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Health effects of Low Emission Zones: Evidence from German hospitals[☆]

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ABSTRACT

This paper studies the impact of Low Emission Zones, restricting the access of high-emission vehicles to inner-city areas, on hospitalizations. For identification, we exploit variation in the timing and the spatial distribution of the introduction of new Low Emission Zones across cities in Germany since 2008. We combine detailed geo-coded hospitalization data from the universe of German hospitals with the geographic coverage of Low Emission Zones over the period from 2006 to 2016. We find that Low Emission Zones reduce levels of air pollution in urban areas. These improvements in air quality translate into small but statistically significant population health benefits by lowering the share of diagnoses related to air pollution for hospitals located within a Low Emission Zone after it becomes effective. The results are mainly driven by reductions in circulatory and chronic lower respiratory diseases.

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 also 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 (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,

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[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., 2018).

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there is limited 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 affects population health through improvements in air quality. In particular, we focus on hospitalizations due to specific diseases related to air pollution. For causal identification of the impact of Low Emission Zones on hospitalizations, we exploit the staggered introduction of this policy measure across German cities since 2008, which induces variation in the timing as well as the exact geographic coverage of Low Emission Zones in a difference-in-differences framework.[2] 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.

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. In our main regression specification, we exploit exact information on hospital locations at the address level and define a binary treatment indicator based on whether a hospital is located within the boundaries of an active Low Emission Zone, but also provide results for alternative treatment specifications using hospital catchment areas. The hospital data further provide annual frequencies of detailed diagnoses based on international standard classification (ICD-10). We mainly focus on circulatory 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). In order to establish that our estimates of Low Emission Zones' health impacts can indeed be attributed to improvements in local air quality, 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 a Low Emission Zone.

Our main results show that Low Emission Zone introductions benefit population health by reducing the frequency of hospitalizations. In a first step, we confirm that Low Emission Zones moderately improve air quality, by lowering annual mean levels and especially by decreasing the frequency of exceeding regulatory thresholds. In a second step, we show that these improvements in air quality translate into small but statistically significant reductions in the prevalence of specific air pollution-related diagnoses among hospitals which are located within the boundaries of an active Low Emission Zone. We find a small and statistically insignificant reduction in the overall share of inpatient cases related to any disease. However, we do find statistically significant effects for diagnoses of specific circulatory and respiratory diseases. In particular, a treated hospital's share of diagnosed ischemic heart diseases, heart problems caused by narrowed heart arteries, is reduced by about 0.5 percentage points on average compared to a mean of about four percent. The share of chronic lower respiratory diseases, characterized by shortness of breath (e.g., asthma) are reduced by about 0.16 percentage points compared to an overall mean of about one percent of annual hospitalizations. These results are statistically significant and robust to a number of controls and specifications.

In addition, we provide evidence suggesting that spillovers of health benefits to hospitals outside the Low Emission Zone appear to be rather limited. We interact the binary treatment for a hospital location being covered by an active Low Emission Zone with a binary indicator for being located in a city with any Low Emission Zone and find that our results are predominantly driven by hospitals located inside a Low Emission Zone. We further show results based on alternative specifications of hospitals' treatment by Low Emission Zone coverage. We exploit the exact information on hospital locations and create hospital catchment areas using geo-referenced data on driving time. We create hospital catchment areas as adjacent polygons around hospital locations that characterize areas in which the driving time to the associated hospital is shorter than the driving time to any other hospital in the surrounding. By overlaying these catchment areas with Low Emission Zone areas, we create the share of a hospital's catchment area covered by an active Low Emission Zone as an alternative indicator capturing the intensity of treatment. The results are very similar to the results obtained from our main binary specification, but are less precise as the share of a constructed catchment area covered by a Low Emission Zone is more prone to measurement error than the simple binary treatment indicator for being located within the Low Emission Zone.

The magnitudes of our findings are rather small in absolute terms and are concentrated among diseases with strong symptoms (chest pain, shortness of breath) that are more likely to trigger a hospital visit than other diseases and symptoms related to poor air quality that would not show up in a hospital. This is not surprising given that the moderate air quality improvements from the implementation of Low Emission Zones, starting from already moderate levels of air pollution in Germany in global comparison, should not give grounds for expecting large reductions in hospitalizations, which is a rather severe health outcome. Therefore, the relatively small effects on hospitalizations documented in this paper do certainly not cover the overall health benefits of implementing Low Emission Zones in German cities, but do contribute to our understanding of the overall effects.

Evaluating the treatment effects of Germany's Low Emission Zones on population health using hospitalizations as the outcome of interest is generally challenging. The analysis presented in this paper is based on aggregate hospital data, which comes with the qualification that detailed information on patients' exposure to the treatment of Low Emission Zones is unavailable. The ideal database for studying our research question would combine *individual*-level hospitalization data with information on patients' residence locations in order to assign the treatment to the residential population. Unfortunately, this is prohibited by German data protection legislation. While the data used in this study provide information on the total inpatient case numbers broken down by detailed diagnoses according to the standard ICD-10 classification and allow a precise geographic assignment of *hospital* locations

[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 https://urbanaccessregulations.eu/).

to Low Emission Zone areas, a major drawback is that we do not have any information on where patients live. Therefore, we have to assume that hospitals draw their pool of patients mainly from the near surroundings, which is supported by the institutional setting as well as suggestive evidence, but still introduces measurement error to our regression analysis which needs to be taken into account when interpreting our results.

One potential alternative data source are hospital statistics provided by the German Statistical Office. These provide information on *individual* patient admissions, but without any information on hospital locations and with patients' residence only available at the aggregate county level, such that treatment assignment is only between cities without distinguishing between treated and untreated populations within cities. Accordingly, using these data, a closely related paper on the population health effects of Germany's Low Emission Zones (Margaryan, 2021) does find reductions in hospital admissions, which are however statistically insignificant. Based on *outpatient* data, which allow to assign patient residences on the postal code level (within cities), Margaryan (2021) documents statistically significant reductions in case numbers of cardiovascular diseases. At the same time, we document that our results appear to be mainly driven by hospitals actually located inside a city's Low Emission Zone, while hospitals of the same city but outside of the Low Emission Zone area itself do not experience similar-sized reductions in case numbers of the relevant circulatory and respiratory diseases. Taken together, the evidence points to a pattern of fairly local effects of Low Emission Zones, such that the population actually treated within an adopting city mainly benefits in terms of improved health while positive health spillovers appear to be limited.

Overall, this paper contributes to the growing literature on the evaluation of the impacts of introducing Low Emission Zones in Germany. The earliest paper in economics on the effects on air pollution is the study by Wolff (2014), complemented by a related literature in transportation research (Morfeld et al., 2014; Malina and Scheffler, 2015; Jiang et al., 2017), documenting significant drops in ambient air pollution after Low Emission Zone introductions in treated cities in Germany. 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 within-city variation. Gehrsitz (2017) evaluates the effects of Low Emission Zones on infant health outcomes in Germany. His 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. However, due to data constraints Gehrsitz (2017) is only able to assign mothers' residential locations to cities but cannot make the distinction between treated and untreated mothers within cities, such that the policy variation is restricted to between-city variation, which may introduce measurement error regarding the in utero exposure to air pollution. As mentioned before, the study by Margaryan (2021) documents reductions in case numbers of cardiovascular diseases by 2–3 percent based on outpatient data from ambulatory care claims. Different from the results of our paper, Margaryan (2021) does not find any effects on respiratory health based on outpatient data. This may point to a pattern that improvements in air quality from Low Emission Zone introductions translate into health benefits in terms of cardiovascular health for moderate to high levels of severity while respiratory health improvements predominantly due to reductions in severe cases that typically lead to hospitalizations. However, using patient-level data from Germany's largest health insurer, Rohlf et al. (2020) find that the introduction of Low Emission Zones significantly reduces expenditures for both heart and respiratory diseases by 15.8 million euros per year in treated cities. Importantly, Rohlf et al. (2020) provide a cost–benefit comparison based on an estimate of the upfront costs of updating the vehicle fleet and conclude that health benefits from reductions in defensive pharmaceutical expenditures alone recover the initial costs over 9–11 years. In this paper, we also provide complementing evidence that there appear to be no negative effects on GDP in counties treated with a Low Emission Zone, such that we feel comfortable to conclude that an overall cost–benefit analysis of the policy, accounting for hospitalizations, outpatient case numbers and pharmaceutical expenditures, appears to be in favor of restricting high-emitting vehicles from urban areas.[3]

More generally, we add to the large literature on the causal impacts of air pollution on human health in both epidemiology (Pope III, 2000; Pope III and Dockery, 2006) as well as in economics (Graff Zivin and Neidell, 2013) and to a recent strand in the economics literature evaluating the impacts of other traffic regulations to improve urban air quality on health outcomes. Simeonova et al. (2019) show that implementing a congestion tax in central Stockholm reduced ambient air pollution and significantly decreased the rate of acute asthma attacks among young children.[4] 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, similar to Margaryan (2021) and Rohlf et al. (2020), we are able to study the full range of diseases potentially affected by ambient air pollution among all age groups. Salvo et al. (2019) 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 mega-city'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 and results. Section 4 concludes.

[3] This is especially true when accounting for potential additional non-health benefits in terms of worker productivity (Graff Zivin and Neidell, 2012; Chang et al., 2016, 2019; Künn et al., 2019) and human capital formation (Ebenstein et al., 2016; Roth, 2018).

[4] Similarly, Green et al. (2020) show that the London congestion charge introduced in 2003 led to significant reductions in several air pollutants, but do not study health outcomes.

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.[5]

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.[6]

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, environmental groups 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.[7] This means that, after there have been violations of air quality standards within a city area, Low Emission Zone policies are exogenously forced 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 Fig. A.1 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).[8]

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.[9] Figs. 1 and 2 show the 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 onward, 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.

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.[10] The main target air pollutants emitted from traffic are particulate matter (PM) and nitrogen dioxide (NO2).[11] In the following, we explain how these air pollutants are generated, how they may affect human health and how they are measured.

[5] 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).

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

[7] 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.

[8] 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.

[9] We use open source polygons of Low Emission Zones in German cities from OpenStreetMap.org. As an example, Fig. A.2 shows the high congruency with official documentation for the largest Low Emission Zone in the Ruhr area.

[10] 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, Fig. A.3 shows that in Germany the vehicle

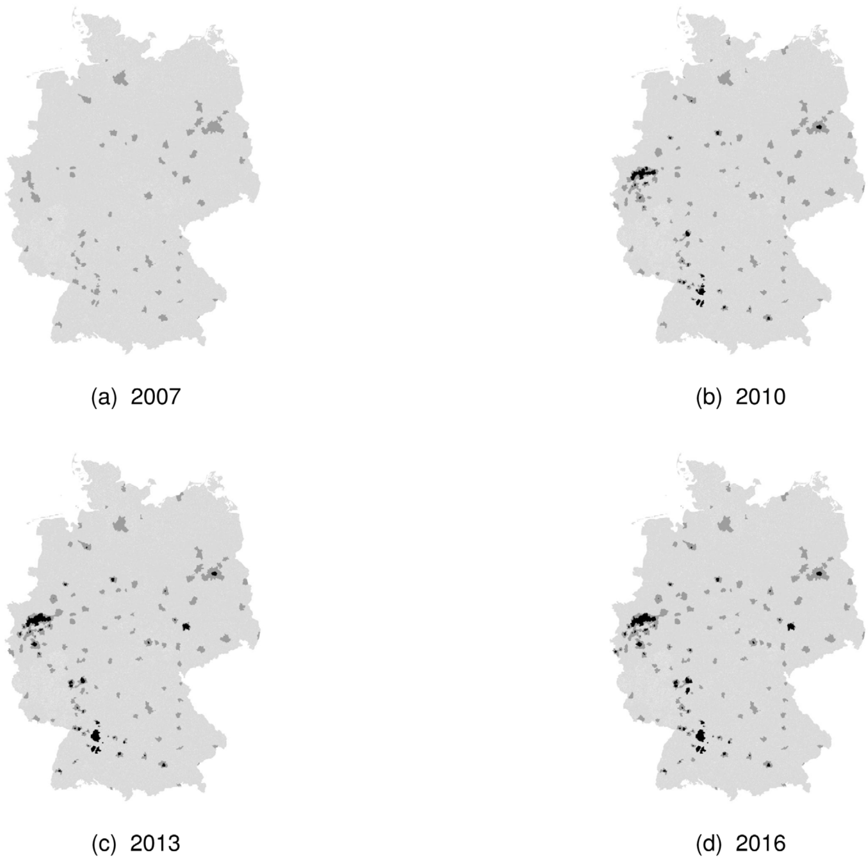


Fig. 1. Clean Air Plans and Low Emission Zones in Germany. *Notes:* This figure overlays Clean Air Plans (gray) and Low Emission Zones (black) over a map of German counties for selected years between 2007 and 2016. The first Clean Air Plans were established in 2007, while Low Emission Zones have been introduced since 2008. The shapefiles for Low Emission Zones come from . Clean Air Plans are not specific to a certain area within a county, therefore we highlight the entire county area for counties where a Clean Air Plan was established.
Source: Federal Environment Agency (*Umweltbundesamt, UBA*).

Particulate matter (PM). Particulate matter 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 diameter, which has been comprehensively measured since 2000 in Germany.[12] Particulate matter is linked to a number of respiratory and circulatory 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 (Kampa and Castanas, 2008; Block and Calderon-Garciduenas, 2009).[13]

Nitrogen dioxide (NO2). Nitrogen dioxide 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

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.

11 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.

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

13 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).

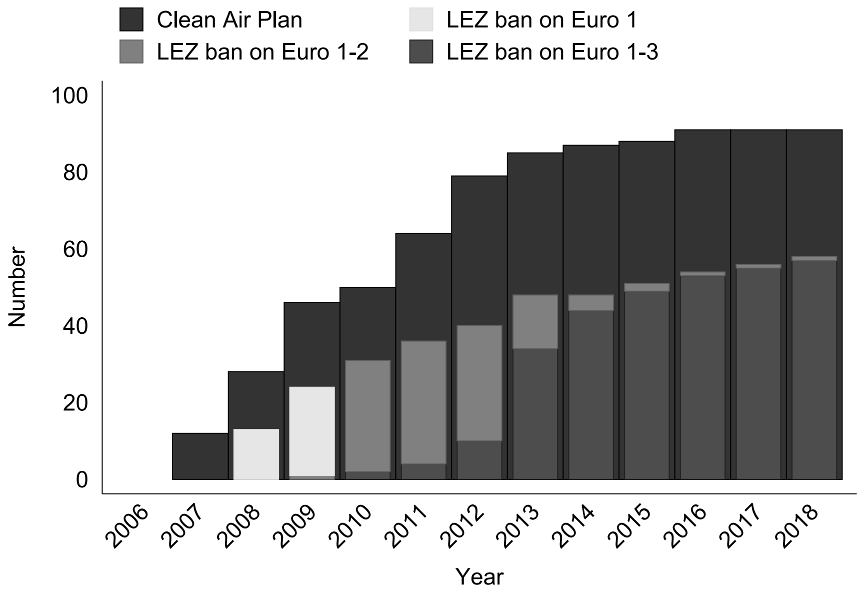


Fig. 2. Clean Air Plans and Low Emission Zones by emission standard over time. *Notes:* This figure shows the total number of Clean Air Plans and Low Emission Zones by policy stringency in Germany from 2006 to 2016. The policy stringency refers to the vehicle emission standard classification that is banned from entering a Low Emission Zone.
Source: Federal Environment Agency (*Umweltbundesamt, UBA*).

to elevated NO2 concentration in ambient air especially causes respiratory problems by inflaming the lining of the lungs.[14] 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. The data come 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.[15] 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.[16] Given that monitor locations are exactly known, we are able to assign whether a monitor is located inside or outside of a Low Emission Zone area.[17] 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. 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).

Control variables. 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

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

15 Since a subset of NO2 pollution monitors does not record hourly readings of NO2 concentrations the number of observations for summary statistics related to the number of hours with an NO2 concentration above 200 $\mu g/m^3$ is lower at 4,365.

16 Fig. A.4 shows how pollution levels and violations evolved over time.

17 Fig. A.5(a) 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 Fig. 1).

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

	Mean	SD	Min	Max	N
A. Pollution outcomes					
Yearly mean PM10 μg/m^3	21.96	5.66	7.00	55.00	4290
Yearly days PM10 > 50 μg/m^3	15.43	14.14	0.00	175.00	4290
Yearly mean PM10 > 40 μg/m^3	0.00	0.05	0	1	4290
Daily PM10 > 50 μg/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	0.34	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)	9.89	1.13	3.97	12.78	4290
Mean precipitation (mm/m^2)	1.98	0.50	0.54	5.59	4290
Mean wind speed (m/s)	3.33	0.71	1.61	7.55	4290
D. City characteristics					
Inhabitants/1000	151.17	450.57	0.04	3574.83	4290
Employed/1000	65.58	181.51	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 shows descriptive statistics for the sample of PM10 pollution monitors. The variables presented in Panel A refer to the measurements of PM10 concentrations while variables in Panel B refer to the exact location of each individual PM10 monitor. The weather variables shown in Panel C are measured at the weather monitor closest to the PM10 monitor. The population variables shown in Panel D refer to the city the PM10 monitor is located in. *Sources:* Federal Environment Agency (*Umweltbundesamt, UBA*), National Meteorological Service (*Deutscher Wetterdienst, DWD*), Federal Statistical Office (*Destatis*).

for confounding effects.[18] Finally, we control for a number of population characteristics provided by the Federal Statistical Office at the level of the city of the pollution monitor location.

2.3. Diagnoses from the universe of German hospitals

For our analysis of the effects of Low Emission Zones on hospitalizations we use a panel dataset of the universe of hospitals in Germany reporting the annual number of detailed diagnoses for inpatient cases. German hospitals are obliged by law to publish structured quality reports since 2006, every second year until 2012 and annually from 2012 onward. 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 health insurances (see Appendix B for a detailed description of the data). Admissions to a hospital are usually due to more severe health issues. Therefore, hospitalization data do not cover milder medical conditions which are reflected in doctor visits or pharmaceutical expenditures. 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. Hence, our analysis of the impact of Low Emission Zones on hospitalizations focuses on a specific aspect of the overall health effects of Low Emission Zones.

The 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 report's intention is to increase transparency, every hospital is non-anonymously identified, allowing us to assign the treatment by a Low Emission Zone at the exact address location. The full dataset includes more than 2,000 hospitals over the period from 2006 to 2016 (see Fig. B.1(a)). 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.). 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). Furthermore, we concentrate on hospitals that are located in cities with a population of at least 100,000 since Low Emission Zones

[18] See Fig. A.5(b) for a map showing the locations of weather stations. We drop measurements from weather stations that are at an altitude of more than 800 meters above sea level as these stations are typically located on mountain peaks and are, hence, not representative for weather conditions experienced by the population.

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

	Mean	SD	Min	Max	N
A. Pollution outcomes					
Yearly mean NO2 μg/m^3	30.86	21.98	0.00	121.35	5237
Yearly hours NO2 > 200 μg/m^3	2.07	24.73	0.00	853.00	4357
Yearly mean NO2 > 40 μg/m^3	0.30	0.46	0	1	5237
Hourly NO2 > 200 μg/m^3	0.02	0.13	0	1	4357
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 (°C)	9.90	1.14	3.97	12.78	5237
Mean precipitation (mm/m^2)	2.02	0.52	0.54	5.59	5237
Mean wind speed (m/s)	3.33	0.70	1.44	7.55	5237
D. City 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 shows descriptive statistics for the sample of NO2 pollution monitors. The variables presented in Panel A refer to the measurements of NO2 concentrations while variables in Panel B refer to the exact location of each individual NO2 monitor. The weather variables shown in Panel C are measured at the weather monitor closest to the NO2 monitor. The population variables shown in Panel D refer to the city the NO2 monitor is located in. *Sources:* Federal Environment Agency (*Umweltbundesamt, UBA*), National Meteorological Service (*Deutscher Wetterdienst, DWD*), Federal Statistical Office (*Destatis*).

have mainly been implemented in larger cities (see Section 2) and therefore hospitals in smaller cities in less urbanized and rural areas may not represent an ideal control group for those hospitals eventually treated by a Low Emission Zone.[19] Fig. B.1(b) in the Appendix shows that hospitalizations in cities with a population above 100,000 follow a similar trend as hospitals in cities that eventually implement a Low Emission Zone. Finally, we employ a balanced sample of hospitals that are covered by the quality reports throughout the period of investigation, i.e., exclude new openings and closings. Note that the data refer to physical hospital locations rather than legal entities running hospitals, such that we still observe location-specific hospital admissions even after mergers of one or more hospitals.

In the end, we employ a sample of 342 hospitals per year and 2,736 hospital-year observations. Panel A of Table 3 shows substantial variation in the characteristics of general hospitals. The mean number of beds ranges from only twelve 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 549 to 198,452 with a mean of 21,471. Non-profit and public general hospitals account for 62 and 25 percent in our dataset. About 13 percent of the general hospitals in our dataset are private.[20] The share of diagnoses according to the ICD-10 classification (indicated in brackets) are shown in Panel B of Table 3. The average share of annual diagnoses of any form of disease among all inpatients is 70 percent. The remaining 30 percent of inpatient cases mainly fall into classifications related to injury, poisoning and other consequences of external causes. We mainly focus on the share of diagnosed diseases of the circulatory system, making up 14 percent of all inpatient cases, and the respiratory system (about six percent), which are also broken down to those more detailed ICD-10 subcategories that have been shown to be closely related to poor air quality exposure.[21]

Hospitals' treatment by Low Emission Zones is assigned based on whether the hospital location is covered by the area of an active Low Emission Zone, which is straightforward given that the data contain exact address locations of hospitals.[22] While knowledge about exact locations is one of the main advantages of the hospital quality report data, one major drawback is that residence locations

[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 city; 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 (Bundestag, 2014).

[21] In additional analyses, we also 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.

[22] In Appendix Table B.1, we present balancing tests between hospitals located in Low Emission Zones and hospitals not located in Low Emission Zones among the estimation sample of hospitals located in cities with a population of 100,000 or more prior to the introduction of Low Emission Zones in 2006. A raw comparison of hospital characteristics between these two groups renders some statistically significant differences, in particular with respect to the ownership structure. This is entirely due to the fact that Low Emission Zones are concentrated in some states (mainly North Rhine Westphalia and Baden–Württemberg,

of patients are unknown since the data do not provide individual characteristics of patients. An alternative data source are hospital statistics provided by the German Statistical Office, which provide information on individual patient admissions, but due to data protection legislation, without any information on hospital locations and patients' residence only available at the aggregate county level, such that it is impossible to distinguish between treated and untreated populations within cities.

Therefore, our empirical analysis relies on the assumption that hospitals' inpatients are mainly drawn from the population residing in the surroundings, such that a hospital location's coverage by a Low Emission Zone serves as a proxy for the assignment of treatment, i.e., exposure to air quality improvements, of its potential patient population. While patients in Germany are in principle free to choose a hospital for treatment, proximity plays an important role for the location choice in hospital admissions for several reasons. First, for self-referral to hospital there is evidence for a strong correlation between hospital location and patients' residences (Friedrich and Beivers, 2008) and that individuals do prefer hospitals close to their residential address (Klauber et al., 2015). Second, there are legal obligations associated with pecuniary incentives to choose a hospital in close proximity for doctors' referrals. Resident doctors are legally obliged to refer patients to one of the two closest hospitals based on the residence of the patient (§73(4) Social Security Code V). In case of non-compliance with the doctor's hospital referral, patients may have to bear the additional costs out-of-pocket (§39(2) Social Security Code V). Third, in case of emergency admission, the directive for ambulance transport (*Krankentransport-Richtlinie*) states that emergencies should be transported directly to the nearest hospital based on the patient's current position which is not necessarily equal to but highly correlated with the place of residence (Klauber et al., 2008).[23] Nevertheless, we acknowledge that proximity between residential and hospital locations is an important but certainly not the only factor driving hospital choice. Therefore, our estimation results based on an indicator for a hospital being covered by an active Low Emission Zone can be interpreted as the result from an intention-to-treat setting.

Panel C of Table 3 shows that in almost 90 percent of hospital-year observations, hospitals are located in a city with an active Clean Air Plan. This suggests that the sample of hospitals used in the regression analysis is very well comparable in terms of air quality levels that are violating the EU standards, such that state governments have to develop a Clean Air Plan in almost all of the cities. While the implementation of Low Emission Zones is preceded by the establishment of a Clean Air Plan (see Section 2), Low Emission Zones as one of the most important measures of the policy bundle is not immediately implemented and is typically restricted to inner-city areas rather than the entire city area. Consequently, the share of observations covered by an active Low Emission Zone is substantially lower since they are implemented over time and do only cover hospitals inside their boundaries and not all hospitals within a city. About 30 percent of observations are covered by Low Emission Zones that ban at least Euro 1 vehicles, 21 percent banning at least Euro 1–2 and 13 percent banning Euro 1–3. Panels D and E of Table 3 show weather and city characteristics associated with the hospital locations, which will be used as additional control variables in the regression analysis.

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 hospitalizations 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:

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

where y_{it} indicates the outcome of interest for observation unit i at time t. For the air pollution analysis, we employ the sample of monitor-by-year observations and look at the effects on levels of air pollution and limit exceedances. For the analysis on hospitalizations using the sample of hospital-by-year observations, we use the share of diagnoses of specific diseases among all inpatient cases of a hospital as the outcome of interest. The main variable of interest is LEZ_{it} and captures the treatment of unit i at time t by a Low Emission Zone, i.e., a binary indicator with a value of one for unit i being located within the boundaries of an active Low Emission Zone at any strictness level at time t and zero otherwise.[24]

The vector $\boldsymbol{X}_{it}$ 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. Further,

see Fig. 1 and Table A.2). The state of North Rhine Westphalia (NRW) alone accounts for half of the hospitals in our sample located in Low Emission Zones (66 out of 130). At the same time, the state of NRW happens to differ substantially in the ownership structure of hospitals with non-profit hospitals accounting for 69.3% of hospitals in the state while this share is only 38.2% in all of Germany (Statistisches Bundesamt, 2008). Accordingly, the shares of public (20.4%) and private hospitals (10.3%) are much lower than the average in Germany (34.1% and 27.8% respectively). Therefore, we additionally present a balancing test of hospital characteristics conditional on state fixed effects, which suggests that these characteristics do not significantly differ between hospitals located in Low Emission Zones and those outside Low Emission Zones once we account for state, which is also captured in our regression specifications by county fixed effects as well as state-by-year fixed effects.

[23] In 2016, 45 percent of hospital admissions were emergency cases (Statistisches Bundesamt, 2017a). The statistics do not allow to distinguish self-referral from referral by emergency services.

[24] 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. In Section 3.4, we present results with alternative specifications of hospitals' treatment by Low Emission Zones using catchment areas based on driving time distances.

Table 3
Descriptive statistics: Sample of hospitals (2006–2016)

	Mean	SD	Min	Max	N
A. Hospital characteristics					
Non-profit	0.62	0.49	0	1	2736
Public	0.25	0.43	0	1	2736
Private	0.13	0.34	0	1	2736
Number of Beds	536.60	402.06	12	2917	2736
Baserate in €	2977.97	227.01	1515	4083	2736
Inpatients	21470.69	17981.52	549	198452	2736
B. Share of Diagnoses					
All diseases (A00–N99)	0.70	0.24	0.13	1.00	2736
Diseases of the circulatory system (I00–I99)	0.14	0.11	0.00	1.00	2736
Hypertension (I10–I15)	0.01	0.03	0.00	0.71	2736
Ischemic heart diseases (I20–I25)	0.04	0.05	0.00	0.51	2736
Cerebrovascular disease (I60–I69)	0.02	0.02	0.00	0.22	2736
Diseases of the respiratory system (J00–J99)	0.06	0.04	0.00	0.46	2736
Acute lower respiratory diseases (J20–J22)	0.01	0.00	0.00	0.05	2736
Chronic lower respiratory diseases (J40–J47)	0.01	0.01	0.00	0.19	2736
C. Treatment characteristics					
In active Clean Air Plan	0.87	0.33	0	1	2736
In LEZ ban on Euro 1	0.29	0.45	0	1	2736
In LEZ ban on Euro 1–2	0.21	0.40	0	1	2736
In LEZ ban on Euro 1–3	0.17	0.37	0	1	2736
Share of a catchment area covered by LEZ:					
Driving time (unweighted)	0.17	0.31	0.00	1.00	2736
Driving time (weighted by pop. density)	0.21	0.33	0.00	1.00	2736
Radius of 10 min driving time	0.17	0.26	0.00	1.00	2736
D. Weather characteristics					
Mean temperature (°C)	10.24	0.94	6.72	12.22	2736
Mean precipitation (mm/m^2)	1.96	0.39	0.97	3.28	2736
Mean wind speed (m/s)	3.31	0.56	2.08	5.77	2736
E. City characteristics					
Inhabitants/1000	761.51	947.49	100.33	3574.83	2736
Employed/1000	329.55	355.43	28.43	1367.68	2736
Share male < 30 years	0.33	0.02	0.27	0.41	2736
Share male 30 - 64 years	0.50	0.02	0.44	0.55	2736
Share male > 64 years	0.17	0.02	0.13	0.23	2736
Share female < 30 years	0.31	0.02	0.24	0.39	2736
Share female 30 - 64 years	0.47	0.02	0.41	0.50	2736
Share female > 64 years	0.22	0.02	0.18	0.31	2736

Notes: This table shows descriptive statistics for the sample of hospitals. The variables presented in Panel A refer to hospital characteristics and the total number of inpatients while the main outcome variables in Panel B are the shares of inpatients broken down by diseases according to the ICD-10 classification. The treatment variables in Panel C refer to the exact location of the hospital. The weather variables shown in Panel D are measured at the weather monitor closest to the hospital. The population variables shown in Panel E refer to the city the hospital is located in. *Sources:* Hospital Quality Reports, Federal Environment Agency (*UBA*), National Meteorological Service (*Deutscher Wetterdienst, DWD*), Federal Statistical Office (*Destatis*).

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.[25] Finally, unit fixed effects δ_i capture any time-invariant monitor or hospital characteristics while state-time fixed effects $\delta_{ts(i)}$ control for any time-specific effects that are uniform across all observation units i within a state s. The error term ε_{it} is clustered at the county level.[26]

In order to capture dynamic effects of Low Emission Zone introductions, we additionally 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. The introduction of a Low Emission Zone should not have any impact in pre-treatment periods. The extended model is:

$$y_{it} = \alpha + \sum_{k=-3,k\neq-1}^{+3} \beta^k \; LEZ_{ik} + \boldsymbol{X}'_{it}\gamma + \delta_i + \delta_{ts(i)} + \varepsilon_{it}, \quad (2)$$

where the dummy variables LEZ_{ik} indicate yearly leads and lags of up to three years before and 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

[25] 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.

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

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.[27]

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 standard. Table 4 shows the main results for the effect of introducing a Low Emission Zone on annual average levels and limit exceedances for PM10 and NO2. Each cell represents an estimate for β according to Eq. (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 and statistically significant 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 city 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 annual PM10 concentrations by 1.3 $\mu g/m^3$ or 5.8 percent of the mean. The average NO2 levels are reduced by 1.6 $\mu g/m^3$ or 5.3 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 6.5 days or more than 40 percent of the mean. 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). The results in Panel C do not indicate 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). However, we do find a significant decrease of yearly mean NO2 levels above 40 $\mu g/m^3$ of about almost five percentage points, which corresponds to a sizable reduction of about 16 percent compared to the mean. Overall, these results confirm that the policy of introducing a Low Emission Zone appears to be very effective in decreasing local air pollution and reducing the incidence of air quality standard violations. While the effects on overall levels are rather moderate with reductions of about five percent, introducing Low Emission Zones effectively reduces the incidence of short-time spikes in PM10 pollution and at the same time reduces the annual mean concentration of NO2.

These findings are based on the straightforward specifications of Eq. (1), where we exploit the treatment of any Low Emission Zone irrespective of the strictness levels in terms of the emission exhaust classification.[28] 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 (see Fig. A.3) 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. The spatial precision of our dataset allows us to analyze the effect of a Low Emission Zone on pollution measured at monitors 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 we see some smaller increases for pollution monitors located at a distance of 10–20 km from a Low Emission Zone.

In Fig. 3 we present results for the event study specification of Eq. (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 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, Fig. 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.

3.3. Hospitalization 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 moderately reduces air pollution, especially 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

[27] We bin up event dummies at the endpoints of the event window (i.e., $k = -3$ and $k = 3$).

[28] 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 μg/m^3			Yearly mean NO2 μg/m^3		
In LEZ	−1.444***	−1.442***	−1.267***	−1.866***	−1.853***	−1.639***
	(0.191)	(0.192)	(0.209)	(0.447)	(0.440)	(0.444)
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 μg/m^3			Yearly hours NO2 > 200 μg/m^3		
In LEZ	−7.002***	−6.991***	−6.515***	−6.935	−6.934	−5.475
	(0.962)	(0.968)	(1.027)	(4.726)	(4.718)	(3.831)
Adj. R^2	0.81	0.81	0.82	0.48	0.48	0.50
N	4290	4290	4290	4357	4357	4357
C. Violations	Yearly mean PM10 > 40 μg/m^3			Yearly mean NO2 > 40 μg/m^3		
In LEZ	−0.002	−0.002	0.000	−0.054***	−0.055***	−0.047**
	(0.006)	(0.007)	(0.006)	(0.019)	(0.019)	(0.020)
Adj. R^2	0.16	0.16	0.17	0.86	0.86	0.86
Number of observations	4290	4290	4290	5237	5237	5237
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
State × Year	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	No	Yes	Yes
City characteristics	No	No	Yes	No	No	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on air pollution, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression of annual-level outcomes related to air pollution (mean levels, number of limit exceedances or air quality standard violations) on a binary indicator variable for a pollution monitor being located in an active Low Emission Zone, while controlling for monitor and state-by-year fixed effects, weather characteristics (mean temperature, precipitation and wind speed) and city characteristics (population, work force, gender-specific age structure) as shown in Tables 1 and 2. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: ***: $p < 0.01$, **: $p < 0.05$, *: $p < 0.1$.

will now turn to the question whether these moderate improvements in air quality induced by Low Emission Zones translate into improvements for human health by reducing hospitalizations, especially for diseases of the circulatory and the respiratory system.

In this section, we present the estimation results for the impact of Low Emission Zones on the share of diagnoses per hospital (in percent).[29] 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. Being located inside the boundaries of an active Low Emission Zone lowers potential exposure to air pollution of people living in the surroundings of a treated hospital location. As discussed before, without any information on the residential locations of hospitals' patients, the analysis relies on the assumption that proximity is an important determinant of hospital choice. Hence, estimation results have to be interpreted as intention-to-treat effects with imperfect compliance. 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 as shown in Eq. (1) of the share of diagnoses relative to all inpatient cases listed in the left column on a binary indicator for hospitals being located within the boundaries of an active Low Emission Zone. All regressions include hospital and year fixed effects to capture any time-invariant hospital characteristics as well as any time-variant changes that are uniform across all hospitals in Germany (e.g., business cycle, policy changes at the national level). Additional fixed effects and further controls included are indicated at the bottom of each column. We control for a number of time-variant hospital and city characteristics and eventually include different time trends and further time-specific fixed effects to capture any confounding changes over time that may affect both the implementation of Low Emission Zones as well as disease-specific hospitalizations. We look at all diseases and then separately at diseases of the circulatory and the respiratory system as well as subgroups thereof. Note that the left-hand side variables have been multiplied by 100 and can hence be directly interpreted as percentage point changes.

We begin with a bivariate fixed effect regression in column (1) of Table 5 only controlling for hospital and year fixed effects. We find a reduction of one percentage point for the share of all diseases (compared to a mean of 70 percent, see Table 3), which is however not statistically significantly different from zero at conventional levels. We do find a significant reduction in the share of all circulatory diseases by about 1.1 percentage points relative to a mean of 14 percent. Given that the mean number of inpatients per year is 21,471 (see Table 3), this corresponds to about 236 cases per hospital and year on average. About half of this effect is accounted for by ischemic heart diseases, showing a reduction of 0.5 percentage points compared to a mean of four percent,

[29] We do not focus on absolute numbers of diagnoses since we are not able to normalize them by population as we cannot assign the underlying population to individual hospitals for normalization. In an alternative specification, we also use the log number of diagnoses (see Table 7).

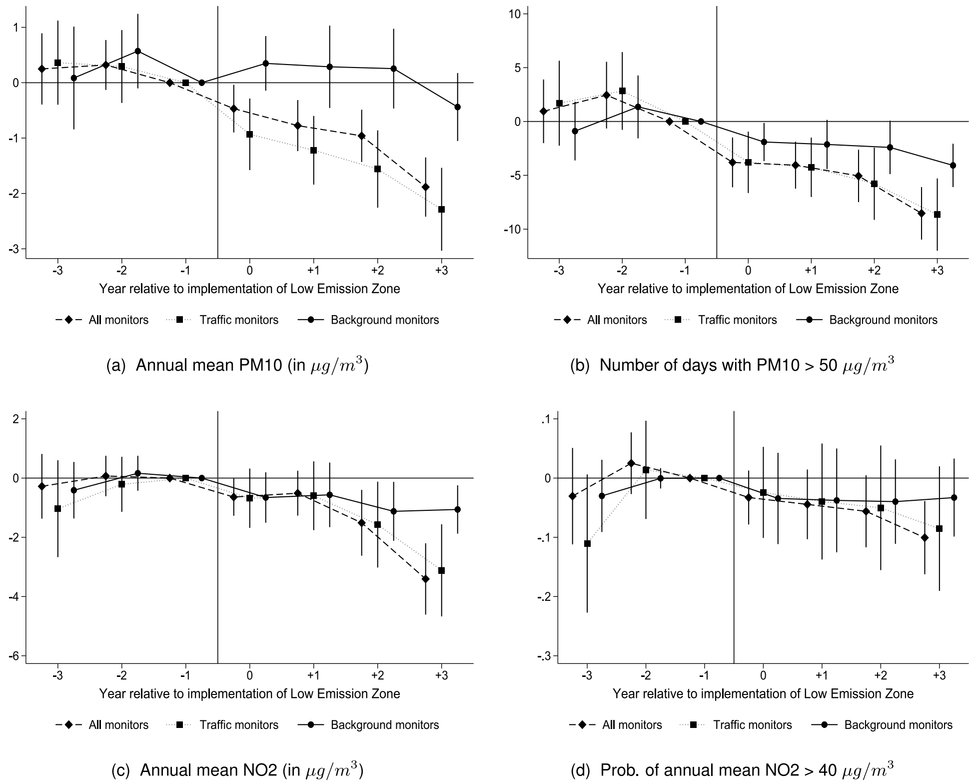


Fig. 3. The effect of Low Emission Zones on air pollution — Event study. *Notes:* These figures display event-study results for the effect of Low Emission Zones on different outcomes related to air pollution (mean levels, limit exceedances or air quality standard violations). The reference period $k = -1$ refers to the year prior to the implementation of the Low Emission Zone. Each coefficient is an estimate for β_k (with 95% confidence intervals) according to Eq. (2) for a binary indicator for monitors being located in the active Low Emission Zone in the respective time period relative to the introduction of the Low Emission Zone, while controlling for monitor and state-by-year fixed effects, weather characteristics (mean temperature, precipitation and wind speed) and city characteristics (population, work force, gender-specific age structure) as shown in Tables 1 and 2. Event-study results are shown for separate regressions for all pollution monitors as well as for the sub-samples of traffic and background monitors as classified by the Federal Environment Agency (*Umweltbundesamt, UBA*). Standard errors are clustered at the county level.

corresponding to about 107 fewer cases per hospital and year. Ischemic heart diseases refer to heart problems caused by narrowed heart arteries, hampering the provision of the heart muscle with blood and oxygen. These diseases cause chest pain or discomfort known as *angina pectoris* and can ultimately lead to heart attacks. Other circulatory diseases are not significantly affected. The overall share of respiratory diseases (about six percent on average) is not significantly affected, but narrowing down to chronic lower respiratory diseases, which accounts for about one percent of total inpatient cases, is significantly reduced by 0.16 percentage points. On average, this effect translates into 34 fewer annual cases per hospital. Chronic lower respiratory diseases comprise three major diseases: chronic bronchitis, emphysema, and asthma, that are all characterized by shortness of breath caused by airway obstruction. While these statistically significant reductions for all circulatory and ischemic heart diseases as well as chronic lower respiratory are small in magnitude in absolute terms, they correspond to non-negligible effects in relative terms ranging between eight and 16 percent relative to the respective mean.

In columns (2) to (5) of Table 5, we subsequently include controls for weather, city and hospital characteristics as well as state-by-year fixed effects to capture any state-specific policy changes over time affecting hospitals. In our preferred specification in column (6), we include city linear time trends to capture any city-specific secular changes over time. These capture any longer-run trends in population growth and composition that would be spuriously correlated with the increases in Low Emission Zone coverage over time. For example, cities that experience a steady increase in the population (share) of inhabitants who are generally more or less likely to have diseases that are also related to air pollution will experience changes in the number and composition of hospitalizations that are not caused by Low Emission Zone introduction.[30] We do not find these controls to affect the main results significantly, with the point estimates becoming slightly stronger. Additionally, this specification renders the effect on the share of acute lower respiratory diseases, including pneumonia and infections of the airways, marginally statistically significant with

[30] Fig. B.1(b) indeed shows that larger cities are characterized by a trend of increasing numbers of hospitalizations which is stronger than in cities below a population of 100,000.

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

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
All diseases (A00–N99)	−1.011	−1.051	−1.522	−1.788	−0.875	−1.412	−1.395
	(1.274)	(1.291)	(1.345)	(1.345)	(1.243)	(1.460)	(1.204)
Diseases of the circulatory system (I00–I99)	−1.123**	−1.134**	−1.214**	−1.215**	−0.851*	−1.262***	−1.606**
	(0.519)	(0.522)	(0.535)	(0.527)	(0.462)	(0.484)	(0.770)
Hypertension (I10–I15)	−0.167	−0.173	−0.235	−0.252*	−0.154	−0.232	−0.211**
	(0.154)	(0.156)	(0.159)	(0.152)	(0.133)	(0.148)	(0.106)
Ischemic heart diseases (I20–I25)	−0.524**	−0.529**	−0.445*	−0.419*	−0.425*	−0.545**	−0.656*
	(0.238)	(0.240)	(0.235)	(0.234)	(0.228)	(0.214)	(0.376)
Cerebrovascular disease (I60–I69)	−0.020	−0.018	−0.039	−0.038	0.001	0.018	0.025
	(0.078)	(0.077)	(0.068)	(0.065)	(0.067)	(0.081)	(0.146)
Diseases of the respiratory system (J00–J99)	−0.181	−0.191	−0.212	−0.203	−0.035	−0.100	−0.204
	(0.182)	(0.181)	(0.183)	(0.183)	(0.203)	(0.233)	(0.327)
Acute lower respiratory diseases (J20–J22)	−0.002	−0.002	−0.015	−0.015	−0.035	−0.053*	−0.061
	(0.026)	(0.025)	(0.023)	(0.024)	(0.026)	(0.030)	(0.041)
Chronic lower respiratory diseases (J40–J47)	−0.164***	−0.163***	−0.153**	−0.157**	−0.128**	−0.160**	−0.133
	(0.061)	(0.061)	(0.063)	(0.062)	(0.056)	(0.075)	(0.106)
Number of observations	2736	2736	2736	2736	2736	2736	2646
Controls:							
Hospital FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	Yes	Yes	Yes	Yes
City characteristics	No	No	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	No	No	No	Yes	Yes	Yes	Yes
State × Year FE	No	No	No	No	Yes	Yes	Yes
Linear county time trends	No	No	No	No	No	Yes	No
County × Year FE	No	No	No	No	No	No	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on the share of diagnoses among all inpatients, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression for the type of disease listed in the left column on a binary indicator variable for a hospital being located in an active Low Emission Zone, while controlling for hospital and year fixed effects. Additional controls are indicated at the bottom of each column. Hospital characteristics are indicators for non-profit, public and private hospitals, the baserate, the number of beds and number of beds squared. Weather characteristics are mean temperature, precipitation and wind speed, city characteristics are population, work force, gender-specific age structure as shown in Table 3. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: ***: $p < 0.01$, **: $p < 0.05$, *: $p < 0.1$.

a very small magnitude of about 0.05 percentage points.[31] Finally, in column (7) we include county-by-year fixed effects, which substantially reduces the variation in the treatment to differences between hospitals inside and outside the Low Emission Zone area within counties, yields slightly stronger results for diseases of the respiratory system but renders the effect of circulatory diseases insignificant.

As mentioned before, the hospital quality report data do not contain any information on their patients' residence locations, which would allow to properly assign exposure to improvements in air quality due to Low Emission Zones. Hence, in order to test whether the introduction of a Low Emission Zone also creates spillover effects to hospitals that are not covered by the area itself but are located in a city that has implemented a Low Emission Zone elsewhere, we interact the binary indicator for being located inside the Low Emission Zone area with another binary indicator for any Low Emission Zone in the city. The results for the share of all diseases, all respiratory and circular diseases as well as the most affected diseases of ischemic heart and chronic lower respiratory diseases are presented in Table 6. It turns out that the baseline effects presented in Table 5 are mainly driven by hospitals that are actually located within the boundaries of an active Low Emission Zone, since the coefficient for being located in a city with any Low Emission Zone is never statistically significant on its own (with one exception), while significant reductions are driven by the interaction effect of a Low Emission Zone city and actually being located inside the area covered by the policy.[32] This means that spillovers of health benefits to hospitals outside the Low Emission Zone appear to be rather limited. This would be consistent with the interpretation that proximity indeed appears to play an important role for hospital choice and that a hospital's treatment by a Low Emission Zone serves as a good proxy for exposure of the inpatient population. However, without detailed information on the composition of hospitals' patients this interpretation cannot be finally confirmed.

In Fig. 4 we present the results for the share of diagnoses in an event study framework We focus on all respiratory and circular diseases as well as the most affected subcategories of ischemic heart and chronic lower respiratory diseases. The findings for all

[31] In Appendix Fig. C.1, we present results of placebo permutation tests, where we randomly allocate the binary treatment of being located within a Low Emission Zone (5,000 replications). In Appendix C.2, we also show p-values associated with the results presented in column (6) of Table 5 after adjusting for multiple hypothesis testing (Table C.5).

[32] Similarly, in Table C.1 in the Appendix, we show that aggregating the share of diagnoses to the county or city level does not yield any statistically significant effects on the share of hospitalizations.

Table 6
The effect of Low Emission Zones on diagnoses in hospitals — Spillover effects.

Diseases	All (A00–N99)		Circulatory (I00–I99)		Respiratory (J00–J99)		Ischemic (I20–I25)		Chr. l. resp. (J40–J47)	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
In LEZ City	−0.420	0.041	−0.189	0.247	−0.005	0.084	−0.142	0.081	−0.120*	−0.064
	(1.232)	(1.501)	(0.392)	(0.493)	(0.166)	(0.191)	(0.124)	(0.145)	(0.067)	(0.075)
In LEZ City ×In LEZ		−1.096		−1.038*		−0.211		−0.531**		−0.134*
		(1.221)		(0.533)		(0.245)		(0.221)		(0.078)
Adj. R^2	0.18	0.18	0.69	0.69	0.81	0.81	0.89	0.89	0.72	0.72
Number of observations	2736	2736	2736	2736	2736	2736	2736	2736	2736	2736
Controls:										
Hospital FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
City characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear county time trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on the share of diagnoses among all inpatients. Each coefficient is the result of a separate regression for the type of disease listed in the column title on a binary indicator variable for a hospital being located in a city with an active Low Emission Zone and in columns (2), (4), (6), (8) and (10) interacted with a binary indicator for a hospital actually being located in the active Low Emission Zone, while controlling for hospital and year fixed effects. Additional controls are indicated at the bottom of each column. Hospital characteristics are indicators for non-profit, public and private hospitals, the baserate, the number of beds and number of beds squared. Weather characteristics are mean temperature, precipitation and wind speed, city characteristics are population, work force, gender-specific age structure as shown in Table 3. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: ***: $p < 0.01$, **: $p < 0.05$, *: $p < 0.1$.

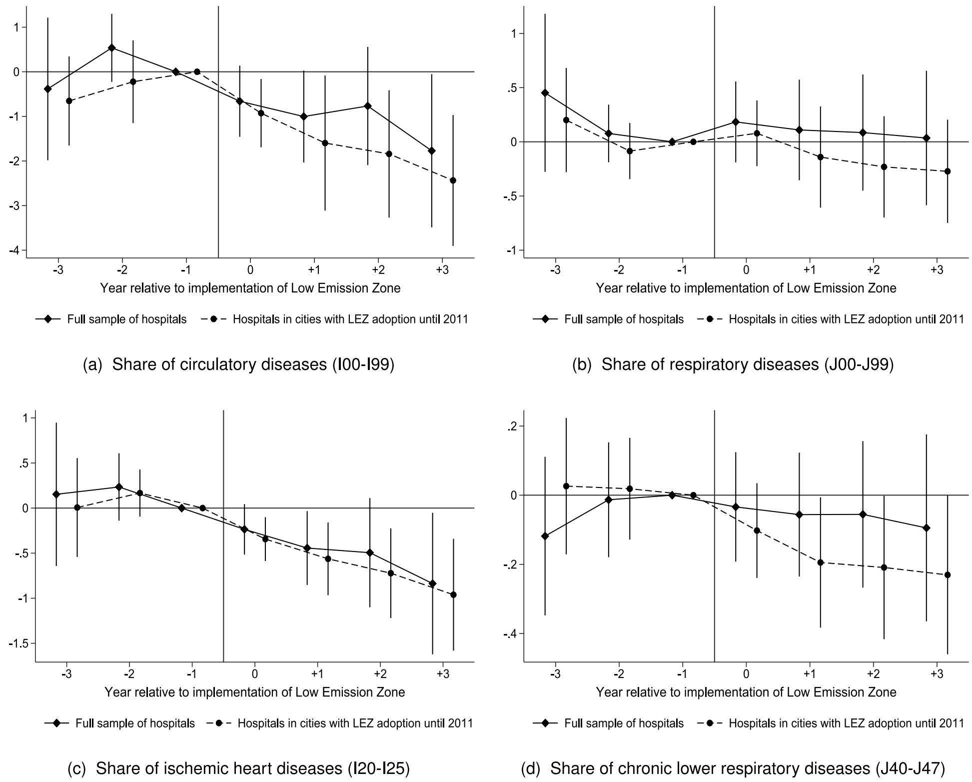
circulatory diseases in Panel (a) indicate that the effects started to appear already in the first year after the introduction and tend to increase in absolute terms over time. This could be due to two reasons. First, the year of Low Emission Zone implementation ($k = 0$) refers to initial adoption. Especially in early years, the policy was typically less strict in terms of vehicles' emission standard excluded from entering the areas but became stricter over time (see Fig. 2). This is also reflected in the increasingly stronger effect on air pollution over time (see Fig. 3). Also, the effects appear to be somewhat, though not significantly, stronger for the subsample of hospitals located in cities that implemented a Low Emission Zone until 2011. Second, health benefits of improving air quality may accrue over time when longer-term rather than short-term exposure to air quality matters more for the types of diseases under consideration here.

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 exclude more specialized hospitals. The results for this baseline sample selection are shown in column (1) of Table 7. 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 sub-sample 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. In our main specification, we employ a binary treatment of hospitals being located within the boundaries of an active Low Emission Zone. As discussed before, lacking information on the residential locations of patients this creates a potential source of measurement error as treated patients residing in a Low Emission Zone may still chose hospitals outside the area and vice versa. In alternative specifications, we define mutually exclusive hospital catchment areas based on driving time. This means that for every hospital in our dataset, we create adjacent polygons around hospital locations that characterize areas in which driving time to the associated hospital is shorter than the driving time to any other hospital in the surrounding, which we also weight by population density. Alternatively, we create hospital catchment areas as non-mutually exclusive areas with a radius of ten minutes driving time around hospital locations.[33] In these specifications, a hospital's treatment by a Low Emission Zone is defined as the share of its catchment area covered by an active Low Emission Zone. On average, the share of the different hospital catchment areas covered by Low Emission Zones varies by specification between 17 and 21 percent (see Panel C of Table 3). The regression results are shown in columns (4)–(6) of Table 7 and largely reflect the main results, particularly for circulatory diseases. However, the coefficients for the share of the catchment area covered by an active Low Emission Zone are less precisely estimated. The underlying assumption that adjacent catchment areas based on driving time distance are a good proxy for hospital choice is stronger and therefore associated with more measurement error than the binary treatment indicator as in the main specification.

33 For this analysis, we use the Open Source Routing Machine (OSRM) with the OpenStreetMap road network of 2016 to create driving time polygons.



(a) Share of circulatory diseases (I00-I99)

(b) Share of respiratory diseases (J00-J99)

(c) Share of ischemic heart diseases (I20-I25)

(d) Share of chronic lower respiratory diseases (J40-J47)

Fig. 4. The effect of Low Emission Zones on diagnoses in hospitals — Event study. *Notes:* These figures display event-study results for the effect of Low Emission Zones on a hospital's share of selected types of diseases. The reference period $k = -1$ refers to the year prior to the implementation of the Low Emission Zone. Each coefficient is an estimate for β_k (with 95% confidence intervals) according to Eq. (2) for a binary indicator for a hospital being located in an active Low Emission Zone in the respective time period relative to the introduction of the Low Emission Zone, while controlling for hospital and year fixed effects as well as indicators for non-profit, public and private hospitals, the baserate, the number of beds and number of beds squared, mean temperature, precipitation and wind speed, population, work force, gender-specific age structure as shown in Table 3. Event-study results are shown for separate regressions for the full sample of hospitals as well as for the sub-sample of hospitals located in cities which adopted a Low Emission Zone until 2011. Standard errors are clustered at the county level.

Aggregating on city and county level. In order to reveal the importance of using high resolution spatial data we aggregate hospital diagnoses at the city and county level by year and regress the aggregate number of diagnoses on the share of a county or city area that is covered by an active Low Emission Zone or on a binary indicator for an active Low Emission Zone. We use the same controls as in the main health regression but at the city 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 city level. While most of the coefficients are negative only one of them is 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.

Effects on traffic volumes, GDP and population. Traffic volume 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 and using data from traffic monitors provided by the Federal Highway Research Institute, 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 county time trends to account for changes in commuting behavior between cities. 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.

Table 7
The effect of Low Emission Zones on diagnoses — Alternative specifications.

Specification	Hospitals			Hospital catchment area by driving time			Diagnoses
	Main	Special	CAP	un-weighted	weighted by pop. dens.	Radius of 10 min.	in logs
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
All diseases (A00–N99)	−1.412	−4.074	−1.472	−0.539	−1.326	−0.974	−0.083**
	(1.460)	(4.828)	(1.431)	(1.266)	(1.870)	(1.573)	(0.033)
Diseases of the circulatory system (I00–I99)	−1.262***	−0.229	−1.347***	−1.344**	−1.304*	−1.092**	−0.145**
	(0.484)	(1.213)	(0.490)	(0.529)	(0.685)	(0.555)	(0.057)
Hypertension (I10–I15)	−0.232	0.628	−0.248*	−0.215	−0.306	−0.297	−0.194***
	(0.148)	(0.644)	(0.143)	(0.157)	(0.224)	(0.212)	(0.065)
Ischemic heart diseases (I20–I25)	−0.545**	0.535*	−0.531**	−0.443*	−0.270	−0.159*	−0.132*
	(0.214)	(0.296)	(0.219)	(0.252)	(0.277)	(0.209)	(0.079)
Cerebrovascular disease (I60–I69)	0.018	−0.201	0.012	0.039	0.130	0.158	−0.097
	(0.081)	(0.293)	(0.083)	(0.114)	(0.135)	(0.115)	(0.073)
Diseases of the respiratory system (J00–J99)	−0.100	0.479	−0.086	0.024	−0.179	−0.026	−0.064
	(0.233)	(0.520)	(0.234)	(0.279)	(0.273)	(0.243)	(0.047)
Acute lower respiratory diseases (J20–J22)	−0.053*	0.070	−0.052*	−0.017	−0.036	−0.034	−0.166***
	(0.030)	(0.086)	(0.031)	(0.030)	(0.050)	(0.032)	(0.061)
Chronic lower respiratory diseases (J40–J47)	−0.160**	−0.093	−0.145*	−0.039	−0.036	−0.081	−0.159**
	(0.075)	(0.209)	(0.079)	(0.109)	(0.150)	(0.112)	(0.066)
Number of observations	2736	2042	2600	2736	2736	2736	2736
Controls:							
Hospital FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes
State × 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
City characteristics	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Linear county time trends	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on the share of diagnoses among all inpatients, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). The results shown in this table differ from the main results shown in Table 5 by either varying the definition of the estimation sample or the treatment. Column (1) mirrors the main specification as shown in column (6) of Table 5. Column (2) presents results for the sample of specialized hospitals. Column (3) shows results for a sample of general hospitals located in cities that eventually implement a Clean Air Plan. Column (4) replaces the binary treatment of being located in an active Low Emission Zone by the share of hospitals' catchment areas being covered by a Low Emission Zone. Column (5) additionally weights the share of hospitals' catchment areas being covered by a Low Emission Zone by population density. Column (6) shows results for the share of hospitals' ten minutes driving time radius being covered by a Low Emission Zone. Finally, column (7) uses the log number of diagnoses instead of the share of diagnoses of all admissions to the hospital. Each coefficient is the result of a separate regression for the type of disease listed in the left column on a binary indicator variable for hospitals being located in an active Low Emission Zone, while controlling for hospital and year fixed effects. Additional controls are indicated at the bottom of each column. Hospital characteristics are indicators for non-profit, public and private hospitals, the baserate, the number of beds and number of beds squared. Weather characteristics are mean temperature, precipitation and wind speed, city characteristics are population, work force, gender-specific age structure as shown in Table 3. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: ***: $p < 0.01$, **: $p < 0.05$, *: $p < 0.1$.

While Low Emission Zones may be associated with benefits for population health, the implementation is costly in terms of upgrading the vehicle fleet but also by introducing restrictions which may hamper economic activity and population growth. Table C.3 shows that the implementation of Low Emission Zones did not significantly reduce economic activity or population. Columns (1) and (2) use the share of a county's area covered by a Low Emission Zone and columns (3) and (4) a binary indicator for any Low Emission Zone in the county. After controlling for county-specific time trends, there is no statistically significant impact on county-level GDP overall, GDP in the retail and traffic sector or a county's population. This supports the interpretation of our results showing a reduction in air pollution-related diagnoses not being driven by population movements or economic activity away from cities where a Low Emission Zone is implemented.

Other diagnoses related to air pollution and traffic. Table C.4 provides further evidence that health effects are driven by improvements in air quality through reductions in respiratory and circulatory 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 effect for diabetes. Additionally, we focus on stress related diagnoses for which we do not find any significant effects. While we do find some statistically significant negative results for injuries, which could be driven by reductions in traffic accidents, they are not robust to the inclusion of all control variables and time trends. This suggests that the main health benefits of Low Emission Zones are improvements in air quality and not necessarily reductions in traffic volumes.

4. Conclusion

In this paper, we study the impact of the implementation of Low Emission Zones, a driving ban for vehicles below certain emission standards within targeted areas, on air pollution and hospitalizations in German cities over the period from 2006 to 2016. To this end, we exploit the staggered introduction of Low Emission Zones across time and space in a difference-in-differences framework.

Our results confirm that Low Emission Zones are an effective policy instrument to reduce levels of air pollution. On average, the implementation of a Low Emission Zone reduces annual mean levels of key target air pollutants, particulate matter (PM10) and nitrogen dioxide (NO2), by about five percent. These improvements are associated with a lower incidence of violations of air quality standards. We further show that these moderate improvements in air quality translate into positive but small impacts on population health in terms of hospitalizations. Using data on the universe of hospitals in Germany with exact address level information on hospitals' locations, we show that hospitals which are located within the boundaries of an active Low Emission Zone diagnose a smaller share of air pollution related diseases. In particular, we find that the share of diseases of the circulatory system as well as the share chronic lower respiratory diseases are statistically significantly reduced following the implementation of Low Emission Zones. The precise information on hospital locations allows us to show that these reductions are mainly driven by hospitals actually located within the boundaries of Low Emission Zones, while hospitals outside of the area but within the same city do not show significant changes in the composition of hospitalizations.

We acknowledge two main limitations of the data underlying our empirical analysis. First, while the data on hospitalizations used in this paper allow to precisely assign hospital locations to whether they are actually located inside the boundaries of an active Low Emission Zone, the data lack information on the residence locations of inpatients. Hence, our analysis relies on the assumption that hospital locations are a relevant proxy for patients' residences, which is supported by the institutional background of the German health care system, but still introduces measurement error that should be taken into account. Second, hospitalizations are a rather severe health outcome which is certainly not representative for the overall population health benefits of the implementation of Low Emission Zones, especially against the background that the first stage effects on local air quality are rather moderate in size. Therefore, it is not surprising that the effect sizes we document are rather small and are confined to specific circulatory and respiratory diseases that are associated with severe symptoms like chest pain and shortness of breath. Despite these limitations, this paper contributes to the recent literature on health effects of Low Emission Zones by showing that even rather severe health outcomes are affected by the policy intervention. Hence, the small benefits in terms of hospitalizations can be viewed as the tip of the iceberg and add to the recently documented health benefits in terms of less severe outcomes, i.e., reductions in ambulatory care claims (Margaryan, 2021) and pharmaceutical expenditures (Rohlf et al., 2020). Looking ahead, future research should overcome data limitations of German hospital data, exploiting other data sources or the experience in other European countries that are increasingly implementing Low Emission Zones. In particular, settings with access to individual-level data on hospitalizations with more detailed information on residence locations would allow to reduce measurement error in assigning exposure to improvements in air quality as well as heterogeneity analyses by health, demographic and socio-economic characteristics. In addition, future research should take into account the longer-term health benefits as well as non-health dimensions, e.g., labor market and educational outcomes, in order to provide a comprehensive evaluation of the policy's costs and benefits.

Overall, the findings of this paper 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.

Appendix A. Low Emission Zones and air pollution in Germany

See Figs. A.1–A.5 and Tables A.1–A.5.

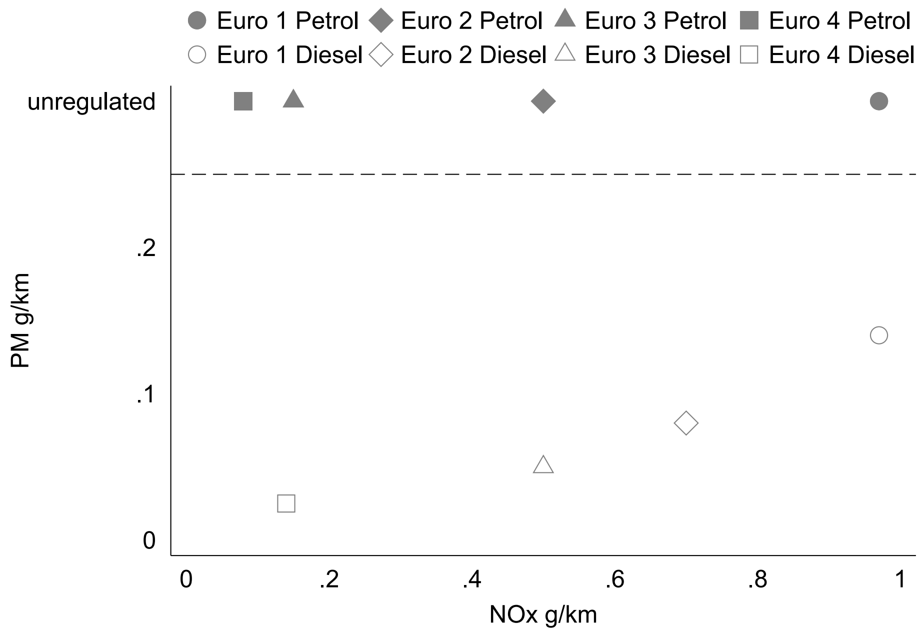


Fig. A.1. European emission standards. *Notes:* This graph displays the European emission standards of maximum limits for exhaust emissions of Particulate Matter (PM) and Nitrogen Oxides (NOx) from new vehicles sold in the European Union and the European Economic Area member states.
Source: Tiwary and Williams (2018).

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

Pollutant	Thresholds	Deadline
PM10	Yearly average limit 40 μg/m^3 Daily average limit 50 μg/m^3 Allowed number of transgression: 35	1 January 2005
NO2	Yearly average limit 40 μg/m^3 Hourly average limit 200 μg/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 sulfur 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.

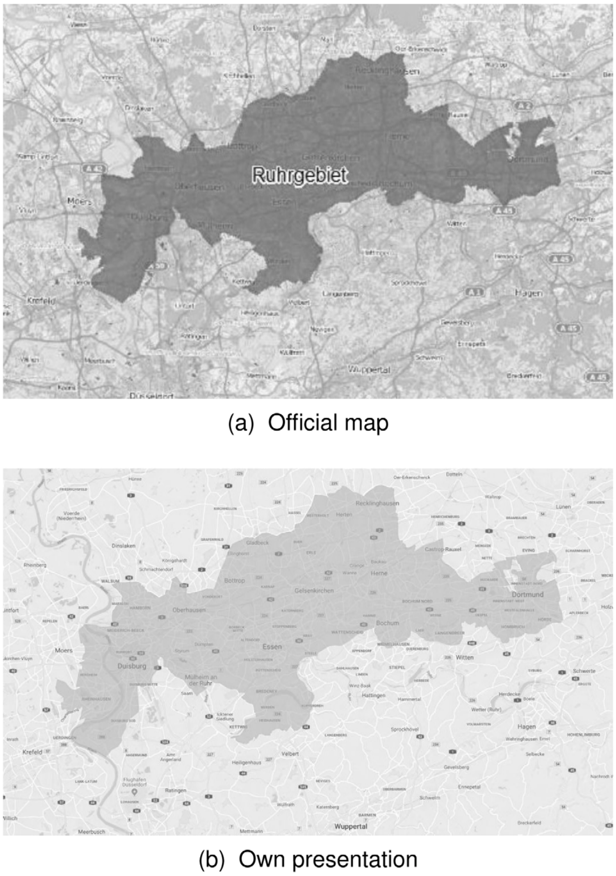


Fig. A.2. Example: Low Emission Zone in the Ruhr area. *Notes:* These figures show the Low Emission Zone in the Ruhr Area in West Germany. Panel (a) displays the official map from the Federal Environment Agency (*Umweltbundesamt, UBA*) while Panel (b) shows the same Low Emission Zone based on polygons available at that we use to assign pollution monitors and hospitals to whether they are located inside or outside of a Low Emission Zone.

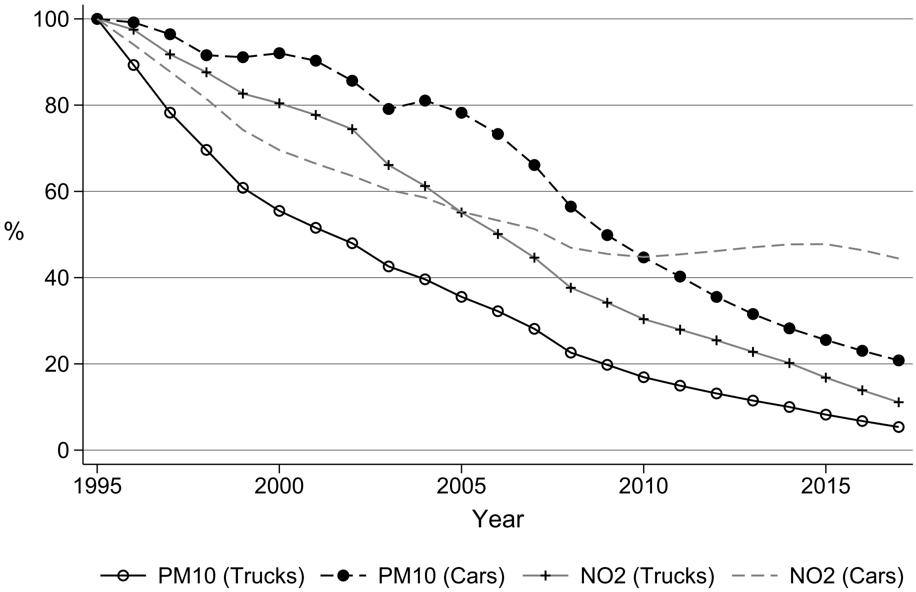
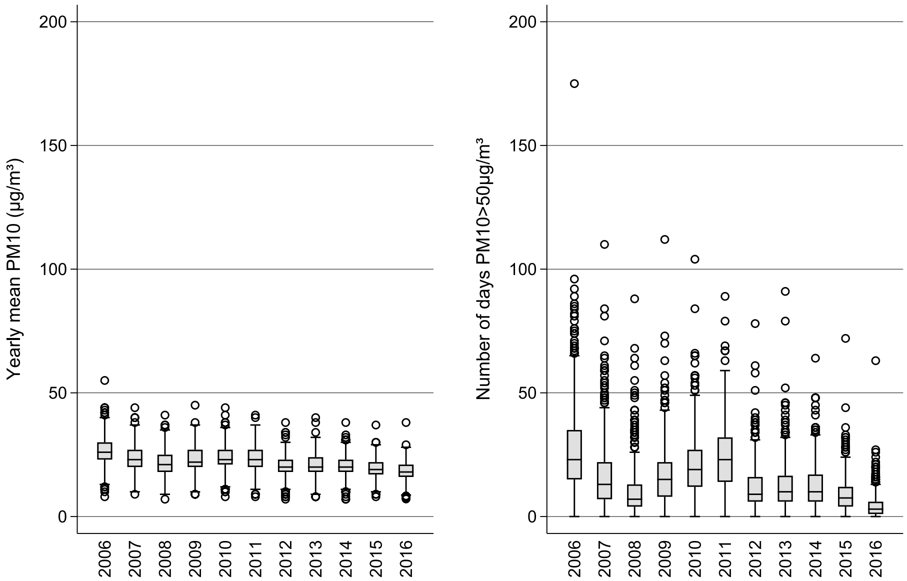
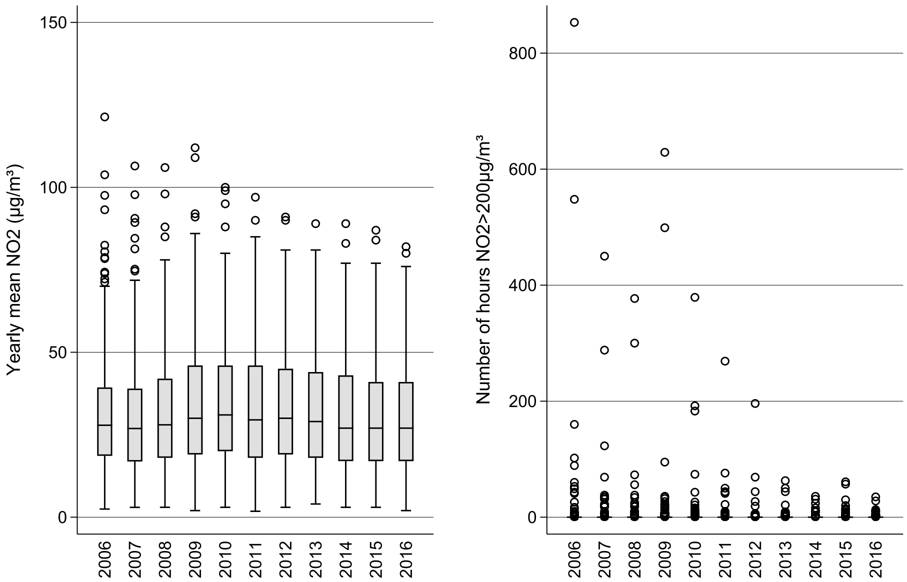


Fig. A.3. Vehicle emissions in Germany. *Notes:* This figure shows how emissions of Particulate Matter (PM10) and Nitrogen Dioxide (NO2) from different types of vehicles in Germany have evolved over time relative to the levels in 1995.
Source: Federal Environment Agency (*Umweltbundesamt, UBA*).

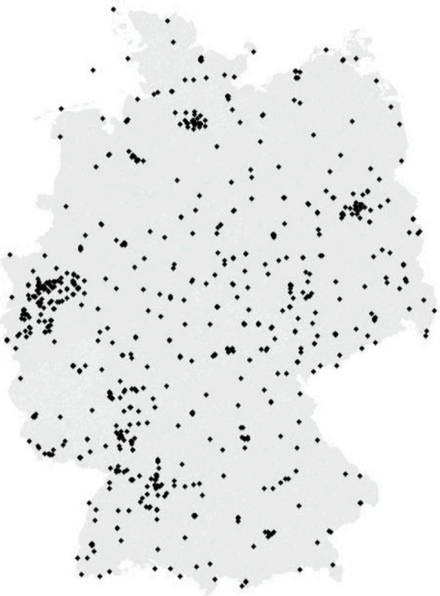


(a) PM10

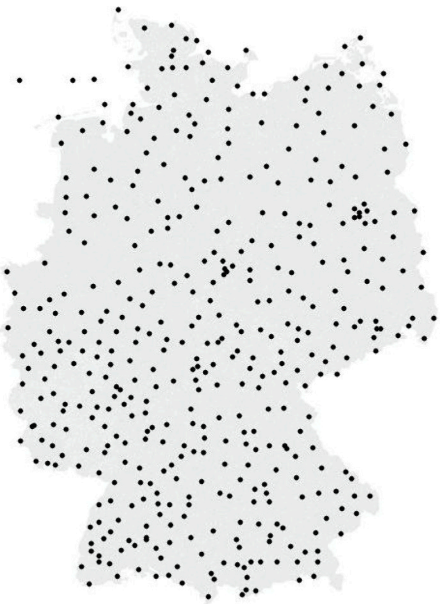


(b) NO2

Fig. A.4. Variation of air pollutants over time. *Notes:* These figures show boxplots representing the distribution of annual means and number of limit exceedances measured at PM10 and NO2 pollution monitors and how they evolved over time.
Source: Federal Environment Agency (*Umweltbundesamt, UBA*).



(a) Pollution monitors



(b) Weather monitors

Fig. A.5. Location of pollution and weather monitors. *Notes:* These maps show the exact locations of pollution and weather monitors across Germany. *Source:* Federal Environment Agency (*Umweltbundesamt, UBA*), National Meteorological Service (*Deutscher Wetterdienst, DWD*).

Table A.2
Low Emission Zones in Germany as of 2018.
Source: Federal Environment Agency (*Umweltbundesamt, UBA*).

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 lists all active Low Emission Zones in Germany as of 2018. We computed the size and perimeter based on OpenStreetMap.org.

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

	PM10		NO2	
	(1)	(2)	(3)	(4)
A. Pollution levels	Yearly mean PM10 μg/m^3		Yearly mean NO2 μg/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
Number of observations	4290	4290	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 μg/m^3		Yearly hours NO2 > 200 μg/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
Number of observations	4290	4290	4357	4357
C. Violations	Yearly mean PM10 > 40 μg/m^3		Yearly mean NO2 > 40 μg/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
Number of observations	4290	4290	5237	5237
Controls:				
Station FE	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes
City characteristics	Yes	Yes	Yes	Yes

Notes: This table displays the estimation results for the effect of Clean Air Plans on air pollution, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression of annual-level outcomes related to air pollution (mean levels, number of limit exceedances or air quality standard violations) on a binary indicator variable for a pollution monitor being located in a city where a Clean Air Plan has been established and in columns (2) and (4) interacted with a binary indicator for a pollution monitor being additionally located within the boundaries of active Low Emission Zone, while controlling for monitor and state-by-year fixed effects, weather characteristics (mean temperature, precipitation and wind speed) and city characteristics (population, work force, gender-specific age structure) as shown in Tables 1 and 2. Standard errors are clustered at the county level and 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 μg/m^3			Yearly mean NO2 μg/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
Number of observations	4290	4290	4290	5237	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 μg/m^3			Yearly hours NO2 > 200 μg/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
Number of observations	4290	4290	4290	4357	4357	4357
C. Violations	Yearly mean PM10 > 40 μg/m^3			Yearly mean NO2 > 40 μg/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
Number of observations	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
City characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on air pollution, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression of annual-level outcomes related to air pollution (mean levels, number of limit exceedances or air quality standard violations) on a binary indicator variable for a pollution monitor being located in an active Low Emission Zone with interactions for the stringency level of the Low Emission, i.e., the minimum emission standard for a vehicle being eligible to enter, while controlling for monitor and state-by-year fixed effects, weather characteristics (mean temperature, precipitation and wind speed) and city characteristics (population, work force, gender-specific age structure) as shown in Tables 1 and 2. Standard errors are clustered at the county level and 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 μg/m^3			Yearly mean NO2 μg/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
Number of observations	4290	4290	4290	5237	5237	5237
B. Limit exceedances	Yearly days PM10 > 50 μg/m^3			Yearly hours NO2 > 200 μg/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
Number of observations	4290	4290	4290	4357	4357	4357
C. Violations	Yearly mean PM10 > 40 μg/m^3			Yearly mean NO2 > 40 μg/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
Number of observations	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
City characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on air pollution, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression of annual-level outcomes related to air pollution (mean levels, number of limit exceedances or air quality standard violations) on a binary indicator variable for a pollution monitor being located in an active Low Emission Zone or within a certain distance from an active Low Emission, while controlling for monitor and state-by-year fixed effects, weather characteristics (mean temperature, precipitation and wind speed) and city characteristics (population, work force, gender-specific age structure) as shown in Tables 1 and 2. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: ***: $p < 0.01$, **: $p < 0.05$, *: $p < 0.1$.

Appendix 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.

Table B.1
Balancing of hospital characteristics.

	Unconditional			Conditional on State FE		
	Never LEZ (1)	Ever LEZ (2)	Diff. (2)–(1) (3)	Never LEZ (4)	Ever LEZ (5)	Diff. (5)–(4) (6)
Baserate in €	2757.55	2686.68	−70.87*	4.36	−7.07	−11.43
	(25.27)	(31.45)	(40.35)	(23.40)	(27.51)	(36.12)
Number of Beds	531.27	497.08	−34.19	5.26	−8.54	−13.80
	(28.66)	(30.32)	(41.72)	(27.74)	(29.40)	(40.42)
Private	0.14	0.08	−0.05	−0.00	0.01	0.01
	(0.02)	(0.02)	(0.03)	(0.02)	(0.02)	(0.03)
Public	0.29	0.19	−0.10**	0.03	−0.05	−0.08*
	(0.03)	(0.04)	(0.05)	(0.03)	(0.03)	(0.05)
Non-Profit	0.57	0.72	0.16***	−0.03	0.04	0.07
	(0.04)	(0.04)	(0.05)	(0.03)	(0.04)	(0.05)
Number of hospitals	212	130		212	130	

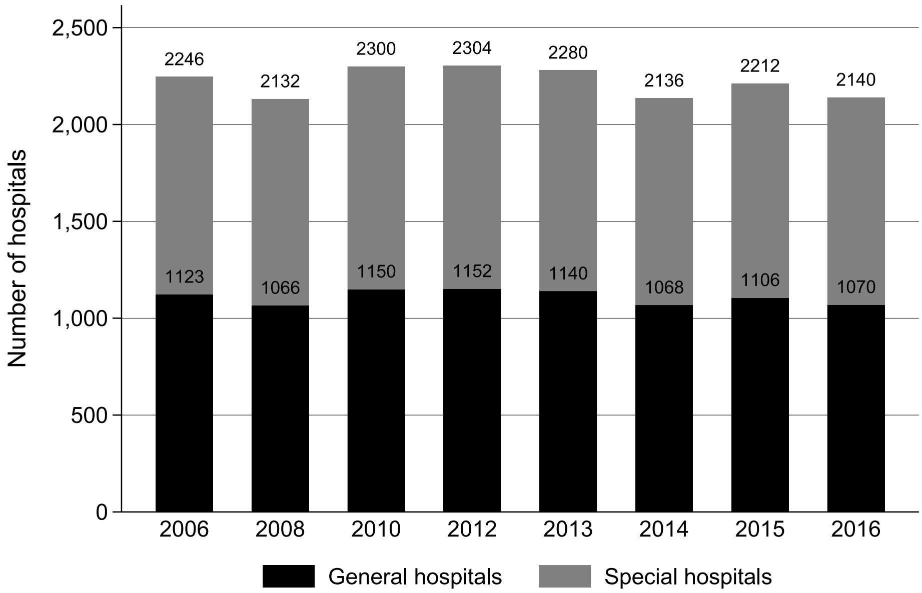
Notes: This table compares characteristics of hospitals as of 2006 before any Low Emission Zone was implemented between hospitals that are eventually located within an active Low Emission Zone (Ever LEZ) and hospitals that are never covered by a Low Emission Zone (Never LEZ) over the period of investigation between 2006 and 2016. Columns (1) and (2) show the raw means and standard deviations, whereas columns (4) and (5) display the residual means and standard deviations after conditioning on state fixed effects. Columns (3) and (6) show the difference between ever-treated and never-treated hospitals and indicate whether the differences are statistically significant. Significance levels: ∗∗∗: $p < 0.01$, ∗∗: $p < 0.05$, ∗: $p < 0.1$.

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.

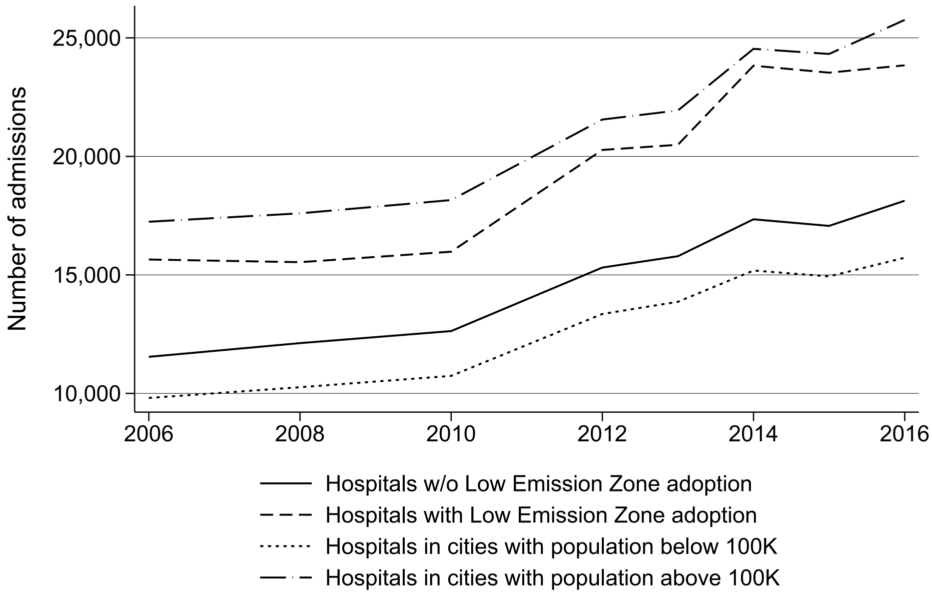
In order to calculate catchment areas, we need the geographic coordinates for each hospital location. We use the full addresses available in the quality reports and convert them using Nokias geocodingHere! API. This involves the input of the hospital address and a street network file provided by navteq 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 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.

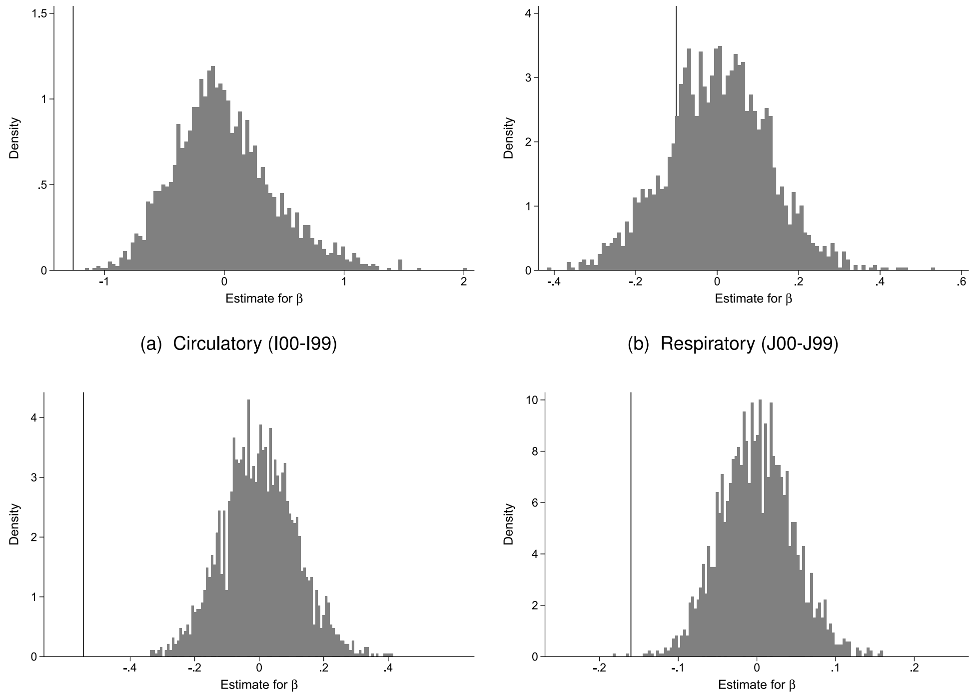


(a) Number of hospital locations



(b) Number of admissions

Fig. B.1. Hospitals and hospitalizations over time. *Notes:* These figures show the total numbers of hospitals and hospitalizations in Germany from 2006 to 2016. Panel (a) shows the number of all German hospital locations separated by general and special hospitals. General hospitals meet the criteria of hospitals of primary care in Germany (*Krankenhäuser der Regelversorgung*), i.e., have a unit for surgery and internal medicine (Ethikrat, 2016) while special hospitals are typically hospices, wellness clinics, rehabilitation centers or sanatoriums. Panel (b) shows the annual number of hospital admissions to general hospitals, broken down by cities that eventually implemented a Low Emission Zone and cities above and below a population of 100,000.
Source: Hospital Quality Reports, Federal Statistical Office (*Destatis*).



(a) Circulatory (I00-I99)

(b) Respiratory (J00-J99)

(c) Ischemic (I20-I25)

(d) Chronic l. respiratory (J40-J47)

Fig. C.1. The effect of Low Emission Zones on diagnoses in hospitals — Placebo permutation test. *Notes:* These figures show histograms of the frequency distribution of estimates from placebo permutation tests for selected categories of hospital diagnoses based on random allocation of the binary treatment variable for a hospital being located within the boundaries of an active Low Emission Zone with 5,000 replications. Controls and fixed effects correspond to the specification in column (6) of Table 5 and the vertical lines indicate the corresponding point estimates.

Appendix C. Additional results

C.1. Additional tables and figures

C.2. Multiple hypothesis testing

Our main analysis presented in Table 5 is based on eight disease categories as outcome variables and we estimate the impact of Low Emission Zones on each outcome in separate regressions. All of these outcomes represent different dimensions of hospital diagnoses, and are thus likely correlated. Such a correlation can lead to an underestimation of the standard errors and to an over-rejection of the null hypothesis. We adjust the p-values from the estimation results in column (6) of Table 5 following the step-down approach by Benjamini and Hochberg (1995). The step-down approach assigns the largest adjustment to the p-value and the smallest adjustment to the highest. We first rank all p-values from highest to lowest, and calculate the adjusted p-values using the formula

$$q = \frac{pm}{m - (i - 1)} \tag{C.1}$$

where p is the unadjusted p-value, m is the number of hypothesis tests, and i is the rank of the p-value, with $i = 1$ being the highest and $i = m$ the lowest. In our case, the lowest p-value is adjusted by a factor 8 and highest p-value is unadjusted. Table C.5 displays the p-values associated with column (6) from our main Table 5 in column (1) and adjusted p-values (q-values) for all eight outcomes in column (2). After the adjustment, from the four statistically significant estimates one is rendered insignificant and two coefficients remain statistically significant at the 5%-level and one at the 10%-level.

Table C.1
The effect of Low Emission Zones on diagnoses — Aggregate level results.

Level of aggregation	County		City	
Treatment by Low Emission Zone	Binary	Share	Binary	Share
	(1)	(2)	(3)	(4)
All diseases (A00–N99)	−0.834	0.852	−2.580	−3.594
	(5.333)	(5.622)	(4.992)	(4.686)
Diseases of the circulatory system (I00–I99)	−0.673	−0.882	−1.749	−2.443
	(1.450)	(1.995)	(1.322)	(1.667)
Hypertension (I10–I15)	−0.299	−0.272	−0.548	−0.869
	(0.578)	(0.695)	(0.534)	(0.563)
Ischemic heart diseases (I20–I25)	−0.268	0.030	−0.560	−0.208
	(0.429)	(0.608)	(0.417)	(0.573)
Cerebrovascular diseases (I60–I69)	0.011	−0.041	0.022	−0.041
	(0.158)	(0.218)	(0.129)	(0.228)
Diseases of the respiratory system (J00–J99)	0.174	0.454	0.414	0.353
	(0.631)	(0.708)	(0.480)	(0.553)
Acute lower respiratory diseases (J20–J22)	−0.179	0.005	0.065	0.108
	(0.178)	(0.202)	(0.177)	(0.286)
Chronic lower respiratory diseases (J40–J47)	−0.097*	0.024	−0.097	0.007
	(0.084)	(0.096)	(0.072)	(0.088)
Number of observations	566	566	638	638

Notes: This table displays the estimation results for the effect of Low Emission Zones on the share of diagnoses among all inpatients, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression for the type of disease listed in the left column. Hospital diagnoses were aggregated to the county or city level and the Low Emission Zone treatment is either a binary indicator for the county or city having an active Low Emission Zone or share of the county or city area covered by an active Low Emission Zone, while controlling for county or city and year fixed effects and for weather characteristics (mean temperature, precipitation and wind speed) and population characteristics (work force, gender-specific age structure) as shown in Table 3. Standard errors are clustered at the county or city level 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 volumes.

	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 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
Number of observations	6032	6032	6032	6032	6032	6032
Controls:						
Monitor FE	Yes	Yes	Yes	Yes	Yes	Yes
LMR × Year FE	Yes	Yes	Yes	Yes	Yes	Yes
City characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes

Notes: This table displays estimation results for the effect of Low Emission Zones on traffic volumes based on data from traffic monitors provided by the Federal Highway Research Institute (*Bundesanstalt für Straßenwesen, BASt*) for traffic volumes of all vehicles and vehicles with a weight of less than 3.5 tons (mainly passenger vehicles). The table shows coefficient estimates for binary indicators for a traffic monitor being located within or within a certain distance of an active Low Emission Zone, while controlling for monitor and labor market region-specific year fixed effects as well as weather characteristics (mean temperature, precipitation and wind speed) and population characteristics (work force, gender-specific age structure) of the city the monitor is located in. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: $***$: $p < 0.01$, $**$: $p < 0.05$, $*$: $p < 0.1$.

Table C.3
The effect of Low Emission Zones on county GDP and population.

Treatment by Low Emission Zone	Share (1)	Share (2)	Binary (3)	Binary (4)
ln(GDP)	−0.103**	0.058	−0.012	0.027
	(0.044)	(0.071)	(0.031)	(0.031)
ln(GDP (Retail/Traffic))	−0.037**	−0.005	−0.007	0.000
	(0.017)	(0.026)	(0.008)	(0.008)
ln(Population)	−0.012	0.011	−0.016	0.006
	(0.022)	(0.019)	(0.013)	(0.010)
Number of observations	566	566	566	566
Controls:				
County FE	Yes	Yes	Yes	Yes
State × Year FE	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes
County characteristics	Yes	Yes	Yes	Yes
Linear county time trends	No	Yes	No	Yes

Notes: This table displays the estimation results for the effect of Low Emission Zones on county-level GDP and population, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression for the outcome listed in the left column, where the Low Emission Zone treatment is either a binary indicator for the county having an active Low Emission Zone or share of the county area covered by an active Low Emission Zone, while controlling for county and state-specific year fixed effects as well as weather characteristics (mean temperature, precipitation and wind speed) and population characteristics (work force, gender-specific age structure) as shown in Table 3. Standard errors are clustered at the county or city level and displayed in parentheses. Significance levels: $***$: $p < 0.01$, $**$: $p < 0.05$, $*$: $p < 0.1$.

Table C.4
The effect of Low Emission Zones on diagnoses in hospitals — Additional outcomes.

	(1)	(2)	(3)	(4)	(5)	(6)
Dementia (F00–F03)	−0.010	−0.011	−0.012	−0.011	0.005	0.002
	(0.017)	(0.017)	(0.017)	(0.016)	(0.014)	(0.015)
Diabetes (E10–E14)	−0.068	−0.070	−0.088	−0.115	−0.053	−0.085
	(0.074)	(0.075)	(0.075)	(0.072)	(0.069)	(0.087)
Stress (F40–F48)	0.032	0.032	0.016	0.021	−0.018	−0.010
	(0.037)	(0.037)	(0.040)	(0.037)	(0.047)	(0.050)
Injuries (S00-S99)	−0.281*	−0.287*	−0.386**	−0.426*	−0.748	−0.770
	(0.158)	(0.156)	(0.193)	(0.229)	(0.634)	(0.800)
Low birth weight (P07) [t+1]	−0.013	−0.012	−0.013	−0.012	−0.014	−0.022
	(0.015)	(0.015)	(0.015)	(0.015)	(0.015)	(0.016)
Number of observations	2736	2736	2736	2736	2736	2736
Controls:						
Hospital FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	Yes	Yes	Yes
City characteristics	No	No	Yes	Yes	Yes	Yes
Hospital characteristics	No	No	No	Yes	Yes	Yes
State × Year FE	No	No	No	No	Yes	Yes
Linear county time trends	No	No	No	No	No	Yes

Notes: This table displays estimation results for the effect of Low Emission Zones on the share of alternative diagnoses among all inpatients, i.e., an estimate for the coefficient β according to the regression model shown in Eq. (1). Each coefficient is the result of a separate regression for the type of disease listed in the left column on a binary indicator variable for a hospital being located in an active Low Emission Zone, while controlling for hospital and year fixed effects. Additional controls are indicated at the bottom of each column. Hospital characteristics are indicators for non-profit, public and private hospitals, the baserate, the number of beds and number of beds squared. Weather characteristics are mean temperature, precipitation and wind speed, city characteristics are population, work force, gender-specific age structure as shown in Table 3. Standard errors are clustered at the county level and displayed in parentheses. Significance levels: $***$: $p < 0.01$, $**$: $p < 0.05$, $*$: $p < 0.1$.

Table C.5
Adjusted p-values for the effect of Low Emission Zones on hospital diagnoses.

	(1)	(2)
All diseases (A00–N99)	0.333	0.445
Diseases of the circulatory system (I00–I99)	0.009	0.045
Hypertension (I10–I15)	0.118	0.189
Ischemic heart diseases (I20–I25)	0.011	0.045
Cerebrovascular disease (I60–I69)	0.820	0.821
Diseases of the respiratory system (J00–J99)	0.667	0.762
Acute lower respiratory diseases (J20–J22)	0.077	0.154
Chronic lower respiratory diseases (J40–J47)	0.033	0.087
Number of observations	2736	2736
Controls:		
Hospital FE	Yes	Yes
Year FE	Yes	Yes
Weather characteristics	Yes	Yes
City characteristics	Yes	Yes
Hospital characteristics	Yes	Yes
State × Year FE	Yes	Yes
Linear county time trends	Yes	Yes

Notes: This table displays the unadjusted p-values associated with the estimation results for the effect of Low Emission Zones on the share of hospital diagnoses shown in column (6) of Table 5. Column (1) displays the conventional p-values, while column (2) shows p-values adjusted for multiple hypothesis testing (also called q-values). The p-values in column (1) are based on standard errors clustered at the county level.

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