# Cars, Air Pollution and Low Emission Zones in Germany[1]

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**Abstract:**

*Low Emission Zones (LEZ) are areas in which vehicular access is restricted to only vehicles that emit low levels of air pollutants. Recently, LEZs have become a popular policy worldwide, and in Germany LEZ are increasingly adopted to comply with the 2005 EU air pollution legislation. We study the effect of LEZs in two ways. First, we assess whether pollution levels do actually decrease. Second, we analyze the spatial substitution effects in new vehicle purchases and retrofits of high emission cars due to the LEZ regulation. We find that LEZs significantly decrease air pollution in urban centers. We, however, also find that outside of the LEZ pollution increases likely because the higher polluting vehicles are forced to drive longer routes around the LEZ. Moreover, we find that German vehicle owners substantially increase the adoption of cleaner technologies the closer they live to an LEZ. In summary, if marginal damages are convex, the overall effect of the LEZ program on air pollution could be positive.*

**Keywords:** Air Pollution, Low Emission Zones, PM10

**JEL: Q20**

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## 1. Introduction

Increased health concerns about air pollution have led many countries to tighten traffic-related policies. Legislators have focused on PM10, defined as the class of particles smaller than 10 micrometers (μm), as PM10 has the ability to enter directly into lungs and partially into the bloodstream. It is estimated that PM10 causes 348,000 premature deaths per year in the European Union (EU), while Ozone—the second most deadly air pollutant—causes about 21,000 premature deaths (Watkiss et al., 2005).

The EU commission has taken these results very seriously and enacted the 2005 EU Clean Air directive, which marks an unprecedented attempt to mandate low levels of PM10. When cities violate the maximum allowable limits on PM10 (by exceeding 50μg/m³ per day on more than 35 days or averaging more than 40μg/m³ within a calendar year), mayors and local governments have to develop so called clean air *action plans.* The contents of these actions plans are determined by the city council but they typically consist of building ring roads and enhancing public transportation. The most drastic measure, however, is the implementation of a Low Emission Zone (LEZ), which defines an urban area where higher-polluting vehicles are - banned from driving.

In Germany, to deal with the large number of cities exceeding the EU PM10 threshold, the government has categorized all vehicles into four mutually exclusive classes of PM10 emissions. All automobiles (all 46 million German vehicles and all visiting foreign cars and trucks) are required to display a colored windshield sticker indicating which class it belongs to—green, yellow, red or no sticker in the order of the lowest to the highest polluting category. Each city can choose which sticker cars it permits into the LEZ. Currently Germany has 32 LEZs which vary in size from just a couple of blocks (particularly in small towns) up to 207 square kilometers in the case of Stuttgart, where the entire town and large portion of the suburbs are affected (see map in Appendix E). While LEZs have become a popular quick fix for local governments to meet the EU PM10 legislation, they have been very controversial because of the significant costs imposed on drivers and business owners, as well as bus and truck companies for whom upgrading fleets to the appropriate sticker is very expensive.[2]

[2] For smaller vehicles, the conversion to the next higher sticker costs 800 to 2500 U.S. dollar. For larger vehicles and trucks the conversion costs 10,000 to 22,000 dollar. For some vehicles the conversion is technologically infeasible.

Germany is not alone in limiting vehicle use. In fact, driving restrictions have been used for decades in some of the world's most polluted cities. In 1989 Mexico City introduced the Hoy No Circula (HNC) policy which prohibits driving between 5am and 10pm one weekday per week based on the last digit of its license plate. Similar restrictions have been implemented in Athens (1982), Bogota (1998), Santiago (1986) and São Paolo (1997), San Jose (2005), La Paz (2003), all of Honduras (2008), and Beijing (2008). Other forms of driving restrictions include partial and total bans (Italy, Athens, Amsterdam, Barcelona, and Tokyo); traffic cell architecture, such that vehicles can drive within the cell but must take a circumferential ring road to get between traffic cells (Goddard 1997; Vuchic 1999); traffic bans on days when air pollution exceeds certain thresholds, such as in Milan and other Northern Italian cities; and congestion charging in combination with an LEZ (such as in London where low emission vehicles do not pay the congestion charge but all other automobiles pay 8 British pounds (=14 U.S. dollar).[3]

Despite the widespread use of driving restrictions, the related empirical literature is sparse. In a recent study, Davis (2008) analyzes the effect of Mexico City's HNC policy on air quality. While he finds no change in weekday pollution levels, pollution actually increased on the weekends and weekday late nights as drivers substituted towards driving when the HNC was not in effect. Davis shows this ineffectiveness is due to a surprising behavioral response: drivers circumvented the restriction by buying older, more polluting vehicles to be second cars with different license plates[4]. Davis also shows that the HNC is a high-cost solution—with social costs exceeding $300 million per year—given its negligible effect on air quality.

While the counterproductive results in Mexico City were due to the particular design of the HNC[5], the German LEZ program may be more successful because it includes a differentiation by

[3] Price-based policies that aim to limit congestion and emissions include road pricing and congestion fees. Singapore (1975), London (2003) and Stockholm (2006) all charge fees for driving into the city center. While New York City's plan to introduce congestion fees stalled in the legislature, San Francisco is currently debating plans to implement a six dollar fee to drive through downtown. Milan has combined congestion pricing and LEZs with its Ecopass program, which charges fees to enter the downtown area based on emissions-level of the car. Even with increasing adoption of such price-based policies, command and control driving restrictions are more often adopted because these policies are easier to implement politically, technologically more feasible, and relatively less expensive to enforce (Levinson and Shetty, 1992; Davis, 2008).

[4] Drivers also increased their use of taxis, which were some or the most polluting vehicles in Mexico City when the policy was first enacted.

[5] The HNC has been modified to include an exhaust monitoring program, Verifcación, such that each car is affixed with a sticker indicating their class of emissions and the cleanest of the classes are exempt from the HNC.

emission level, creating incentives to adopt cleaner technologies.[6] Even with this incentive, though, such command and control policies may prove inefficient since they lack market-based incentives that equalize the marginal cost of abatement across polluters. LEZs may also cause unintended consequences such as increased driving outside of the LEZ, especially by the more polluting vehicles that cannot enter the LEZ.

Therefore, whether LEZs are effective is an empirical question. We think, that this is also a very urgent question, since in 2010 the EU PM10 standards will be drastically tightened and as a consequence many more cities will have to aggressively implement air control strategies[7].

To this end, the first task of this paper is to estimate the causal effect of LEZs on PM10 levels using panel data of hourly PM10 levels and weather conditions across Germany from 2005 through 2008. Both the pre-regulation PM10 levels and the staggered nature of LEZ implementations produce rich identification of the zones' treatment effects. Using difference-in differences regressions we analyze whether being in non-attainment status—and thus implementing an action plan—has had an effect on PM10 levels. We then look at whether this effect is different for cities whose action plans did and did not include LEZs.

One important argument in favor of the four-tier PM10 categorization is that it leads to a more rapid adoption of cleaner technologies since even vehicle owners who do not typically drive into an LEZ may want to keep the option value of free passage. The next task of this paper therefore is to study changes in the composition of the vehicle fleet. Using a unique panel dataset that provides the emission category and registration location of each privately and commercially owned German vehicle from 2006 to 2009, we analyze the spatial substitution in vehicles' emission categories due to the LEZ regulation.

In our preliminary analysis we find that while action plans alone have no significant effect on lowering PM10 levels, LEZs decrease PM10 by four to seven percent within the area of the LEZ. We, find that at background stations off of major roads, however, pollution increases. This is likely because higher polluting vehicles are forced to drive longer routes around the LEZ.

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[6] Evidence that a small percentage of high-emission vehicles contribute the bulk of pollution leads Roson and Small (1998) to argue that targeting dirty vehicles may be the most effective way to decrease emissions. For example, Small and Kazimi (1995) find heavy-duty diesel trucks have social costs per mile ten times higher than gasoline vehicles.

[7] We estimate that based on the 2010 EU PM10 standards, currently 253 cities are in violation. The 2010 standard allows for seven (7) days only to exceed the 50μg/m³ per day average (instead of the current rule of 35 exceedance days. In addition the yearly average will be set to 20μg/m³.

Moreover, we find that German vehicle owners substantially increase the adoption of cleaner technologies the closer they live to an LEZ. In summary, if marginal damages are convex, the overall effect of the LEZ program on air pollution could be positive.

This papers proceeds as follows. Section two details the EU PM10 regulation and the implementation of LEZs. We describe our data in section three and discuss the empirical strategy in section four. Section five presents econometric results of the causal impact of the LEZs on PM10 levels. Section six discusses the spatial substitution effects of high to low emission cars and we conclude with policy recommendations in section seven.

## 2. Background

### 2.1. Air Pollution regulation in Europe

In response to concerns about the health effects of PM10,[8] the 2005 EU Clean Air directive[9] introduced EU-wide limits on ambient PM10 such that: (a) the daily average does not exceed 50µg/m³ on more than 35 days annually and (b) the yearly average must not exceed 40µg/m³. In Germany, the 35 day limit has been particularly troublesome and has been exceeded by 81 cities.[10] Starting January 1, 2010, however, these thresholds will be drastically tightened to a yearly average of 20µg/m³ and a maximum of seven days exceeding 50µg/m³. We estimate that with these stricter 2010 limits, 285 German cities would be in nonattainment based on the emissions from 2005-2008.[11] The policy changes and implications are summarized in Table 1.

Compared to other pollutants (i.e. $NO_x$, $SO_2$), the limits on PM10 are by far the most often violated; As of 2007, 70 percent of EU cities greater than population 250,000 had violated the limits at some point, and, as of 2006, all EU member countries except Ireland and Luxembourg had cities in violation of the PM10 threshold, mostly due to traffic in urban city centers (Europa Press Release, 2008).

[8] PM10 have been linked to serious cardiopulmonary diseases, acute respiratory infection, trachea, bronchus and lung cancers. (EPA, 2004). Worldwide, about 6.4 million years of healthy life are lost due to long-term exposure to ambient PM10 (Cohen et al., 2005).
[9] See the European legislation on air quality 1999/30/EC and 96/62/EC.
[10] No German city violated the standard based on the 40µg/m³ annual limit that did not also violate the exceedance day limit.
[11] Both of the 2010 standards are even violated by the national average city in each year since 2005, which ranges from 12 to 27 days exceeding the 50µg/m³ limit (instead of 7 days) with an annual average above the 20µg/m³ limit. See Table 2 for details.

**Table 1: EU PM10 limits**

**Panel A: European Union PM10 pollution thresholds**

| | Phase 1 since 1 January 2005 | Phase 2 starting 1 January 2010 |
|---|---|---|
| Yearly average limit | 40 µg/m³ | 20 µg/m³ |
| Daily average (24-hour) limit | 50 µg/m³ | 50 µg/m³ |
| Allowed number of exceedences per year | 35 | 7 |
| Numbers of German cities violating the standard | 81 | 285* |

**Panel B: Germany violations of PM10 limits**

| | 2005 | 2006 | 2007 | 2008 |
|---|---|---|---|---|
| National average PM10 [µg/m³] | 24.4<br>(5.2) | 26.2<br>(5.5) | 23.1<br>(5.3) | 21.2<br>(4.9) |
| Mean number of days** above 50 µg/m³ | 19.6<br>(20.9) | 26.8<br>(21.1) | 16.2<br>(15.8) | 11.6<br>(12.9) |
| Cities in violation of 2005 standard | 36 | 65 | 31 | 18 |
| Cities in violation of 2010 standard | 226 | 246 | 200 | 134 |

*The calculation of the expected number of cities violating the 2010 standard is based on the number of cities that would have violated the standard between 2005 and 2008 either because of exceedance days or high annual averages

**: Average of the highest exceeding station per city; Standard deviations in parentheses

When any air pollution station exceeds the EU PM10 limit, the city must immediately develop an "action plan" and in order to enforce the legislation, the European Court of Justice (ECJ) can impose financial penalties. In fact, in January 2009 the EC initiated infringement proceedings against 10 EU countries that have not attained the EU PM10 limit[12]. Moreover, EU citizens are entitled by law to demand action plans from local authorities.[13]

[12]These 10 countries are Cyprus, Estonia, Germany, Italy, Poland, Portugal, Slovenia, Spain, Sweden and the U.K.. Given the difficulty many countries have had meeting the PM10 limits, in June 2008 the EC began allowing countries to request an extension for meeting PM10 limits from January 2005 to January 2010. These extensions are only granted when a country has taken steps to combat PM10 at the local, regional and national level, such that exceedances are unavoidable due to "site-specific dispersion characteristics, adverse climatic conditions or transboundary contributions." " (Europa Press Release 2009)

[13] Following an important recent ruling in July 2008 from the European Court of Justice, EU citizens can force their local councils to rapidly tackle air pollution. The EU's court was asked to judge the case of Dieter Janecek, a resident of Munich, who said that under the EU Air Quality Directive, the city of Munich is obliged to take action to stop pollution exceeding the specified target. The judges reconfirmed with prior statements that concluded that EU citizens are entitled to demand air quality action plans from local authorities if the EU limits are exceeded. The LEZ of Munich was then implemented in October of 2008.

## 2.2. Low Emission Zones in Germany

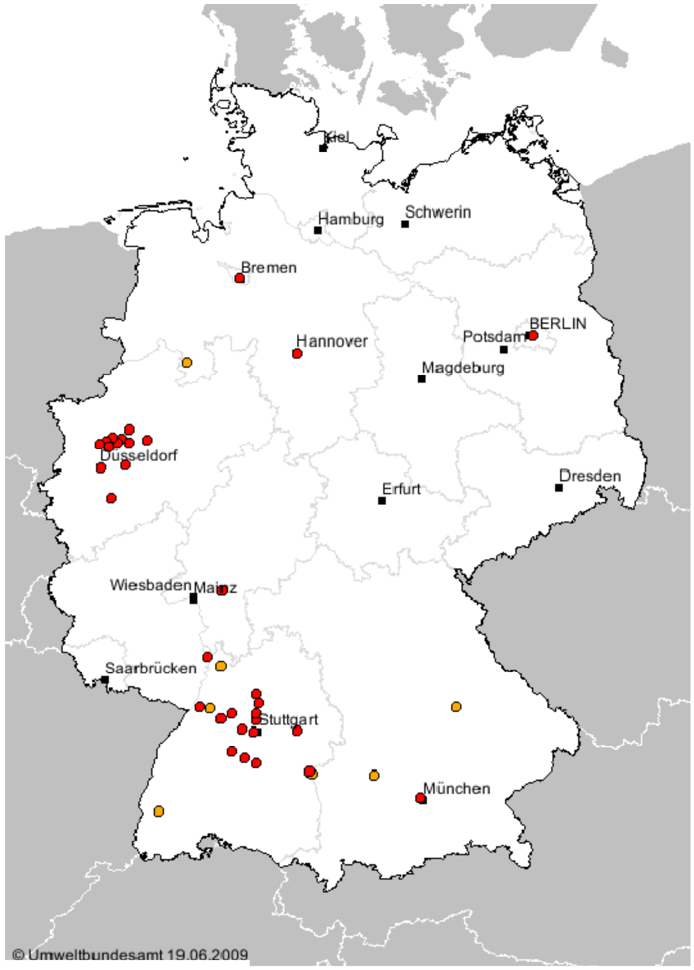
Road transport is the primary source of ambient PM10 in most European urban areas (Krzyzanowski, 2005).[14] Given this primacy of vehicle-based PM10, action plans (AP) try to constrain emissions through expanding public transportation, utilizing ring roads or improving traffic flow. However, implementing an LEZ has emerged as an important—and controversial—element of the German action plans. German cities began instituting LEZs starting January 1, 2008. The LEZs mostly cover city centers, but vary in size. In Berlin, for example, the LEZ covers 88 square kilometers ($km^2$), populated by 1.1 million people. Munich's LEZ covers 44 $km^2$ with 431,000 inhabitants and Frankfurt's LEZ spans 110 $km^2$. The largest LEZs is in Stuttgart, which covers 207 $km^2$ with 590,000 habitants, compared to nearby smaller LEZs like Illsfeld with 2.5 $km^2$ and 4,000 habitants or Pleidelsheim with 7$km^2$ and 7,000 habitants. Figure 1 below shows a map of current and planned LEZs and Appendix B for a list of characteristics of all LEZs.

Each German car—as well as each visiting foreigner—that wants to enter an LEZ must display a colored windshield sticker based on EU-wide emissions categories. There are four PM10 classes. The highest emitting vehicles obtain no sticker (and hence cannot enter any LEZ), while red, yellow and green stickers are given to progressively 'cleaner' cars. In some cases vehicles can improve one class by retrofitting the engine or diesel particulate filter. As Table 2 shows, there are two pollutant classes for gasoline-powered vehicles (Green and No Sticker) and diesel vehicles can attain any of the four pollution classes.

The implementation date and the types of cars restricted by an LEZ vary across German cities. In Berlin, for example, all vehicles with a red sticker and "cleaner" (yellow and green) have been allowed into the LEZ since January 2008, while access will be restricted to green stickers only starting January 1, 2010. The LEZ of Dortmund (Brackler Strasse), on the other hand, has only permitted yellow and green sticker cars since beginning in January 2008. Of the 23 LEZs implemented in 2008, four began in January, eight began in March, one began in July and the rest began in October. A summary of all the current LEZs can be seen below in Table 3.

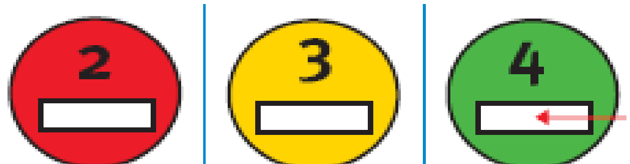
[14] Road transport is also largely responsible for all $NO_X$, CO, benzene and black smoke emissions. Although historically these toxins have been debated, the magnitude in terms of threshold violations and health impacts (premature deaths) is substantially higher for PM10.

**Figure 1: Current (in red) and Future (in yellow) German LEZs**



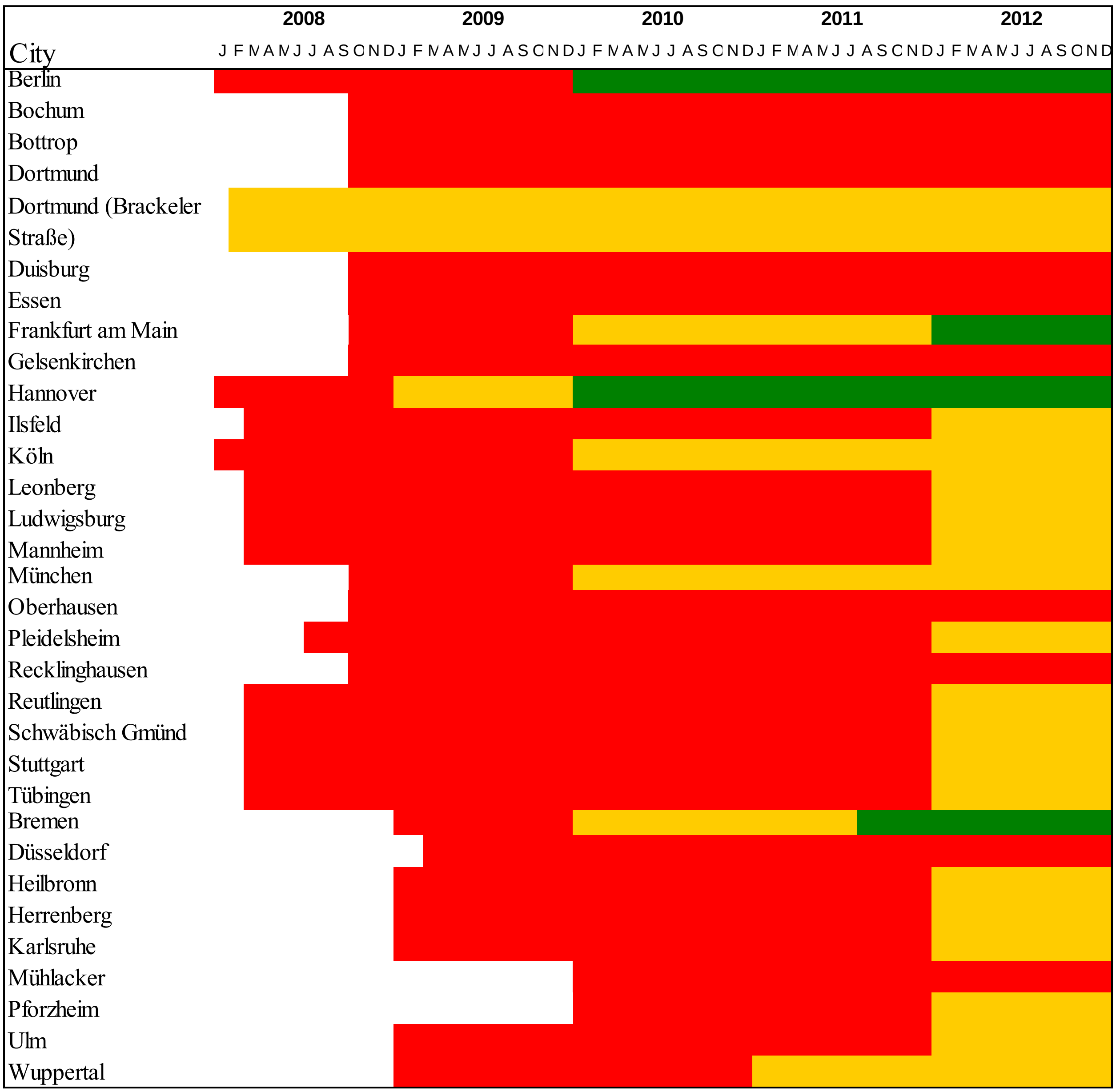

Source: Umweltbundesamt

**Table 2: German vehicle stickers**

| | Sticker categories | | | |
|---|---|---|---|---|
| | No sticker | Red | Yellow | Green |
| | |   | | |
| Requirement for diesel vehicles | Euro 1 or worse | Euro 2 or Euro 1 with particle filter | Euro 3 or Euro 2 with particle filter | Euro 4 or Euro 3 with particle figure |
| Requirement of gasoline vehicles | Without 3-way catalytic converter | | | Euro 1 with regulated catalytic converter or better |

The fine for violating the LEZ is 40 Euros plus one driver's license penalty point[15]. There are exceptions that allow certain emergency and other work related vehicles to enter the LEZs without a sticker. These include agricultural and forestry tractors; ambulances and doctor's cars; vehicles driven by or carrying persons with serious mobility impairments; police, fire brigades, Bundeswehr and NATO vehicles.

**Table 3: German LEZ restrictions 2008 to 2012**




[15] There is a staggered system of consequences due to penalty points, ending in loss of driver license with 18 points.

## 3. Data

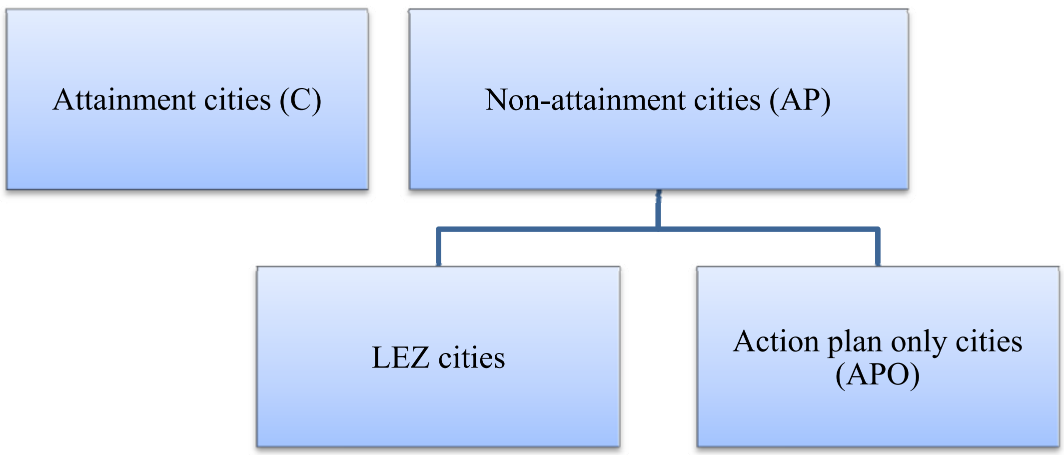
We collected a panel of German air quality readings from 2005 through October of 2008 from the Federal Environment Agency of Germany, the Umweltbundesamt (UBA). This data set includes a combination of half-hourly, hourly or daily readings of PM10, for 1285 stations in 388 cities. All stations are characterized by the UBA as being traffic, background or industrial stations based on their location. This data is merged with weather data from the German national weather service, Deutscher Wetterdienst. We obtained hourly weather readings for 34 stations and daily reading for 74 stations. Because the air quality and weather monitoring stations are not in the same location, we use the geographic coordinates to match each air quality station with the closest air quality station. We use the PM10 readings from only stations that have a weather station within 50 kilometers distance that are no more than 300 meters higher or lower in altitude. The primary weather variables are summarized in Table 4 below. Using the procedures detailed in Appendix A for cleaning data, calculating daily weather and PM10 readings and handling missing values, we end up with complete PM10 and matched weather data for 185 stations covering 122 cities.

**Table 4: Summary of weather data**

| Weather Variables | Unit | Mean | St. Dev. | Min | Max |
|---|---|---|---|---|---|
| Daily average temperature | 1C | 9.6 | 7.7 | -27 | 31 |
| Daily min temperature | 1C | 5.6 | 6.9 | -29.7 | 24.4 |
| Daily max temperature | 1C | 13.8 | 8.9 | -23.1 | 40.2 |
| Daily avg. vapor pressure | 1 hpa | 9.9 | 4.1 | 0.2 | 26.9 |
| Daily average air pressure | 1 hpa | 981 | 49 | 679 | 1047 |
| Daily avg. relative humidity | % | 78.1 | 12.9 | 7 | 101 |
| Daily avg. wind speed | 1 m/s | 2.6 | 1.1 | 0 | 10 |
| Daily max wind speed | 1 m/s | 10.9 | 4.9 | 1.3 | 64.8 |
| Daily avg. cloud cover | Tenths | 7.1 | 1.3 | 0 | 9 |
| Sun in day | 1 hour | 4.8 | 4.4 | 0 | 16.7 |
| Precipitation during day | 1 mm | 2.1 | 4.7 | 0 | 158 |
| Snow depth | cm | 4.1 | 28.6 | 0 | 550 |
| New snow depth | cm | 0.2 | 1.9 | 0 | 150 |

Figure 2 illustrates the classifications of cities that we use in our analysis. First, we divide stations into 2 categories, ‘attainment cities’ that do not violate the PM10 limit (and thus do not need to develop an action plan) and 'non-attainment cities' that develop an action plan. Next, among the non-attainment cities we differentiate between 'action plan only' (APO) cities, whose action plan do not include an LEZ, and 'LEZ cities' that do include an LEZ in their action plan.

**Figure 2: Main structure of treatment and control cities.**

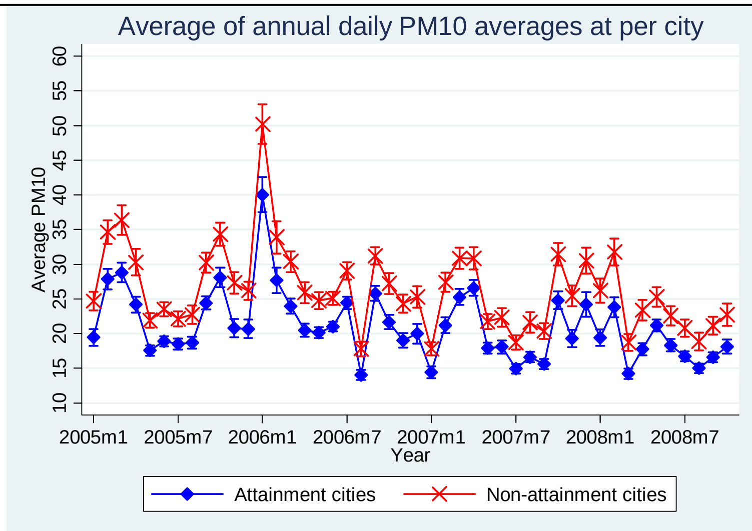


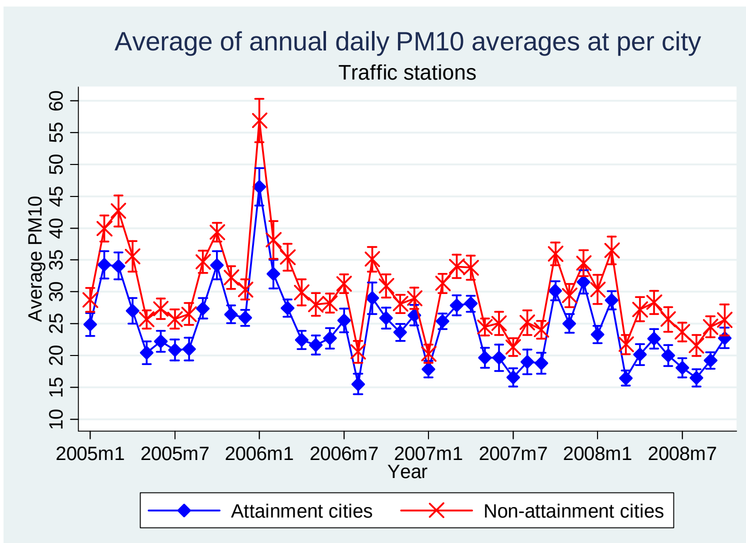

An examination of average PM10 levels shown in Figure 3 below shows that pollution levels have been decreasing since 2006 for attainment cities and non-attainment cities, including both action plan only cities, and LEZ cities. While the daily averages do not appear to have decreased by more in LEZ cities than the action plan only cities, there may be effect once we control for covariates such as station type, weather, city characteristics, holidays and others.

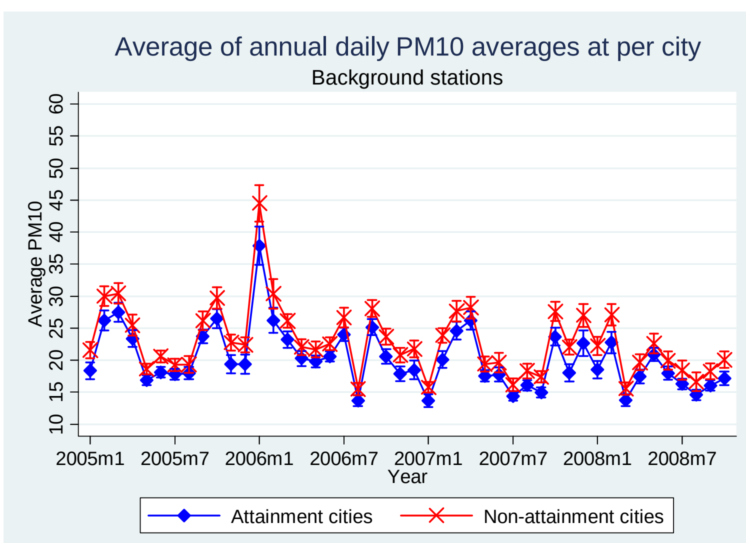
Finally, our data set is complemented by covariates that control for state-level school breaks and legal holidays, both obtained by Johannsen (2009) as well as city-level 2006 population data obtained by the Federal Statistical Office Germany Genesis database[16].

[16] Surprisingly, many smaller German cities are not included in the Genesis population file. For these cities we obtained the population estimates by internet search, e.g. from local city websites.

**Figure 3: Average of city annual PM10 levels**




Note: Plots of average of city averages per year, with 95 percent confidence intervals

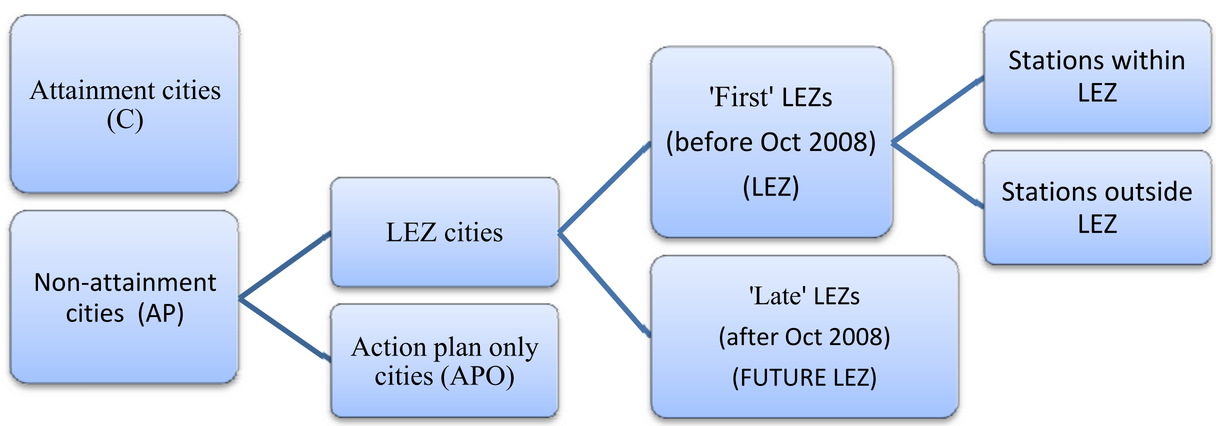
## 4. Empirical Identification Strategy

### 4.1. Difference-in-Differences Approach

Our primary analysis uses two main difference-in-differences (DD) specifications (see Meyer 1995; Bertrand et al., 2004). First, at a national level, we match cities based on PM10 levels in 2005, before the action plans came into effect. To determine the effect being found in violation of the PM10 limits, we compare PM10 levels in the non-attainment cities with action plans (AP) to those of the control attainment cities (C). To differentiate the effect of LEZs, we then separate the LEZ cities from the action plan only cities (APO).

Second, our next identification strategy takes advantage of the staggered nature of the LEZ introduction, comparing the earliest LEZ cities to cities whose LEZ has not yet come into effect (FUTURE LEZ). Because of the heterogeneity across states in term of weather, geography and regional policies, for this analysis we look at changes in PM10 at the major LEZs one-by-one, comparing them to nearby future LEZ cities. Finally, within the LEZ cities, we compare PM10 levels at stations that are located within the LEZ to those stations outside of the LEZ. Figure 4 summarizes the different treatment categories of cities and stations.

**Figure 4: Classification of cities treatment status**




To indentify the effect of an action plan (AP) on PM10, we estimate Equation (1), where *k* indexes city, *i* indexes station and *t* indexes time:

$$(1) \quad \ln(y_{k,i,t}) = \alpha + \beta_1 postACTION_t + \beta_2 ACTION_k + \beta_3 treatACTION_{k,t} + \Psi X_{k,i,t} + \upsilon_{k,i,t}$$

The dependent variable $y_{k,i,t}$ is the average daily PM10 reading for each station. $ACTION_k$ is an indicator variable for whether a city is in non-attainment of the PM10 limit and $postACTION_t$ is an indicator for time periods after the assignment of non-attainment status and implementation of an action plan. $treatACTION_{k,t} = ACTION_k * postACTION_t$ is an indicator variable that equals one for non-attainment cities after being found in non-attainment and implementing an action plan, such that $\beta_3$ measures the treatment effect of the action plan. $X_{k,i,t}$ includes station-, city- and time-specific covariates such as weather variables[17], holidays, station type and city population. Because location of the air quality station has a large impact on pollution readings, we include station fixed-effects in all models. Identification comes from the assumption that, after controlling for changes in observables such as weather and time-invariant unobserved heterogeneity between cities, PM10 levels would change the same over the time frame studied in treatment and control cities in the absence of the PM10 regulation.

In our second specification, we separate the treatment of action plans that do and do not include LEZs. To isolate the effect of LEZ's we estimate (2), where $LEZ_k$ is an indicator for being an LEZ city:

$$\text{(2)} \qquad \ln(y_{k,i,t}) = \alpha + \beta_1 \boldsymbol{postLEZ_t} + \beta_2 LEZ_k + \beta_3 LEZtreat_{k,t} + \Psi X_{k,i,t} + v_{k,i,t}$$

Because there are multiple time periods in which LEZs are introduced, the time indicator variables, $\boldsymbol{postLEZ_t}$, are a vector of time periods (Imbens and Wooldridge, 2008). We include year-month fixed effects for this vector, which inherently includes a dummy for the introduction date of all the LEZs[18]. $LEZtreat_{k,t}$ is an indicator variable that equals one for cities having LEZs after the introduction of its LEZ, such that $\beta_3$ measures the treatment effect of the LEZ.

When we compare LEZ cities to cities with LEZs planned but not in effect during our sample (FUTURE LEZ), we use the same specification as in (2), with the FUTURE LEZ cities as the control group.

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[17] Weather variables include daily values of temperature, temperature squared, maximum daily temperature, minimum daily temperature, 1-day lag temperature and maximum temperature, relative humidity, relative humidity squared, 1-day lag relative humidity, wind velocity interacted with whether it rained that day, maximum daily wind velocity, 1-day lag wind velocity, visibility, precipitation, precipitation squared, days without precipitation, temperature interacted with precipitation, temperature interacted with relative humidity, temperature interacted with wind, air pressure, 1-day lag air pressure.

[18] There is one LEZ that started on 1/12/2008, but this was only one street in Dortmund.

Finally, we are interested in to compare traffic stations that are located strictly within an LEZ to the traffic stations outside of the LEZ but in the same city. Analysis of (3) mirrors (2), except that the indicator for having an LEZ, $LEZstation_i$, and the treatment indicator, $LEZstationtreat_{i,t}$, equal unity only for stations within the borders of a city's LEZ. We use this specification to study the effect of the zones within LEZ cities, by comparing the station within LEZs to other stations in the same city outside the LEZ.

(3) $$\ln(y_{k,i,t}) = \alpha + \boldsymbol{\beta_1 postLEZ_t} + \beta_2 LEZstation_i + \beta_3 LEZstationtreat_{i,t} + \Psi X_{k,i,t} + \upsilon_{k,i,t}$$

In all analyses, standard errors are clustered at the city-week level. This allows us to correct for the serial correlation in PM10 levels and any heteroskedacity across stations within a city (see Bertrand et al., 2004).

### 4.2 Matching Stations and Cities

Our identification relies on matching treatment and control cities based on a similar PM10 level prior to the implementation of the clean air action plans. Specifically, we match cities on the annual daily average of the cities' highest-polluting station[19] in 2005. The year 2005 is used since this is the last year that PM10 levels were not affected by action plans or LEZs; at the end of this year, cities in non-attainment of the regulation would have had to institute action plans. Table 5 shows the similarity in 2005 highest-average PM10 levels for the cities used in this analysis. The complete list of cities in Appendix C shows that there are 80 cities that have 2005 highest-station PM10 averages in the range of 25 to 33.5 µg/m³. We do not use cities with PM10 levels below and above the 25 to 33.5 range, since at those ranges there do not exist appropriate pairings of treatment and control cities based on the 2005 PM10 level. Cities found in non-attainment (based on exceedance days) in 2005 are mixed throughout this range, meaning the attainment cities and the non-attainment cities had relatively similar PM10 characteristics in the base year of 2005. We assume, then, that within this group of cities, the 35 day threshold makes the designation of non-attainment status and subsequent development of action plans exogenous. Of these cities, 31 are cities that have never violated the PM10 limits or have had an action plan,

[19] We use the station with the highest 2005 average PM10 reading to match cities since the exceedance of the PM10 regulation is determined by the highest-polluting stations, not the averages across all stations, and thus it is the highest reading within the city that is most important in determining PM10 levels.

which hence serve as our controls C. Nine cities violated the limit in 2005 or 2006 and have an action plan but no LEZ, and 4 cities violated the limit in 2005 or 2006 and have implemented an LEZ before October 2008. There are also four cities that implement an LEZ in October 2008, six cities that have LEZs beginning in 2009 and 2010, and 26 cities that are considering implementing an LEZ as part of their action plan. Since we only have data through October 2008, we count these as action plan only (APO) rather than LEZ cities. We exclude 17 of these cities who either developed an action plan despite never violating the PM10 limit[20] or didn't violate the limit until 2007 (but violated the limit i 2007 or 2008)[21], as these are not unambiguously control or treatment cities.

**Table 5: Treatment and control characteristics**

| | Number of cities | 2005 highest-polluting station avg. | Avg. number of exceedance days | Cities violating PM10 standard 2005-06 |
|---|---|---|---|---|
| No violation or AP | 31 | 27.0 | 22.8 | 31 |
| AP only | 9 | 28.6 | 25.6 | 5 |
| AP with LEZ before Oct. 2008 | 4 | 28.9 | 22.5 | 3 |
| AP with LEZ starting 2009-10 | 10 | 29.2 | 27.8 | 5 |
| AP with LEZ planned with no start date | 26 | 29.1 | 32.2 | 18 |

## 5. Results

### 5.1 Effect of Non-Attainment Status

First we test the effect of being found in violation of the PM10 standard by comparing the cities that developed an action plan without an LEZ only (APO cities) to the attainment cities (C). Although action plans would have started being implemented as early as 2006, there is a lot of variation in exactly when cities were able to enact the details of the plans, i.e. building ring roads or promoting public transportation. To avoid this ambiguity, we compare PM10 levels in

[20] Some cities preemptively implement an action plan to avoid violating the limits in the future, especially considering the tightened limits that go into effect January 1, 2010.

[21] We drop the three cities that did not exceed the threshold until 2007 because those cities' action plans, although formally in effect, might not be yet fully implemented.

the period before being found in non-attainment, 2005, to 2008, when cities violating the standard in 2005 or 2006 had two to three years to implement action plans[22].

Table 6 below shows that the treatment effect is not significantly different from zero at both traffic and background stations for all cities (columns 1-3). When only looking at cities over pop. 100,000, adopting an action plan only is associated with a 4.5 percent decrease in PM10 at traffic stations, significant at the five percent level (column 5), although the effects at background stations and both stations together are insignificant (column 4 and 6).

**Table 6: Effect of action plan only on log PM10, Jan-Oct 2005 vs. 2008**

| | All cities | | | All cities >100,000 | | |
|---|---|---|---|---|---|---|
| | All station types | Traffic stations | Background stations | All station types | Traffic stations | Background stations |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Treatment effect | 0.000459 | 0.00336 | -0.0229 | -0.00658 | -0.0447** | 0.00521 |
| | [0.0123] | [0.0147] | [0.0180] | [0.0175] | [0.0208] | [0.0214] |
| Observations | 35097 | 18710 | 16387 | 19354 | 9036 | 10318 |
| Adjusted R-squared | 0.599 | 0.624 | 0.564 | 0.616 | 0.639 | 0.583 |

All regressions include year-month fixed effects, weather, holiday, station type and population covariates
*** p<0.01, ** p<0.05, * p<0.1; Robust standard errors clustered by city-week in brackets

Next Table 7 shows how PM10 changed for all AP cities (all APO cities and all LEZ cities) compared to the control cities (C). Again, for the larger cities with a population above 100,000, there is no significant change in PM10 except for a small increase among background stations that is only significant at the ten percent level (columns 4-6). Among all cities, including the smaller cities below 100,000 PM10, however, PM10 slightly increases by 2.8 percent for AP cities (column 1), with most of this increase coming from a 3.0 percent increase at traffic stations while there is no increase at background stations (columns 2 and 3).

In summary, despite the fact that overall PM10 levels decreases since 2006, there is little evidence that implementing an action plan contributes to additional decreases in PM10. We now turn to the evaluation of the LEZ program.

[22] These regressions only include January through October since we do not have 2008 PM10 data in November and December.

**Table 7: Effect of non-attainment status on log PM10, Jan-Oct 2005 vs. 2008**

| | All cities | | | All cities >100,000 | | |
|---|---|---|---|---|---|---|
| | All station types | Traffic stations | Background stations | All station types | Traffic stations | Background stations |
| | (1) | (2) | (3) | (4) | (5) | (6) |
| Treatment effect | 0.0282** | 0.0304** | 0.00831 | 0.0206 | -0.0204 | 0.0368* |
| | [0.0117] | [0.0143] | [0.0168] | [0.0168] | [0.0204] | [0.0204] |
| Observations | 38613 | 20405 | 18208 | 22288 | 10149 | 12139 |
| Adjusted R-squared | 0.603 | 0.624 | 0.569 | 0.621 | 0.641 | 0.589 |

All regressions include year-month fixed effects, weather, holiday, station type and population covariates
*** p<0.01, ** p<0.05, * p<0.1; Robust standard errors clustered by city-week in brackets

### 5.2 Effect of action plans and LEZs

In this section, we isolate the treatment effect of having LEZs as part of an action plan. Table 8 below shows the results of comparing the four LEZs within our 25 to 33.5 range of 2005 PM10 levels that began before October 2008—Cologne, Mannheim, Reutlingen and Leonberg—to the attainment control cities as above. Since there is a set date for the LEZ treatment to begin in 2008, whereas the action plan treatment was spread out over 2006 to 2008, we use 2007 as the baseline year. This allows us to avoid any other confounding events that might have affected PM10 differently due to the city specific contents of the action plans between 2004 and 2006. We use April through October data to estimate Equation (2), since the Mannheim, Reutlingen and Leonberg LEZs didn't take effect until March 2008 and we are allowing a one month lag for the city to adjust to the policy[23].

**Table 8: LEZ vs. Attainment cities, April-October 2007 vs. 2008**

| | (1) | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|---|
| | All cities | | | Cities >100,000 | | |
| | All station types | Traffic stations | Background stations | All station types | Traffic stations | Background stations |
| Treatment effect | -0.0169 | -0.0647*** | 0.0197 | 0.0184 | -0.0482* | 0.0611** |
| | [0.0182] | [0.0193] | [0.0236] | [0.0215] | [0.0249] | [0.0251] |
| Observations | 16,240 | 7,252 | 8,988 | 8,561 | 3,425 | 5,136 |
| Adjusted R-squared | 0.595 | 0.636 | 0.543 | 0.621 | 0.617 | 0.581 |

All regressions include year-month fixed effects, weather, holiday, station type and population covariates
*** p<0.01, ** p<0.05, * p<0.1; Robust standard errors clustered by city-week in brackets

[23] In some of the early LEZs, like Berlin, in the first few weeks often drivers were only warnings and not tickets. not ticketed immediately, but first a warning was spelled out.

As Table 8 shows, these four LEZs have lowered PM10 levels at traffic stations. On average there is a decrease of 6.5 percent among all traffic stations (column 2) and 4.8 percent among traffic stations in cities over population 100,000 (column 4). The treatment effect at background stations is opposite, however. In the bigger cities, there is actually a 6.1 percent increase in PM10 after the LEZ takes effect (column 6). Thus while pollution may decrease on the major roads, this decrease is not being realized outside of these high-traffic areas. In the regressions to follow we find this result holds for most LEZ cities: they see an increase in PM10 at background stations relative to their counterparts who have not initiated LEZs yet. This could be further evidence that traffic is being diverted from downtown areas, actually increasing PM10 in the outlying areas.

Table 9 shows the effect of each of the four LEZs separately. Each LEZ is compared to a smaller three to four PM10 µg/m³ band of control cities based on the 2005 PM10 readings.[24] Panel A shows that the Mannheim LEZ decreased PM10 considerably at traffic stations—between 14 and 22 percent when looking at all control and the larger control city[25], respectively—while PM10 levels rose 10 percent at background stations. Panel B shows that none of the treatment effects are significant for the Cologne LEZ, although the coefficients are negative for the traffic stations, while mixed for all background stations versus background stations in large cities. The Reutlingen LEZ, on the other hand, is actually associated with an increase in PM10 according to Panel C, although the coefficients are only significant when using large comparisons for background stations only (9.2 percent) and background and traffic stations together (6.1 percent). Panel D shows that the Leonberg LEZ decreased PM10 at its only traffic station between 5 and 7 percent depending on whether controlled to all cities or only cities under population 100,000 (Leonberg is under pop. 100,000). Thus while it is clear there is some heterogeneity if the effects of these LEZs, there is a trend that LEZs are associated with decreases in PM10 primarily at traffic stations, while PM10 increases at background stations.

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[24] Colonge and Leonberg are compared to attainment cities with highest 2005 PM10 readings between 25 and 27.5; Reutlingen is compared to attainment cities with 2005 readings between 27.7 and 30.2; Mannheim is compared to attainment cities between 30 and 33.5.

[25] Columns 1a-3a compare Mannheim to Münster and Fürth, while columns 4a-6a only compare to the Münster, which is closer in size and 2005 PM10 levels.

## Table 9: Effect of individual LEZs on log PM10

| | All cities | | | All cities >100,000 | | |
|---|---|---|---|---|---|---|
| | All station types | Traffic stations | Background stations | All station types | Traffic stations | Background stations |
| | Mannheim LEZ (Apr-Oct) | | | | | |
| | (1a) | (2a) | (3a) | (4a) | (5a) | (6a) |
| Treatment effect | -0.0159 | -0.144*** | 0.109** | -0.0272 | -0.222*** | 0.109** |
| | [0.0394] | [0.0367] | [0.0535] | [0.0442] | [0.0404] | [0.0535] |
| Observations | 2542 | 1258 | 1284 | 2114 | 830 | 1284 |
| Adjusted R-squared | 0.639 | 0.679 | 0.563 | 0.641 | 0.677 | 0.563 |
| | Cologne LEZ (Feb-Oct) | | | | | |
| | (1b) | (2b) | (3b) | (4b) | (5b) | (6b) |
| Treatment effect | -0.0121 | -0.0227 | -0.00758 | 0.0152 | -0.00744 | 0.0267 |
| | [0.0334] | [0.0396] | [0.0347] | [0.0330] | [0.0396] | [0.0342] |
| Observations | 12582 | 5471 | 7111 | 5471 | 1642 | 3829 |
| Adjusted R-squared | 0.59 | 0.616 | 0.571 | 0.595 | 0.604 | 0.574 |
| | Reutlingen LEZ (Apr-Oct) | | | | | |
| | (1c) | (2c) | (3c) | (4c) | (5c) | (6c) |
| Treatment effect | 0.0167 | 0.00819 | 0.0413 | 0.0607* | 0.0493 | 0.0923** |
| | [0.0319] | [0.0381] | [0.0450] | [0.0331] | [0.0401] | [0.0421] |
| Observations | 4307 | 1739 | 2568 | 2595 | 1311 | 1284 |
| Adjusted R-squared | 0.556 | 0.58 | 0.52 | 0.639 | 0.612 | 0.627 |
| | Leonberg LEZ (Apr-Oct) | | | | | |
| | All cities | | | All cities <100,000 | | |
| | (1d) | (2d) | | (4d) | (5d) | |
| Treatment effect | -0.0567* | -0.0567* | | -0.0738** | -0.0619* | |
| | [0.0298] | [0.0307] | | [0.0308] | [0.0318] | |
| Observations | 8963 | 4255 | | 5967 | 3399 | |
| Adjusted R-squared | 0.584 | 0.618 | | 0.596 | 0.627 | |

All regressions include year-month fixed effects, weather, holiday, station type and population covariates

*** p<0.01, ** p<0.05, * p<0.1; Robust standard errors clustered by city-week in brackets

### 5.3 Individual LEZ results

As a robustness check of whether the preceding results hold, we more carefully analyze the major LEZs by comparing them to nearby cities using the difference-in-differences approach specified in Equation (2). There are multiple advantages of looking at each LEZ one-by-one. First, weather and geography vary considerably across Germany and this approach allows us to fit a separate weather model for each region. Second, given the differences in the size of the LEZs, it is likely that there will be heterogeneity in their effectiveness. we make use of the staggered system of the introduction of LEZs, by comparing current LEZ to future LEZ cities. Hence we compare LEZ cities that violated the limits in 2006 and/or 2007 to cities that are also in non-attainment, also violating the limits in 2006 and/or 2007 but decided--for one reason or another--to set the introduction date of the LEZ at a later point. This procedure, however, comes at the cost that we do not primarily match on 2005 PM10 levels, but we rather match on (a) the fact that all cities consider to implement an LEZ, (b) geography and (c) city size.The identification in this section comes from the assumption that there are no systematic differences in changes in LEZ cities' PM10 levels based on when they implemented their LEZ beyond the effect of the LEZ.

In the plots below, for each LEZ city we present the DD treatment effect coefficients with 95 percent confidence intervals from comparing both the background and traffic stations to neighboring future LEZ cities[26]. These control cities are ranked in terms of how similar they are to the LEZ city in terms of location, population and pre-regulation PM10 levels, such that the top cities in each plot are the 'best' controls for each LEZ. In addition, for the LEZ cities that have stations both within and outside of the LEZ, we show how PM10 levels have changed within the city, per Equation (3).

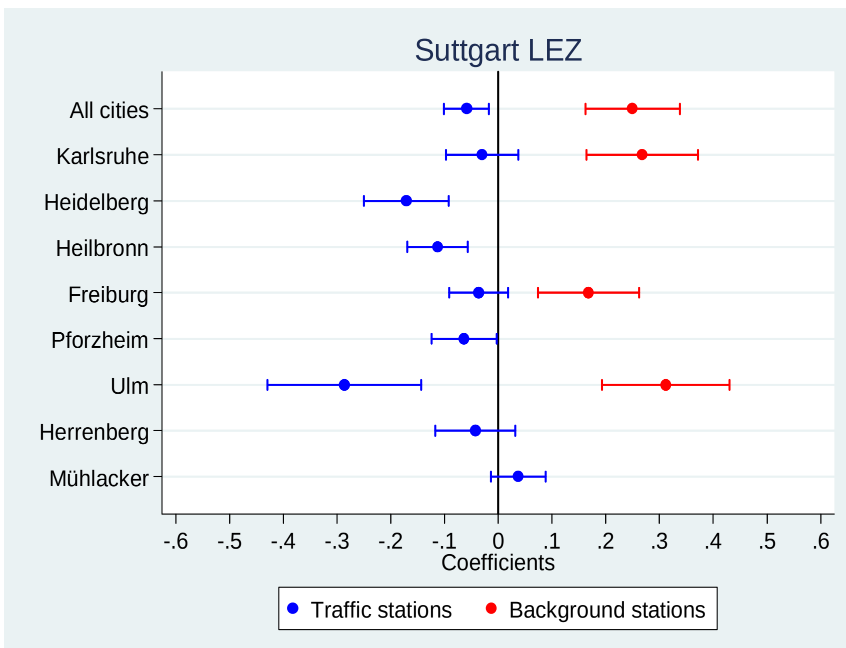
The following regional regressions are consistent with the above findings. LEZs decrease air pollution in high-traffic areas, but outside of these areas emissions tend to increase.

[26] Regressions control for year-month fixed effects, station fixed effects, day of week fixed effects, holidays, polynomial and lagged weather variables.

### 5.3.1 Baden-Württemberg

The largest concentration of early LEZs is in the state of Baden-Württemberg. In the greater Stuttgart area, LEZs came into effect on March 1, 2008, in Stuttgart, Ludwigsburg, Tubingen, Leonberg, Reutlingen, Ilsfeld and Pleidelsheim. For the Stuttgart LEZ—the largest city in Baden-Württemberg and largest LEZ by area in Germany—the LEZ has had a negative effect on PM10 levels at traffic stations when compared to traffic stations at all but the least appropriate nearby future LEZ control city (Mühlacker). As shown below in Figure 5, except for one outlier, Ulm, all the coefficients are close to the average treatment effect of a 6.0 percent decrease in PM10. At background stations, however, all the coefficients are positive, meaning there has been an increase in background levels of PM10 in Stuttgart relative to other non-LEZ cities.

**Figure 5: Stuttgart LEZ**




**For the Tübingen, a city 44 kilometers southwest of Stuttgart, the story is very similar. As shown in**

Figure 6, the treatment effect is negative for all nearby future LEZ cities except Mühlacker, and all the coefficients besides Ulm are around the average 5.9 percent decrease in PM10. Again, the coefficients on background stations are all positive.

In nearby Ludwigsburg (Figure 7), the effect of the LEZ is not as clear. With the exception of Ulm, all the coefficients are close to zero, with most confidence intervals including positive and negative numbers. This may be because although Ludwigsburg is the second largest city in Baden-Württemberg, its LEZ is much smaller—30 km$^2$ and 55,000 inhabitants, versus Stuttgart's 207 km$^2$ and 590,000 inhabitants.

Leonberg is a considerably smaller city in the greater-Stuttgart area. As shown in Figure 8 above, the results when comparing to other smaller future LEZ cities are mixed and generally not significantly different from zero. We do not study the LEZs in Ilsfeld and Pleidelshiem because these cities are very small.

**Figure 6: Tübingen LEZ**

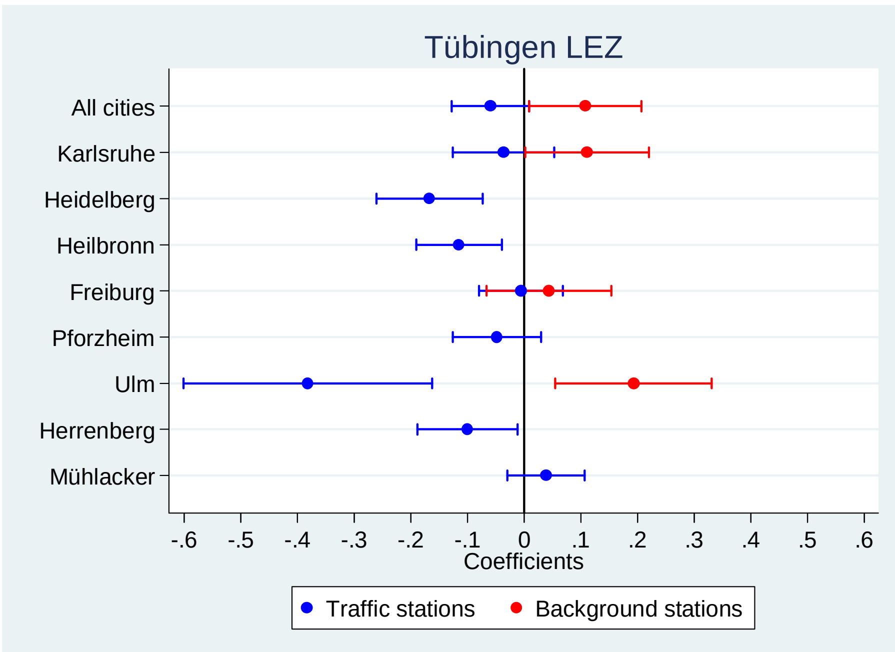


**Figure 7: Ludwigsburg LEZ**

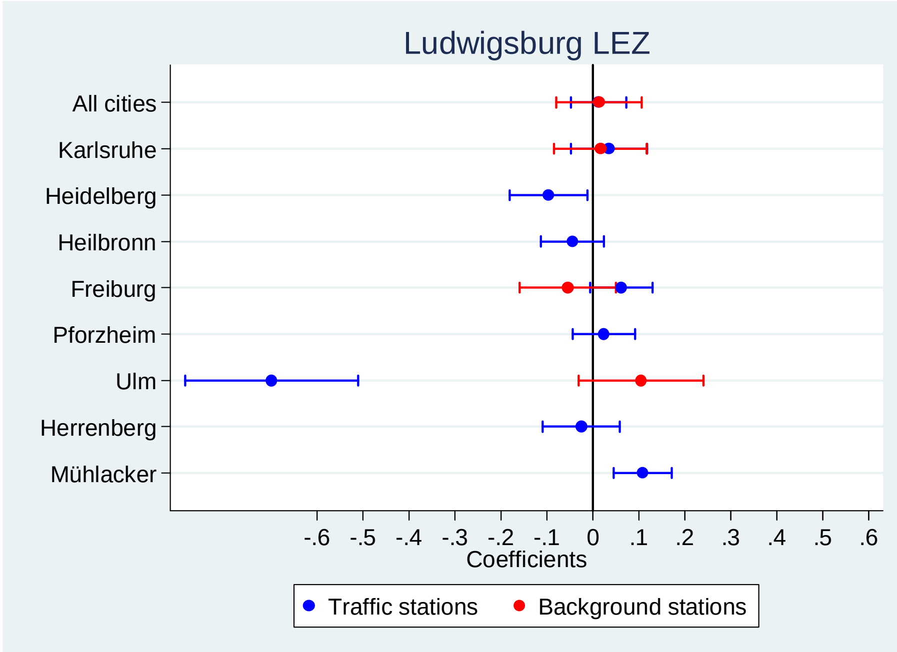
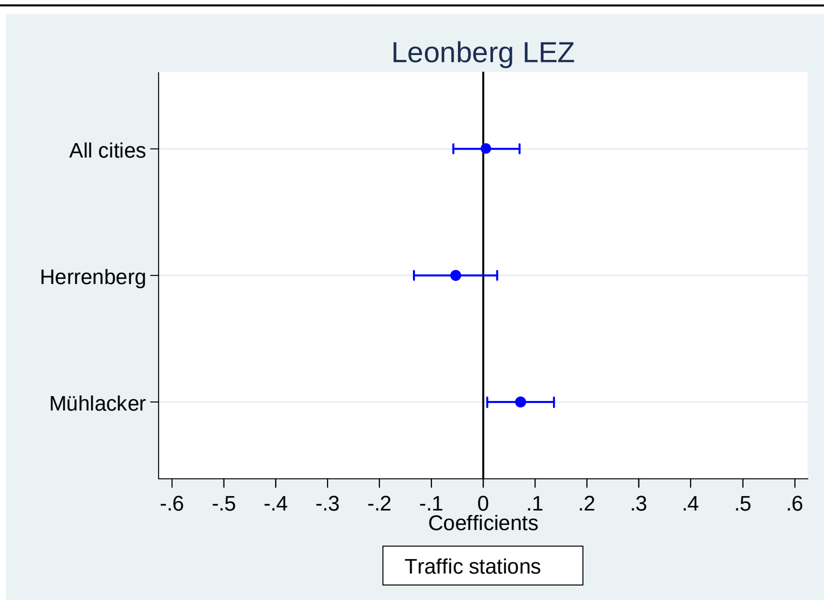


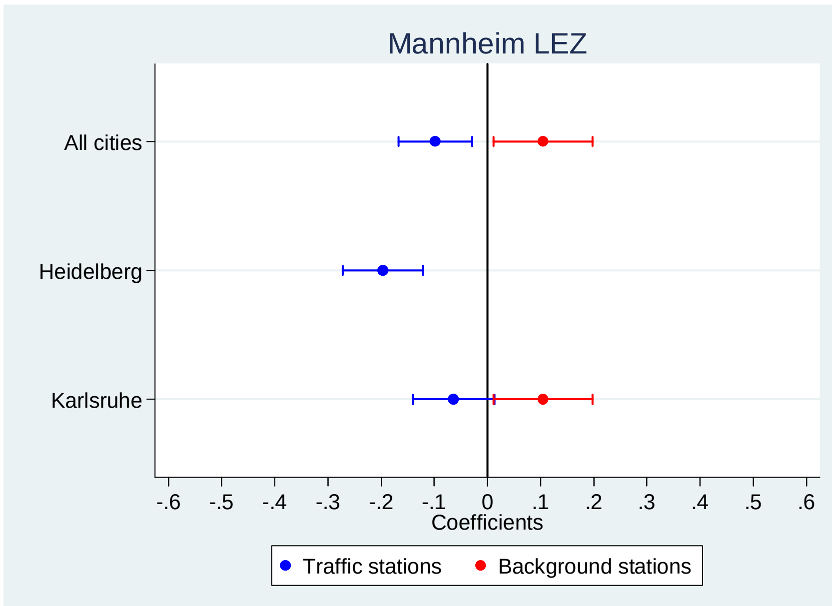

**Figure 8: Leonberg LEZ**




Outside of the greater-Stuttgart area, there is an LEZ in Mannheim, Baden-Württemberg's third-largest city. While this LEZ is relatively small at 7.5 $km^2$, it covers 93,000 inhabitants.

The treatment effect when comparing Mannheim (Figure 9) to nearby future LEZ cities Heidelberg and Karlsruhe are negative for traffic stations (average -9.7 percent) and positive for background stations (average 10.4 percent).

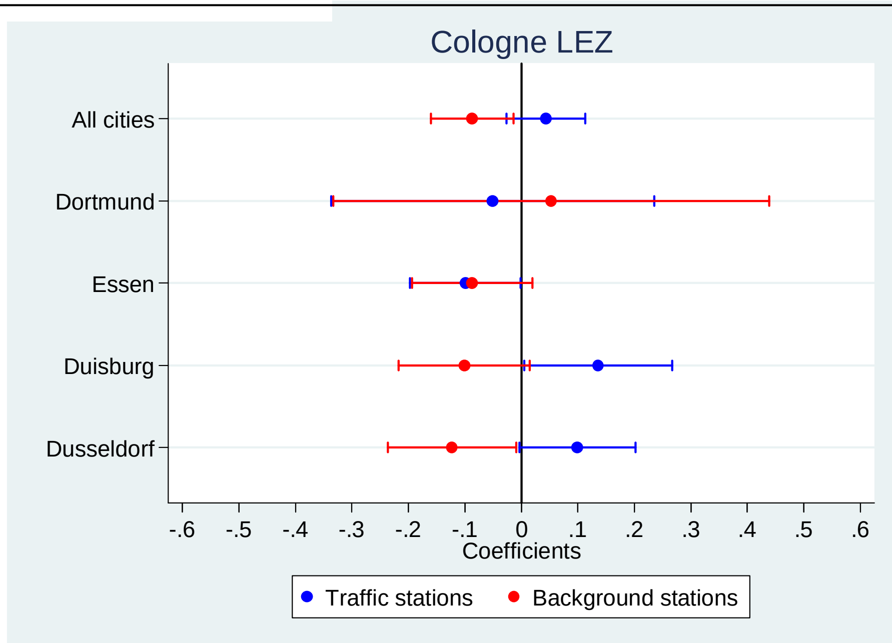
**Figure 9: Mannheim LEZ**




### 5.3.2 North Rhine-Westphalia

Cologne is the only LEZ in North Rhine-Westphalia that came into effect in January 2008. After Cologne, the next four largest cities in the state—Dortmund, Essen, Düsseldorf and Duisburg—all have LEZs planned (all starting October 2008 except Düsseldorf, which began February 2009). As seen in Figure 10 below, the coefficients for the Cologne LEZ regressions are rather different from those seen in Baden-Württemberg, with the traffic stations experiencing more increases in PM10 after the LEZ took effect and the background stations experienced more decreases in PM10.

**Figure 10: Cologne LEZ**

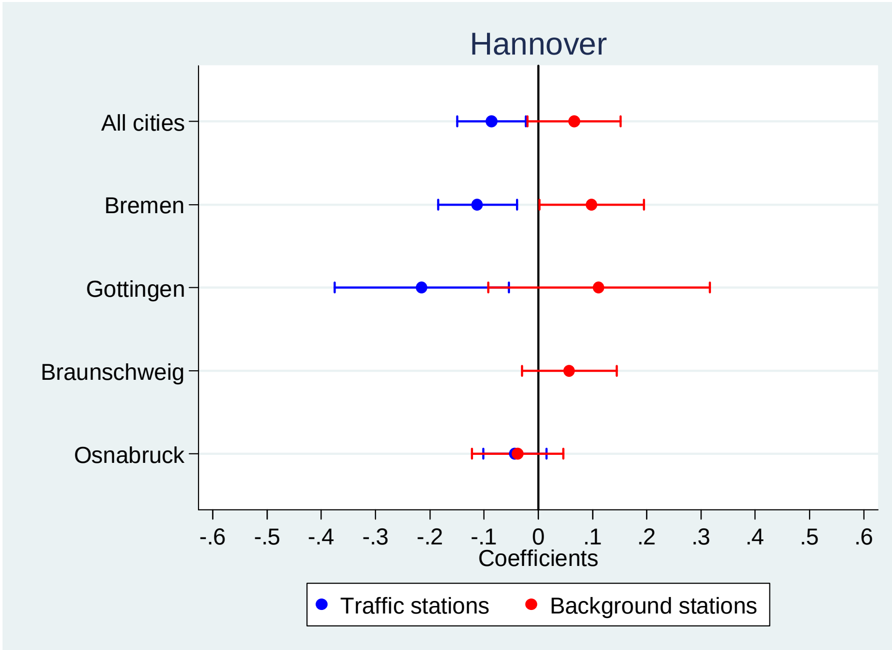



### 5.3.3 Hannover

The LEZ in Hannover is mid-size, covering 50 km$^2$ and 218,000 inhabitants. Similar to the other LEZs, Figure 11 shows that all of the coefficients for traffic stations are negative (average 8.6 percent decrease), and all but one of the coefficients for background stations is positive (average 6.6 percent increase).[27]

[27] In this case we compare Hannover to two action plan cities without LEZs planned, Göttingen and Osnabruck, since there were not many nearby similar cities with LEZs planned.

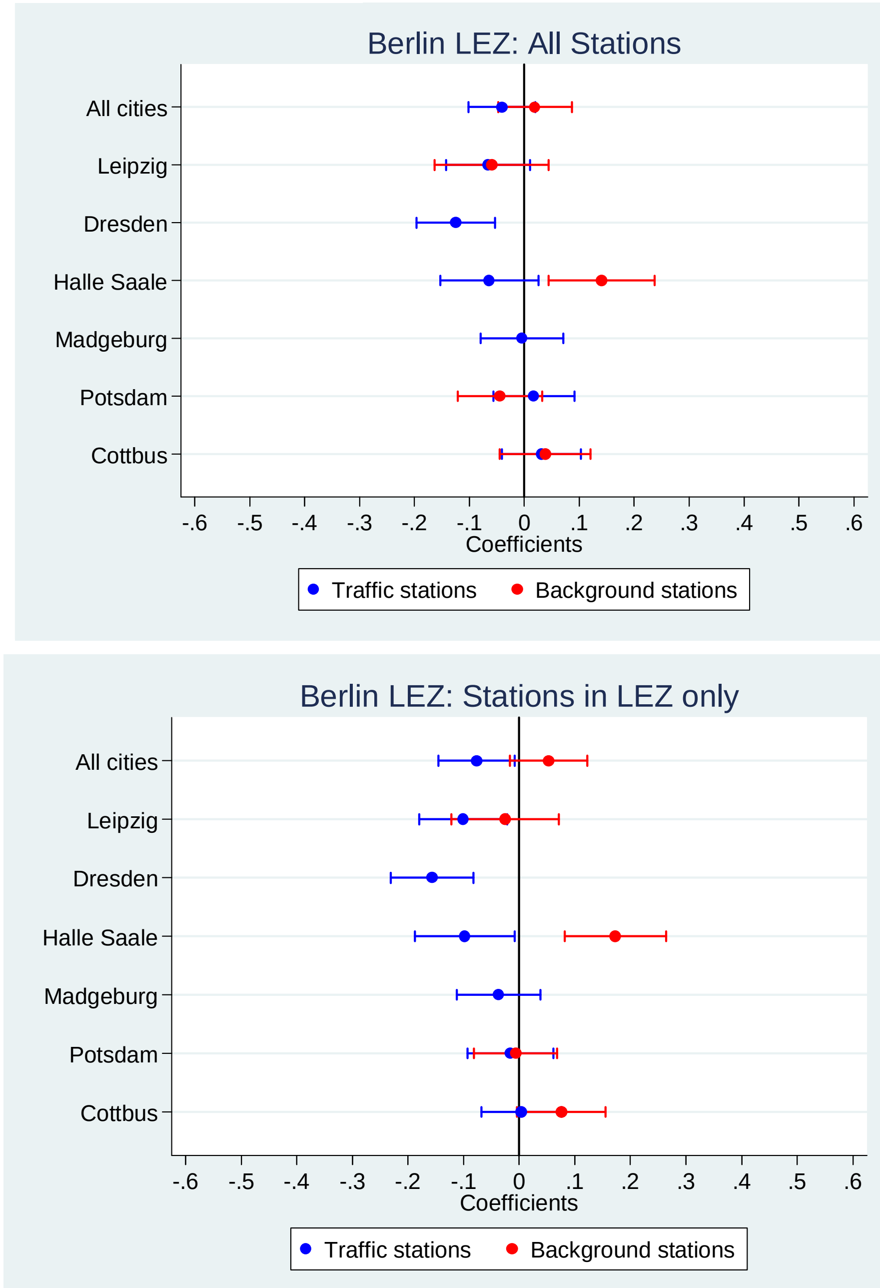
**Figure 11: Hannover LEZ**




### 5.4 Berlin

Our last section analyzes Berlin, the only city for which we have background and traffic stations both within the LEZ and outside of the LEZ. The Berlin LEZ is the largest by inhabitants, covering 88 $km^2$ and 1.1 million people. While the LEZ officially started January 1, 2008, police did not start ticketing cars until March 1, 2008, so we define the LEZ treatment as starting in March and drop January and February since the effect of the LEZ will be ambiguous in these months. Unlike most LEZ cities, we have both traffic and background stations within and outside of the Berlin LEZ. The first panel of Figure 12 shows the coefficients when including all Berlin stations in the city-by-city comparisons, while the second panel looks only at stations within the LEZ. The treatment effect of the LEZ is mostly negative for traffic stations, especially amongst the 'better' control cities. The coefficients are larger when looking at stations within the LEZ only, with an average decrease in PM10 of 7.6 after introduction of the LEZ, implying that the LEZ lowered PM10 more on roads within the LEZ that roads outside of the LEZ. The story at background stations is less clear, with the treatment effect being positive when comparing to some cities and negative when comparing to others.

**Figure 12: Berlin LEZ**




To further explore this, Table 10 shows the results of estimating (3), where the stations within the Berlin LEZ are compared to those stations within Berlin but outside of the LEZ. The traffic stations within the LEZ experience a 6.7 percent decrease in PM10 relative to traffic stations outside the LEZ, either because PM10 emissions are decreasing within the LEZ, or emissions are increasing outside of the LEZ as cars are forced to drive around it. This decrease is 7.7 percent during for weekdays, implying the LEZ is slightly more binding for weekday commutes. Conversely, the background stations within the LEZ see an increase in PM10 after the LEZ takes effect than the background stations outside the LEZ.

**Table 10: Berlin LEZ: Stations within LEZ compared to those outside**

| | (1) | (2) | (3) | (4) |
|---|---|---|---|---|
| | Traffic stations | | Background stations | |
| | All days | Mon-Fri | All days | Mon-Fri |
| LEZ treatment | -0.0668*** | -0.0768*** | 0.0568*** | 0.0585*** |
| | [0.0217] | [0.0243] | [0.0127] | [0.0145] |
| Observations | 1960 | 1400 | 2938 | 2098 |
| Adjusted R-squared | 0.628 | 0.632 | 0.675 | 0.69 |

Robust standard errors in brackets, *** p<0.01, ** p<0.05, * p<0.1

## 6. Spatial Substitution between low and high emission cars.

One important argument in favor of the four-tier PM10 categorization is that it leads to a more rapid adoption of cleaner technologies since even vehicle owners who do not typically drive into an LEZ may want to keep the option value of free passage. The next task of this paper studies the adoption of lower emitting vehicles and changes in the spatial composition of the vehicle fleet. Using a unique panel dataset that provides the emission category and registration location of each privately and commercially owned German vehicle from 2006 to 2009, we analyze the spatial substitution effects in purchasing new vehicles and retrofitting existing high emission cars due to the LEZ regulation.

### 6.1 Data

Data were obtained by Federal Motor Transport Authority (Kraftfahrtsbundesamt Flensburg) in Germany. Yearly observation of the total number of cars by emission type (red, yellow, green, no sticker) for all German districts, recorded as of January 1st, are available for the period of 2006 to 2009. Also, we have information on whether the vehicle is privately owned or commercial used, including all of the commercial trucks.

Various German district reforms led to changes in the geographical boundaries of the districts between 2006 and 2009. To account for these changes, several original counties had to be merged into larger geographical units. As a result, the 411 current German districts (as of 2009) are reduced in our final dataset to 405 "counties".[28] The details of this procedure are outlined in Appendix E. **Error! Reference source not found.** summarizes the composition of the German vehicle fleet and **Error! Reference source not found.** shows how it has changed since 2006.

**Table 11: Vehicle Registration by emissions sticker category private vehicles**

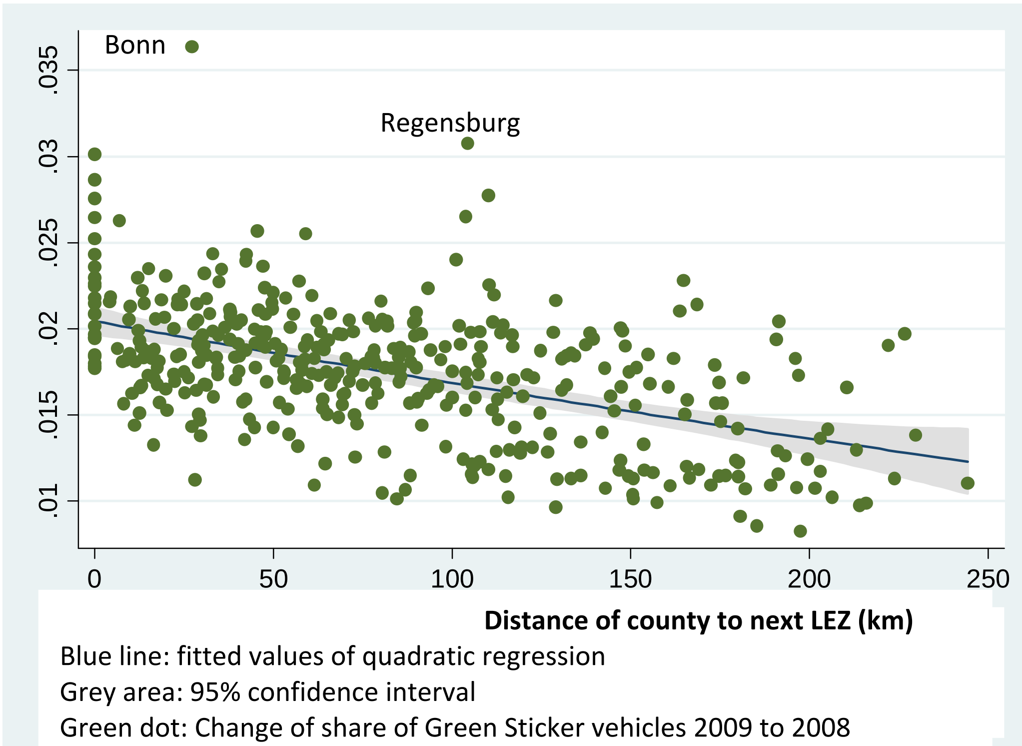
| | Private Vehicles | | | | | |
|---|---|---|---|---|---|---|
| | 2006 | 2007 | 2008 | 2009 | % change 2007 vs. 06 | % change 2009 vs. 08 |
| Green | 31,039,096 | 33,226,606 | 34,020,748 | 34,862,420 | 7.05 | 2.47 |
| Yellow | 7,839,624 | 6,428,598 | 3,931,262 | 3,597,594 | -18.00 | -8.49 |
| Red | 1,781,310 | 1,634,275 | 1,267,825 | 1,092,315 | -8.25 | -13.84 |
| No Sticker | 4,885,299 | 4,656,493 | 1,597,089 | 1,381,064 | -4.68 | -13.53 |
| Total | 45,545,329 | 45,945,972 | 40,816,924 | 40,933,393 | 0.88 | 0.29 |

**Table 12: Vehicle Registration by emissions sticker category commercial vehicles**

| | Private Vehicles | | | | | |
|---|---|---|---|---|---|---|
| | 2006 | 2007 | 2008 | 2009 | % change 2007 vs. 06 | % change 2009 vs. 08 |
| Green | 1,005,633 | 897,017 | 609,948 | 792,577 | -10.80 | 29.94 |
| Yellow | 1,045,213 | 1,132,907 | 945,181 | 844,803 | 8.39 | -10.62 |
| Red | 28,408 | 163,166 | 469,853 | 413,133 | 474.37 | -12.07 |
| No Sticker | 734,275 | 658,928 | 524,542 | 518,545 | -10.26 | -1.14 |
| Total | 2,813,529 | 2,852,018 | 2,549,524 | 2,569,058 | 1.37 | 0.77 |

[28] Counties is written in parenthesis because these "counties" include larger geographical regions due to the various mergers.

**Figure 13: Change of share of Green Sticker vehicles 2009 to 2008 as function of distance of the county to LEZ (privately owned cars)**




In the following we analyze the composition of the fleet of privately owned vehicles in 2008 and 2009. Figure 13 shows that between 2009 and 2008 the difference in the share of Green Sticker vehicles (the cleanest technology) is between 0.01 and 0.035 share points. Moreover, the Figure shows that closer the counties are located to an LEZ, the starker the increase in green stickers.

Visually, in the scatter plot of Figure 13, Regensburg and Bonn are outliers. It turns out however, that these cities' special circumstances can easily explain their greater adoption of green sticker cars. In 2007, the local government of Regensburg announced the introduction of an LEZ in spring 2008, then decided to postpone the introduction until September 1st of 2008. However, this date was then again postponed for prospectively January of 2010 (Stadt Regensburg, 2008). We see that with the announcements however, the inhabitants of Regensburg already preemptively responded in upgrading their vehicles. The second outlier is Bonn. It is just a very short drive to Cologne–over highway 555 or highway 59–with (partially) no speed limits. This closeness of Bonn to Cologne provides an incentive to obtain a green sticker.

Figure 14 shows that between 2009 and 2008, the difference of the share is negative of private cars that have the dirtiest technology (No sticker) for all counties in Germany. Moreover, the Figure shows that closer the counties are located to an LEZ, the starker the decrease in No stickers.

Figure 15 and Figure 16 show the changes in shares of yellow and red sticker vehicles, respectively. Here the changes are more uniformly across different counties. This is not too surprising since these are middle categories, which are banned by few of the current LEZs.

In summary, we find evidence that the introduction of LEZs does create an incentive for drivers to substitute towards lower-emitting vehicles.  The closer a county is to an LEZ, the more likely its citizens have been to substitute away from the dirtiest cars and towards the cleanest cars.

**Figure 14: Change of share of No Sticker vehicles 2009 to 2008 as function of distance of the county to LEZ (privately owned cars)**

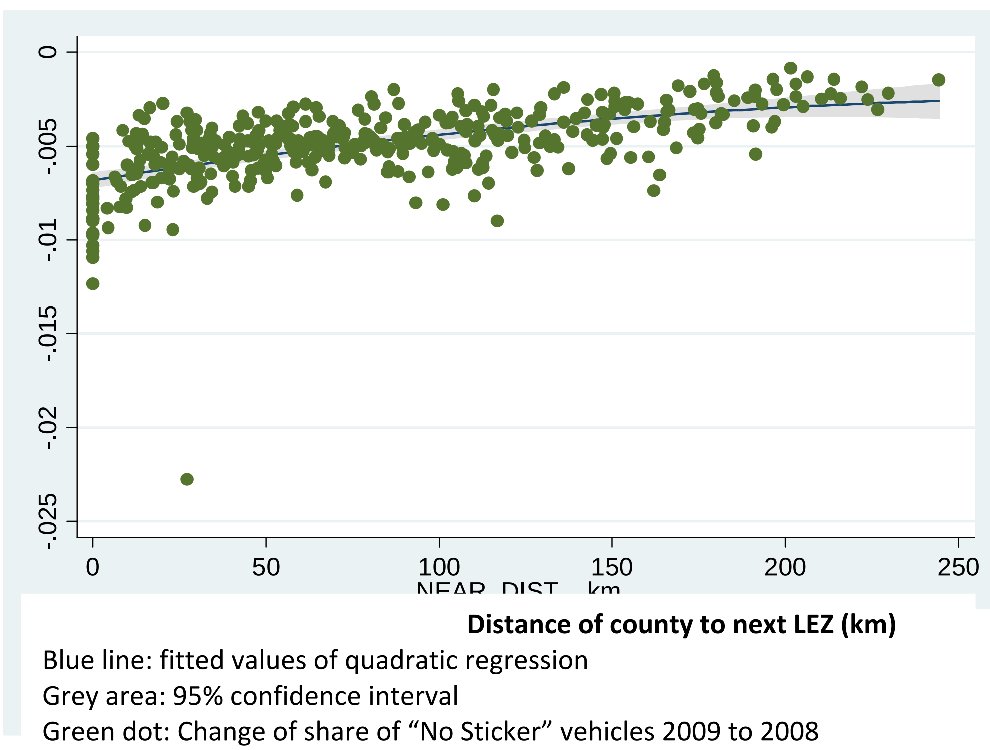
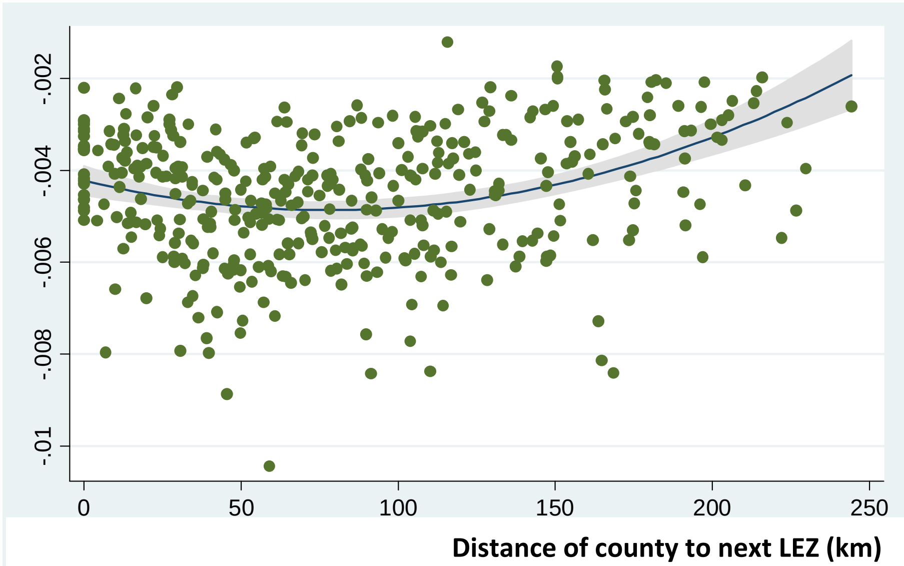
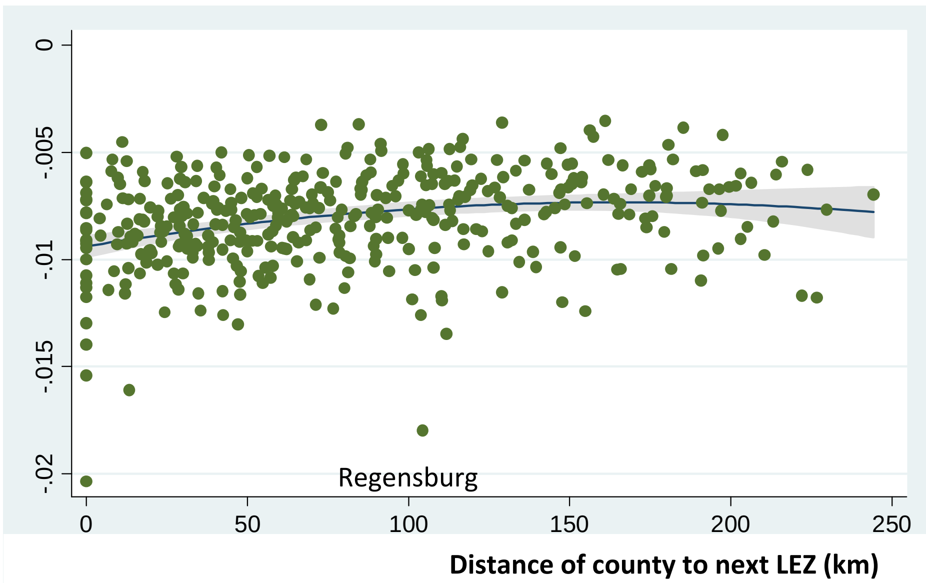


**Figure 15: Change of share of Red Sticker vehicles 2009 to 2008 as function of distance of the county to LEZ (privately owned cars)**




Blue line: fitted values of quadratic regression
Grey area: 95% confidence interval
Green dot: Change of share of Red Sticker vehicles 2009 to 2008

**Figure 16: Change of share of Yellow Sticker vehicles 2009 to 2008 as function of distance of the county to LEZ (privately owned cars)**




Blue line: fitted values of quadratic regression
Grey area: 95% confidence interval
Green dot: Change of share of Yellow Sticker vehicles 2009 to 2008

## 7. Conclusions

The 2005 passage of the European Union Clean Air directive and the resulting establishments of the Low Emission Zones (LEZ) marked an unprecedented attempt to mandate lower levels of air pollution in order to protect the public health in the European Union. In the case of particulate matter, thought to be the most malicious form of air pollution, the EU set maximum allowable concentrations that every measurement station in the EU is required to meet. Those cities exceeding the allowable concentration must implement clean air action plans, which have led to a multiplicity of urban policy measures. Different forms of implemented traffic restrictions range from increasing traffic toll payments (i.e. London), environmental zones (i.e. Berlin, Munich) or temporal complete traffic restrictions (Milan). It is debated however, whether these methods work efficiently and which one is the most appropriate. This is of urgent importance as the PM10 regulations will be substantially tightened in 2010, and many more cities will have to implement policies to decrease pollution levels. This paper quantitatively assesses LEZs, a policy popular in Germany, in terms of (a) air pollution outcomes and (b) the effects on the spatial substitution between high and low emission cars.

This paper seeks to contribute to the environmental evaluation literature by assessing the consequences of the widespread adoption of LEZs across German cities. Our results imply that success of LEZs in lowering PM10 levels is mixed. Some of the biggest LEZs, such as Stuttgart and Berlin, appear to have lowered PM10 at traffic air quality monitors within the LEZ. For the one LEZ where we can compare traffic stations both inside and outside of the LEZ, Berlin, there is a difference in the effectiveness of the LEZ—either the PM10 is decreasing more in the LEZ than in surrounding areas, or drivers are increasing emissions outside of the LEZ by driving around it. Consistently with the last assertion, most LEZ cities have seen an increase in PM10 at background stations relative to their counterparts who have not initiated LEZs yet. This could be further evidence that traffic is being diverted from downtown areas, actually increasing PM10 in the outlying areas. It could also imply that cities that implement LEZs later may spend more time on other action plan items that decrease pollution across the city, not just in urban city centers.

To summarize, we find that the there is some evidence that LEZs have been effective at lowering PM10 levels by four to seven percent. Furthermore we find that developing an action plan only, but not having an LEZ, so far has not led to significant reductions in PM10 levels. Most cities' LEZs will become more stringent in the coming years, however, so the ultimate effect of LEZs is still an open question.

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## APPENDIX A: Data

To calculate daily averages, we first simply linearly impute the missing hourly readings throughout the day[29]. Once we have daily averages, we interpolate the missing daily averages for the 1.4 percent of days with no readings.

To make sure our results are not driven by changes in monitoring station composition, we restrict our analysis to PM10 readings for stations that have readings for all of the years included in each analysis[30].

[29] Among stations reporting half-hourly or hourly data, less than seven percent of days are missing observations for some hours over 70 percent of these being three hours or less. This imputation is done through linear interpolation

[30] We define a station as having complete data for 2007 if there is data for at least 340 of the 365 days of the year. Since we only have data through October of 2008, a station has complete data for 2008 if there is data for 280 of the 305 possible days.

## Appendix B: Current and Future German LEZs

| City | Start date | Excluded vehicles | Size of LEZ | Inhabitants | Dates of future restrictions (2nd round, 3rd round) | Future excluded vehicles (2nd round, 3rd round) |
|---|---|---|---|---|---|---|
| **Study LEZs (LEZs beginning in 2008)** | | | | | | |
| Berlin | 1/1/2008 | no sticker | 88 sq. km | 1.1 mill | 1/1/10 | red + yellow |
| Bochum | 10/1/2008 | no sticker | 58.1 sq. km | 150,000 | end of 2010 | red + yellow |
| Bottrop | 10/1/2008 | no sticker | ≈50 sq. km | n/a | end of 2010 | red + yellow |
| Dortmund | 10/1/2008 | no sticker | 19.1 sq. km | 587,137 | 1/1/11 | red |
| Dortmund (Brackeler Strasse) | 1/12/2008 | no sticker + red | < 0.1 sq. km | 300 | 1/1/10 | not yet planned |
| Duisburg | 10/1/2008 | no sticker | ≈ 100 sq. km | Unknown | end of 2010 | red + yellow |
| Essen | 10/1/2008 | no sticker | 140 sq. km | 14,00 | 1/1/11 | red |
| Frankfurt | 10/1/2008 | no sticker | 110 sq. km | n/a | 01/01/10, 01/01/12 | red, yellow |
| Gelsenkirchen | 10/1/2008 | no sticker | 20 sq. km | n/a | end of 2010 | red + yellow |
| Hannover | 1/1/2008 | no sticker | 50 sq. km | 218,000 | 01/01/09, 01/01/10 | red, yellow |
| Ilsfeld | 3/1/2008 | no sticker | 2.5 sq. km | 4,000 | 01/01/12, not yet planned | red, yellow |
| Köln | 1/1/2008 | no sticker | 16 sq. km | 130 | 01/01/10, not yet planned | red, yellow |
| Leonberg | 3/1/2008 | no sticker | 30 sq. km | 40,000 | 01/01/12, not planned | red, yellow |
| Ludwigsburg | 3/1/2008 | no sticker | 30 sq. km | 55,000 | 1/1/12 | red |
| Mannheim | 3/1/2008 | no sticker | 7.5 sq. km | 93,900 | 01/01/12, not yet planned | red, yellow |
| München | 10/1/2008 | no sticker | 44 sq. km | 431,000 | 01/01/10, not planned | red, yellow |
| Oberhausen | 10/1/2008 | no sticker | 23.8 sq. km | 91,000 | end of 2010 | red + yellow |
| Pleidelsheim | 7/1/2008 | no sticker | 7 sq. km | 7,000 | 01/01/12, not yet planned | red, yellow |
| Recklinghausen | 10/1/2008 | n/a | <20 sq. km | n/a | n/a | n/a |
| Reutlingen | 3/1/2008 | no sticker | <10 sq. km | n/a | 1/1/12 | red |
| Schwäbisch Gmünd | 3/1/2008 | no sticker | 5 sq. km | 20,000 | 01/01/12, not yet planned | red, yellow |
| Stuttgart | 3/1/2008 | no sticker | 207 sq. km | 590,000 | 01/01/12, not yet planned | red, yellow |
| Tübingen | 3/1/2008 | no sticker | n/a | n/a | 1/1/12 | red |
| **City** | **Start date** | **Excluded** | **Size of LEZ** | **Inhabitants** | **Dates of future** | **Future excluded** |

| | vehicles | | | | restrictions (2nd round, 3rd round) | vehicles (2nd round, 3rd round) |
|---|---|---|---|---|---|---|
| **Future LEZs (2009 and beyond)** | | | | | | |
| Augsborg | open | no sticker | 5.2 sq. km | n/a | 1/1/10 | red |
| Bremen | 1/1/09 | no sticker | 7 sq. km | 56,000 | 1/1/10 | red |
| Dresden | 1/1/10 | no sticker | 4.2 sq. km | 6,500 | Unexplained | n/a |
| Düsseldorf | 2/15/09 | n/a | 13.8 sq. km | 36,500 | 1/1/11 | n/a |
| Freiburg | 1/1/2010 | no sticker | 28 sq. km | 120 | 1/1/12 | red + yellow |
| Heidelberg | 1/1/10 | no sticker | 10.3 sq. km | 170 | 1/1/12 | red |
| Herrenberg | 1/1/09 | no sticker | n/a | 28,000 | 1/1/12 | red |
| Karlsruhe | 1/1/09 | no sticker | n/a | n/a | 1/1/12 | red |
| Mühlacker | 1/1/10 | no sticker | n/a | n/a | 2012 | red |
| Mülheim | 10/1/2008 | no sticker | n/a | n/a | End of 2010 | red |
| Neu-Ulm | 1/1/09 | no sticker | n/a | n/a | 1/1/12 | red |
| Osnabrück | 1/4/10 | no sticker | 14sq. km | 7,000 | 1/4/11 | red |
| Pfinztal | 8/1/2008 | no sticker | 31sq. km | 18,000 | 1/1/12 | red |
| Pforzheim | 1/1/09 | no sticker | n/a | n/a | 1/1/12 | red |
| Regensburg | n/a | no sticker | n/a | n/a | n/a | n/a |
| Ruhrgebiet | 10/1/2008 | n/a | n/a | n/a | 1/1/11 | orange |
| Ulm | 1/1/09 | n/a | n/a | n/a | n/a | n/a |
| Weitere mögliche | n/a | n/a | n/a | n/a | n/a | n/a |

## Appendix C: Sample Cities

| City | Avg 2005 reading at highest polluting station | Violate PM10 limits in 2005-06 | Exceedance days in 2005 | Attainment status | LEZ start date | Total population |
|---|---|---|---|---|---|---|
| Mönchengladbach | 25.0 | 0 | 24 | Attainment | | 261,216 |
| Schwedt | 25.0 | 0 | 23 | Attainment | | 37,001 |
| Ulm | 25.1 | 1 | 18 | AP with 'late' LEZ | not set | 120,748 |
| Schweinfurt | 25.1 | 0 | 14 | Attainment | | 54,097 |
| Altenburg | 25.2 | 0 | 27 | Attainment | | 37,236 |
| Coburg | 25.4 | 0 | 15 | Attainment | | 41,768 |
| Aschaffenburg | 25.6 | 0 | 12 | Attainment | | 68,645 |
| Wiesbaden | 25.8 | 0 | 18 | Attainment | | 275,085 |
| Bernhausen | 25.9 | 1 | 21 | AP only | | 13,216 |
| Bautzen | 25.9 | 0 | 20 | Attainment | | 148,945 |
| Weiden i.d.OPf. | 26.0 | 0 | 22 | AP with 'late' LEZ | not set | 42,603 |
| Kelheim | 26.1 | 0 | 26 | Attainment | | 113,100 |
| Stralsund | 26.2 | 0 | 22 | Attainment | | 58,563 |
| Heilbronn | 26.2 | 1 | 22 | AP with 'late' LEZ | 1/1/2009 | 121,498 |
| Lindau (Bodensee) | 26.3 | 1 | 28 | AP only | not set | 79,636 |
| Emden | 26.3 | 0 | 20 | Attainment | | 51,666 |
| Nauen | 26.4 | 0 | 25 | AP with 'late' LEZ | not set | 16,674 |
| Hanau | 26.5 | 0 | 20 | Attainment | | 88,251 |
| Weißenfels | 26.6 | 0 | 32 | Attainment | | 73,624 |
| Pirmasens | 26.6 | 0 | 16 | Attainment | | 42,761 |
| Bamberg | 26.7 | 0 | 20 | Attainment | | 69,746 |
| Freiberg | 26.7 | 0 | 33 | Attainment | | 144,094 |
| Leonberg | 26.8 | 1 | 16 | AP wtih LEZ | 3/1/2008 | 45,537 |
| Burghausen | 26.8 | 1 | 27 | AP with 'late' LEZ | not set | |
| Stendal | 26.9 | 0 | 18 | Attainment | | 130,436 |
| Saal a.d. Donau | 26.9 | 0 | 25 | Attainment | | 5,484 |
| Sulzbach-Rosenberg | 26.9 | 0 | 27 | Attainment | | 20,409 |
| Köln | 27.0 | 0 | 14 | AP wtih LEZ | 1/1/2008 | 986,317 |
| Gelsenkirchen | 27.0 | 0 | 24 | AP with 'late' LEZ | 10/1/2008 | 267,418 |
| Mülheim | 27.0 | 0 | 21 | AP with 'late' LEZ | 10/1/2008 | 169,651 |
| Zittau | 27.0 | 0 | 31 | Attainment | | 29,898 |
| Arzberg | 27.0 | 0 | 24 | AP with 'late' LEZ | not set | 5,893 |
| Bösel | 27.1 | 0 | 25 | Attainment | | 7,562 |
| Itzehoe | 27.1 | 0 | 21 | AP with 'late' LEZ | not set | 33,800 |
| Dessau | 27.2 | 0 | 18 | Attainment | | 77,914 |
| Schwandorf | 27.3 | 0 | 30 | AP with 'late' LEZ | not set | 144,644 |
| Worms | 27.5 | 1 | 27 | AP with 'late' LEZ | not set | 81,984 |
| Würzburg | 27.7 | 0 | 30 | AP with 'late' LEZ | not set | 134,080 |
| Glauchau | 27.8 | 0 | 24 | Attainment | | 25,760 |
| Norderney | 27.8 | 0 | 17 | Attainment | | 5,986 |
| Wuppertal | 28.0 | 0 | 20 | AP with 'late' LEZ | 5/12/2009 | 358,813 |
| Aachen | 28.0 | 0 | 18 | AP only | | 258,055 |
| Plauen | 28.1 | 1 | 33 | AP only | | 68,614 |

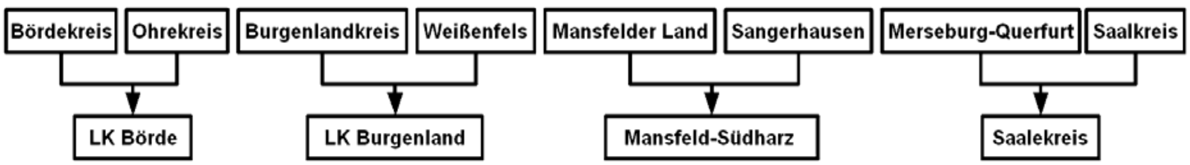
| City | Avg 2005 reading at highest polluting station | Violate PM10 limits in 2005-06 | Exceedance days in 2005 | Attainment status | LEZ start date | Total population |
|---|---|---|---|---|---|---|
| Ingolstadt | 28.2 | 1 | 35 | AP with 'late' LEZ | not set | 121,687 |
| Magdeburg | 28.3 | 1 | 22 | AP with 'late' LEZ | not set | 229,344 |
| Erlangen | 28.3 | 0 | 22 | AP only | | 103,469 |
| Bielefeld | 28.4 | 0 | 19 | Attainment | | 326,336 |
| Gera | 28.4 | 1 | 31 | AP with 'late' LEZ | not set | 103,446 |
| Reutlingen | 28.5 | 1 | 17 | AP wtih LEZ | 3/1/2008 | 281,933 |
| Saarbrücken | 28.5 | 0 | 18 | Attainment | | 340,702 |
| Neuwied | 28.5 | 0 | 23 | AP with 'late' LEZ | not set | 184,849 |
| Koblenz | 28.6 | 0 | 20 | Attainment | | 106,238 |
| Ratzeburg | 28.8 | 0 | 28 | AP only | | 13,671 |
| Krefeld | 29.0 | 1 | 24 | AP with 'late' LEZ | not set | 237,336 |
| Datteln | 29.0 | 0 | 30 | Attainment | | 36,297 |
| Borna | 29.1 | 0 | 31 | Attainment | | 22,561 |
| Neu-Ulm | 29.1 | 1 | 34 | AP with 'late' LEZ | 1/1/2009 | 163,477 |
| Jena | 29.6 | 1 | 29 | AP with 'late' LEZ | not set | 102,291 |
| Landshut | 29.7 | 1 | 39 | AP with 'late' LEZ | not set | 61,757 |
| Nürnberg | 29.7 | 0 | 33 | AP with 'late' LEZ | 1/1/2009 | 498,936 |
| Weimar | 29.8 | 1 | 35 | AP with 'late' LEZ | not set | 64,541 |
| Trier | 29.9 | 0 | 26 | AP with 'late' LEZ | not set | 100,198 |
| Karlsruhe | 29.9 | 1 | 22 | AP with 'late' LEZ | 1/1/2009 | 285,756 |
| Bottrop | 30.0 | 0 | 33 | AP with 'late' LEZ | 10/1/2008 | 119,195 |
| Fürth | 30.1 | 0 | 30 | Attainment | | 113,596 |
| Wetzlar | 30.2 | 0 | 24 | AP only | | 52,831 |
| Ansbach | 30.2 | 1 | 29 | AP only | | 40,531 |
| Brandenburg an der Havel | 30.7 | 1 | 53 | AP with 'late' LEZ | not set | 73,886 |
| Lutherstadt Wittenberg | 31.2 | 1 | 42 | AP with 'late' LEZ | not set | 47,540 |
| Regensburg | 31.6 | 1 | 37 | AP with 'late' LEZ | not set | 130,153 |
| Ludwigshafen | 31.7 | 1 | 37 | AP with 'late' LEZ | not set | 163,536 |
| Görlitz | 31.8 | 1 | 42 | AP with 'late' LEZ | not set | 57,418 |
| Hagen | 32.0 | 1 | 27 | AP only | | 196,295 |
| Halle/Saale | 32.2 | 1 | 51 | AP with 'late' LEZ | not set | 236,576 |
| Kassel | 32.2 | 1 | 48 | AP with 'late' LEZ | not set | 193,842 |
| Aschersleben | 32.2 | 1 | 38 | AP with 'late' LEZ | not set | 31,717 |
| Freiburg | 32.5 | 1 | 21 | AP with 'late' LEZ | 1/1/2010 | 216,448 |
| Münster | 32.5 | 0 | 33 | Attainment | | 271,404 |
| Frankfurt | 32.5 | 1 | 48 | AP with 'late' LEZ | 10/1/2008 | 648,925 |
| Mannheim | 33.4 | 1 | 43 | AP with LEZ | 3/1/2008 | 307,847 |

NOTE: AP with 'late' LEZs are Action Plans only cities in our analyses since we have no data while their LEZs are in effect.

## Appendix D: Spatial Substitution Data Irregularities

To merge the car registration data from 2006 to 2009, we had to take into account several reforms of districts. Sachsen-Anhalt had a district reform in 2007[31] The first row in Figure E.1 shows the districts as of 2006, which merged into the districts of 2007, displayed in the second row.

Figure E.1: Merged districts in Sachsen Anhalt in 2007:




However, as it was not possible to do so for LK Harz, Salzandkreis, LK Anhalt-Bitterfeld, LK Wittenberg and Jerichower Land, we created two virtual districts corresponding to the union of LK Harz and Salzandkreis in one hand, and LK Anhalt-Bitterfeld, LK Wittenberg and Jerichower Land, in another hand.

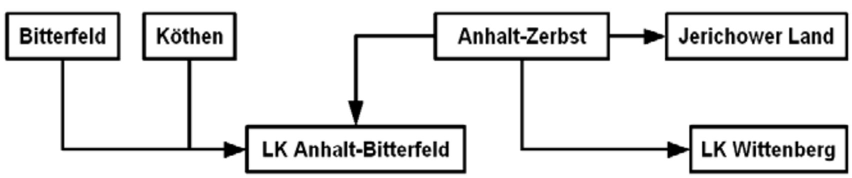
Hence, we created a new artificial district, as displayed in Figure E.2. For the years 2006 and 2007, we added the number of vehicles from the former districts to get a virtual number of cars for the artificial new district. In 2008 this artificial new district is simply the merger of LK Harz and Salzlandkreis. This had to be done because it is not possible to distinguish from the data, how the number of cars in the district Aschersleben-Strassburg are divided into LK Harz and Salzlandkreis.

[31] This reform is a law in Saxony-Anhalt, Germany, which came into effect on July 1, 2007, which outlines a reform of the districts of Saxony-Anhalt. It reduces the districts from 21 to 11. Nine new districts are created by amalgamating existing districts, while Altmarkkreis Salzwedel and Stendal as well as the urban districts of Halle and Magdeburg are untouched.

Figure E.2: Merged new artificial district in Sachsen Anhalt (SAR1) in 2007:


Similarly we proceeded with the merged districts displayed in Figure E.3 below.

Figure E.3: Merged new artificial district in Sachsen Anhalt (SAR2) in 2007

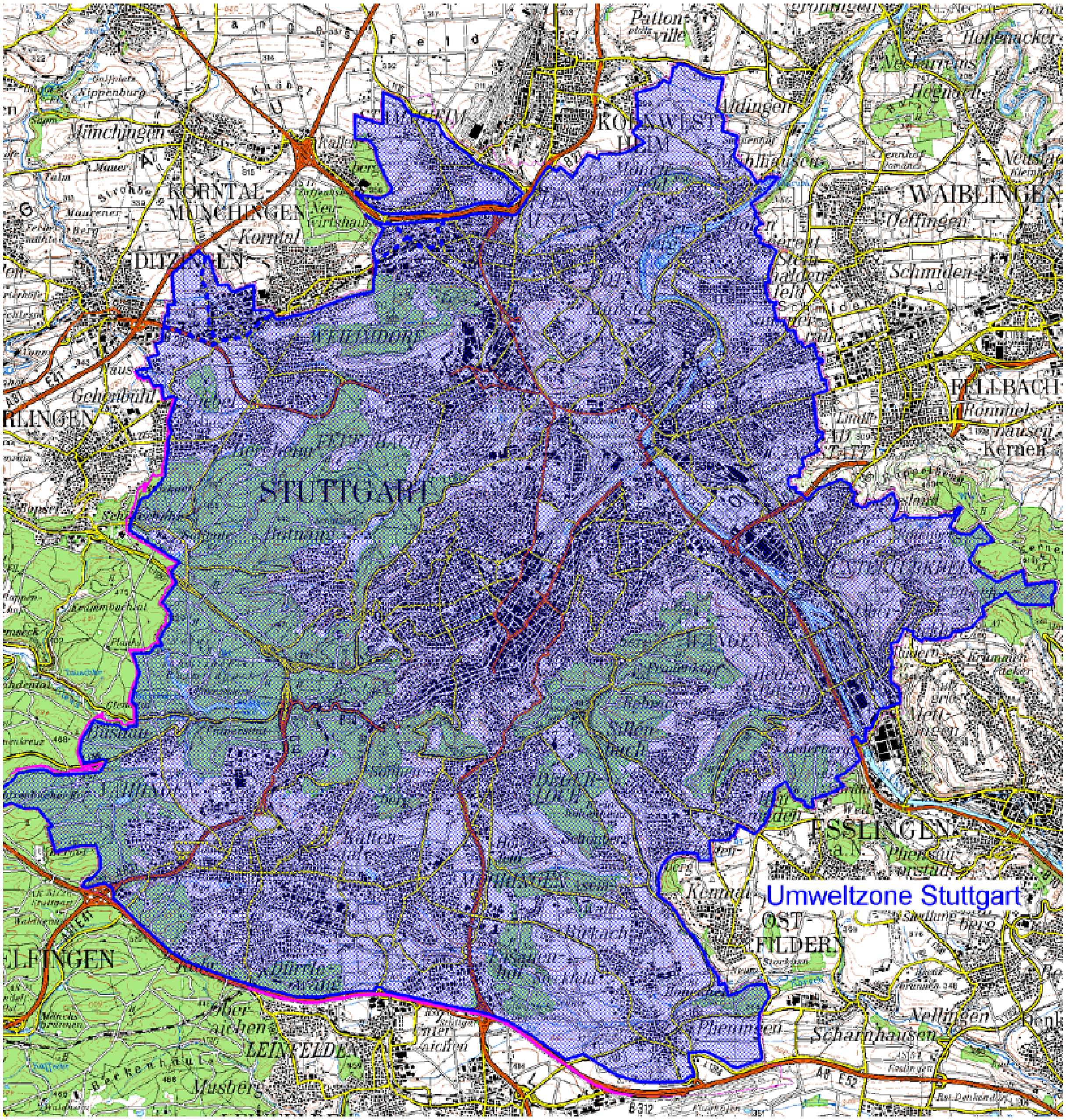



Moreover, we dropped Dessau-Rosslau as we do not have data for Rosslau in 2006 and 2007. Similarly, to match the districts between 2008 and 2009 another 26 districts had to be merged.

For 2006 and 2007, the number of cars in each emission category are recorded separately for petrol and diesel. For the data beginning of 2008, however, the number of cars powered by gas and ethanol were added to the category of the cars that are powered by petrol. Typically cars powered by gas an ethanol account for a very small number of the cars only.

The data from 2006 to 2007 include vehicles that were under temporal suspension (i.e. vacation vehicles). From 2008 onwards however, all suspended cars are no longer listed in the dataset. Hence from 2007 to 2008 the total number of officially recorded cars in Germany dropped by 10%. Unfortunately it is unknown which sticker vehicles dropped most, but likely the dropped ones belong to the higher/older polluting vehicles. In the current draft regressions and Figures we hence use the consistent 2008 and 2009 data only.

## Appendix E: Stuttgart LEZ






The English term “Low Emission Zones” is commonly known in German as Umweltzone (Environmental Zone)