Low Emission Zones for Better Health: Evidence from German Hospitals

Nico Pestel[*] Florian Wozny[†]

January 31, 2019

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Abstract

This paper studies health effects from restricting the access of high-emission vehicles to inner-cities by implementing low emission zones. For identification, we exploit variation in the timing and the spatial distribution of the introduction of new low emission zones across cities in Germany. We use detailed hospitalization data combined with geo-coded information on the coverage of low emission zones. We confirm that low emission zones significantly reduce levels of air pollution in urban areas and that these improvements in air quality translate into population health benefits. We find that the number of diagnoses related to exposure to air pollution is significantly reduced for hospitals located within or in close proximity to a low emission zone after it becomes effective. In particular, the number of diagnosis for diseases of the circulatory and the respiratory system are significantly reduced.

JEL Classification: I18, Q52, Q53
Keywords: Low Emission Zone, air pollution, health, Germany

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[*] Institute of Labor Economics (IZA), E-mail: pestel@iza.org.

[†] **Corresponding author:** Institute of Labor Economics (IZA), Schaumburg-Lippe-Str. 5–9, 53113 Bonn, Germany, Tel.: +49 228 3894–139, E-mail: wozny@iza.org.

1 Introduction

Air pollution is the single largest environmental risk for human health. About seven million premature deaths globally per year as well as a wide range of health hazards, in particular respiratory and cardiovascular diseases, are attributed to poor air quality (WHO, 2018).[1] While adverse health effects may be more severe in the developing world, many places in high-income countries are also faced with serious violations of air quality standards for various target pollutants. This creates large economic costs through hampered human capital formation (Graff Zivin and Neidell, 2013) and increasing defensive medical spending (Deschênes et al., 2017).

Traffic is a major source of ambient air pollution, particularly in urban areas (Karagulian et al., 2015). Emissions from traffic are especially harmful to human health because they are mostly emitted close to the ground. Thus, reducing air pollution in cities is a main concern for policy makers. In the European Union, a key policy measure to reduce ambient air pollution in inner-cities is the implementation of low emission zones. A low emission zone (LEZ) is a signposted area where access of vehicles is restricted based on their exhaust emission standard, typically banning high-emitting vehicles from entering the zone altogether.

In this paper, we study whether the introduction of a low emission zone is an effective policy to improve population health by evaluating LEZ adoptions across German cities using rich panel data from the universe of hospitals for which we know the exact location. Germany is currently the country which has established most LEZs based on relatively strict European Union legislation requiring legal actions against air quality standard violations.[2] For causal identification of the health impact of this policy measure, we exploit variation in the timing as well as the exact geographic coverage of LEZ implementations across Germany. Starting in 2008, eleven German cities had implemented an LEZ, initially only banning the most polluting vehicles and then gradually becoming stricter over time. As of 2018, there are 58 active LEZs across Germany. In some cities, the LEZ covers the entire city area whereas other cities have implemented an LEZ for specific subareas, usually the city center. This allows us to exploit variation of LEZ coverage between hospitals within the same city.

Several studies have documented the direct effect of LEZs on ambient air pollution. For example, Wolff (2014) shows that in Germany particulate pollution (PM10) dropped by nine percent after an LEZ introduction in treated cities, the effect being driven by an improvement of the vehicle fleet in terms of emission standards.[3] However, relatively little is known about indirect effects on human health by means of improved air quality. This is remarkable since policy interventions aiming at improving air quality, including LEZs, are justified by population health benefits. For Germany, the

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[1] Air pollution is also the main cause for premature death in Europe with more than 440,000 premature deaths per year (European Environmental Agency, 2018) and 62,000 or every 15th death in Germany (Landrigan et al., 2017).

[2] 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 LEZs have been established in European cities and this number will increase to more than 300 until 2025 (see figure A.1).

[3] Also see Morfeld et al. (2014); Malina and Scheffler (2015); Jiang et al. (2017).

study by Gehrsitz (2017) looks at the effects of LEZ introductions on infant health. While finding a reduction by 4–8 percent in PM10 levels and a 3–4 percent decrease in nitrogen dioxide (NO2) concentration, the results do not indicate substantial reductions in the prevalence of low birth weight or the number of stillbirths.[4] However, the data on birth outcomes used in Gehrsitz (2017) only allow to assign mothers' residential locations to cities but not whether the residences are actually covered by an LEZ or not. Hence, like most LEZ evaluations, the variation in LEZ coverage is restricted to between cities with and without some active LEZ, which may introduce measurement error regarding the exposure to ambient air pollution in uterus. Furthermore, health measures considered by Gehrsitz (2017) are limited to outcomes at birth. 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).

Against this background and after confirming previous findings on the direct impact of LEZ adoptions on ambient air pollution in German cities (Wolff, 2014; Gehrsitz, 2017), this paper contributes to the literature in two ways. First, we analyze the effects of LEZ introductions on population health by taking into account the exact geographic coverage of all existing 58 LEZs in Germany, allowing us to exploit detailed variation in the policy between and within cities. We link detailed information on the geographic expansion of LEZs to official hospital records, covering the universe of hospitals in Germany, on the annual number of diagnoses over the period from 2006 to 2016. While the dataset does not contain information on individual patients' residential or workplace locations, we employ several approaches to precisely calculate the share of a hospital's catchment area covered by an LEZ, given that pollution-related hospital admissions, particularly in case of emergency, should be related to air pollution levels within the surrounding catchment area. Second, we extend previous findings on the health impacts of LEZs for children (Gehrsitz, 2017) to the full range of health outcomes potentially affected by ambient air pollution. To this end, we exploit that the hospital records provide information on the frequency of detailed diagnoses based on international standard classification (ICD-10). We focus on specific cardiovascular and respiratory diseases, which have been shown to be affected by key target pollutants like particulate matter and nitrogen oxides (Graff Zivin and Neidell, 2013). Additionally, we complement the analysis by looking at further outcomes related to infant health (low birth weight) as well as to outcomes potentially affected by reduced traffic within LEZs (injuries, stress).

The results of our paper show that LEZ introductions led to substantial improvements in both ambient air quality as well as population health. We confirm that within an LEZ average air quality improves, mainly driven by decreases in limit exceedances. These improvements in air quality translate into significant decreases in the prevalence of several air pollution-related diagnoses, especially diseases of the circulatory and the respiratory system, among hospitals whose catchment areas

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[4] The paper by Simeonova et al. (2018) studies the health effect of another policy measure to improve inner-city air quality, showing that implementing a congestion tax in central Stockholm reduced ambient air pollution and significantly decreased the rate of acute asthma attacks among young children.

are covered by an LEZ. Furthermore, we find that LEZs reduce the incidence of low birth weight significantly. We do not find significant effects on injuries or diagnoses of stress potentially related to changes in traffic volume.

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

2 Institutional Background and Data

2.1 Low emission zones in Germany

Starting in the mid-1990s, the European Union (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 member states. In particular, the legal framework, which has to be adopted by national law, defines measurement procedures, limit values and alert thresholds for various target air pollutants in ambient air, among others nitrogen dioxide and particulate matter.[5] 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.[6]

In Germany, federal states in collaboration with municipalities are responsible for compliance with the EU air quality standards. In case of violations, the responsible local authorities are obliged to develop area-specific Clean Air Plans (CAPs, in German: *Luftreinhaltepläne*), defining a bundle of measures aiming at lasting improvements of air quality in compliance with the EU standards. Low emissions zones are one potential measure from the CAP tool box to reduce the emissions of air pollutants from traffic in urban areas.[7]

Low emission zones (LEZs) are signposted areas where entry by polluting 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.[8] Typically, low emission zones were introduced in phases. In phase one, only the dirtiest Euro 1 vehicles were banned. Subsequently, the LEZs became stricter, banning Euro 2 and Euro 3 classes in the second

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[5] See Table A.1 for limit value threshold values for particulate matter (PM10) and nitrogen dioxide (NO2).

[6] 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) (European Commission, 2018).

[7] For example, less restrictive measures of Clean Air Plans typically aim at enhancing the use of public transportation, bicycles or electric powered vehicles.

[8] See Table A.2 for details. As of 2019, access to individual LEZs (e.g., in Stuttgart) requires a minimum emission standard of Euro 5 by diesel-fueled vehicles.

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 LEZs allow access only to vehicles with a green sticker.[9]

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 1–4 vehicles) as well as the precise geographic coverage of each zone at all stages.[10] Figure 1 shows the spatial diffusion (as of 2018) as well as the number of implemented clean air plans (CAPs) and low emission zones (LEZs) over the period from 2007 to 2018. The first CAPs were established in 2007, the number increased to more than 80 by 2018. In 2008, eleven LEZs were established at stage one (only banning Euro 1 vehicles) followed by a gradual increase of new LEZs across the country. The earliest second stage (banning Euro 1–2) was introduced in 2009, while over the course of 2010 all LEZs switched at least to the second stage, some already introduced the third stage (ban on Euro 1–3). From 2013 onwards, the third stage dominated. As of 2018, there are 58 active LEZs in Germany. Whereas in 2018 clean air plans are rather equally distributed across Germany, most LEZs are located in urban areas in the West or South-West of Germany.

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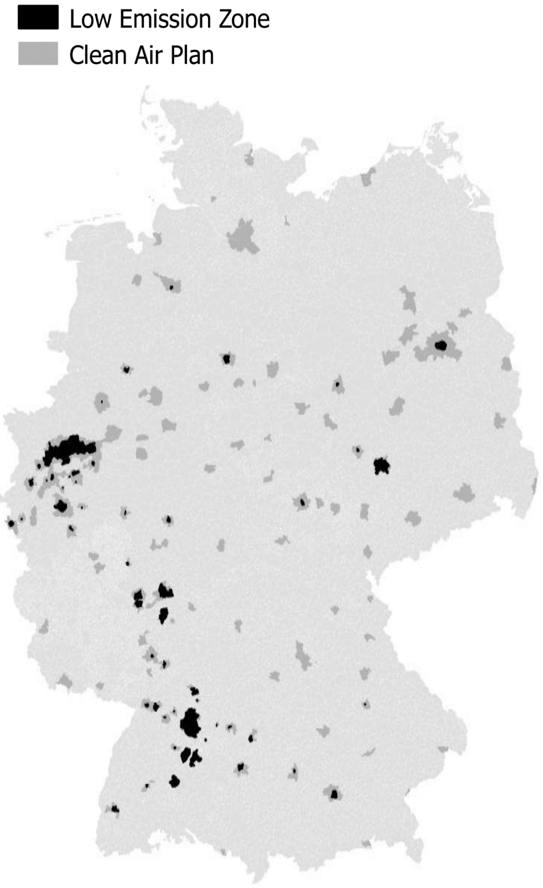
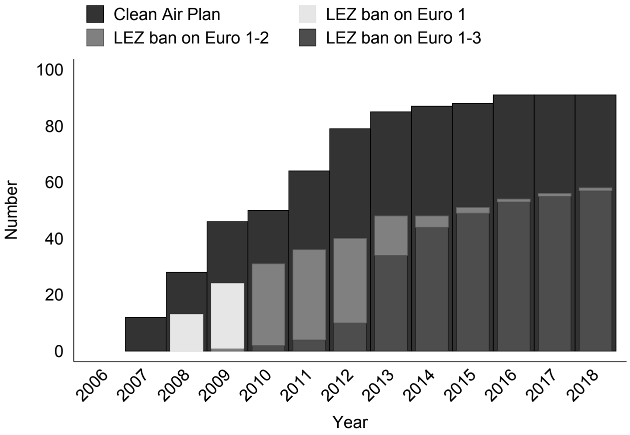
[9] See Table A.3 for an overview. In 2018, the penalty for violation is 80 Euros. The LEZ policies are enforced by the police and by local public order authorities. Two-wheeled vehicles, vintage cars, police, fire brigade and emergency vehicles and farm machinery are exempt from the scheme.

[10] Since the UBA does not provide digitized maps of German LEZs, we use open source polygons of LEZs in German cities from OpenStreetMap.org, which has been shown to be comparable to Google Maps or Bing Maps in terms of accuracy (Cipeluch et al., 2010) and does not deviate much from official land surveying (Haklay, 2010). Figure A.2 shows the high congruency between official documentation from the UBA (Figure A.2a) and open source polygons from OpenStreetMap (Figure A.2b) for the example of the largest German LEZ in the Ruhr area.



(a) Spatial distribution as of 2018



(b) Evolution over time

Figure 1: Clean Air Plans and Low Emission Zones in Germany

Notes: Panel (a) displays the spatial distribution of Clean Air Plans (Grey) and Low Emission Zones (Black) in Germany in 2018. Panel (b) shows the development of CAPs and LEZs and their different phases over time.

2.2 Air pollution: Risks to human health and measurement

The purpose of low emission zones is to improve air quality in urban areas by reducing the emission of harmful air pollutants from traffic. This may be achieved by reducing traffic volume, by decreasing the vehicle fleet's share of high-emission cars or a combination of both.[11] The main target air pollutants emitted from traffic are particulate matter (PM) and nitrogen dioxide (NO2).[12] In the following, we explain how these air pollutants are generated and how they may affect human health.

Particulate matter (PM) measures the concentration of small airborne particles including dust, dirt, soot, smoke and liquid droplets which are emitted to ambient air from a variety of sources. Natural sources are bush fires, dust storms, pollens and sea spray while anthropogenic sources include motor vehicle emissions and industrial processes. Small particulates may enter the lungs, the smallest particles may even enter the blood stream and overcome the blood-brain barrier causing inflammation. We focus on PM10, i.e., the concentration of particles that are smaller than 10 μm in diameter, which has been comprehensively measured since 2000 in Germany.[13] Particulate matter is linked to a number of respiratory and cardiovascular diseases, among others ischemic heart diseases (which may lead to heart attacks), cerebrovascular diseases (e.g. strokes), chronic and acute lower respiratory diseases as well as low birth weight among newborns (Kampa and Castanas, 2008; Block and Calderon-Garciduenas, 2009).[14]

Nitrogen dioxide (NO2) results from burning fossil fuels like coal, oil and gas. In cities, the major source of nitrogen dioxide is motor vehicle exhaust (up to 80 percent, see Environmental Protection Agency, 2016). Nitrogen dioxide contributes to the formation of photochemical smog, which can have significant impacts on human health (Vitousek et al., 1997). Nitrogen oxides are often linked to nose and throat irritation, and increase sensitivity to respiratory infections (Kampa and Castanas, 2008). Exposure to elevated NO2 concentration in ambient air especially causes respiratory problems by inflaming the lining of the lungs.[15] Based on a systematic literature review Schneider et al. (2018) identified possible NO2 cause-specific hospital admissions: cardiovascular and respiratory morbidity, hypertension, heart failure, ischemic heart diseases and low birth weight.

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[11] Wolff (2014) shows that LEZ introductions in German cities encouraged a shift to a less emitting car stock. Additionally, Figure A.3 shows that in Germany the vehicle fleet has become substantially cleaner in terms of average PM10 and NO2 emissions since the mid-1990s. In particular, average emissions of trucks decreased by more than 80%. NO2 emissions of cars decreased since 2007 but remained rather constant while PM10 emissions further decreased.

[12] 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.

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

[14] 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).

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

Data on air pollution comes from the air pollution monitoring system of the German Federal Environment Agency (*Umweltbundesamt, UBA*) to show how the introduction of LEZs affected air pollution levels in cities. We use data on all geo-coded monitors measuring the concentration of particulate matter (PM10) and 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 4,229 and 4,583 monitor-by-year observations for PM10 and NO2 respectively. Panel A of Table **??** shows 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 29 $\mu g/m^3$ 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 23 percent of observations exceed the annual mean NO2 limit of 40 $\mu g/m^3$.[16]

Combined with the data on LEZs, we are able to assign whether a monitor is located inside or outside of an LEZ area and, if outside, to compute the distance to the closest LEZ boundary.[17] Panel B of Table **??** shows 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 an LEZ banning at least Euro 1 vehicles (red sticker) is 14 percent, the share is 9–10 percent for LEZs banning at least Euro 1–2 (yellow sticker) and 7–8 percent for LEZs banning Euro 1–3 (green sticker).

Further control variables for the sample of pollution monitors are shown in Panels C and D of Table **??**. Since weather conditions are important environmental confounders we further supplement our dataset with a rich set of weather controls. The data are provided by the German Meteorological Service (*Deutscher Wetterdienst*) and contain information on temperature, precipitation and wind speed. We retrieve the yearly averages at the closest weather station for each pollution monitor to control for confounding effects.[18] Finally, we control for a number of population characteristics at the level of the municipality of the pollution monitor location.

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[16] Figure A.4 shows how pollution levels and violations evolved over time.

[17] Figure A.5a shows that the location of pollution monitors across Germany largely reflects more densely populated urban areas, which are also typically covered by clean air plans and low emission zones (see Figure 1a).

[18] Different than pollution monitors weather stations are rather equally distributed across the country (see Figure A.5c).

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

	Mean	SD	Min	Max	N
A. Pollution outcomes					
Yearly mean PM10 ($\mu g/m^3$)	21.94	5.68	7.00	55.00	4229
Yearly days PM10 > 50 $\mu g/m^3$	15.41	14.18	0.00	175.00	4229
Yearly mean PM10 > 40 $\mu g/m^3$	0.00	0.06	0	1	4229
Daily PM10 > 50 $\mu g/m^3$	0.08	0.28	0	1	4229
B. Treatment characteristics					
In active Clean Air Plan	0.54	0.49	0	1	4229
In LEZ ban on Euro 1	0.14	0.33	0	1	4229
In LEZ ban on Euro 1-2	0.09	0.28	0	1	4229
In LEZ ban on Euro 1-3	0.07	0.25	0	1	4229
C. Weather characteristics					
Mean temperature (° C)	9.70	1.44	2.75	12.78	4229
Mean precipitation (mm/m^2)	2.05	0.61	0.54	5.82	4229
Mean Wind speed (m/ss)	3.46	0.98	1.66	11.19	4229
D. Municipality characteristics					
Inhabitants/1000	151.06	453.30	0.04	3574.83	4229
Employed/1000	65.76	182.65	0.00	1367.68	4229
Share male < 30 years	0.32	0.03	0.23	0.41	4229
Share male 30 - 64 years	0.50	0.02	0.43	0.55	4229
Share male > 64 years	0.18	0.02	0.13	0.27	4229
Share female < 30 years	0.29	0.03	0.20	0.39	4229
Share female 30 - 64 years	0.47	0.02	0.41	0.52	4229
Share female > 64 years	0.24	0.03	0.17	0.34	4229

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

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

	Mean	SD	Min	Max	N
A. Pollution outcomes					
Yearly mean NO2 ($\mu g/m^3$)	28.85	16.45	1.80	121.35	4583
Yearly hours NO2 > 200 $\mu g/m^3$	2.07	24.76	0.00	853.00	4354
Yearly mean NO2 > 40 $\mu g/m^3$	0.23	0.42	0	1	4583
Hourly NO2 > 200 $\mu g/m^3$	0.02	0.13	0	1	4354
B. Treatment characteristics					
In active Clean Air Plan	0.55	0.49	0	1	4583
In LEZ ban on Euro 1	0.14	0.34	0	1	4583
In LEZ ban on Euro 1-2	0.10	0.29	0	1	4583
In LEZ ban on Euro 1-3	0.08	0.26	0	1	4583
C. Weather characteristics					
Mean temperature (° C)	9.65	1.47	1.60	12.78	4583
Mean precipitation (mm/m^2)	2.06	0.63	0.54	7.52	4583
Mean Wind speed (m/ss)	3.49	1.06	1.18	11.25	4583
D. Municipality characteristics					
Inhabitants/1000	152.96	465.35	0.04	3574.83	4583
Employed/1000	66.78	186.72	0.00	1367.68	4583
Share male < 30 years	0.32	0.03	0.23	0.41	4583
Share male 30 - 64 years	0.50	0.02	0.43	0.55	4583
Share male > 64 years	0.18	0.02	0.13	0.27	4583
Share female < 30 years	0.29	0.03	0.20	0.39	4583
Share female 30 - 64 years	0.47	0.02	0.41	0.52	4583
Share female > 64 years	0.24	0.03	0.17	0.34	4583

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

2.3 Diagnoses from the universe of German hospitals

For our analysis of health effects from low emission zones we use a panel dataset of the universe of hospitals in Germany reporting the annual number of detailed diagnoses for inpatient cases.[19] German hospitals are obliged by law to publish structured quality reports (QR) since 2006, bi-annually until 2012 and annually from 2012 onwards. The structure and content of these reports are specified legally and misreporting leads to financial penalties. These reports provide information on structure and performance of a hospital at the hospital department level. The quality reporting was implemented to demonstrate hospitals' performance in a transparent manner to enable a well-informed choice of hospitals by patients and to guide and support referring physicians as well as sickness funds.

Hospital quality report data comprise hospital characteristics like number of beds and ownership structure but also yearly number of inpatient cases and diagnoses based on the full International Statistical Classification of Diseases and Related Health Problems (ICD-10). Given that the data's intention is to increase transparency, every hospital is non-anonymously identified, allowing us to assign the treatment of coverage by an LEZ at the exact address location.[20] The full QR dataset includes more than 2,000 hospitals over the period from 2006 to 2016 (see Figure B.1). We exclude hospitals that do not meet the criteria of hospitals of primary care in Germany (*Krankenhäuser der Regelversorgung*), i.e., having a unit for surgery and internal medicine (Ethikrat, 2016). Hence, we focus on **general hospitals** and exclude specialized hospitals like hospices, wellness clinics, rehabilitation centers, sanatoriums etc., resulting in a sample of around 1,100 hospitals per year and 8,837 hospital-year observations. This reduces measurement error because the excluded hospitals perform an over-proportional amount of planned treatments where spatial proximity is less crucial and often do not treat air pollution related diseases (Klauber et al., 2015).[21]

Panel A of Table 3 shows substantial variation in the characteristics of general hospitals. The mean number of beds ranges from only four to 6,885, revealing that the definition of a hospital is independent of its size but rather a legal concept based on permanent availability and equipment. Inpatients per year range from 77 to 198,452 with a mean of 15,667. Non-profit and public general hospitals account for 43 and 40 percent in our dataset. About 17 percent of the general hospitals in our dataset are private. However, private general hospitals in Germany are obliged to provide the same health services to the same conditions as non-private.[22]

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[19] 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 (if at all). Inpatient cases are even more severe because hospitals are obliged to justify that an outpatient treatment is not sufficient. Otherwise, they jeopardize the full reimbursement by health insurances However, hospital discharge rates in Germany are relatively high, also due to the fact that Germany is among the countries with the highest hospital density (Kumar and Schoenstein, 2013).

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

[21] We will use the specialized hospitals for robustness checks.

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

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

Hospital catchment areas are assigned based on hospitals' locations since, unlike other data sources, the QR data do not provide information on the residence of patients. There is a free choice of hospitals in Germany. However, there is a strong correlation between hospital location and patients' residences (Friedrich and Beivers, 2008). Individuals do prefer hospitals close to their residential address (Klauber et al., 2015). Furthermore, resident doctors are legally obliged to send patients to one of the two closest hospitals based on the residence of the patient. Knowing the location of the hospital is even more advantageous when analyzing more severe emergency cases where admission is based on the patient's current position which is not necessarily equal to the place of residence (Klauber et al., 2008). In 2016, 45 percent of hospital admissions were emergency cases (Statistisches Bundesamt, 2017a).[23] According to the directive for ambulance transport (*Krankentransport-Richtlinie*), emergencies should be transported directly to the nearest hospital. For our main analysis, we use Voronoi tessellation to define hospital catchment areas. This means that for every hospital in our dataset, we create adjacent polygons around the hospital location corresponding to regions comprising all points that are closer to the hospital than to any other hospital in the surrounding. These regions are the catchment areas. Hence, each point on a border between two catchment areas based on Voronoi tessellation has the exact same distance to the two corresponding hospital locations.[24] Figures A.5b and B.2 shows the location of hospitals and their Voronoi catchment areas for across Germany and zoomed in for the Ruhr area in West Germany.

Hospitals' treatment by low emission zones is assigned by overlaying the LEZ areas with the hospital locations and catchment areas. Panel C of Table 3 shows that one third of hospital-year observations are located in a municipality with an active clean air plan and ten percent of the observations in LEZs that ban at least Euro 1 vehicles, seven percent banning at least Euro 1–2 and six percent banning Euro 1–3. Further, we calculate the proportion of a hospital catchment area that is covered by an active LEZ. At the extensive margin, 17 percent of all general hospital obser-

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entities (Wissenschaftliche Dienste, 2014).

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

[24] Voronoi tessellation is a well established technique to define hospital catchment areas (McLafferty, 2003) and has been validated for such approaches (Schuurman et al., 2006). Phibbs and Luft (1995) showed that the linear distance is a good proxy for driving time with a correlation above 0.95.

vations have a catchment area that is at least partly covered by an active LEZ. The overall share of catchment areas that is covered by LEZs is six percent. Furthermore, we calculate the share of the population in a catchment area based on Voronoi tessellation that is covered by an LEZ by supplementing our dataset with satellite population grids.[25] Based on an alternative approach, we define catchment areas by a seven kilometer radius around the hospital as robustness check (Figure B.4). The distance is based on the median distance between residence and hospital for emergency cases in 2006 (Klauber, 2006).

Figure B.7 reveals a constant increase of hospitals which are located in LEZs over time. Whereas in 2006 no hospital was located in an LEZ this share increased to 22 percent in 2016. Hospitals whose catchment areas overlap with LEZs account for almost 30 percent of all hospitals. Figure B.6 shows that hospitals become a more important supplier of health services in Germany by diagnosing more. This trend is true for hospitals in and outside LEZs, although a bit stronger for hospitals in LEZs due to migration into cities and a trend of urbanization of hospital supply (Klauber et al., 2015). At the same time, the number of beds in 2016 is comparable to the number of beds in 2006, revealing the increase in efficiency in hospital treatments.

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[25] We use the GEOSTAT 2006 which is a dataset of 1km $\times$ 1km population grid approximate by the building structure in each grid.

Table 3: Descriptive statistics of hospital characteristics

	Mean	(SD)	min	max	N
A. Hospital characteristics					
Non-profit	0.43	0.50	0	1	8837
Public	0.40	0.49	0	1	8837
Private	0.17	0.38	0	1	8837
Number of Beds	375.46	312.68	4	2917	8837
Baserate in €	2990.37	260.82	871	14238	8837
Inpatients	15666.47	14257.88	77	198452	8837
Catchment area in km^2	311.55	291.65	1	3130	8837
Population in catchment area	72396.60	39256.43	1120	345711	8837
B. Diagnoses					
All diseases (A00-N99)	10505.66	10253.39	32	155406	8837
Diseases of the ciculatory system (I00-I99)	2293.20	2577.95	0	55735	8837
Hypertenion (I10-I15)	258.67	398.79	0	18855	8837
Ischemic heart diseases (I20-I25)	564.75	867.15	0	17668	8837
Heart failure (I50)	353.17	324.35	0	7494	8837
Cerebrovascular disease (I60-I69)	277.27	420.81	0	6118	8837
Diseases of the respiratory system (J00-J99)	944.47	989.13	0	15512	8837
Chronic lower respiratory diseases (J40-J47)	203.79	221.62	0	3812	8837
Acute lower respiratory diseases (J20-J22)	103.80	122.80	0	1392	8837
Low birth Weight (P07) [t+1]	46.04	104.87	0	1840	7516
Stress (F40-F48)	74.66	141.61	0	2614	8837
Injuries (S00-S99)	1184.86	1118.89	0	19174	8837
C. Treatment characteristics					
In active clean Air Plan	0.33	0.47	0.00	1.00	8837
In LEZ ban on Euro 1	0.10	0.30	0.00	1.00	8837
In LEZ ban on Euro 1-2	0.07	0.26	0.00	1.00	8837
In LEZ ban on Euro 1-3	0.06	0.23	0.00	1.00	8837
Catchment areas covered by LEZ (voronoi)	0.17	0.38	0.00	1.00	8837
Overall share of catchment area covered by LEZ (voronoi)	0.06	0.20	0.00	1.00	8837
Overall share of population covered by LEZ (voronoi)	0.07	0.22	0.00	1.00	8837
Catchment areas covered by LEZ (buffer)	0.20	0.40	0.00	1.00	8837
Overall share of catchment area covered by LEZ (buffer)	0.06	0.17	0.00	1.00	8837
D. Weather characteristics					
Mean temperature in ° C	9.63	1.43	-5.27	12.64	8837
Mean precipitation in mm/m^2	2.05	0.58	0.80	5.89	8837
Mean Wind speed (m/ss)	3.41	0.98	1.18	11.19	8837
E. Municipality characteristics					
Inhabitants/1000	263.21	633.71	0.40	3574.83	8837
Employed/1000	113.79	249.25	0.00	1367.68	8837
Share male < 30 years	0.32	0.03	0.23	0.41	8837
Share male 30 - 64 years	0.50	0.02	0.43	0.55	8837
Share male > 64 years	0.18	0.02	0.13	0.27	8837
Share female < 30 years	0.29	0.03	0.20	0.39	8837
Share female 30 - 64 years	0.47	0.02	0.41	0.53	8837
Share female > 64 years	0.23	0.03	0.16	0.34	8837

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

3 Empirical Analysis

3.1 Regression Model

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

$$y_{ict} = \alpha + \beta \; LEZ_{it} + \boldsymbol{X'_{ict}}\gamma + \delta_i + \delta_t + \varepsilon_{ict}, \tag{1}$$

where y_{ict} indicates the outcome – a measure of air pollution or the number of diagnoses – in year t measured at observation unit i – a pollution monitor or a hospital – located in city c. The main variable of interest is LEZ_{it} and captures the treatment of unit i in year t by an LEZ, which differs depending on the sample. For the sample of air pollution monitors, LEZ_{it} is simply a binary indicator with a value of one for monitor i being located within the boundaries of an active LEZ at any strictness level in year t and zero otherwise.[26] For the sample of hospitals, we equate LEZ_{it} with the share of hospital i's catchment area covered by an LEZ, ranging between zero and one.

The vector $\boldsymbol{X_{ict}}$ controls for a number of time-varying characteristics at the level of monitors and hospitals as well as for city population characteristics. In both samples, we include the set of weather controls measured at the closest weather monitor to the pollution monitor or hospital respectively. Further, we include population size, employment as well as the city population's composition by age groups and gender (see Tables 1–3 for details). For the sample of hospitals, we further control for time-varying hospital characteristics, the number of hospital beds, ownership and the baserate.[27] Finally, unit fixed effects δ_i capture any time-invariant monitor or hospital characteristics while year fixed effects δ_t control for any time-specific effects that are uniform across all observation units. To capture urbanization processes we also include city-specific linear time trends. The error term ε_{ict} is clustered at the county level.[28]

In order to capture dynamic effects of LEZ introductions, we conduct event studies where we test whether LEZ 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 an LEZ should not have any impact in pre-treatment periods. The extended model is:

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[26] In the Appendix, we show that the reductions in pollution are rather similar across LEZ strictness levels and also vary the treatment by taking into account that pollution monitors just outside but in close proximity to an LEZ may also be partially treated by the policy. Further, most LEZs were introduced on January 1. If not, we multiply LEZ_{it} by 0.5 if the LEZ was established not later than June 30 in the introduction year t and set LEZ_{it} to zero if the LEZ was introduced later than June 30.

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

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

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

where the dummy variables LEZ_{ik} indicate yearly leads and lags of up to four years before and five years after the enactment of an LEZ. The reference category is $k = -1$, hence the post treatment effects are relative to the year immediately before the policy change and are interpreted as the effect of LEZs k periods before or after their introduction. We use the same controls as before.[29]

3.2 The impact of LEZs on air quality

In a first step, we document how the implementation of LEZs affects local air pollution by regulating the entry of vehicles based on their emission exhaust.[30] Table 4 shows the main results for the effect of introducing an LEZ on annual average levels, limit exceedances and violations for PM10 and NO2. Each entry represents an estimate for β according to equation (1) from a separate regression of the respective outcome on the LEZ indicator, i.e., for a monitor being located within the boundaries of an active LEZ.

The results in Panel A of Table 4 show a negative impact on pollution levels for both PM10 and NO2 concentrations in all three specifications where we start with a fixed effect regression and gradually add time-variant control variables. Controlling for weather characteristics does not change the estimates. By adding additional controls for municipality characteristics effect sizes for most coefficients slightly decrease in absolute terms by capturing different changes in demographic compositions between areas. This is why we prefer the specification in columns (3) and (6) in the following analysis. The introduction of a ban of at least Euro 1 emission classes decreases PM10 by 1.4 $\mu g/m^3$ or six percent of the mean. The average NO2 levels are reduced by 1.5 $\mu g/m^3$ or five percent of the mean. Both effects are statistically significant at the one percent level.

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

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

[30] In Appendix **??** we provide some evidence that low emission zones reduced traffic volume within the boundaries of the zones but did not significantly affect traffic volumes in close proximity based on traffic monitor data. However, most traffic monitors are located outside of low emission zones.

standard violations. Introducing LEZs effectively reduces the incidence of short-time spikes in PM10 pollution and at the same time reduces the longer-term annual mean concentration of NO2.

These findings are based on the straightforward specifications of equation (1), where we exploit the treatment of any low emission zone irrespective of the strictness levels in terms of the emission exhaust classification.[31] While LEZ introductions typically begin with banning the dirtiest Euro 1 vehicles from entering the inner-city areas, essentially all LEZs by now ban Euro 1–3 vehicles. In Table A.5 we show results for interacting the LEZ treatment with different strictness levels, i.e., banning Euro 2 and Euro 3 additionally. It turns out that all strictness levels contribute to the average effects for most pollution outcomes shown in Table 4. These results also reflect the general improvement of emissions from vehicles and an upgrade of the vehicle fleet towards lower emission cars in cities with LEZs (Wolff, 2014) since more restrictive LEZs have been implemented later in time (see Figures 1b and A.3). The spatial precision of our dataset allows us to analyze the effect of an LEZ on pollution in its surroundings. Table A.6 shows that air quality in close proximity to an LEZ (within a radius of 10 km) is not affected while do some smaller increases for pollution monitors located at a distance of 10–20 km from an LEZ, which may be due to some traffic shifting.

In Figure 2 we present results for the event study specification of equation 2. Focusing on those pollution outcomes with statistically significant effects as shown in table 4, we use the presence of an active LEZ at the location of a pollution monitor as treatment independent of its strictness with the reference period $k = -1$, the year before an LEZ became effective. The event study results do not reveal any pre-trends that could bias our results. Corresponding to the difference-in-differences estimates, we find that air pollution levels as well as the incidence of violating regulatory thresholds for air quality are significantly reduced right after after the introduction of a low emission zone. With the exception of the yearly mean of NO2 being above 40 $\mu g/m^3$ the effects become stronger over time. This could be due to the fact that since 2012 the majority of the car fleet in Germany reached at least the Euro 4 emission class for the first time, qualifying cars for a green sticker (Kraftfahrt-Bundesamt, 2018). This is why we additionally analyze effects of LEZ introductions before and after 2012 separately, expecting smaller effect sizes since 2012. Indeed, the results in Figure 2 show that LEZs became less effective over time because most coefficients' magnitude and statistical significance is lower for LEZs introduced since 2012. This means that improvements in the emission standards of vehicles and stricter LEZ levels tend to balance out.

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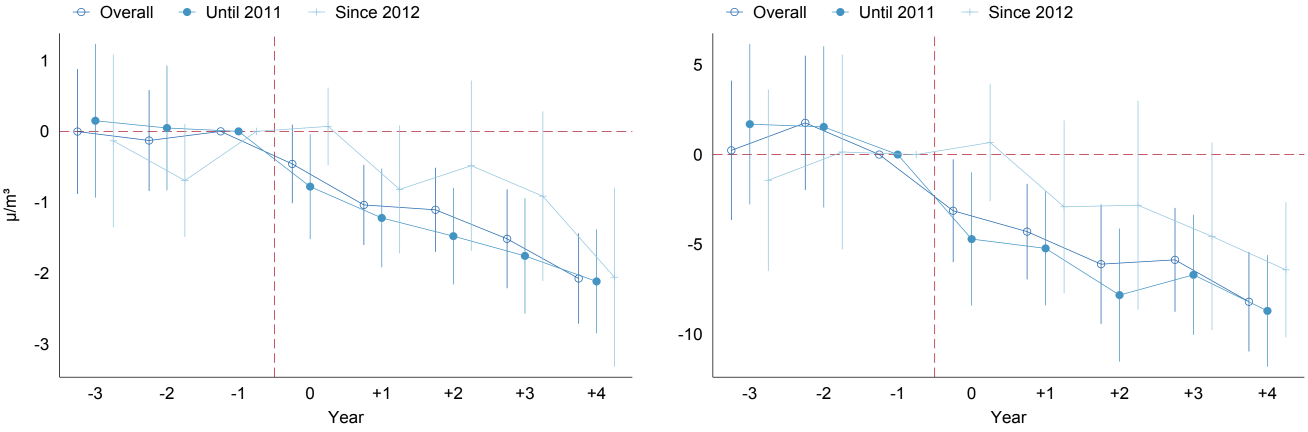
[31] In Table A.4 we present results on the effects of introducing a Clean Air Plan, typically preceding low emission zones by a few years, interacted with the introduction of an LEZ. We find that CAPs indeed have a negative effect on air pollution but that this is mainly driven by LEZ introductions. However, we refrain from putting too much emphasis on these findings since CAPs are very heterogeneous measures with unclear spatial extent.

Table 4: The effect of low emission zones on air pollution

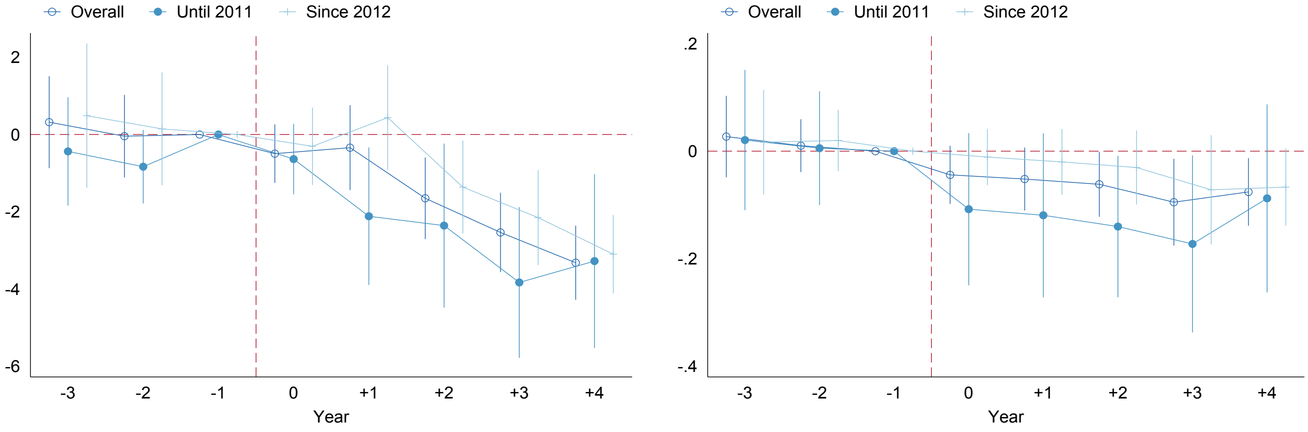
	PM10			NO2		
	(1)	(2)	(3)	(4)	(5)	(6)
A. Pollution levels (yearly mean)						
In LEZ	-1.459***	-1.459***	-1.400***	-1.712***	-1.713***	-1.526***
	(0.229)	(0.229)	(0.238)	(0.417)	(0.417)	(0.393)
Adj. R^2	0.91	0.91	0.91	0.97	0.97	0.98
N	4229	4229	4229	4583	4583	4583
B. Limit exceedances (days or hours above threshold)						
In LEZ	-7.669***	-7.677***	-7.574***	-6.473	-6.496	-5.446
	(1.166)	(1.167)	(1.169)	(5.195)	(5.220)	(4.553)
Adj. R^2	0.76	0.76	0.77	0.48	0.48	0.49
N	4229	4229	4229	4346	4346	4346
C. Violations (yearly mean above threshold)						
In LEZ	-0.002	-0.002	-0.000	-0.065***	-0.065***	-0.057**
	(0.008)	(0.008)	(0.007)	(0.023)	(0.023)	(0.022)
Adj. R^2	0.17	0.17	0.18	0.87	0.87	0.87
N	4229	4229	4229	4583	4583	4583
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	No	Yes	Yes	No	Yes	Yes
Municipality characteristics	No	No	Yes	No	No	Yes

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



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

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



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

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

Figure 2: Event study for pollutants

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

3.3 Health effects of LEZs

The results presented so far have shown that the introduction of a low emission zone in an inner-city area significantly reduces air pollution and violations of EU air quality standards mainly inside the LEZ areas. These results are driven by earlier adoptions of LEZ policies and effect sizes become weaker and mostly insignificant for LEZs introduced 2012 or later when the vehicle fleet had already been substantially improved on emission exhaust such that even stricter LEZs banning vehicles with emission standards Euro 1–3 were less effective. 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 LEZs effectively reduce air pollution, we will now turn to the question whether improvements in air quality induced by low emission zones translate into improvements for human health.

In this section, we present the estimation results for the impact of LEZs on the number of diagnoses per hospital (in logs) as a proxy for general health. Given that the introduction of LEZs 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 an LEZ introduction on hospital diagnoses. Therefore, results should be interpreted as reduced-form effects. A higher share of a hospital's catchment area covered by an LEZ lowers potential exposure to air pollution of people living or working in the catchment area. In addition, β captures the direct physiological impact of air pollution on the human body but may also be partly driven by reductions in traffic noise as well as behavioral responses to air pollution, such as changes in exercise habits or internal migration.

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

We begin with a bivariate fixed effect regression and gradually add control variables. Including hospital fixed effects is particularly important because observable characteristics vary considerably between areas with and without LEZs since low emission zones are primarily located in densely populated urban areas. By using fixed effects we control for time-invariant structural differences. In addition, we control for a number of time-variant hospital and municipality characteristics and eventually include linear municipality-specific time trends to capture the effects of changing population characteristics over time.[32]

Almost all point estimates in columns (1) to (5) of Table 5 are negative irrespective of additional control variables, indicating that the introduction of an LEZ potentially has a beneficial impact on

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[32] Table C.3 shows that hospital pre-treatment characteristics differ in almost every aspect between hospitals that are eventually treated by an LEZ and those never affected by an LEZ. According to column (4), ever LEZ hospitals are larger (more beds, patients and diagnoses). Columns (5) and (6) show that these differences increase over time.

population health. After including hospital controls in column (2), in particular hospital capacity proxied by the number of beds, most point estimates become larger in absolute terms. This is not surprising, given that hospitals treated by an LEZ tend to be located in growing urbanized areas, which increases the number of diagnoses simply because the number of potential patients in the area increases. In columns (3) and (4), once we control for weather and municipality characteristics, coefficient estimates are only slightly affected. Controlling for linear municipality-specific time trends in column (5), capturing differential effects from urbanization, yields strong negative and statistically significant estimates for most of the diagnoses.

Based on the results in column (5), an increase in hospital's catchment area covered by an LEZ by one standard deviation (corresponding to 30 percentage points, see Table 3) reduces the total number of diagnosed diseases by about two percent, the estimate being statistically significant at the 0.1 level. Focusing on diagnoses that are closely related to air pollution, we find an effect for diseases of the circulatory system by five percent, or 115 cases at the mean. Among this broad category of diseases, the corresponding effects are between 4.6 and 7.5 percent. The point estimates suggest that a LEZ has the largest impact on circulatory diseases like ischemic heart diseases and cerebrovascular diseases, implying a reduction of diagnoses between 44 and 21 cases per year at the respective means. We do not find statistically significant effects for the aggregate category of respiratory diseases in general. However, chronic diseases of the lower respiratory system are significantly reduced by more than five percent (or 11 cases at the mean) for a one standard deviation increase in the LEZ coverage of a hospital's catchment area while there is no significant impact on acute lower respiratory diseases.[33] Furthermore, we do observe an impact on low birth weight. A standard deviation increase in the share of a catchment area covered by an LEZ decreases low birth rates by six percent, or three cases of the mean.[34]

In Figure 2 we present the results for the log number of respiratory and circulatory diagnoses in an event study framework. The findings for circulatory diseases in Panel (a) indicate that the effects started to appear already in the first year after the introduction and tend to increase over time, in line with the decrease in pollutants after the introduction of LEZs. Additionally, and in line with the results for pollution we find that reductions in circulatory diagnoses are essentially entirely driven by the period before 2012. Panel (b) shows the event study for respiratory diseases. In the immediate year after the introduction respiratory diseases decrease. However, this effect is not sustainable.[35]

Since we found some slight increases in air pollution in a radius of 10–20 km around LEZs, we analyze the effect of active LEZs on hospitals in their surroundings by defining the share of hospital catchment areas that is covered by a 20 km buffer zone around active LEZs (see Figure B.3) and exclude hospitals with catchment areas covered by LEZs. In Table 6 we focus on the same diagnoses and use the same specification as in Table 5. We do not find any effects on health once

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

[34] We do not observe an effect on stress related diagnoses or injuries, thus not indicating additional health channels but air pollution (Table C.1).

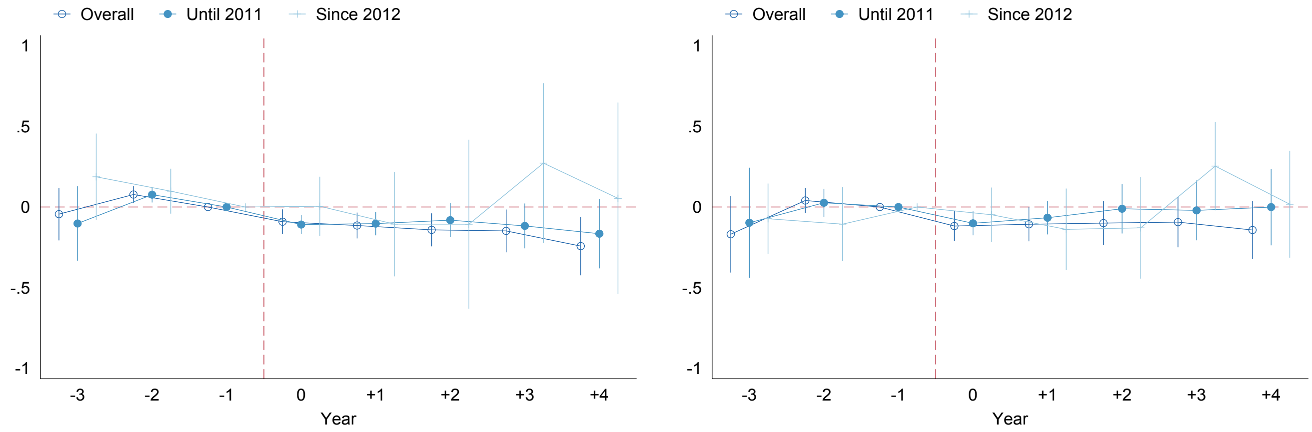
[35] We show event studies for every diagnose in the appendix (see Figure C.1).

we control for linear time trends. Controlling for linear time trends work in the opposite direction as in Table 5. This is a simple mechanical effect. If linear time trends capture urbanization tendencies it captures an increase in diagnoses in urban but a decrease in diagnoses in sub-urban areas.

Table 5: The effect of LEZs on diagnoses in general hospitals

	(1)	(2)	(3)	(4)	(5)
All diseases (A00-N99)	-0.029	-0.028	-0.028	-0.028	-0.065*
	(0.033)	(0.032)	(0.032)	(0.035)	(0.037)
Diseases of the ciculatory system (I00-I99)	-0.098*	-0.106**	-0.107**	-0.103**	-0.156***
	(0.052)	(0.048)	(0.048)	(0.051)	(0.046)
Hypertension (I10-I15)	-0.107	-0.089	-0.088	-0.095	-0.154**
	(0.072)	(0.072)	(0.072)	(0.073)	(0.073)
Ischemic heart diseases (I20-I25)	-0.117	-0.119	-0.120	-0.159*	-0.251***
	(0.076)	(0.075)	(0.074)	(0.082)	(0.075)
Heart failure (I50)	-0.133**	-0.159***	-0.159***	-0.137**	-0.174***
	(0.064)	(0.060)	(0.060)	(0.062)	(0.060)
Cerebrovascular disease (I60-I69)	-0.170*	-0.242***	-0.241***	-0.252***	-0.248***
	(0.090)	(0.084)	(0.084)	(0.082)	(0.079)
Diseases of the respiratory system (J00-J99)	0.018	0.009	0.010	-0.001	-0.074
	(0.054)	(0.050)	(0.050)	(0.052)	(0.065)
Acute lower respiratory diseases (J20-J22)	0.043	0.057	0.058	0.053	-0.122
	(0.093)	(0.097)	(0.096)	(0.091)	(0.091)
Chronic lower respiratory diseases (J40-J47)	-0.115*	-0.129**	-0.130**	-0.130*	-0.176**
	(0.064)	(0.065)	(0.065)	(0.067)	(0.076)
Low birth weight (P07) [t+1]	-0.026	-0.068	-0.068	-0.051	-0.173**
	(0.082)	(0.075)	(0.076)	(0.080)	(0.086)
N	8837	8837	8837	8837	8837
Controls:					
Hospital FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	No	Yes	Yes	Yes	Yes
Weather characteristics	No	No	Yes	Yes	Yes
Municipality characteristics	No	No	No	Yes	Yes
Linear municipality time trends	No	No	No	No	Yes

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



(a) Circulatory diseases

(b) Respiratory diseases

Figure 3: Event study for selected diagnoses

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

Unfortunately, the hospital quality report data do not offer detailed information on patients, making it hard to estimate heterogeneous effects by population. Instead of looking at diagnoses by subgroups, we calculate the share of top ten diagnoses for women and for people above age 65 for each hospital in 2006 which we use as a proxy for a high share of female and old patients and interact it with the share of the catchment area covered by an active LEZ. Table 7 shows the results for these estimates for three strongly affected diagnoses: ischeamic, cerebrovascular and low birth weight. LEZs do have stronger effects on low birth weight for hospitals with a high share of female patients. We do not find further significant interaction effects.

Table 6: The effect of LEZs on diagnoses in 20 km proximity around general hospitals

	(1)	(2)	(3)	(4)	(5)
All diseases (A00-N99)	-0.063	-0.065*	-0.065*	-0.065	0.002
	(0.039)	(0.034)	(0.035)	(0.040)	(0.039)
Diseases of the ciculatory system (I00-I99)	-0.114**	-0.118***	-0.119***	-0.110**	-0.011
	(0.050)	(0.045)	(0.045)	(0.051)	(0.060)
Hypertenion (I10-I15)	-0.076	-0.079	-0.081	-0.067	0.033
	(0.079)	(0.072)	(0.072)	(0.075)	(0.084)
Ischemic heart diseases (I20-I25)	-0.076	-0.085	-0.086	-0.082	0.077
	(0.088)	(0.081)	(0.082)	(0.083)	(0.091)
Heart failure (I50)	-0.116*	-0.125**	-0.127**	-0.109*	-0.025
	(0.067)	(0.059)	(0.059)	(0.064)	(0.079)
Cerebrovascular disease (I60-I69)	-0.109	-0.122*	-0.123*	-0.099	0.035
	(0.074)	(0.071)	(0.071)	(0.076)	(0.088)
Diseases of the respiratory system (J00-J99)	-0.058	-0.064	-0.065	-0.064	-0.023
	(0.051)	(0.050)	(0.050)	(0.050)	(0.056)
Chronic lower respiratory diseases (J40-J47)	-0.053	-0.063	-0.062	-0.060	0.004
	(0.076)	(0.068)	(0.068)	(0.072)	(0.085)
Acute lower respiratory diseases (J20-J22)	-0.098	-0.104	-0.104	-0.123*	-0.104
	(0.077)	(0.072)	(0.072)	(0.073)	(0.098)
Low birth weight (P07)	-0.076	-0.076	-0.076	-0.051	0.013
	(0.076)	(0.075)	(0.075)	(0.083)	(0.099)
N	8837	8837	8837	8837	8837
Controls:					
Hospital FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	No	Yes	Yes	Yes	Yes
Weather characteristics	No	No	Yes	Yes	Yes
Municipality characteristics	No	No	No	Yes	Yes
Linear municipality time trends	No	No	No	No	Yes

Notes: This table displays the results on diagnoses for general hospitals in 20 km proximity of LEZs. The catchment area is calculated by voronoi tessellation. Treatment is calculated by catchment areas covered by a 20 km zone around LEZs. Each coefficient is the result of a separate regression of diagnose listed on the left on a indicator variable for an active LEZ (share of catchment area covered by LEZ), while controlling weather the catchment area is covered by an active LEZ or not and an interaction term indicating coverage by an active LEZ and the share of catchment area in the 20 km proximity of an LEZ. Additional controlling for hospital and year fixed effects as well as hospital characteristics (non-profit, public, private, baserate, number of beds, number of beds^2*), hospital size (small, medium, large) × years, municipality characteristics (mean temperature, precipitation and wind speed, population, work force, age structure (share men(min-30, 31-64, 65-max), women(min-30, 31-64, 65-max)), linear time trends (Municipality × Years). Standard errors are clustered at county level and displayed in parentheses. Significance levels:* $*** : p < 0.01$, $** : p < 0.05$, $* : p < 0.1$. ^{1}) Based on 7516 observations.

Table 7: Heterogeneous effect of LEZs

	(Ischaemic)	(Cerebrovascular)	(Low birth weight)
Women			
Share of catchment area covered by LEZ	-0.202***	-0.086	-0.092
	(0.078)	(0.086)	(0.084)
Share of catchment area covered by LEZ × High share of female diagnoses	0.123	0.064	-0.277*
	(0.142)	(0.116)	(0.155)
Adj. R^2	0.87	0.87	0.90
N	8092	8092	6970
Old people			
Share of catchment area covered by LEZ	-0.118**	-0.026	-0.185*
	(0.058)	(0.070)	(0.106)
Share of catchment area covered by LEZ × High ahre of elderly diagnoses	-0.113	-0.106	-0.005
	(0.114)	(0.123)	(0.228)
Adj. R^2	0.87	1	1
N	8092	8092	6970
Controls:			
Hospital FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Hospital characteristics	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes
Linear municipality time trends	Yes	Yes	Yes

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

4 Conclusion

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

This is the first paper showing that the introduction of LEZs in Germany actually improved population health, whereas the circulatory system is stronger affected than the respiratory system. We also find reductions for low birth weight. These findings have strong implications for policy makers. First, in 2015, overall costs for health care in Germany were around 340 billion euros, of which 46 billion euros for diseases of the circulatory system, making it the most expensive type of disease caused by 2.9 million cases (Statistisches Bundesamt, 2017b). Hence, reductions in the incidence of diseases of the circulatory system may directly reduce society's health costs. Besides, improving population health has sizable indirect costs on human capital and growth (Graff Zivin and Neidell, 2013). Second, the results of this study are informative for policy debates about further regulation of emissions from traffic. While the introduction of LEZs 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 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. In fact, our results are mainly driven by earlier adoptions of LEZs before the vehicle fleet was updated to the Euro 4 standard. Whether further regulation of Euro 5–6 yields further health improvements should be addressed by future research.

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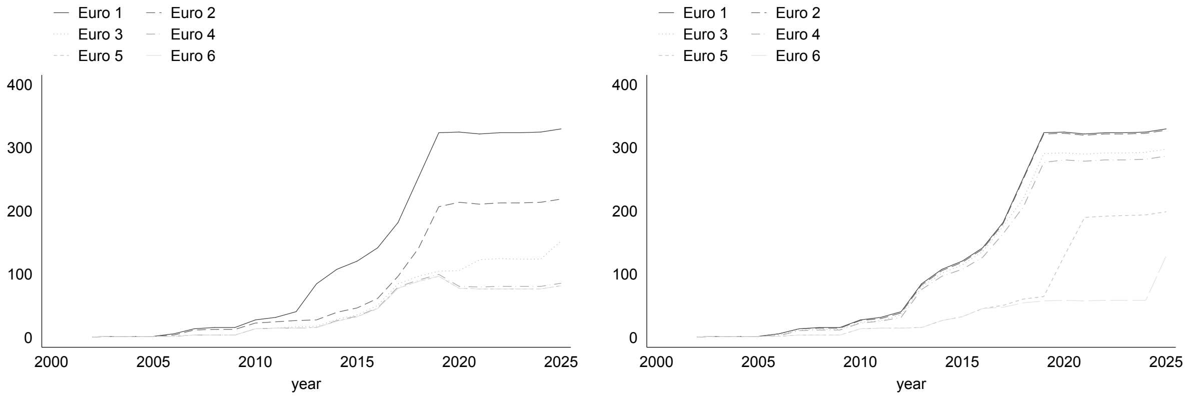
Appendices

A Low emission zones and air pollution in Germany



(a) Petrol (b) Diesel

Figure A.1: Low emission zones in Europe

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

Table A.1: Air pollution thresholds (EU Directive 1999/30/EC)

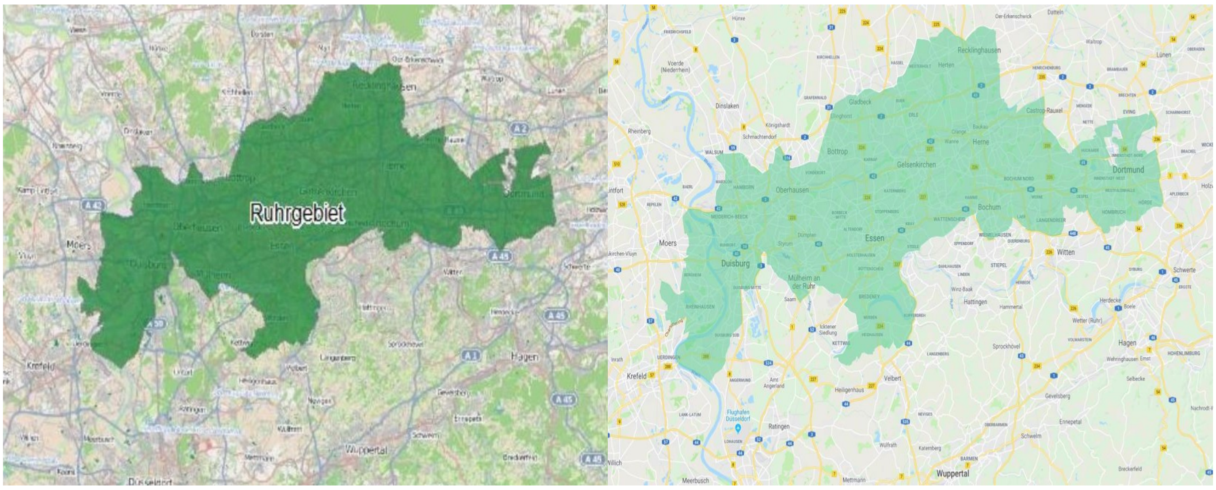
(Pollutant)	(Thresholds)	(Deadline)
PM10	Yearly average limit 40$\mu g/m^3$ Daily average limit 50$\mu g/m^3$ Allowed number of transgression: 35	1 January 2005
NO2	Yearly average limit 40$\mu g/m^3$ Hourly average limit 200$\mu g/m^3$ Allowed number of transgression: 18	1 January 2010

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

Table A.2: Vehicle emission standards

(Class)	(Sticker)	(Limits)
Euro 4	Green	Petrol: CO: 1.00g/km HC: 0.10g/km NOx: 0.08g/km
		Diesel: CO: 2.72g/km HC + NOx: 0.97g/km PM: 0.14g/km
Euro 3	Yellow	Petrol: CO: 2.30g/km HC: 0.20g/km NOx: 0.15g/km
		Diesel: CO: 0.64g/km HC: 0.56g/km NOx: 0.50g/km PM: 0.05g/km
Euro 2	Red	Petrol: CO: 2.20g/km HC + NOx: 0.50g/km
		Diesel: CO: 1.00g/km HC + NOx: 0.70g/km PM: 0.08g/km
Euro 1	None	Petrol: CO: 2.72g/km HC + NOx: 0.97g/km
		Diesel: CO: 2.72g/km HC + NOx: 0.97g/km PM: 0.14g/km

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



(a) Official map

(b) Own presentation

Figure A.2: Low emission zone of the Ruhr area

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

Table A.3: Low Emission Zones in Germany as of 2018

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

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

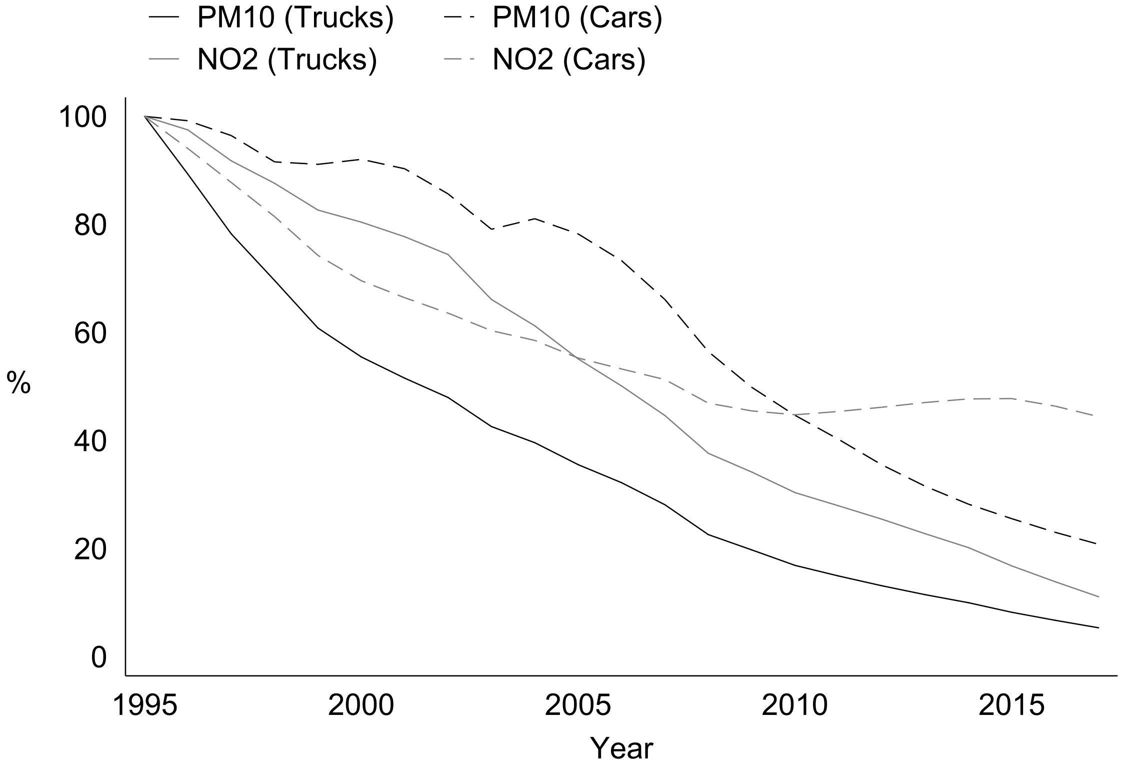
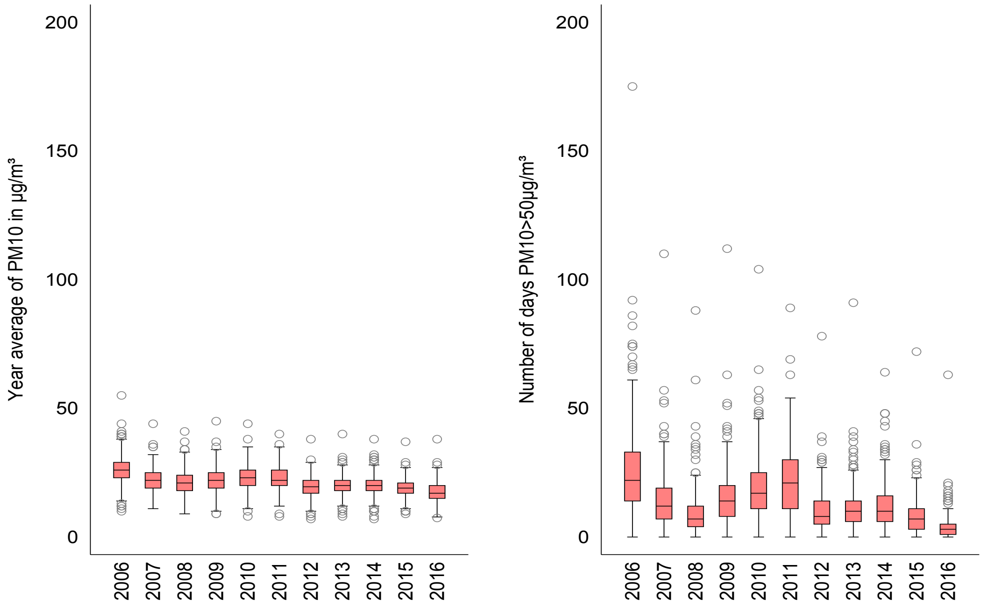
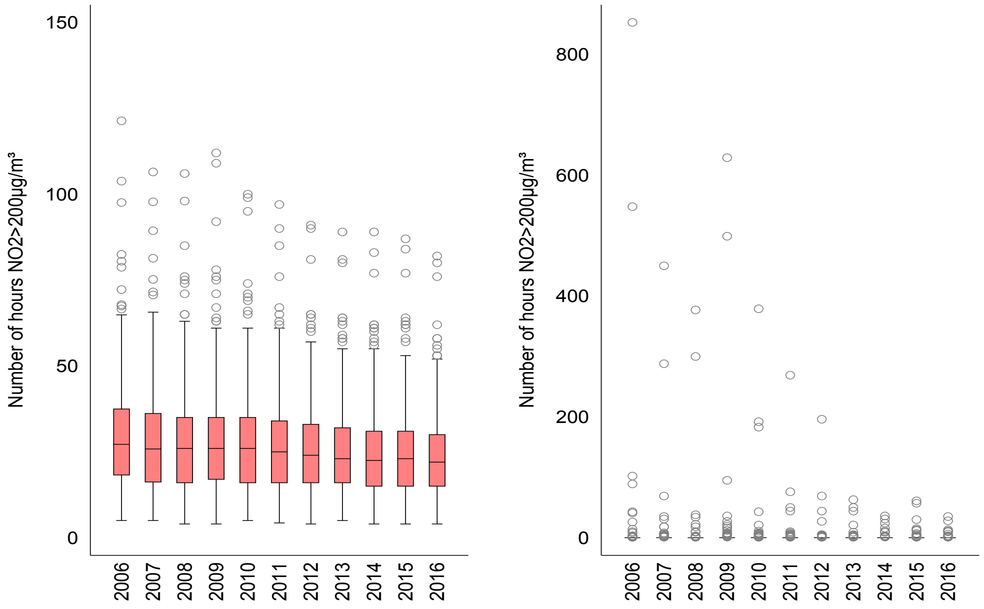


Figure A.3: Average emissions of vehicles

Notes: German Environment Agency (Umweltbundesamt)



(a) Average air pollution



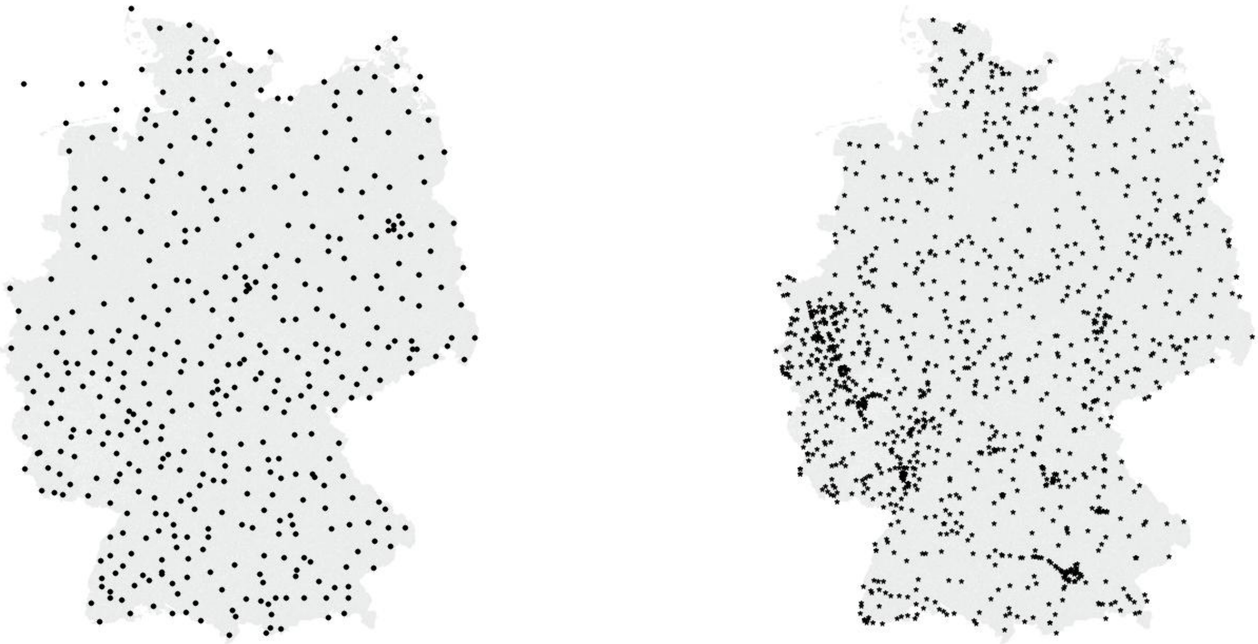
(b) Limit exceedances

Figure A.4: Variation of pollutants and diagnoses over time

Notes: Figure A.4 displays the variation of pollutants over time.

(a) Pollution monitors

(b) Hospital catchment areas



(c) Weather monitors

(d) Traffic monitors

Figure A.5: Locations of monitors and hospitals

Notes: This figure displays the location of monitors for pollution (A.5a), weather (A.5c) and traffic (A.5d) used in our sample. It further displays all hospital locations and their catchment areas in 2006 based on voronoi tessellation and all Clean Air Plans (gray) and Low Emission Zones (black) established until 2018 (A.5b).

Table A.4: The effect of Clean Air Plans on air pollution

	PM10		NO2	
	(1)	(2)	(3)	(4)
A. Pollution levels (yearly mean)				
Clean Air Plan	-0.597**	-0.286	-0.597**	-0.113
	(0.239)	(0.226)	(0.298)	(0.329)
Clean Air Plan × In LEZ		-3.335***		-4.477***
		(1.100)		(1.100)
Adj. R^2	0.91	0.91	0.98	0.98
N	4229	4229	4583	4583
B. Limit exceedances (days or hours above threshold)				
Clean Air Plan	-3.838***	-2.275**	4.306	5.375
	(1.000)	(0.946)	(2.907)	(3.665)
Clean Air Plan × In LEZ		-12.225***		-5.334
		(1.446)		(4.286)
Adj. R^2	0.76	0.77	0.49	0.50
N	4229	4229	4346	4346
C. Violations (yearly mean above threshold)				
Clean Air Plan	0.014***	0.015**	-0.004	0.008
	(0.005)	(0.006)	(0.020)	(0.019)
Clean Air Plan × In LEZ		-0.019**		-0.082*
		(0.008)		(0.045)
Adj. R^2	0.18	0.18	0.87	0.87
N	4229	4229	4583	4583
Controls:				
Station FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes

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

Table A.5: The effect of LEZs on pollutants

	PM10			NO2		
	(1)	(2)	(3)	(4)	(5)	(6)
A. Pollution levels (yearly mean)						
In LEZ	-1.400***	-0.662***	-0.804***	-1.526***	1.005**	0.331
	(0.238)	(0.252)	(0.253)	(0.393)	(0.484)	(0.488)
In LEZ × Euro 2		-1.127***			-3.584***	
		(0.257)			(0.746)	
In LEZ × Euro 3			-1.107***			-3.158***
			(0.233)			(0.750)
Adj. R^2	0.91	0.91	0.91	0.98	0.98	0.98
N	4229	4229	4229	4583	4583	4583
B. Limit exceedances (days or hours above threshold)						
In LEZ	-7.574***	-4.688***	-4.972***	-5.446	2.252	-0.684
	(1.169)	(1.203)	(1.186)	(4.553)	(1.563)	(4.413)
In LEZ × Euro 2		-4.410***			-10.892	
		(1.450)			(6.799)	
In LEZ × Euro 3			-4.836***			-8.219
			(1.188)			(6.037)
Adj. R^2	0.77	0.77	0.77	0.49	0.50	0.50
N	4229	4229	4229	4346	4346	4346
C. Violations (yearly mean above threshold)						
In LEZ	-0.000	0.011	0.007	-0.057**	-0.012	-0.029
	(0.007)	(0.010)	(0.010)	(0.022)	(0.026)	(0.024)
In LEZ × Euro 2		-0.017*			-0.064	
		(0.010)			(0.028)	
In LEZ × Euro 3			-0.014			-0.048*
			(0.008)			(0.025)
Adj. R^2	0.18	0.18	0.18	0.87	0.87	0.87
N	4229	4229	4229	4583	4583	4583
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes

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

Table A.6: The effect of LEZs on its surrounding air pollution

	PM10			NO2		
	(1)	(2)	(3)	(4)	(5)	(6))
A. Pollution levels (yearly mean)						
In LEZ	-1.400***	-1.392***	-1.364***	-1.526***	-1.479***	-1.478***
	(0.238)	(0.239)	(0.238)	(0.393)	(0.388)	(0.387)
10 km around LEZ		0.069	0.105		0.458	0.459
		(0.220)	(0.224)		(0.391)	(0.398)
10-20 km around LEZ			0.822***			0.014
			(0.285)			(0.557)
Adj. R^2	0.91	0.91	0.91	0.98	0.98	0.98
N	4229	4229	4229	4583	4583	4583
B. Limit exceedances (days or hours above threshold)						
In LEZ	-7.574***	-7.609***	-7.526***	-5.446	-5.227	-5.199
	(1.169)	(1.159)	(1.157)	(4.553)	(4.407)	(4.399)
10 km around LEZ		-0.300	-0.196		1.999	2.037
		(0.801)	(0.811)		(1.879)	(1.894)
10-20 km around LEZ			2.414**			0.777*
			(1.132)			(0.459)
Adj. R^2	0.77	0.77	0.77	0.49	0.49	0.49
N	4229	4229	4229	4346	4346	4346
C. Violations (yearly mean above threshold)						
In LEZ	-0.000	-0.000	-0.000	-0.057**	-0.056**	-0.056**
	(0.007)	(0.007)	(0.007)	(0.022)	(0.023)	(0.023)
10 km around LEZ		-0.002	-0.002		0.014	0.014
		(0.007)	(0.009)		(0.023)	(0.014)
10-20 km around LEZ			0.003*			-0.001
			(0.002)			(0.025)
Adj. R^2	0.18	0.18	0.18	0.87	0.87	0.87
N	4229	4229	4229	4583	4583	4583
Controls:						
Station FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes

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

B Hospital Data

B.1 Hospital quality reports

Hospital quality reports are written by every hospital and transferred to The Federal Joint Committee (Gemeinsamer Bundesausschuss) which collects and provides reports for the period 2006-2016. The Federal Joint Committee (Gemeinsamer Bundesausschuss) is a supreme decision-making body of the conjoint self-administration of physicians, dentists, psychotherapists, hospitals, and health care funds in Germany . The Federal Joint Committee, with the participation of privat health insurances, German Medical Council (Bundesaerztekammer) and the representative organisations of nursing professions, are responsible for the content and extent of reports based on legal guidelines (Section 1 sentence 3 no. 6 § 137 SGB V) formulated in 2002 (Selbmann, 2004). Starting in 2004 hospitals were obliged to publish reports. However, only from 2006 onwards reports were standardized and collected by The Federal Joint Committee. The obligation to report only 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.

Its obligated to provide one report for one hospital location if hospitals do have more than one 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 2000 meters can be defined as one location. Thus, if hospitals report several locations within a radius of 2000 meter around the main location, which we define as the location with the highest initial number of inpatients, we merge these locations to one location which happened 380 times. Otherwise we would define competing hospital catchment areas for one hospital.

We use the full addresses available in the QR 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 address to the street network can take place to calculate 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. The accuracy of the geocode then is directly related to the quality of both the source data supplied and the quality of the reference data utilized.

In the following, we will provide information for the variables we are using in our analysis. One important information are the number of beds in a hospital location. Hospitals are obliged to provide information about the number of beds (following § 108/109 SGB V) based on the closing date. Another important information are inpatient cases which include cases covered by the following funding schemes: Krankenhausentgeltgesetzes (KHEntgG) and Bundespflegesatzverordnung (BPflV). Readmission do not increase the number of inpatients. The BPflV covers a relative narrow scope, mainly settlements 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 inpatients. Under the KHEntgG scheme, one case equals one settled patient in the year of dismissal. Different than under the KHEntgG system, reallocation of patients between medical departments increase the number of inpatients under the BPflV scheme. Thus, the number of inpatients can differ from the number of main diagnoses.

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" translated into German by the DIMDI (the number 10 refers to the 10th revision of the classification, GM means "German Modification"). ICD-10-GM forms an important basis for the G-DRG fixed sum payment systems. 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 6 patients per year equal 5. These data are merged with with information on base rate factors provided by AOK, a group of health insurers. Payment for a hospital admission is the product of two factors: a cost-weight factor for diagnoses in year t, multiplied with the hospital-specific base rate factor for a hospital in year t.

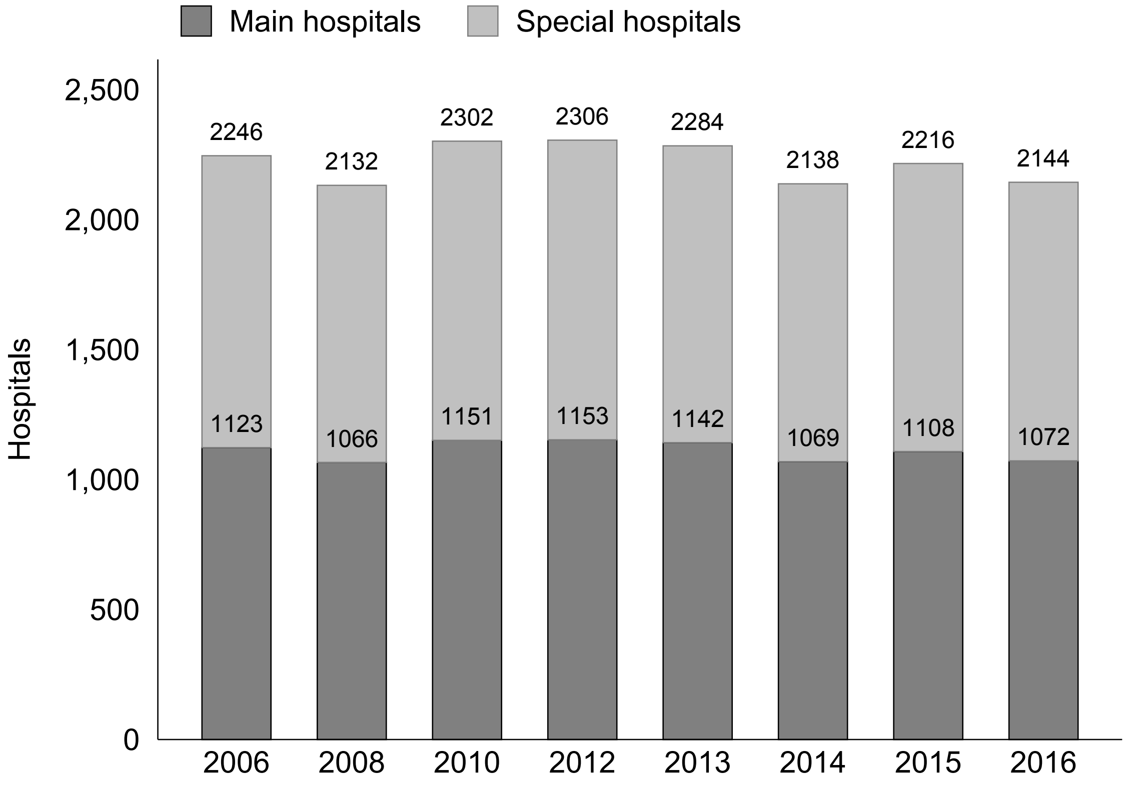


Figure B.1: Number of hospital locations

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

B.2 Catchment areas

Figure B.2: Hospital catchment areas (voronoi tessellation)

Notes: This graph displays the LEZ of the Ruhr area (colored area) and hospital locations (black dots) as well as their corresponding catchment areas (black lines)

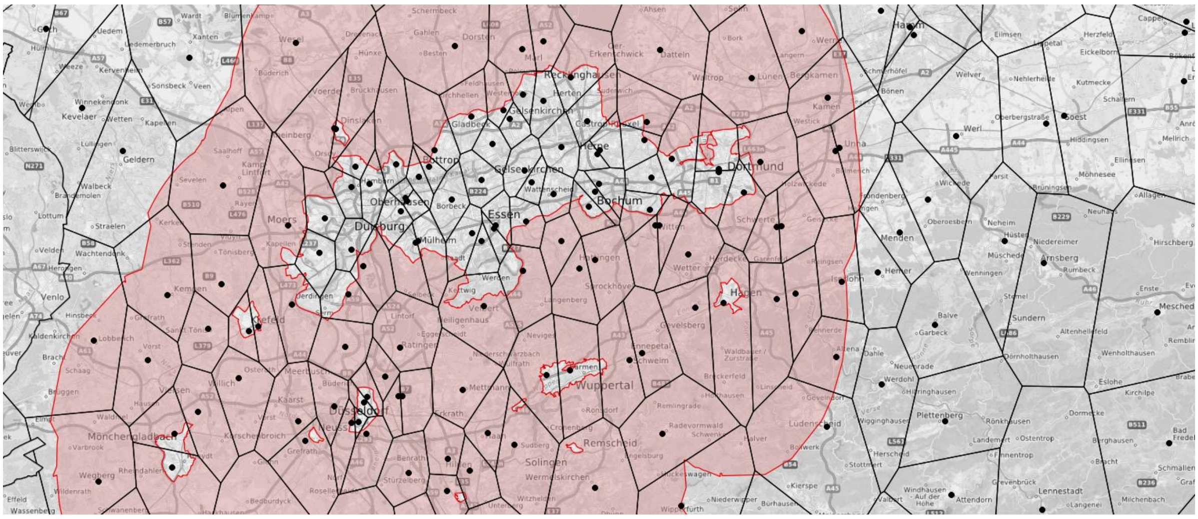


Figure B.3: Catchment area affected by traffic shifting

Notes: This figure shows the 20 km zone (colored) around LEZs, which we identify as affected by traffic shifting.

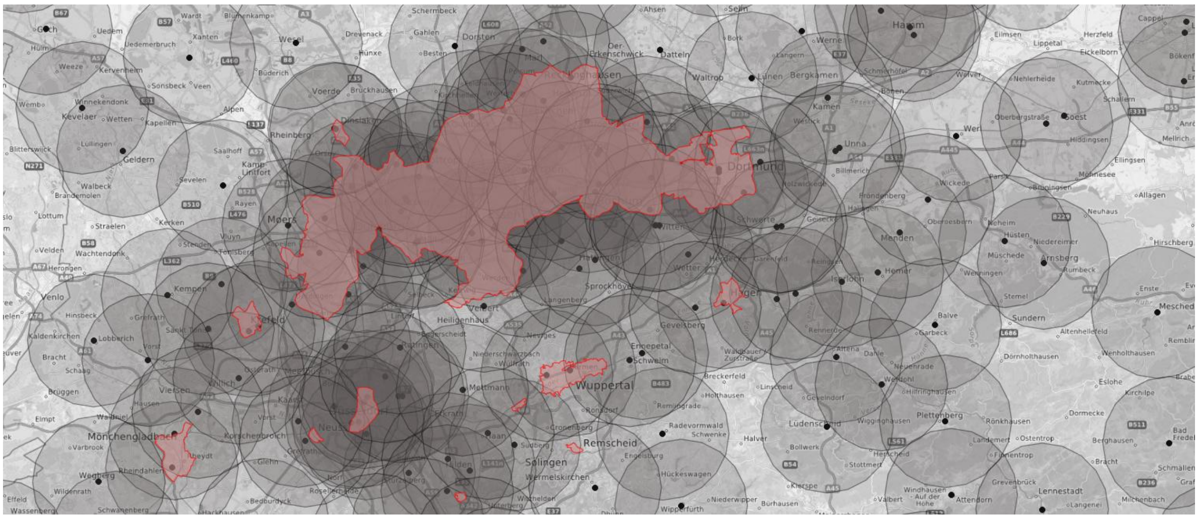


Figure B.4: Hospital catchment areas (7 km buffer)

Notes: his graph displays the LEZ of the Ruhr area (colored area) and hospital locations (black dots) as well as their corresponding catchment areas (gray circles)

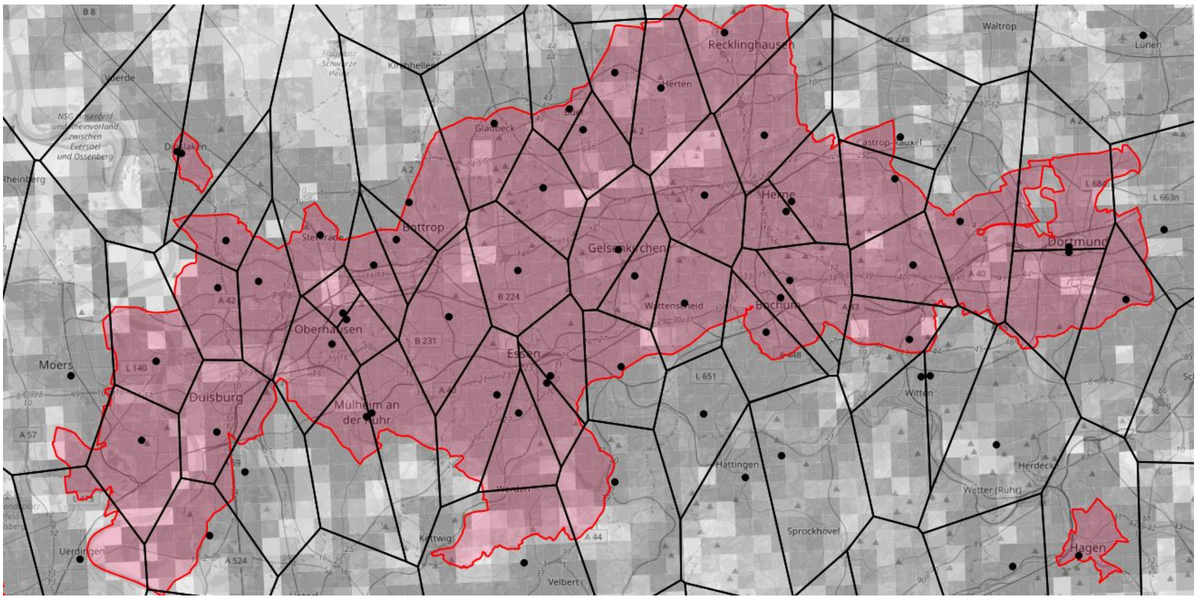
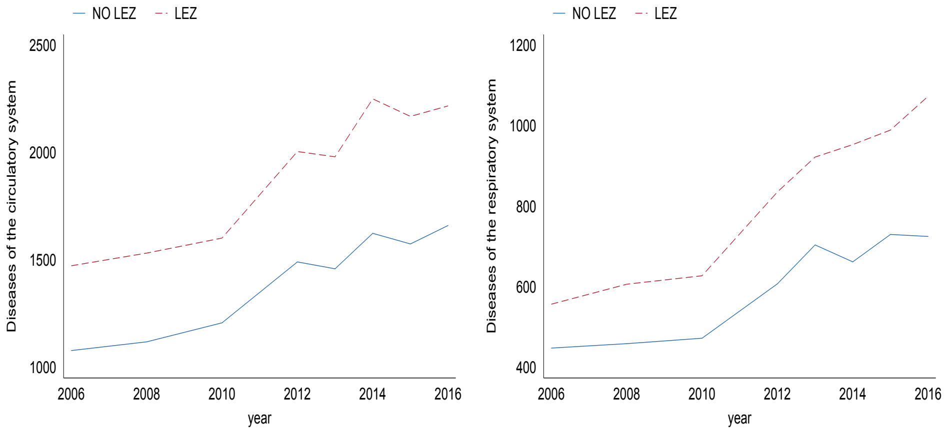


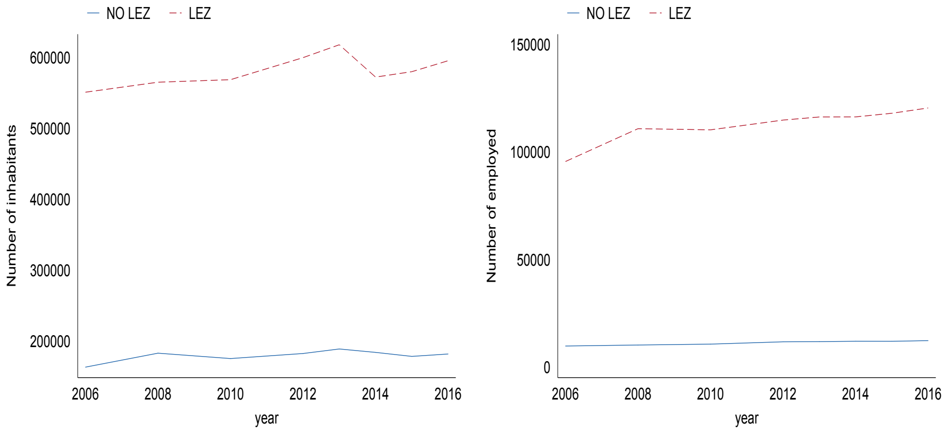
Figure B.5: Hospital catchment areas (voronoi tesselation) and population grids

Notes: his graph displays the LEZ of the Ruhr area (colored area) and hospital locations (black dots) as well as their corresponding catchment areas (black lines) and 1km × 1km total population grids

(a) Beds (b) Diagnoses



(c) Circulatory system (d) Respiratory system



(e) Population (f) Employed

Figure B.6: Common trends between hospitals in and outside LEZs

Notes: This graph shows different time trends for selected observables for hospitals whose catchment area is or will be covered and those whose catchment area is never covered by an active LEZ.

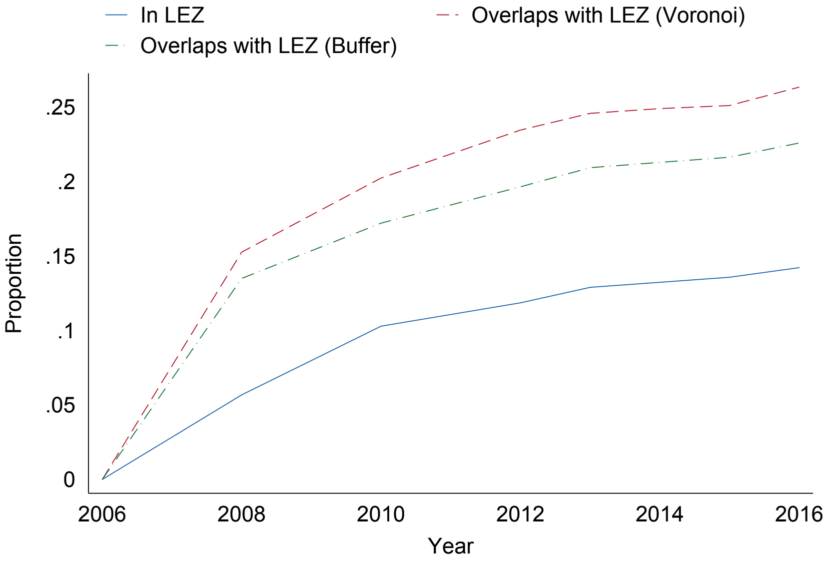


Figure B.7: Trends in LEZs

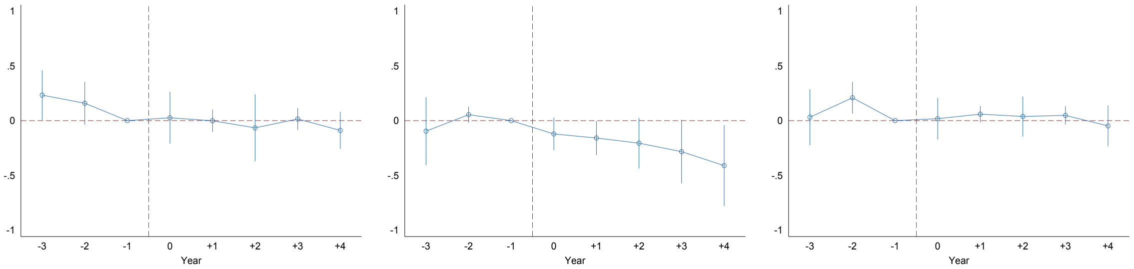
Notes: This graph displays time trends for the share of hospitals that are either located in an active LEZ or have catchment areas covered by an active LEZ.

C Additional Results

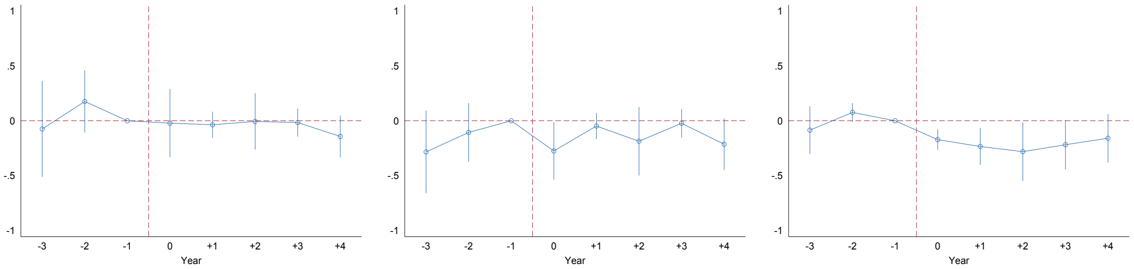
Table C.1: The effect of LEZs on additional hospital diagnoses in main hospitals

	(1)	(2)	(3)	(4)	(5)
Dementia (F00-F03)	-0.042	-0.069	-0.069	-0.111	-0.090
	(0.121)	(0.123)	(0.123)	(0.128)	(0.135)
Neoplasm (C00-D49)	-0.015	-0.016	-0.018	-0.050	-0.103
	(0.078)	(0.076)	(0.076)	(0.080)	(0.078)
Stress (F40-F48)	0.056	0.043	0.039	0.049	-0.051
	(0.099)	(0.097)	(0.096)	(0.091)	(0.111)
Injuries (S00-S99)	0.000	-0.013	-0.012	-0.042	-0.143
	(0.064)	(0.065)	(0.064)	(0.071)	(0.099)
N	8837	8837	8837	8837	8837
Controls:					
Hospital FE	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	No	Yes	Yes	Yes	Yes
Weather characteristics	No	No	Yes	Yes	Yes
Municipality characteristics	No	No	No	Yes	Yes
Linear municipality time trends	No	No	No	No	Yes

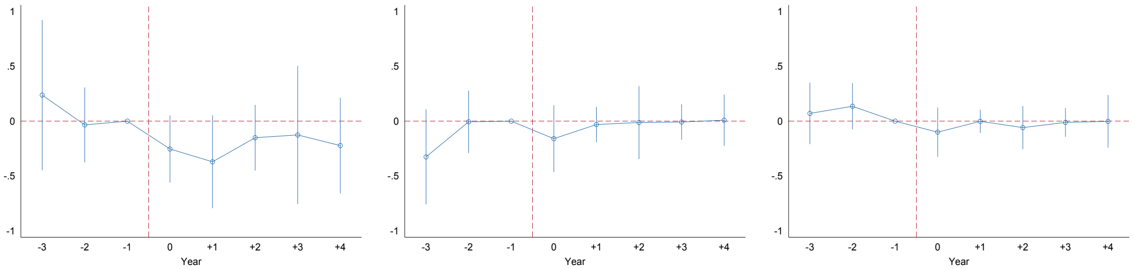
Notes:This table displays the results for hospital diagnoses, for main hospitals. The catchment area is calculated by voronoi tessellation. Each coefficient is the result of a separate regression of diagnose listed on the left on a indicator variable for an active LEZ (share of catchment area covered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



(a) I10-I15 (b) I20-I25 (c) I50



(d) I60-I69 (e) J20-J22 (f) J40-J47



(g) P07 (h) F40-F48 (i) S00-S99

Figure C.1: Event study for all main diagnoses

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

Table C.2: The effect of LEZs on diagnoses using several specifications

Treatment		Voronoi		Voronoi POP	Buffer	In
Hospitals	(Main)	(Special)	(In CAP)	(Main)	(Main)	(Main)
	(1)	(2)	(3)	(4)	(5)	(6)
All diseases (A00-N99)	-0.062*	-0.059	-0.079	-0.051	-0.067	-0.056*
	(0.036)	(0.087)	(0.050)	(0.035)	(0.045)	(0.034)
Diseases of the ciculatory system (I00-I99)	-0.151***	-0.102	-0.263**	-0.142***	-0.143**	-0.105*
	(0.045)	(0.225)	(0.123)	(0.052)	(0.066)	(0.058)
Hypertenion (I10-I15)	-0.153**	0.122	-0.132	-0.174**	-0.144*	-0.164**
	(0.072)	(0.172)	(0.090)	(0.076)	(0.087)	(0.064)
Ischemic heart diseases (I20-I25)	-0.251***	0.014	-0.226**	-0.246***	-0.196*	-0.177*
	(0.075)	(0.152)	(0.113)	(0.093)	(0.100)	(0.096)
Heart failure (I50)	-0.170***	0.128	-0.143	-0.136*	-0.116	-0.080
	(0.058)	(0.164)	(0.102)	(0.078)	(0.087)	(0.071)
Cerebrovascular disease (I60-I69)	-0.243***	-0.038	-0.255***	-0.209***	-0.237**	-0.111
	(0.080)	(0.177)	(0.067)	(0.070)	(0.103)	(0.068)
Diseases of the respiratory system (J00-J99)	-0.072	-0.109	-0.111	-0.063	-0.081	-0.072
	(0.064)	(0.297)	(0.132)	(0.061)	(0.074)	(0.051)
Acute lower respiratory diseases (J20-J22)	-0.120	-0.139	-0.157	-0.114	-0.087	-0.157*
	(0.092)	(0.250)	(0.147)	(0.096)	(0.113)	(0.081)
Chronic lower respiratory diseases (J40-J47)	-0.176**	-0.044	-0.144	-0.191**	-0.210**	-0.210***
	(0.075)	(0.164)	(0.109)	(0.081)	(0.089)	(0.073)
Low birth weight (P07)	-0.173**	0.064	-0.020	-0.155*	-0.203*	-0.043
	(0.085)	(0.085)	(0.067)	(0.081)	(0.114)	(0.060)
Stress (F40-F48)	-0.059	-0.334	-0.237**	-0.023	-0.078	-0.105
	(0.111)	(0.284)	(0.119)	(0.101)	(0.112)	(0.096)
Injuries (S00-S99)	-0.142	-0.059	-0.098	-0.097	-0.181	-0.099
	(0.097)	(0.220)	(0.127)	(0.090)	(0.112)	(0.065)
Dementia (F00-F03)	-0.087	-0.050	-0.097	-0.007	-0.109	-0.105
	(0.134)	(0.151)	(0.085)	(0.130)	(0.188)	(0.106)
Neoplasm (C00-D49)	-0.105	0.121	-0.091	-0.104	-0.090	-0.114**
	(0.076)	(0.192)	(0.075)	(0.070)	(0.071)	(0.057)
N	8837	6876	5599	8837	8837	8837
Controls:						
Hospital FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Hospital characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Weather characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Municipality characteristics	Yes	Yes	Yes	Yes	Yes	Yes
Linear municipality time trends	Yes	Yes	Yes	Yes	Yes	Yes

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

Table C.3: Balancing table of hospital characteristics

	(Never LEZ)	(Pre LEZ)	(Post LEZ)	(Pre LEZ - Never LEZ)	(Post LEZ - Never LEZ)	(Post LEZ - Pre LEZ)
	(1)	(2)	(3)	(4)	(5)	(6)
Non-Profit	0.39	0.53	0.61	0.14***	0.22***	0.08***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Public	0.43	0.34	0.29	-0.09***	-0.14***	-0.05***
	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)
Privat	0.19	0.13	0.10	-0.06***	-0.08***	-0.03***
	(0.00)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
Number of Beds	332.41	514.03	522.72	181.62***	190.31***	8.69***
	(3.25)	(14.18)	(11.49)	(9.42)	(9.42)	(9.42)
Baserate in €	2995.32	2875.19	3039.05	-120.13***	43.73***	163.86***
	(3.27)	(11.29)	(4.03)	(6.01)	(6.01)	(6.01)
All diseases (A00-N99)	9576.44	12302.81	14599.47	2726.37***	5023.02***	2296.65***
	(117.83)	(412.52)	(332.05)	(278.10)	(278.10)	(278.10)
Diseases of the ciculatory system (I00-I99)	2142.38	2706.82	2900.63	564.44***	758.26***	193.81***
	(29.89)	(109.66)	(82.89)	(70.44)	(70.44)	(70.44)
Diseases of the respiratory system (J00-J99)	880.11	987.49	1278.77	107.38***	398.66***	291.28***
	(11.41)	(37.03)	(33.64)	(27.19)	(27.19)	(27.19)
Low birth weight (P07)	36.16	65.43	77.38	29.27***	41.22***	11.94***
	(0.96)	(4.74)	(4.55)	(3.46)	(3.46)	(3.46)
Stress (F40-F48)	72.99	79.71	81.88	6.71***	8.88***	2.17***
	(1.72)	(5.12)	(4.07)	(3.55)	(3.55)	(3.55)
Injuries (S00-S99)	1152.13	1197.15	1375.60	45.02***	223.47***	178.45***
	(13.33)	(40.07)	(35.50)	(29.31)	(29.31)	(29.31)
Population/1000	170.08	310.51	704.18	140.43***	534.10***	393.67***
	(6.39)	(20.05)	(25.41)	(19.62)	(19.62)	(19.62)
Work force/1000	73.47	127.40	313.05	53.93***	239.58***	185.66***
	(2.54)	(6.86)	(9.86)	(7.48)	(7.48)	(7.48)
Share male < 30 years	0.32	0.33	0.33	0.02***	0.01***	-0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Share male 30 - 65 years	0.50	0.49	0.50	-0.00	0.00	0.00
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Share male > 65 years	0.18	0.17	0.17	-0.01***	-0.01***	-0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Share female < 30 years	0.29	0.31	0.31	0.02***	0.02***	0.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Share female 30 - 65 years	0.47	0.47	0.47	-0.01***	-0.00***	0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
Share female > 65 years	0.24	0.23	0.22	-0.01***	-0.02***	-0.01***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
N	6831	674	1234			

Notes:This table displays the pre-treatment characteristics of hospital characteristics and (Panel A) and diagnoses (Panel B) in areas with and without LEZs, exlusing those areas which established a LEZ already in 2008. Columns (1) and (2) display the raw means in 2006, whereas Columns (4) and (5) display the raw means in changes between 2006 and 2008. In Columns (3) and (6), we perform t-tests for equality in means. Standard errors of the test statistics are displayed in parentheses. Significance levels: $***: p < 0.01$, $**: p < 0.05$, $*: p < 0.1$.