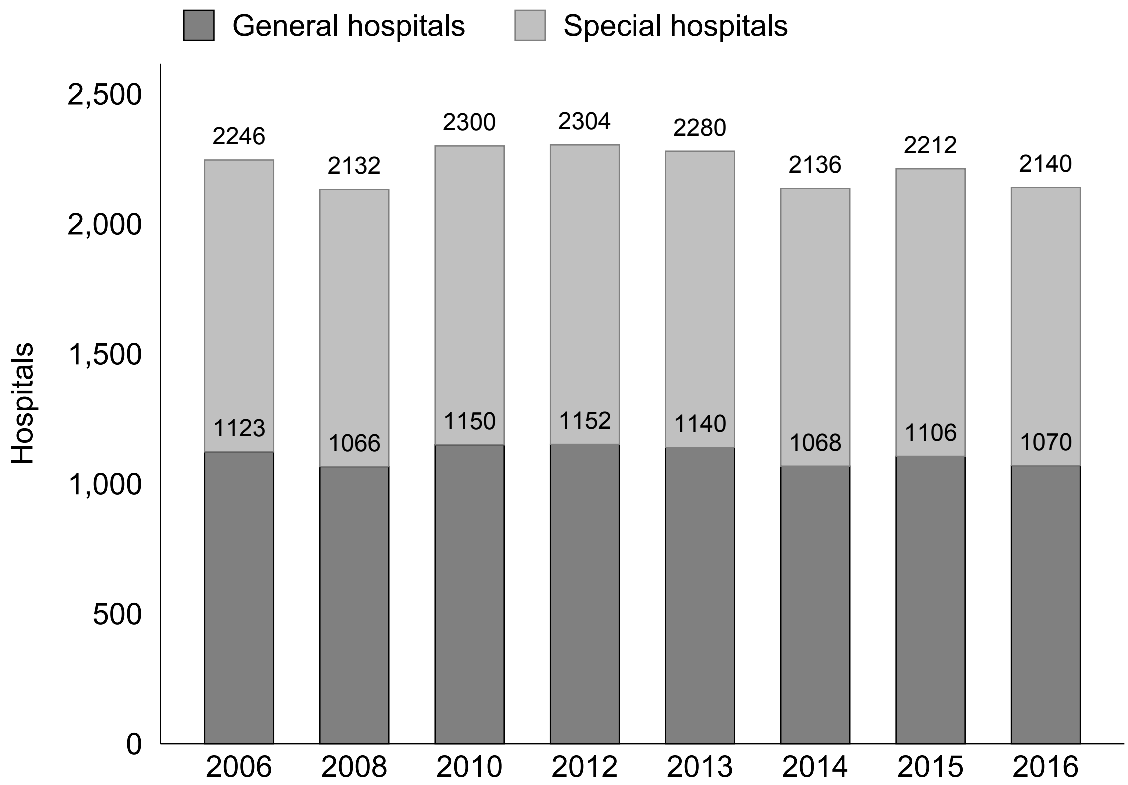


Figure B.1: Number of hospital locations

Notes: This figure shows the number of all German hospital locations separated by general and special hospitals

B.2 Catchment areas

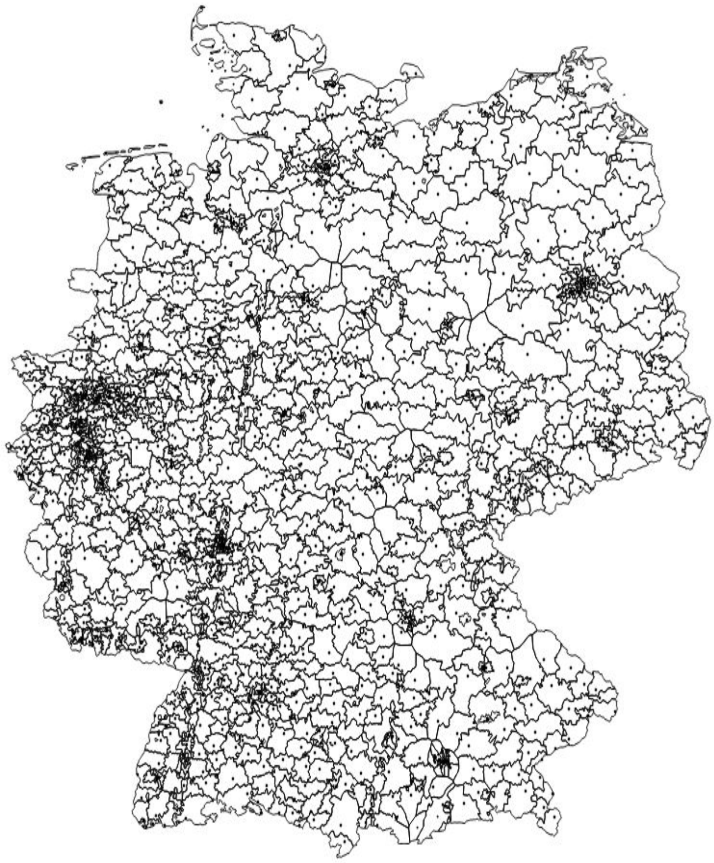


Figure B.2: Hospital locations and catchment areas (all Germany)

Notes: This figure displays all hospital locations and their catchment areas as of 2006 based on driving time.

Figure B.3: Hospital locations and catchment areas (Bonn)

Notes: This graph displays the Low Emission Zone in the city of Bonn (dark colored area: initial zone implemented in 2010, light area: extension as of 2012) as well as hospital locations (black dots) and their corresponding catchment areas (black lines) based on driving time.

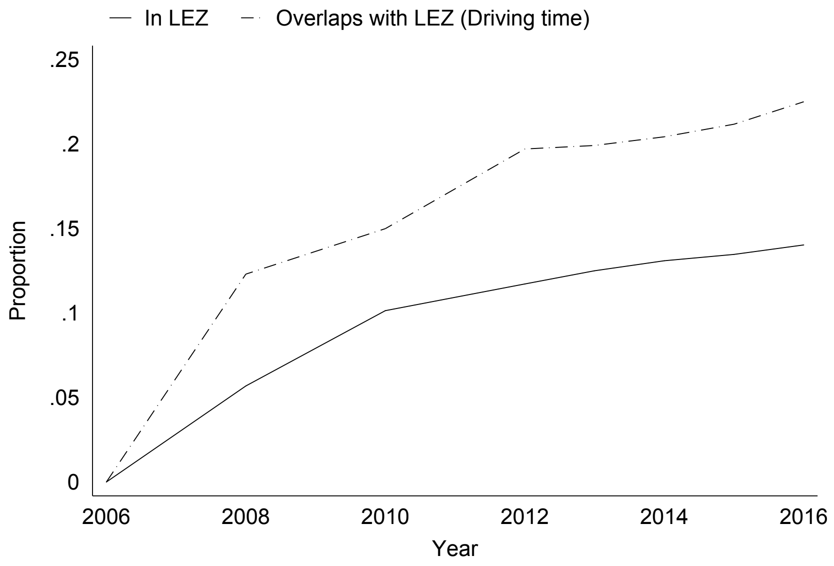
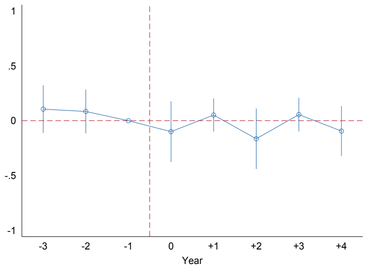


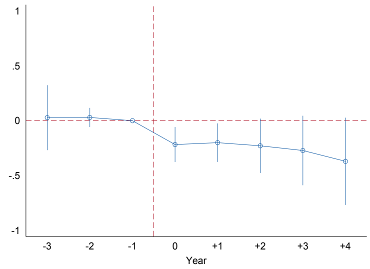
Figure B.4: Proportion of hospitals covered by Low Emission Zones

Notes: This graph displays time trends for the share of hospitals that are either located in an active LEZ or have catchment areas covered by an active LEZ.

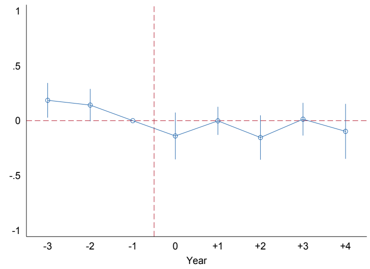
C Additional Results



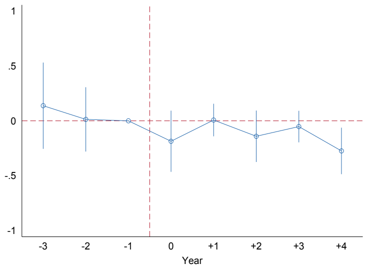
(a) I10-I15



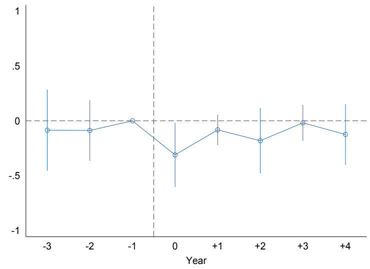
(b) I20-I25



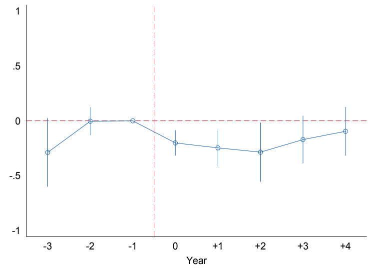
(c) I50



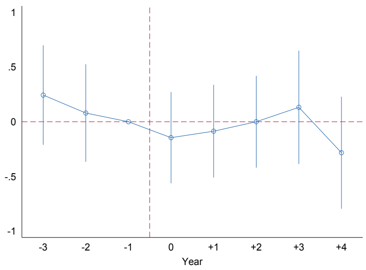
(d) I60-I69



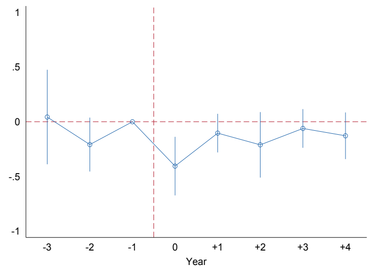
(e) J20-J22



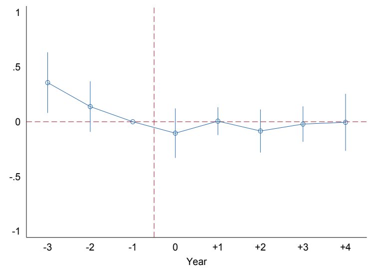
(f) J40-J47



(g) P07



(h) F40-F48



(i) S00-S99

Figure C.1: Event study for all main diagnoses

Notes: These figures display event studies revealing the impact of $\beta\ shareLEZ_{it}$ on all main diagnoses). The reference period is k = -1. Each coefficient is the result of a separate interactions of dummy variables counting the years before and after the introduction of an LEZ and an indicator variable showing if the share of a hospital catchment area covered by an active LEZ, while controlling for hospital and year fixed effects as well as federal state time trends, hospital characteristics (non-profit, public, private, baserate, number of beds, number of beds^2), hospital size (small, medium, large) $\times$ years, weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)) and linear municipality time trends. Standard errors are clustered at county level

Table C.1: The effect of Low Emission Zones on diagnoses on the county level

	County-level		Municipality-level	
	(Binary)	(Share)	(Binary)	(Share)
	(1)	(2)	(3)	(4)
All diseases (A00-N99)	-0.014	0.026	0.017	0.000
	(0.034)	(0.078)	(0.033)	(0.078)
Diseases of the ciculatory system (I00-I99)	-0.041	-0.123	0.046	-0.100
	(0.062)	(0.135)	(0.058)	(0.129)
Hypertension (I10-I15)	-0.066	-0.232	0.063	-0.084
	(0.062)	(0.147)	(0.101)	(0.187)
Ischemic heart diseases (I20-I25)	-0.026	-0.019	0.118	0.109
	(0.093)	(0.179)	(0.107)	(0.219)
Cerebrovascular disease (I60-I69)	-0.062	-0.321	-0.020	-0.375*
	(0.063)	(0.240)	(0.072)	(0.219)
Diseases of the respiratory system (J00-J99)	0.035	0.008	0.048	0.024
	(0.051)	(0.150)	(0.057)	(0.148)
Acute lower respiratory diseases (J20-J22)	-0.030	0.014	-0.053	0.036
	(0.067)	(0.184)	(0.091)	(0.218)
Chronic lower respiratory diseases (J40-J47)	-0.010	-0.241*	0.028	-0.185
	(0.055)	(0.140)	(0.068)	(0.158)
Low birth weight (P07) [t+1]	0.071	-0.128	0.127	-0.021
	(0.111)	(0.271)	(0.105)	(0.247)
N	3024	3024	6292	6292

Notes: This table displays the results for hospital diagnoses, at the municipality and county level. Each coefficient is the result of a separate regression of diagnose listed on the left on a indicator variable for an active LEZ (share of municipality or county covered by LEZ, or a binary indicator being one if a municipality or county has an active LEZ and 0 otherwise), while controlling for municipality or county and year fixed effects as well as federal state time trends, municipality or county characteristics (mean temperature, precipitation and wind speed, population, work force, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)). Standard errors are clustered at unit level of observation and displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$.

Table C.2: The effect of Low Emission Zones on traffic

	All vehicles			<3.5t		
	(1)	(2)	(3)	(4)	(5)	(6)
In and 10 km around LEZ	-0.002	-0.003	-0.003	-0.003	-0.004	-0.004
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
10-20 km km around LEZ		-0.010	-0.009		-0.011	-0.010
		(0.006)	(0.006)		(0.007)	(0.007)
20-30 km around LEZ			0.006			0.007
			(0.013)			(0.013)
Adj. R^2	0.23	0.23	0.23	0.21	0.21	0.21
N	12052	12052	12052	12052	12052	12052
Controls:						
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
LMR $\times$ Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Notes:Notes: Each column reports the result from a regression of traffic volume on the treatment listed on the left, while controlling for monitor and year fixed effects well as labor market region (LMR) time trends, weather characteristics (mean temperature, precipitation and wind speed) and municipality characteristics (population, workforce, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)).. Standard errors are clustered at county level are displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$. .

Table C.3: The effect of Low Emission Zones on further diagnoses in general hospitals

	(1)	(2)	(3)	(4)	(5)
Dementia (F00-F03)	-0.049	-0.048	-0.113	-0.078	-0.083
	(0.121)	(0.122)	(0.128)	(0.126)	(0.129)
Diabetes (E10-E14)	0.049	0.050	0.048	-0.004	0.007
	(0.146)	(0.147)	(0.152)	(0.123)	(0.121)
Stress (F40-F48)	0.014	0.011	0.003	-0.103	-0.111
	(0.105)	(0.104)	(0.098)	(0.102)	(0.099)
Injuries (S00-S99)	0.016	0.017	-0.027	-0.138	-0.145
	(0.067)	(0.066)	(0.077)	(0.103)	(0.104)
N	8828	8828	8828	8828	8828
Controls:					
Hospital FE	Yes	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	Yes	Yes
Municipality characteristics	No	No	Yes	Yes	Yes
Linear municipality time trends	No	No	No	Yes	Yes
Hospital characteristics	No	No	No	No	Yes

Notes:This table displays the results for hospital diagnoses, for main hospitals. The catchment area is calculated by driving time. Each coefficient is the result of a separate regression of diagnose listed on the left on a indicator variable for an active LEZ (share of catchment area covered by LEZ), while controlling for hospital and year fixed effects as well as federal state time trends, hospital characteristics (non-profit, public, private, baserate, number of beds, number of beds^2), hospital size (small, medium, large) × years, municipality characteristics (mean temperature, precipitation and wind speed, population, work force, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)), linear time trends (Municipality × Years). Standard errors are clustered at county level and displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$.

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