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Keep Your Clunker in the Suburb: Low Emission Zones and Adoption of Green Vehicles

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Forschungsinstitut
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of Labor

Keep Your Clunker in the Suburb: Low Emission Zones and Adoption of Green Vehicles

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Discussion Paper No. 8180
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ABSTRACT

Keep Your Clunker in the Suburb: Low Emission Zones and Adoption of Green Vehicles*

Spatial distribution and leakage effects are of great policy concern and increasingly discussed in the economics literature. Here we study Europe's most aggressive recent air pollution regulation: Low Emission Zones are areas in which vehicular access is allowed only to vehicles that emit low levels of air pollutants. Using new administrative datasets from Germany, we assess the distribution of air pollution and the spatial substitution effects in green versus dirty vehicles. We find that LEZs decrease air pollution by around nine percent in urban traffic centers while pollution is unchanged in non-traffic areas. These results are driven by our finding that vehicle owners have an incentive to adopt cleaner technologies the closer they live to an LEZ. We reject the widespread concern that dirty vehicles contribute to higher pollution levels by increasingly driving longer routes outside of the LEZ. Back of the envelope calculations suggest that the health benefits of roughly two billion dollars have come at a cost of just over 1 billion dollars for upgrading the fleet of vehicles. Moreover, we find that non-attainment cities that decided not to include an LEZ but engaged in other methods (building ring roads, enhancing public transportation), experience no decrease in pollution.

JEL Classification: Q58, R48

Keywords: air pollution, low emission zones, PM_{10}

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1. Introduction

Recently, increased public health concerns have elevated the role of clean air policies. In particular, focus is on PM_{10}—the class of particulate matter smaller than 10 micrometers—a major air pollutant from vehicle emissions. Because PM_{10} can enter the lungs and bloodstream, it is often considered the most lethal air pollutant. In the European Union alone, PM_{10} is estimated to cause 348,000 premature deaths annually. To put this into context, ozone—Europe's second most deadly air pollutant—only causes about 21,000 premature deaths (Watkiss *et al*. 2005).

In response to these health risks, the European Commission[2] enacted the 2005 Clean Air Directive, which marks an unprecedented attempt to mandate low levels of PM_{10}. When cities violate the maximum allowable limits, mayors and local governments have to develop so-called *clean air action plans*. While these action plans can consist of various traffic measures, the most drastic has been the Low Emission Zone (LEZ), which defines an area where higher-polluting vehicles are completely banned from driving (Wolff and Perry 2010).

In Germany, to deal with the large number of cities exceeding the EU threshold, the government has categorized vehicles into four mutually exclusive classes of PM_{10} emissions. All 46 million German cars, buses and trucks are required to display a colored windshield sticker indicating its PM_{10} pollution class. As of 2010, 41 German cities have implemented LEZs banning vehicles based on the colors of these stickers. These zones have been controversial, however, because of the costs imposed on drivers and especially truck companies, for whom upgrading fleets to the appropriate sticker can be quite expensive.[3] According to a recent online survey, over 91 percent of Germans disapprove of LEZs, considering them too bureaucratic with likely having little effect (DSM 2009). In an earlier survey, 70 percent of drivers stated they might drive around LEZs to avoid upgrading their vehicle (Vienken 2008). Despite these criticisms, LEZs have become a popular quick fix for local governments struggling to avoid the large financial penalties imposed for exceeding the EU limits. For example, a recently

[2] The European Commission is the executive body of the European Union (EU). It proposes, implements, and enforces EU legislation for all of its twenty seven current member states.

[3] Conversion to the next higher sticker costs 800 to 2,500 USD for passenger cars and 7,000 to 22,000 USD for larger vehicles and trucks, although conversion is technologically infeasible for some vehicles. Major newspapers' headlines noted '*Particulate Matter: The insanity of LEZs*' (Bild 2009), or '*Driving Ban in LEZs: Much Dust for Nothing*' (Süddeutsche 2009).

announced penalty for the city of Leipzig is 700,000 Euro per day, or 1,050,000 U.S. Dollar (USD) per day, because of non-attainment with the EU clean air regulation.

Germany is not alone in limiting vehicle use. 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 one's license plate.[4] 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 cells but must take circumferential ring roads between cells (Goddard 1997, Vuchic 1999); traffic bans on days when air pollution exceeds certain thresholds (Milan and other Italian cities); and emissions fees combined with LEZ (in Greater London's LEZ, larger vans and lorries pay a daily PM_{10} emission charge of 250 to 500 British pounds (392 USD to 784 USD) if they do not meet the Euro IV PM_{10} standard[5]). Uncertainty about the effectiveness, however, creates difficulties to make informative decisions among policy options and to gain public support by policy makers. As a result, often choices seem ad hoc and regionally clustered.[6]

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 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

[4] Similar license plate programs 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).

[5] In 2008, the Greater London Authority established one of the largest current LEZs in Europe, which roughly includes the area within the ring highway M25 that encircles Greater London. It restricts the most polluting vehicles according to the PM_{10} standard of the Euro IV norm, including buses, coaches, vans, utility vehicles, minibuses of weight 1.205 tones and more and diesel-engined heavy goods vehicles. This LEZ is different from London's Congestion Charging Zone of eight pounds per day which operates on workdays during daytime only in London's Center District (Leape 2006, TFL 2008).

[6] Low Emission Zones (LEZs) are particularly popular in Europe, license plate programs implemented in Latin America and congestion charging mostly considered in northern Europe and major Asian urban centers. Instead, price-based policies that aim to limit congestion and emissions include road pricing and congestion fees. Singapore (1975), London (2003) and Stockholm (2006) charge fees to drive into the city center. While New York City's congestion fee stalled in the legislature, San Francisco is currently debating a six dollar fee to drive through downtown. Milan has combined congestion pricing and LEZs with its Ecopass program, which charges fees to drive downtown based on emissions-level. Despite the increase in price-based policies, command and control driving restrictions are still adopted. These latter policies are argued to be often easier to implement politically, technologically feasible, and relatively less expensive to enforce (Levinson and Shetty, 1992; Davis, 2008).

the restriction by buying older, more polluting second cars to have different license plates.[7] Davis finds that the HNC is a high-cost solution—with social costs exceeding 300 million USD 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,[8] the German LEZ program may be more successful because it includes a differentiation by emission level, creating an incentive to adopt cleaner technologies.[9] However, whether LEZs are effective is an empirical question.

This study is related to the growing literature on estimating the costs of air pollution and its regulations (Dockery *et al*. 1993, Pope *et al*. 1995, Chay and Greenstone 2003 and 2005, Davis 2008). Our work adds to this literature presenting the first empirical paper on traffic restrictions which examines both the within-city and across city effects on pollution outcomes as well as the spatial substitution effects of the LEZ regulation on the adoption of abatement technology. To this end, the first task of this paper is to estimate the causal effect of LEZs on PM_{10} levels using panel data of daily pollutions and weather conditions across Germany from 2005 through 2008. Both the pre-regulation pollution levels and the staggered nature of LEZ implementations produce rich identification for our estimation of the zones' treatment effects.

One argument for the four-tier PM_{10} categorization is that it promotes a more rapid adoption of clean technologies since even vehicle owners who do not typically drive into an LEZ may want to keep the option value of free passage. To evaluate this, next this paper studies changes in the composition of the vehicle fleet. Using a unique administrative panel dataset of emission category and registration location of each vehicle from 2008 to 2010, we analyze the spatial substitution in vehicles' emission categories attributable to LEZs.

We find that LEZs decrease PM_{10} around nine percent in traffic areas. The LEZ's decrease in PM_{10} is larger for traffic stations inside the LEZs than those outside, although PM_{10} does not decrease at all in background areas away from major roads. This shows that cities target pollution-reducing strategies at those traffic areas which are responsible for violating the PM_{10} limits. Recently several papers (Fowlie 2010, Auffhammer and Kellogg 2010) have shown that

[7] Drivers also took more taxis, which were among the most polluting cars in Mexico when the HNC was enacted.

[8] Meanwhile the HNC has been modified to include an exhaust monitoring program (Verifcación). Each car is affixed with a sticker indicating its class of emission and the cleanest cars are exempt from the HNC restrictions.

[9] Small and Kazimi (1995) find heavy-duty diesel trucks have social costs per mile ten times higher than gasoline vehicles. Also Roson and Small (1998) find evidence that a small percentage of high-emission vehicles contribute the bulk of pollution and conclude that policies targeting dirty vehicles may be the best way to decrease emissions.

spatial (unintended) consequences can substantially change cost-benefit calculations of regulations on firms. In terms of individual choices, Graff Zivin and Neidell (2009) and Moretti and Neidell (2010) discuss settings in which the total welfare cost of air pollution is much larger due to avoidance behavior. LEZs may also cause unintended consequences. We reject the widespread concern that dirty vehicles contribute to higher pollution by increasingly driving longer routes outside of the LEZ.

In terms of the spatial capital substitution, we find that drivers substantially increase the adoption of low emission vehicles the closer they live to an LEZ. In particular, the green commercially used vehicles, that presumably depend more on access to city centers, increased sharply by 88%. Privately used green vehicles increased by about 5%. Still, this represents a substantial shift in the spatial vehicle fleet composition due to the clean air regulation. Overall, back of the envelope calculations suggest that the health benefits of nearly two billion dollars have come at a cost of just over 1 billion dollars for upgrading the fleet of vehicles.

Finally, this paper directly contributes to the EU policy debate of the design and choices of air pollution regulations. We find that all non-attainment cities that decided to not include an LEZ but engaged in other methods (building ring roads, enhancing public transportation), experience no statistical significant decrease in air pollution.

This papers proceeds as follows. Section two details the PM_{10} 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 LEZs on PM_{10} levels and discusses the spatial substitution effects of high to low emission vehicles. Section six combines these results in cost-benefit analysis and we conclude in section seven.

2. Background

2.1 Air Pollution regulation in Europe

Motor vehicle emission is the primary source of ambient PM_{10} in urban areas,[10] although, share of vehicle based PM_{10} can range widely both over time and spatially. We surveyed all recent studies investigating the sources of PM_{10} in Europe (see Table A1 of Appendix A). The

[10] Road transport is also largely responsible for all NO_X, CO, benzene and black smoke emissions. While these toxins are regulated, threshold violations and health impacts are substantially higher for PM_{10}.

main contributing factors are vehicle exhaust, resuspension of dust particles (caused by automobiles and by natural phenomena), combustion by industry and individuals, and other natural sources such as marine aerosol and pollen (Viana et al., 2008). In particular, for *traffic* stations measuring PM_{10} in close proximity to roads, the share of vehicle exhaust is estimated to range from 25% to 55%. In contrast, for urban *background* stations the percentage of observed PM_{10} that is attributed to vehicle emissions is only 8% to 23%.

In response to concerns about the health effects of PM_{10},[11] the EU Clean Air Directives[12] introduced in 2005 EU-wide limits on ambient PM_{10} such that: (a) the daily average does not exceed 50μg/m³ on more than 35 days annually and (b) the yearly average does not exceed 40μg/m³. When any air pollution station exceeds the EU PM_{10} limit, the city is asked to develop a *clean air action plan*. In the beginning years of the EU regulation, often cities did not comply with the timely delivery of their action plans and the enforcement was lax. As a result, 70 percent of EU cities greater than population 250,000 had violated the limits at some point and, as shown in Table 1, the 35-day limit has caused violations in 81 German cities.[13] As a consequence, in order to better enforce the legislation, the European Commission asked the European Court of Justice to impose financial penalties (Council Directive 2008/50/EC), such as the recently announced 700,000 Euro per day (1,000,500 USD per day) penalty on Leipzig for repeatedly violating the 35-day limit rule. The formula for the daily penalty payments is described in Wolff and Perry (2010). Further, in January 2009, the Europe Commission initiated infringement proceedings against 10 EU countries that have not attained the PM_{10} limit. Moreover, EU citizens are entitled by law to demand action plans from local authorities.

Under Council Directive 1999/30/EC, a second phase of the PM_{10} policy was scheduled to begin on January 1, 2010. In this phase, the thresholds were to have been drastically tightened to a yearly average of 20μg/m³ and a maximum of seven days exceeding 50μg/m³. These limits would have been very difficult for many European cities to meet; for example, we estimate that

[11] PM_{10} has long 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 PM_{10} (Cohen *et al*. 2005).

[12] EU Clean Air Directives refers to a set of Council Directives including 1996/62/EC, 1999/30/EC and 2008/50/EC.

[13] No German city violated the 40μg/m³ annual limit that did not also violate the exceedance day limit.

285 German cities would have violated the 2010 limits based on 2005-2008 emissions.[14] In response, in 2008 the EU passed Council Directive 2008/50/EC, which abolished the second phase of the PM_{10} policy, continuing the 2005 limits instead. While there is currently no indication that the 2010 limits will be reinstated, the prior threat of facing these limits were important in driving the widespread adoption of LEZs.

2.2 Low Emission Zones in Germany

Given the primacy of vehicle-based PM_{10}, clean air action plans (AP) try to curtail emissions through

(i) expanding public transportation

(ii) utilizing ring roads

(iii) improving traffic flow

(iv) the implementation of an LEZ.

The fourth option, implementing an LEZ, has emerged as the most drastic and controversial element of the action plans. The LEZs mostly cover city centers, but vary considerably 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 LEZ in Stuttgart covers 207 km^2 with 590,000 inhabitants (see map of Figure B1 of Appendix B), while the nearby smaller LEZ in Illsfeld is only 2.5 km^2 with 4,000 inhabitants. Figure 1 shows a map of current and planned LEZs and Appendix Table B1 and Table B2 list their characteristics.

Each German vehicle—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 PM_{10} classes for diesel vehicles. The highest emitting vehicles obtain no sticker (and hence cannot enter any LEZ), while red, yellow and green stickers are given to progressively "cleaner" vehicles, as shown in Table 2. There are two classes for gasoline vehicles, green and no sticker. In some cases vehicles can improve one class by retrofitting the engine or diesel particulate filter.

The fine for illegally entering an 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 LEZs

[14] Even the national average in each year since 2005 violates both the 2010 exceedance day and annual average limits, as shown in Table 1.

[15] There is a series of consequences for penalty points, ending with loss of driver's license at 18 points.

without a sticker, including agricultural and forestry tractors; ambulances and doctor's cars; vehicles driven by or carrying persons with serious mobility impairments; and police, fire brigades, Bundeswehr and NATO vehicles.

The implementation date and the types of vehicles restricted by an LEZ vary across cities, as shown in Table 3. In Berlin, for example, all vehicles with a red sticker and "cleaner" (yellow and green) were allowed into the LEZ starting January 2008, while access has been further restricted to only green stickers since January 1, 2010. The LEZ of Dortmund (Brackler Strasse), on the other hand, has only permitted yellow and green sticker vehicles since January 2008. By 2012 more than 50 percent of all LEZ cities will allow only yellow sticker and cleaner vehicles, and by 2013 most of the LEZs will permit green sticker vehicles only. Of the 23 LEZs implemented in 2008, four began in January, eight in March, one in July and the rest in October.

We categorize cities into various treatment groups based on this variation in implementation date and action plan components. Figure 2 illustrates the classifications. First, we divide stations into 2 categories, 'attainment cities' (in Figure 2 abbreviated as AC) that do not violate the PM_{10} limit (and thus do not need to develop an action plan) and 'non-attainment cities' that must develop an action plan (AP). Next, we divide the non-attainment cities into 'action plan only' (APO) cities, whose action plan do not include an LEZ, and 'LEZ cities' (LEZ). Finally, we also separate out APO cities that include a 'future LEZ,' instituted in or after October 2008 (FLEZ).[16]

3. Data

We collect a panel of air quality readings from January 2005 through October 2008 from the German Federal Environment Agency, the Umweltbundesamt (UBA). This data set includes a combination of half-hourly, hourly or daily readings of PM_{10} for 554 stations in 388 cities. Stations are characterized by the UBA as being *traffic* stations, located on main arterial roads, or *background* stations, usually located in more residential and green areas such as public parks or at soccer fields. Using the coordinates for each station, we classify all stations as 'inside' or 'outside' of an LEZ.

[16] There are some cities that have discussed implementing an LEZ but have not finalized a plan for doing so. We do not include these as FUTURE LEZ cities since a) it is unclear how serious these cities are about implementing an LEZ and b) these cities have PM_{10} levels closer to APO cities than FLEZ cities.

Figure 3 displays how PM_{10} levels have evolved since 2005. The way in which PM_{10} levels drastically vary over time over the range from below 20μg/m³ to over 100μg/m³ underscores the difficulty modeling PM_{10} data; some of the variation is dependent on local weather conditions such as temperature, wind speed, rain and mixing layer height (Klinger and Sahn, 2008). To control for these factors, we collect the most detailed possible weather data available from the national weather service, Deutscher Wetterdienst. We obtain 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 geographic coordinates to match each air quality station with the closest weather station. We only use the PM_{10} readings from stations that have a weather station within 50 kilometers in distance and 300 meters in altitude. The primary weather variables are summarized in Table 4. After calculating daily weather and PM_{10} readings while handling missing values[17], we end up with complete PM_{10} and matched weather data for 185 stations covering 122 cities.

Moreover, PM_{10} levels can highly depend on locational and temporal events. PM_{10} levels in our data often rise suddenly by several hundred percent, which could be attributable to activities such as open coal-fired barbeques or construction sites. While we cannot collect information on all particular events, we do aim to control for temporal changes as carefully as possible. First, we include as covariates all information on state-level specific school vacation and legal holidays, both obtained from Johannsen (2009). Second, we exclude New Years Eve and Day to avoid outliers caused by fireworks. We further control for the day of the week and we include flexible state-specific weather models. As long as confounding events are correlated with these variables

[17] To calculate PM10 daily averages, we first linearly impute the missing hourly readings throughout the day. Once we have daily averages, we interpolate the missing daily averages for the 1.4 percent of days with no readings. Among those stations reporting half-hourly and hourly data, less than seven percent of days are missing observations for some hours, with over 70 percent of these being three hours or less. To make sure our results are not driven by changes in monitoring station composition, we restrict our analysis to stations that have "complete readings" for all of the years included in each analysis. We define a station as having "complete data" for 2005 to 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. Finally, on Google Maps, we studied the locations of all our stations in LEZ cities. This analysis led us to drop one station in Mannheim and one station in Berlin that were at rail yards, as both of these readings are presumably mostly picking up train emissions.

and uncorrelated with the LEZ treatment, our results should be unaffected. Finally, we include city-level 2006 population data from the Federal Statistical Office Germany Genesis database.[18]

4. Empirical Identification Strategy

4.1 Difference-in-Differences Approach

To study the effect of LEZs on air quality we use difference-in-differences (see Meyer 1995; Bertrand *et al*. 2004) in which we compare LEZ cities to a set of control cities. This approach calculates the difference between how much PM_{10} changes after adoption of LEZs in LEZ cities and how much PM_{10} changes over the same time frame in control cities. This allows us to control both for underlying differences between LEZ and control cities and temporal changes in PM_{10} levels common across all cities. We estimate Equation (1), where *k* indexes city, *i* indexes station and *t* indexes time

$$(1)\ \ln(y_{k,i,t}) = \alpha + \beta_1 postLEZ_t + \beta_2 LEZ_k + \beta_3 treatLEZ_{k,t} + \Psi X_{k,i,t} + \upsilon_{k,i,t}$$

Our main parameter of interest, β_3, measures the percentage by which the LEZ affects PM_{10}. The dependent variable, $y_{k,i,t}$, is the average daily PM_{10} reading for each station. LEZ_k is an indicator variable for whether a city has an LEZ and $postLEZ_t$ is an indicator for time periods after implementation of an action plan. $TreatLEZ_{k,t} = LEZ_k * postLEZ_t$ is an indicator variable that equals one for non-attainment cities after implementing an LEZ. $X_{k,i,t}$ includes station-, city- and time-specific covariates including weather variables,[19] school vacation, holiday and day of the week indicator variables. Because the specific locational conditions of air quality stations have a large impact on pollution readings, $X_{k,i,t}$ includes station fixed-effects in all models and we analyze background and traffic stations separately. $X_{k,i,t}$ also include year-month fixed effects to control for any time trends or any other climatic effect that our weather model does not

[18] In the German Genesis population file, the variable of population per city contains a number of missing observations in particular for small cities. We collected the missing population estimates by various internet searches.

[19] Weather variables include daily values of mean temperature, mean temperature squared, maximum daily temperature, minimum daily temperature, 1-day lag mean temperature and maximum temperature, mean relative humidity, mean relative humidity squared, 1-day lag mean relative humidity, mean wind velocity interacted with whether it rained that day, maximum daily wind velocity, 1-day lag mean wind velocity, mean visibility, total precipitation, total precipitation squared, days without precipitation, mean temperature interacted with total precipitation, mean temperature interacted with mean relative humidity, mean temperature interacted with mean wind velocity, mean air pressure, 1-day lag mean air pressure. For regressions spanning multiple states, weather variables are interacted by state to control for the variation in climate across Germany.

capture. Identification comes from the assumption that, after controlling for changes in these observables, PM_{10} levels would have evolved in the same way in treatment and control cities in the absence of an LEZ. Finally, in all analyses, we cluster standard errors by city to correct for serial correlation over time as well as spatial correlation across stations within a city (Bertrand *et al*. 2004).[20]

Clearly LEZs may not be the only driver of the observed changes in PM_{10}. Local governments in non-attainment areas can choose including other measures in their clean air action plans. To investigate the mechanisms driving PM_{10} reductions, first we compare PM_{10} in all AP cities to those of the attainment control (AC) cities. Next, to differentiate the effects of action plans with and without LEZs, we test the treatment of having an action plan only (APO) and having a future LEZ (FLEZ). We use Equation 1 to estimate these three treatments, replacing *LEZ* with *AP, APO* and *FLEZ*, respectively.

In our analyses, we follow two different identification strategies to estimate these treatment effects. The first relies on matching cities based on pollution levels in the year 2005, and the second relies on matching cities based on location by comparing LEZ to FLEZ cities. These strategies are described next.

4.2 Matching Cities based on 2005 PM_{10}

Our first identification relies on matching treatment and control cities based on similar PM_{10} levels prior to implementation of action plans. Specifically, we match cities on annual daily averages of cities' highest-polluting station in 2005. Note, instead of using the PM_{10} average across all stations, we use the cities' highest PM_{10} polluting station because it is this station that determines whether cities exceed the PM_{10} threshold. We match on 2005 because this is the last year in which PM_{10} levels were not affected by action plans or LEZs.[21] In order to obtain a group of cities with similar initial conditions in PM_{10} levels, we use the 73 cities that have 2005 highest-station PM_{10} averages in the range of 25 to 35 μg/m³. We use the following rule for selecting our range 25 to 35 μg/m³. First we calculated the 2005 median PM_{10} annual average

[20] As a robustness test, we also have clustered by state, city-week and state-week and we found standard errors to be similar. Results are available upon request.

[21] We acknowledge the limitation that we have no PM_{10} data prior to 2005 to detect potential pre-emptive behavior by cities to lower emissions. Note, however, below we find that all non-LEZ measures (i.e. increasing public transportation, building ring roads) do not lead to PM_{10} reductions between 2005 and 2008. This result does suggest that any potential pre-emptive non-LEZ measure was not successful in altering PM10 levels.

among highest-polluting-stations, which equals to 30 µg/m³, and then we add ±5 µg/m³ to get the range. We decided on the range of ±5 µg/m³ to obtain a mix of attainment, non-attainment, APO, LEZ and FLEZ cities. There is only one LEZ below this range and no attainment city above the range. Table B2 of Appendix B lists all cities and their treatment status. We assume that within this group of 73 cities, the 35 exceedance day threshold (none of these cities violated the yearly average PM_{10} standard) makes the designation of non-attainment status and subsequent development of action plans exogenous.

Of these 73 cities, 22 cities serve as our control 'attainment cities' (AC) that have never violated the PM_{10} limits and do not have an action plan. Another twenty-two cities have an action plan but no LEZ (APO). We define these cities as APO cities if the first violation occurred in 2005 or in 2006. If the violation occurred instead in 2007 (or later), we drop the city from the analysis. This is necessary because not enough time has passed from the date of the violation until the end of our data (October 2008) in order to likely see an effect of the more long term action plan elements (i) to (iii). We also exclude 10 APO cities that developed an action plan despite never violating the PM_{10} limit,[22] as these are not unambiguously control or treatment cities. We ultimately use four cities that implemented an LEZ before October 2008 (LEZ) and seven cities with LEZs scheduled to begin between 2009 and 2011 (FLEZ). Table 5 compares these different groups. Average 2005 PM_{10} levels are very similar across groups, ranging from 26.8 in attainment cities to 30.7 in APO cities. The cities only differ based on the number of exceedance days, with APO, FLEZ and LEZ cities exceeding the 50 µg/m³ threshold on more than 35 days, and the attainment cities less than 35 days. In this sense, this first identification approach can be also interpreted in the spirit of the regression discontinuity design (RDD) on the threshold of the number of exceedance days. This RDD advantage comes at a cost, however, since there are only four LEZ cities in our treatment group. The following second approach aims to increase the number of LEZ cities.

4.3 Geographical LEZ Approach

[22] Some cities preemptively implement action plans to avoid violating the limits in the future, especially considering the tightened 2010 limits. There is one city, the city of Cologne, that implemented an LEZ despite never having violated the EU PM_{10} limit. Since our focus is on LEZ, we do not drop Cologne from our main regressions and, per suggestion of the referee, analyze Cologne separately below.

Our second identification strategy takes advantage of the staggered introduction of LEZs, individually comparing the earliest LEZ cities to nearby cities whose LEZ has not yet come into effect (FLEZ). There are multiple advantages of looking at each LEZ separately. First, weather and geography vary considerably across Germany and this allows us to fit a separate weather model for each region. Second, it ensures results aren't driven by other state or regional policies or events. Third, this geographical approach includes all cities with LEZs (compared to the first approach that limited the analysis to cities only within the interval of 2005 PM_{10} levels from 25 to 35 μg/m³).[23] Having more cities also allows us to analyze the heterogeneity between LEZs of different sizes. We make use of the staggered introduction of LEZs by comparing cities that instituted LEZs before October 2008 to other non-attainment cities that decided—for one reason or another—to introduce an LEZ at a later date. While this procedure comes at the cost of not primarily matching on 2005 PM_{10} levels, we can instead match on the fact that (a) all cities plan to implement an LEZ, (b) geography and (c) city size. Identification in this section comes from the assumption that there are no systematic differences in changes in LEZ cities' PM_{10} levels based on when they implemented their LEZ beyond the effect of the LEZ.

4.4 Common Trends Assumption

One concern with our differences-in-differences framework is that differential trends in the level of the PM_{10} between treatment and control cities can make the identification strategy invalid. Furthermore, our above strategy to use FLEZ cities (as control units) requires that the timing of the LEZ implementation is unrelated to the prior PM_{10} levels. To test for these common trends, Panel a of Table 6 regresses 2007 PM_{10} levels on date of LEZ introduction, along with the station, time, holiday and weather covariates used in all other regressions below. In our main regressions, the PM_{10} levels are taken from the year 2007, which immediately precedes the introduction of LEZs in 2008. Panel 6a shows that the coefficients on LEZ start date are small and insignificant, for both traffic and background stations. Similarly (as per suggestion of the referees), Panel 6b to Panel 6c repeat the analysis by using the years 2005 and 2006 as well as the changes in PM_{10} levels between years (Panel d). Overall, the regression results at *traffic stations* show strong support that the timing of the introduction of the LEZ is not influenced by previous pollution levels. Inconsistent with these results is column (3) of Table 6c, which shows

[23] Out of the 12 cities that implemented LEZ by March of 2008 (see Appendix B), we cannot analyze Schwäbisch Gmünd, Ilsfeld or Dortmund (Brackeler Road) because these cities have insufficient data.

that cities with larger 2006 PM_{10} levels at *background* stations introduce LEZs later. This result is significant at the 10% level. Note that this effect of column (3) is in the opposite direction of the concern that high polluting cities introduce LEZs earlier—not later. To summarize, overall Table 6 indicates that the prior PM_{10} levels of a city do not predict when the LEZ is introduced. This supports our identification strategy to use FLEZ cities as control units in our Differences-in-Differences framework. Finally, Figure 3 as well as the Figures in Appendix C depict average daily PM10 levels over the entire sample period for treatment and control cities utilizing each matching approach. These Figures visually illustrate that these groups of cities are not inherently different in terms of differential trends of PM10 levels and provides additional support to our identification strategies.

4.5 Spatial Substitution in Emission Categories of Vehicle Fleet

This analysis examines whether LEZs promote spatial adoption of cleaner vehicles and technologies. We perform this analysis using an administrative panel dataset containing data on vehicle emission categories and registration location from the German Federal Motor Transport Authority (Kraftfahrtsbundesamt Flensburg). Total number of private and commercial vehicles by emission category are observed for all districts from 2008 to 2010. We estimate Equation (2),

$$\Delta s_{icp} = \alpha_{pc} + \beta_{pc} Min\{Distance_{ij}\} + \gamma_{pc} X_i + \varepsilon_{ipc} \quad (2)$$

where $\Delta s_{icp} = s_{icp2010} - s_{icp20008}$ is the change in the share of vehicles with sticker color c = {*green*, *yellow*, *red*, *no sticker*} in county i of vehicle usage type p = {private, commercial}. This adoption function depends on the minimum distance in kilometers of the centroid of county i to the set of LEZ cities j and X_i includes characteristics of county i, county income per capita, population size and state fixed effects. For each sticker color and vehicle usage type the regression function (2) is estimated separately by OLS with robust standard errors resulting in the set of estimates of interest β_{pc}.

5. Results

This section presents our results of estimating the effect of the clean air action plan policies on air quality. The following two subsections 5.1 and 5.2 are based on the 'matching on PM_{10} in 2005' approach described in 4.2, while subsection 5.3 presents our results based on the geographical matching approach.

5.1 Effect of Non-Attainment Status

One challenge with evaluating Germanys LEZs is to disentangle the 'LEZ effect' from the other possible clean air action plan instruments enacted simultaneously. To investigate into this, first we test the overall effect of violating the PM_{10} standard by comparing cities that developed any type of action plan (AP) to attainment cities (AC). Table 7 compares PM_{10} levels in 2005, the period before being found in non-attainment, to 2008, when cities violating the standard had at least two to three years to implement clean air action plans.[24] Columns 1 and 2 show that APs in general have not had a significant effect on PM_{10} at either stations located in high traffic areas or stations located in background areas.

This apparent non-effectiveness of APs may be driven by the heterogeneity between plans with and without LEZs. To test this, we next isolate APs from those cities that have no LEZ planned (APOs) and those who have future LEZs (FLEZ). One may expect that the APO treatment effect may be greater than the FLEZ treatment, since FLEZ cities, anticipating the planned LEZ, may not meanwhile take other (costly) steps to combat PM_{10}. Columns 3 and 4 of Table 7 show that APOs have had no significant effects on PM_{10}. Next columns 5 and 6 show the FLEZ treatment effect. Again, there are no significant changes at either traffic or background stations.

In summary, it does not appear that the APO measures of building ring roads, increasing public transportation or enhancing the traffic flow have had any influence on PM_{10} levels. Moreover, these results imply that prior to implementing their LEZs, FLEZ cities take no other effective measures to combat vehicle-based PM_{10}. Thus in the regressions to follow, we feel comfortable attributing changes in current LEZ cities' PM_{10} to the LEZ rather than other APO or FLEZ policies.

5.2 Effect of LEZs

In this section, we isolate the treatment of having LEZs as part of an action plan as specified in Equation 1. Table 8 compares the LEZs that began before October 2008 to the attainment control cities. The timing of the difference-in-differences is to compare the months in 2008 following the implementation of the LEZs, to the same months of the previous year 2007. We

[24] These regressions only include January through October since we do not have PM_{10} data for November and December 2008.

use April through October data, since the Mannheim, Reutlingen and Leonberg LEZs didn't take effect until March 2008 and we are allowing a one month lag for cities to adjust to the LEZs.[25]

The main result of Table 8 is that LEZs on average over all cities have lowered PM_{10} levels by nine percent (columns 1) in urban traffic areas. This main result of this paper will be tested below by using alternative identification strategies below. To investigate the situation at background stations, columns 2 and 4 show statistically insignificant increases of four to seven percent. Thus the decrease in PM_{10} along major roads within the LEZ is not being realized outside of these high-traffic areas, which shows that PM_{10} from road traffic is a local pollutant. Note, no LEZ city violated the PM_{10} standard because a background station exceeded the EU threshold. Hence, cities first focus on reducing emissions in those traffic areas that caused the city to violate the standard. All of the background stations in the above LEZ cities are located outside of the LEZs. This also suggests that drivers of non-conforming vehicles did not increase driving around LEZ to avoid upgrading their vehicles, but we will investigate this question further below.[26]

One concern with our 2005 matching identification strategy is that results depend on our fixed range of 25 to 35 $\mu g/m^3$ of pre-intervention PM_{10} emissions. In Table 9 we symmetrically increase this range to investigate how sample selection affects our results. The upper panel is based on matching on the 25-35 PM_{10} range, corresponding to Table 8. The panels below symmetrically increase the PM_{10} ranges to [23, 37], [21-39], [20-40] and $(0, +\infty)$ $\mu g/m^3$. As one might expect, *widening* the 2005 emission ranges attenuates regression results (hence showing reduced magnitudes and decreased significance) as the similarities in initial PM_{10} levels decreases for the group of included treated and control cities. However, overall, the results are fairly robust. We view the strictest 25 to 35 emission range as our preferred matching strategy used in the manuscript. Before proceeding, we note that our results are robust to alternative specifications. In particular whether or not to include weather covariates, holiday or population

[25] In some of the early LEZs, like Berlin, drivers were often only given warnings and not tickets in the first few weeks after the LEZ was introduced (Climate Company, 2009).

[26] We expand on the analysis of background stations in the next subsections. In Section 5.3 shows results of background stations that are located within an LEZ. In Section 5.4, we examine Berlin's LEZ (in which there are both traffic and background stations inside and outside the LEZ) which allows for explicit analysis of the hypothesis whether PM_{10} increases around LEZs due to avoidance behavior.

information does not change our overall treatment effect. Details on these robustness checks are provided in Appendix D.

To investigate the heterogeneity between LEZs, Table 10 displays the treatment effects from regressing each LEZ city separately to the same set of control cities. At traffic stations, PM_{10} decreases in the range of five percent in Cologne[27] to 13 percent in Mannheim. At background stations, again, none of the treatment effects are significantly different from zero. In summary, while there is some heterogeneity, all the LEZs are associated with significant decreases in PM_{10} at traffic stations.

5.3 Geographical LEZ results

This subsection presents the results from our geographical identification strategy, which compares LEZ cities to nearby future LEZ (FLEZ). First, Table 11 displays the estimates from combining all the LEZs and their control cities. Across all traffic stations, column 1a shows that LEZs are associated with a 7.3 percent decrease in PM_{10} (which is qualitatively similar to the result of columns 1 and 3 of Table 8 in the previous section). Auffhammer, Bento and Lowe (2009) show that *within* U.S. counties in non-attainment of pollution standards, pollution abatement plans have bigger effects in the areas that cause the non-attainment than those that do not violate the standards. To look for any similar heterogeneity, we analyze PM_{10} pollution only at cities' dirtiest stations and find the treatment effect increases to minus 10.7 percent (column 2a).

One main question with the implementation of LEZs is whether air pollution decreases inside LEZs only, or whether outer areas of cities also benefit from the adoption or cleaner vehicles. To explore this question we coded the PM_{10} traffic measurement stations as inside or outside of the LEZ. Column 3a of Table 11 shows that the treatment effect at stations inside LEZs is 8.6 percent, slightly larger than the average treatment effect. In comparison, at traffic stations outside of LEZs, PM_{10} decreases by a statistically insignificant 3.6 percent (column 4a). These results imply that the benefits of PM_{10} reduction within the zones are not fully carried over to the traffic

[27] It is an interesting to note, that Cologne realized the lowest PM10 reduction (5%). Cologne is the only LEZ city that implemented an LEZ despite never violating the EC regulation. In Cologne therefore not the police is enforcing the regulation, but the much less representative agency "Stadt Koeln", which only issued a couple hundred of tickets. See http://www.spiegel.de/auto/aktuell/start-der-umweltzonen-kontrolle-vielleicht-strafe-spaeter-a-526151.html and http://www.ksta.de/innenstadt/verkehr-kaum-bussgelder-in-der-umweltzone,15187556,21405348.html.

stations outside of LEZs, a result that we will investigate in more detail in the case of Berlin below. Hence, again, we do not find statistical support for the stated hypotheses that PM_{10} levels increase around LEZs due to increased driving by dirty vehicles that cannot enter the LEZs. Again, consistent with the results of the previous subsection, at background stations LEZs are not associated with any significant change in PM_{10}, as displayed in Columns (1b) to (4b).

To further study the heterogeneity of LEZ cities, Figure 4 shows the treatment effect coefficients from comparing both background and traffic stations of each LEZ city to neighboring future LEZ cities.[28] The cities in the figure are ranked in descending order by the number of inhabitants within the LEZ,[29] such that Berlin has the most people residing within its LEZ. Consistent with the above findings, PM_{10} decreases at all LEZ cities' traffic stations (except for the smallest two cities by inhabitants, Ludwigsburg and Leonberg, where there is no statistically significant change in PM_{10}). At 12 percent, this decrease is greatest in Berlin—the most-populous LEZ—and the treatment effects tend to diminish with lower populous LEZs. The effect of LEZs is again more heterogeneous for background stations. There are significant increases in PM_{10} for Stuttgart, Mannheim, Reutlingen and Tübingen, while the changes are insignificant for Berlin, Hannover, Cologne[30] and Ludwigsburg.[31]

The above Differences-in-Differences estimates could overstate our LEZ treatment effect if PM_{10} data are subject to mean reversion. In particular, this is a serious concern due to the noisy outcome of PM_{10} which in reality depends on many variables that we cannot control for.[32] If cities are assigned into nonattainment status purely due to random shocks of emissions and then PM_{10} reverses to its mean, our numerical LEZ estimate will also represent this mean reversion

[28] See Table E1 of Appendix E for the control cities used for each LEZ city. The numerical results of the regressions are provided in Table E2.

[29] The number of inhabitants in the LEZ of Reutlingen and Tübingen has not been published. By geographical analysis of the boundaries of the LEZ (available from Climate Company, 2009), we estimate that the number inhabitants for Reutlingen and Tübingen is 78,523 and 78,300.

[30] The statistically insignificant yet relatively large decrease at Cologne's background station could be because one station is located about 340 meters southwest of a major interstate.

[31] Compared to the city by city results of the 'matching on 2005' identification, these city by city geographical regressions use much fewer control cities and the standard errors are larger. In both versions we cluster standard errors by city to be conservative.

[32] Local construction sites, open coal barbeques or similar events can temporary drastically increase PM_{10} emissions. If PM_{10} exceeds 50 mg per cubic meter more than 35 days per calendar year in part due to such outlier events, unrelated to traffic, and then PM_{10} reverses in the following years to its statistical mean, this phenomenon is described in the literature as mean reversion (Chay *et al*. 2005).

effect and hence overstate the true LEZ treatment effect. In following regressions of Table 12 and Table 13, we introduce placebo treatments as if the LEZs were introduced one year earlier. Hence using the year 2007 as the placebo treatment and 2006 as the control year in our Differences-in-Differences framework.[33] We perform this placebo test for both

(a) the 2005 PM_{10} matching strategy and

(b) the geographical matching approach.

In our placebo regressions below, we expect to see no significant effect of LEZs on PM_{10} because no LEZ was introduced prior to 2008. The two tables below list the results for each matching approach (a) and (b). The Tables are built analogue to the main original LEZ regression Table 8 and Table 11 presented earlier, with the LEZ treatment effect replaced by the placebo dummy. In summary, the general lack of significance of the placebo dummies in Table 12 and Table 13 indicates that both of our matching strategies are robust to these tests of mean reversion.

5.4 Spatial Spillover Effects: The LEZ of Berlin

The LEZ policy of Berlin is of particular interest. It covers over 88 square kilometers and it is the largest LEZ in terms of the 1.1 million inhabitants that live within the LEZ. Furthermore, Berlin already tightened its regulation, such that only green sticker vehicles have been allowed to enter the zone since January 1st of 2010.[34] As we are fortunate to have a particular large set of background and traffic stations both located within and outside of the LEZ of Berlin, we next analyze this city further.[35]

We first compare stations inside the LEZ of Berlin to the stations outside of the LEZ. In particular, the control group is defined as the set of four stations that are located outside of the LEZ of Berlin yet strictly within the greater urban area of Berlin. Column 1 of Table 14 shows that traffic stations within the LEZ experience a 6.0 percent decrease in PM_{10} relative to traffic

[33] Flagging treatment and control cities identically to our main regressions in the paper where 2008 is the treatment year and 2007 is the control year.

[34] This is a drastic tightening which implies that from 2010 onward, 62% of all commercially used vehicles in Germany (including all commercial trucks and buses) are banned to enter the city of Berlin since they do not have the green sticker. Further 13% of all privately used vehicles are non-green and hence excluded to enter the city of Berlin. See Table 15 for details.

[35] This section uses fifteen air pollution stations. Four stations are located within the LEZ boundary of Berlin, four are located within the greater city of Berlin, but are outside of the boundary of the LEZ and seven stations are drawn from the FLEZ cities that serve as controls in below regression. Of these, eight are traffic stations and seven are background stations.

stations outside the LEZ. This decrease could be either because PM_{10} emissions decrease within the LEZ, or because emissions increase outside of the LEZ as vehicles are forced to drive around it. To explore this, column 3 separately compares Berlin's four inside- and four outside-LEZ stations to the seven nearby control stations used in the geographical approach. Traffic stations within the LEZ experienced a significant reduction of 15.0 percent, which is the largest treatment effect among all our LEZ cities and likely attributable to the size of the LEZ and the stricter implementation scheme. Stations located outside of the Berlin LEZ also reduce PM_{10} levels by a significant 9.1 percent. Again, this is substantially larger than the (insignificant) average reduction of 3.6 percent for all German outside-LEZ traffic stations, as displayed in Table 11, column 4a. These results suggest that the benefits of adopting cleaner vehicles are also realized outside of the LEZ. In other words, even if more vehicles need to drive outside of the LEZ to circumvent it, this effect would be more than offset by the increased use of cleaner vehicles. Columns 2 and 4 show that background stations within the LEZ see no significant change in PM_{10} relative to those outside of the LEZ, again supporting the evidence that adopting an LEZ does little to improve air quality in areas away from major roads.

Finally, the case of Berlin also allows us to check our identification assumption whether FLEZ cities are appropriate control cities. Note that the 6% decrease in Column (1) is 'reflected' in the LEZ versus FLEZ regression of Column (3): the 'inside LEZ' coefficient of -.15 is exactly .06 larger compared to the 'outside LEZ' coefficient of minus 9%. This shows internal consistency of these two separate estimations in Columns (1) and (3). This lends additional support to our identification assumption of using FLEZs as credible control cites.[36]

5.5. Spatial Substitution between low and high emission vehicles

One important argument for the four-tier PM_{10} categorization is that it prompts a more rapid adoption of cleaner technologies, as even those who do not typically drive into an LEZ may want to keep the option value of free passage. To test this, next we construct an unique panel dataset of German vehicles to analyze spatial substitution effects in purchasing new vehicles and retrofitting existing vehicles attributable to LEZs.

[36] Also note that the same calculations hold for the background stations showing that the two (insignificant) treatment effects of minus 0.046 and minus 0.040 in column (4) are roughly equal to the (insignificant) treatment effect of minus 0.007 in column (2).

Data from the German Federal Motor Transport Authority (Kraftfahrtsbundesamt Flensburg) includes yearly observations of the total number of private and commercial vehicles by emission category (green, yellow, red or no sticker) for all districts from 2008 to 2010, reported on January 1 of each year. Table 15 summarizes the composition of the vehicle fleet; with 84%, the vast majority of vehicles now belong to the green sticker category. The changes over the two year time period are drastic. While on average the private vehicle fleet increased by only 1.3%, the green sticker group increased over-proportionally by 5.2%. This increase was driven by a drastic reduction of the red and no sticker vehicles, which decreased by 28 and 23 percent respectively (panel (A) Table 15). For commercially owned vehicles these changes are even more remarkable. As displayed in panel (B), their green sticker category increased by 88 percent, while red and no sticker vehicles decrease by 21 and 26 percent respectively. Because commercial vehicles are used for business activities and often rely on access to the city center, the pressure to upgrade the commercial vehicle fleet is more pronounced.

Figure 5 displays changes in the share of green sticker private vehicles by county between 2008 and 2009 as a function of the county's distance to the next LEZ.[37] The change in green sticker share is between 0.01 and 0.035 share points, while counties close to an LEZ experience the largest increase in green stickers. Visually, Regensburg and Bonn are outliers. It turns out that these cities' special circumstances explain their greater adoption of green sticker cars. In 2007, the local government of Regensburg announced an LEZ for spring 2008, then decided to postpone the introduction until September 1, 2008. This date was then again postponed to be tentatively scheduled for January 2010 (Stadt Regensburg, 2008). To this date the LEZ of Regensburg is still not implemented (Climate Company, 2010). It is therefore likely that the inhabitants of Regensburg responded to these announcements by preemptively upgrading their vehicles. The second outlier, the city of Bonn with 300,000 inhabitants, is very well connected to the LEZ city of Cologne (one million inhabitants) via a system of highways with mostly no speed limits, providing an incentive for Bonn's drivers to obtain green stickers

Next, Figure 6 shows how the share of the private vehicles without stickers (i.e. the highest-emitting vehicles) changed as a function of distance to the closest LEZ. All counties experience a decrease in the share of dirtiest vehicles, while once again the counties closest to an LEZ see the

[37] We use February 15, 2009 to determine the status of the city whether it contains an LEZ or not.

largest drop. Similarly, Figure 7 and Figure 8 show the change in shares of yellow and red sticker vehicles, respectively. Here the changes are more uniform across different counties. This is not surprising because these middle emissions categories are banned by few of the current LEZs.

Consistent with these figures, we present regression results in Table 16, which show that the adoption of green technology increases the closer the vehicle is registered to a city that has an LEZ. The change between 2008 and 2010 in each county's percentage of vehicles with green stickers is regressed on the distance from the county to the nearest LEZ city. In Table 16, the results are given separately for private and commercial vehicles and repeated for the change in percent of vehicles without stickers, the dirtiest. In particular, we find that for each km closer a vehicle is to an LEZ, the incentive to upgrade to a green sticker increases by about one percent for commercial vehicles and 0.6 percent for private vehicles. Hence, again, the effect is larger for commercial vehicles, as these rely more on access to city centers for business.

In summary, we find evidence that the introduction of LEZs creates 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. The incentives are particularly strong for the commercial vehicles, which more aggressively updated their fleet due to the LEZs.

6. Cost Benefit Analysis

To get sense of LEZ's efficiency, we use our results to calculate back-of-the-envelope costs and benefits of LEZs.[38] In order to calculate the changes in health benefits, we use epidemiological estimates measuring the effect of PM_{10} on long-term mortality from Medina *et al*. (2004). For the calculation we apply the *Value of the Statistical Life* of $7.9 million (2008$) to monetize these benefits (EPA 2000). Using our city-specific estimates (from the geographical) approach of Section 5 and applying the reductions in PM_{10} to the exposure of the number of inhabitants residing within each LEZ, we monetize these health benefits to be $1.98 billion dollar.

[38] Appendix F provides the details about the specific calculations involved of the costs and the benefits .

These health benefits stand against the costs of the LEZ program. The largest costs are due to the upgrading of the vehicle fleet. To calculate these costs, we use the vehicle spatial substitution results of Section 5. First, we use the vehicle registration data to fit regressions of the change in share of green-sticker private and commercial vehicles[39] on the distance from an LEZ. To avoid counting vehicles that would have switched to the green sticker category in the absence of the LEZ regulation, we use as the baseline the change in share of green stickers for the point furthest away from any LEZ. For each location, we subtract this baseline from our regressions' predicted change in share of green sticker vehicles. This is what we consider as the change in share of green stickers attributable to the LEZ. We then multiply this coefficient by the location's number of vehicles to obtain the number of new green vehicles attributable to the LEZ. Finally, we sum these numbers for all locations and multiply by the weighted average cost for upgrading cars, buses and trucks to get the total cost of $1.09 billion dollar due to LEZ induced vehicle upgrading.

These calculations are clearly approximate in nature and we omit some potentially important factors. First, the benefits may even be larger if congestion decreased within the LEZ reducing the amount of the time spend in stop and go traffic. This time saving effect would need to be compared to the additional time needed for those drivers that need to driver longer routes to circumvent the LEZ. Second, ancillary pollutants are not considered in the calculation of the health benefits. Third, business within the LEZ and outside of the LEZ can adversely or positively be affected. Fourth, the upgrading of the vehicle can potentially have other benefits to the driver, such as having a safer or more comfortable vehicle. Fifth, in our calculation we only considered the benefits to the residents that strictly live within the LEZ area. In the Appendix F we include calculations for all inhabitants of the cities which increases the benefits from $1.98 to $5.22 billion. Sixth, we consider only the changes at traffic stations. In some cities, however, also background stations were affected. Taking these changes into account reduces the estimated health benefit by $0.3 billion, in the case of the geographical matching approach. For our '2005 matching' approach, the welfare estimate however remains unchanged. With these limitations in mind our main results indicate health benefits of roughly two billion U.S. dollars, which came at a cost of about one billion U.S. dollar to upgrade the German vehicle fleet.

[39] Since vehicle registration data is measured as of January 1of every year, the data really measures vehicles purchased or upgraded in 2007 versus the vehicles purchased or upgraded in 2008.

7. Conclusions

With over half of the world's population living in increasingly motorized cities, urban traffic policies are receiving much interest to manage congestion, protect public health and to reduce emissions of air pollutants. A wide range of tools have been implemented, including the license plate program, permanent driving bans, congestion pricing, traffic cell architecture, temporary driving bans, the building of ring roads or the implementation of Low Emission Zones (LEZs). Uncertainty about the effectiveness, however, creates difficulties to make informative decisions among policy options and to gain public support by policy makers. As a result, often choices seem ad hoc and regionally clustered.

This paper is the first to study the effect of Low Emission Zones (LEZs), which is one of the most aggressive tools intended to rapidly decrease air pollutants, widely adopted across the European Union but also exists in Asia (i.e. Tokyo) and variations of the program are frequently discussed in combination with other traffic options, i.e. to exclude traffic charges for low emission vehicles in the U.S.[40] and elsewhere.

Our main findings are that (a) LEZs reduce particulate emissions by nine percent, whereas other air quality policies (which do not include a LEZ) had surprisingly no effect; (b) avoidance behavior of driving around the LEZ does not lead to significant spatial spillover effects; (c) there is heterogeneity across zones, with larger LEZs having stronger impacts; (d) spatial vehicle fleet composition changed drastically as a response to the announcements of LEZs in Germany.

Overall, our back of the envelope calculations predict health benefits of nearly two billion dollars that have come at a cost of just over 1 billion dollars for vehicle upgrading. While many more cities will have to implement stricter policies soon to circumvent EU penalties, this is the first timely paper to assess this popular and rapidly growing policy. More studies of related policies (congestion charging, public transportation etc.) are in order to better inform this public policy debate and to evaluate the relative efficiencies[41] of competing policies.

[40] In New York Bloomberg's popular plan was to introduce a fee system of congestion charges with exceptions and discounts for certain low-emission vehicles. Other major U.S. cities are discussing similar programs.

[41] See Fowlie et al., (2011) for a recent study on the relative efficiency of policies effecting stationary and non-stationary pollution sources.

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Table 1: EU PM_{10} limits

Panel A: European Union PM_{10} pollution thresholds

	Phase 1 since 1 January 2005	Phase 2 (now defunct) originally planned to start 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 PM_{10} limits

	2005	2006	2007	2008
National average PM_{10} [µg/m³]	24.4 (5.2)	26.2 (5.5)	23.1 (5.3)	21.2 (4.9)
Mean number of days** above 50 µg/m³	19.6 (20.9)	26.8 (21.1)	16.2 (15.8)	11.6 (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

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

Table 3: German LEZ restrictions 2008 to 2012

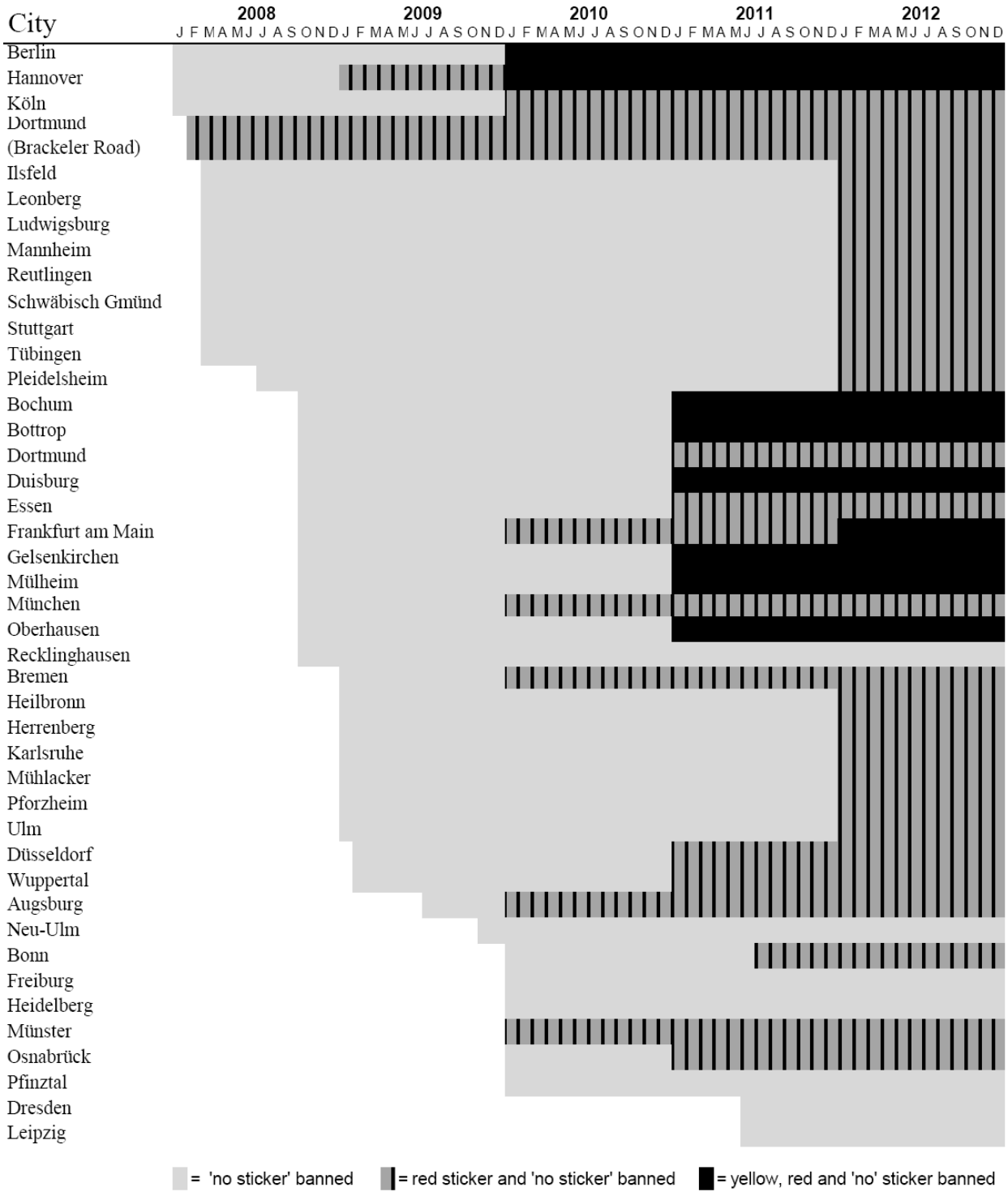


Table 4: Summary of weather data

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

Table 5: Treatment and control characteristics

	Number of cities	2005 highest-polluting station avg.	Avg. number of exceedance days
Attainment cities (AC)	22	26.8	22.4
Action Plan only cities (APO)	22	30.7	36.8
AP with LEZ after Oct. 2008 (FLEZ)	7	30.0	34.7
AP with LEZ before Oct. 2008 (LEZ)	4	28.9	28.9

These are the cities that make up our sample for the 2005 PM_{10} matching analysis.

Table 6: Effect of LEZ start date on 2007 PM_{10} levels

Panel 6a: Effect of LEZ start date on 2007 PM_{10} levels

	All Stations	Traffic stations	Background stations
	(1)	(2)	(3)
LEZ start date	-0.000173	-0.000225	0.0000811
	[0.000958]	[0.00117]	[0.000890]
Observations	24942	15478	9464
Adjusted R-squared	0.719	0.711	0.681

Panel 6b: Effect of LEZ start date on 2005 PM_{10} levels

	All Stations	Traffic stations	Background stations
	(1)	(2)	(3)
LEZ start date	0.00137	0.00164	0.00167
	[0.00163]	[0.00112]	[0.00262]
Observations	19409	10757	8652
Adjusted R-squared	0.694	0.697	0.622

Panel 6c: Effect of LEZ start date on 2006 PM_{10} levels

	All Stations	Traffic stations	Background stations
	(1)	(2)	(3)
LEZ start date	0.00282	0.00251	0.00386*
	[0.00193]	[0.00199]	[0.00205]
Observations	25813	16359	9454
Adjusted R-squared	0.717	0.718	0.672

Panel 6d: Effect of LEZ start date on change in PM_{10} levels between 2006 & 2007

	All Stations	Traffic stations	Background stations
	(1)	(2)	(3)
LEZ start date	-0.00120	-0.00188	0.0000886
	[0.00118]	[0.00139]	[0.00231]
Observations	23085	13991	9094
Adjusted R-squared	0.469	0.478	0.467

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

Table 7: Effect of Action Plans on Log PM_{10}

Matching based on 2005 PM_{10} in range 25 to 35

	All Action Plans (AP)		Action Plans Without LEZs (APO)		Action Plans With Future LEZs (FLEZ)	
	Traffic Stations (1)	Background Stations (2)	Traffic Stations (3)	Background Stations (4)	Traffic Stations (5)	Background Stations (6)
AP treatment	0.0117	0.0404	-0.0125	0.0440	0.0316	-0.0523
	[0.0366]	[0.0466]	[0.0357]	[0.0484]	[0.0530]	[0.0706]
Observations	28859	21236	22378	16380	12746	11532
Adj. R-squared	0.657	0.618	0.656	0.622	0.604	0.608

All regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for January-October 2005 vs. 2008.
Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

Table 8: LEZ vs. Attainment cities

Matching based on 2005 PM_{10} in range 25 to 35

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0910***	0.00724	-0.0686*	0.0448
	[0.0241]	[0.0285]	[0.0302]	[0.0354]
Observations	6723	7704	2896	4280
Adj. R-squared	0.657	0.591	0.653	0.653

All regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for April-October 2007 vs. 2008.
Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

Table 9: LEZ vs. Attainment cities: Sample Selection Effects

Matching based on 2005 PM_{10} in range **25 to 35**

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0910***	0.00724	-0.0686*	0.0448
	[0.0241]	[0.0285]	[0.0302]	[0.0354]
Observations	6723	7704	2896	4280
Adj. R-squared	0.657	0.591	0.653	0.653

Matching based on 2005 PM_{10} in range **23 to 37**

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0822***	0.00973	-0.0686*	0.0283
	[0.0203]	[0.0236]	[0.0302]	[0.0402]
Observations	7977	11984	2896	5992
Adj. R-squared	0.654	0.591	0.653	0.612

Matching based on 2005 PM_{10} in range **21 to 39**

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0486*	0.0249	-0.0362	0.0431
	[0.0272]	[0.0264]	[0.0346]	[0.0415]
Observations	10942	17974	5861	9842
Adj. R-squared	0.645	0.581	0.618	0.611

Matching based on 2005 PM_{10} in range **20 to 40**

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0486*	0.0228	-0.0362	0.0412
	[0.0272]	[0.0251]	[0.0346]	[0.0370]
Observations	10942	19686	5861	10698
Adj. R-squared	0.645	0.582	0.618	0.612

Matching based on 2005 PM_{10} **No Range**

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0554**	0.0347	-0.0322	0.0477
	[0.0240]	[0.0290]	[0.0299]	[0.0376]
Observations	14583	22682	8688	12410
Adj. R-squared	0.669	0.587	0.661	0.618

All regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for April-October 2007 vs. 2008.
Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

Table 10: Effect of Individual LEZ on log PM_{10}

Matching based on 2005 PM_{10} in range 25 to 35

	All station types	Traffic stations	Background stations
		(A) Mannheim LEZ	
	(1a)	(2a)	(3a)
LEZ treatment	-0.0837***	-0.132***	-0.0345
	[0.0182]	[0.0187]	[0.0263]
Observations	11958	5538	6420
Adj. R-squared	0.592	0.618	0.578
		(B) Cologne LEZ	
	(1b)	(2b)	(3b)
LEZ treatment	-0.00605	-0.0475**	0.0132
	[0.0170]	[0.0192]	[0.0251]
Observations	12412	5564	6848
Adj. R-squared	0.601	0.628	0.586
		(C) Reutlingen	
	(1c)	(2c)	(3c)
LEZ treatment	-0.0461**	-0.130***	0.0342
	[0.0206]	[0.0197]	[0.0271]
Observations	8555	3965	6420
Adj. R-squared	0.632	0.658	0.592
		(D) Leonberg	
	(1d)	(2d)	
LEZ treatment	-0.0765***	-0.0693***	
	[0.0194]	[0.0187]	
Observations	11531	5539	
Adj. R-squared	0.601	0.631	

All regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for April-October 2007 vs. 2008.
Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

Table 11: All Early LEZs vs. Nearby Future LEZs

	All stations	Dirtiest stations	Inside LEZ	Outside LEZ
		Traffic stations		
	(1a)	(2a)	(3a)	(4a)
LEZ treatment	-0.0733**	-0.107**	-0.0862***	-0.0363
	[0.0319]	[0.0392]	[0.0289]	[0.0465]
Observations	15794	7849	14156	10885
Adj. R-squared	0.683	0.707	0.692	0.677
		Background stations		
	(1b)	(2b)	(3b)	(4b)
LEZ treatment	0.0163	0.148	0.0145	0.0178
	[0.0381]	[0.0549]	[0.0643]	[0.0327]
Observations	9842	1284	6848	8130
Adj. R-squared	0.633	0.556	0.633	0.627

All regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for April-October 2007 vs. 2008.

Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

Table 12: Placebo Regression: 2005 PM_{10} Matching Approach – Analogue to Table 8, but using 2007 as the placebo treatment

LEZ vs. Attainment cities – 2006 vs. 2007

	All cities		**Cities > 100,000**	
	Traffic stations	Background stations	Traffic stations	Background stations
	(1)	(2)	(3)	(4)
Placebo dummy	0.139	-0.0137	0.121	0.0191
	[0.144]	[0.0743]	[0.0953]	[0.0630]
Observations	6420	8132	2896	4280
Adj. R-squared	0.670	0.645	0.653	0.653

All regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for April-October 2006 vs. 2007.
Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

Table 13: Placebo Regression of Geographical Matching Approach— Analogue to Table 11, but using 2007 as the placebo treatment

All Early LEZs vs. Nearby Future LEZs – 2006 vs. 2007

	All stations	Dirtiest stations	Inside LEZ	Outside LEZ
		Traffic stations		
	(1a)	(2a)	(3a)	(4a)
Placebo dummy	-0.0256	-0.0066	-0.0189	-0.0528
	[0.0405]	[0.0764]	[0.0470]	[0.0674]
Observations	17110	7271	15612	11332
Adj. R-squared	0.692	0.700	0.696	0.685
		Background stations		
	(1b)	(2b)	(3b)	(4b)
Placebo dummy	-0.0515	0.0376	0.0034	-0.0845
	[0.0443]	[0.100]	[0.0300]	[0.0555]
Observations	10690	1707	7694	8555
Adj. R-squared	0.656	0.622	0.650	0.647

All regressions include year-month fixed effects, weather, holiday, station type and population covariates. Regressions include data for April-October 2006 vs. 2007. Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05 * p<0.1

Table 14: Berlin LEZ: Stations within LEZ compared to those outside

Stations within LEZ compared to those outside			**Compared to nearby FLEZ cities**	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
LEZ treatment	-0.0596**	-0.0066		
	[0.0251]	[0.0236]		
LEZ treatment: inside LEZ			-0.150**	-0.0462
			[0.0210]	[0.0133]
LEZ treatment: outside LEZ			-0.0906**	-0.0402
			[0.0210]	[0.0142]
Observations	2188	1639	4376	2186
Adjusted R-squared	0.599	0.615	0.591	0.591

All regressions include year-month fixed effects, weather, holiday, station type and population covariates. Regressions include data for February-October 2007 vs. 2008.
Robust standard errors in brackets are clustered by month for columns (1) and (2) and city for columns (3) and (4), *** p<0.01, ** p<0.05, * p<0.1.

Table 15: Vehicle Registration by emissions sticker category private vehicles

(A) Private Vehicles

	2008	2009	2010	% change 2008 vs. 2010
Green	34,020,748	34,862,420	35,795,940	5.2
Yellow	3,931,262	3,597,594	3,425,119	-12.9
Red	1,267,825	1,092,315	907,543	-28.4
No Sticker	1,597,089	1,381,064	1,236,204	-22.6
Total	40,816,924	40,933,393	41,364,806	1.3

(B) Commercial Vehicles

	2008	2009	2010	% change 2008 vs. 2010
Green	524,542	792,577	985,245	87.8
Yellow	945,181	844,803	793,008	-16.1
Red	469,853	413,133	372,962	-20.6
No Sticker	609,948	518,545	451,169	-26.0
Total	2,549,524	2,569,058	2,602,384	2.1

Table 16: Effect of distance from LEZ city on green technology adoption

	Change in % of green sticker vehicles from 2008 to 2010	
	Private vehicles	Commercial vehicles
	(1)	(2)
Distance to nearest LEZ, km	-0.0061***	-0.0108***
	[0.0005]	[0.0025]
Observations	405	405
Adj R-squared	0.265	0.042
	Change in % of no sticker vehicles from 2008 to 2010	
	Private vehicles	Commercial vehicles
	(3)	(4)
Distance to nearest LEZ, km	0.0030***	0.0070***
	[0.00021]	[0.0012]
Observations	405	405
Adj R-squared	0.333	0.080

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

Figure 1: Current and Future German LEZs

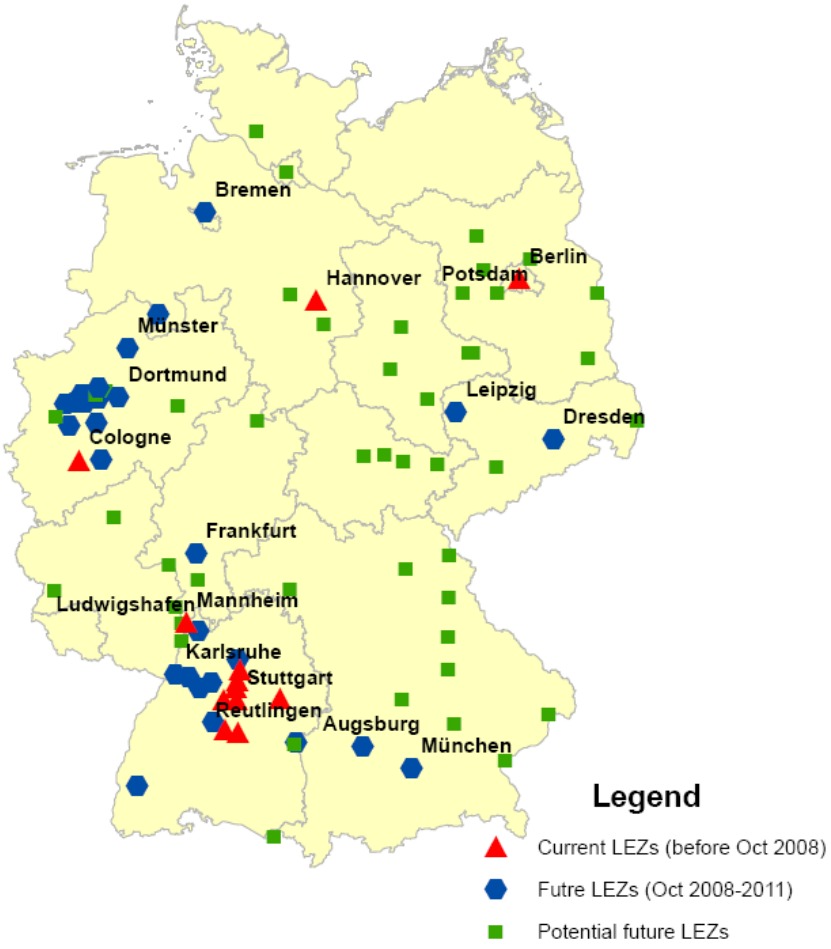


Figure 2: Classification of cities treatment status

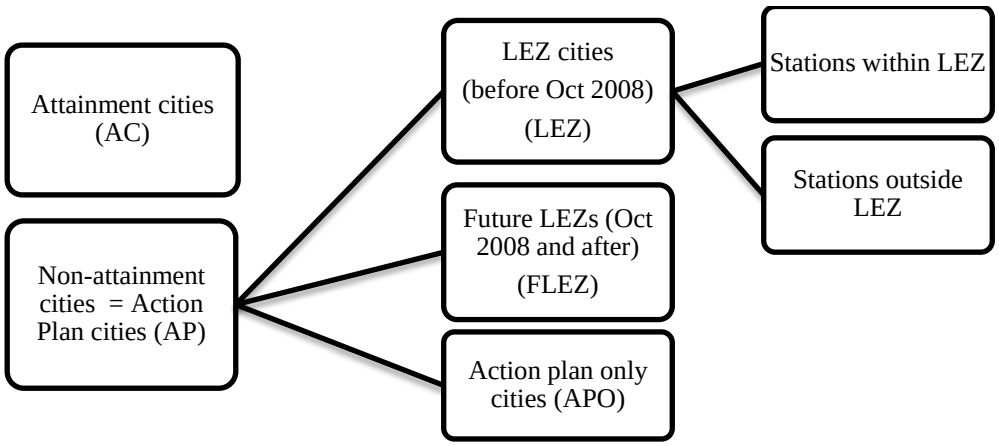
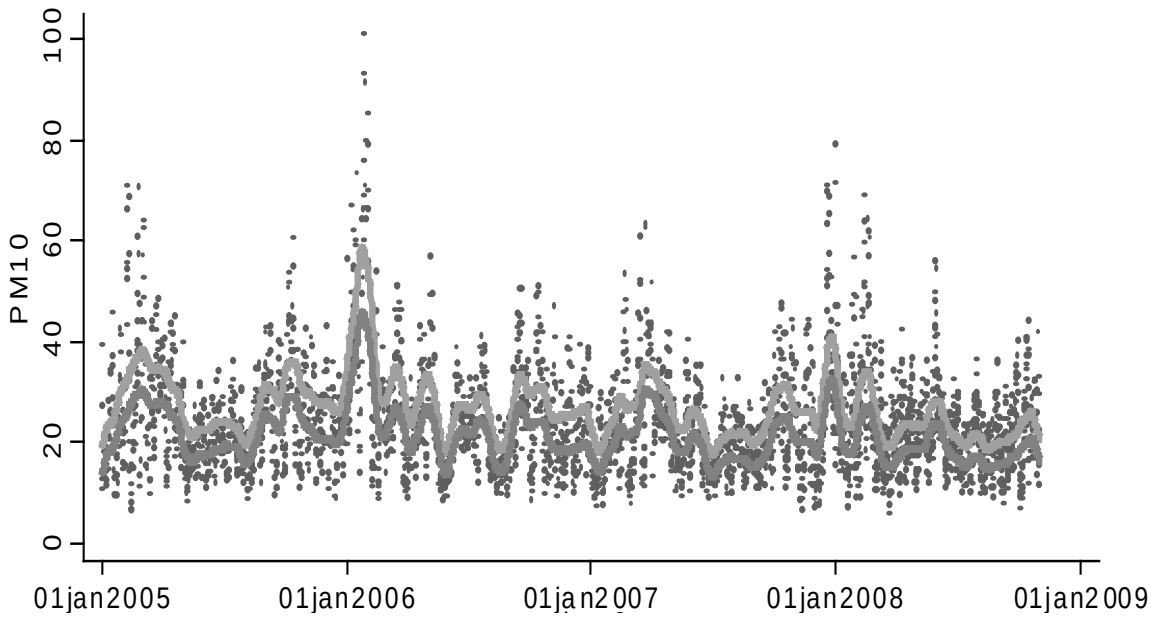
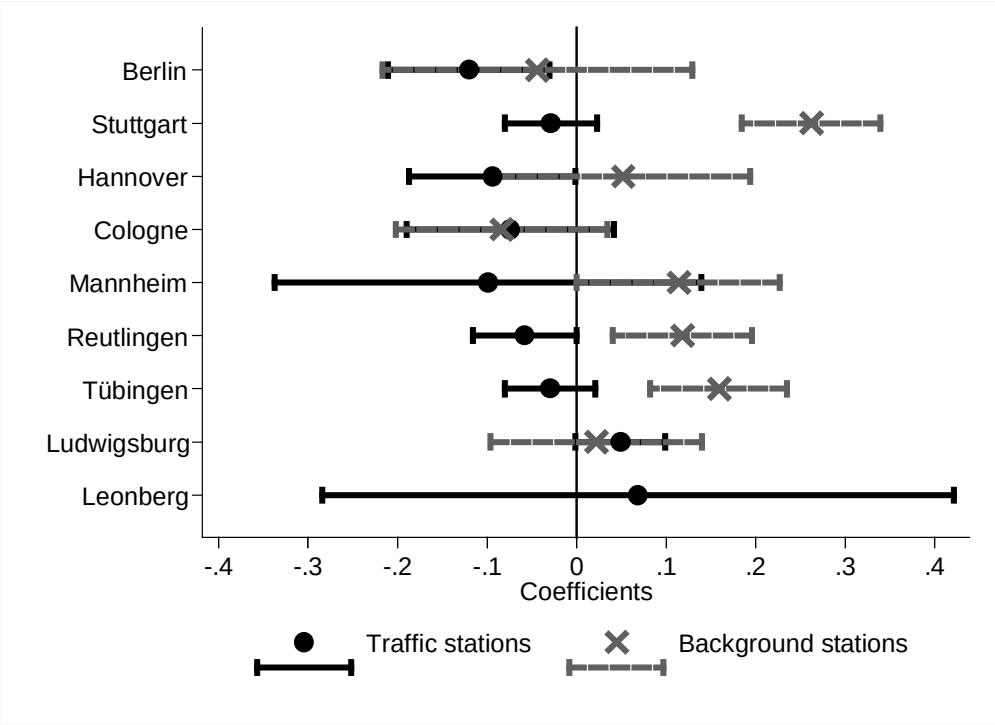


Figure 3: Average daily PM10 levels by Attainment Status



Note: Each dot represents the national average daily PM10 level. The bold light grey line displays average daily PM10 level for non-attainment cities and the black bold black line the average daily PM10 level for attainment cities both estimated by the locally weighted scatterplot smoothing method with bandwidth of 0.03.

Figure 4: Treatment Effects of Individual LEZs Using Regional Approach



Note: Plots include 95% confidence intervals of treatment effects

Figure 5: Change of share of green sticker vehicles 2008 to 2009 as function of distance of the county to LEZ (privately owned cars)

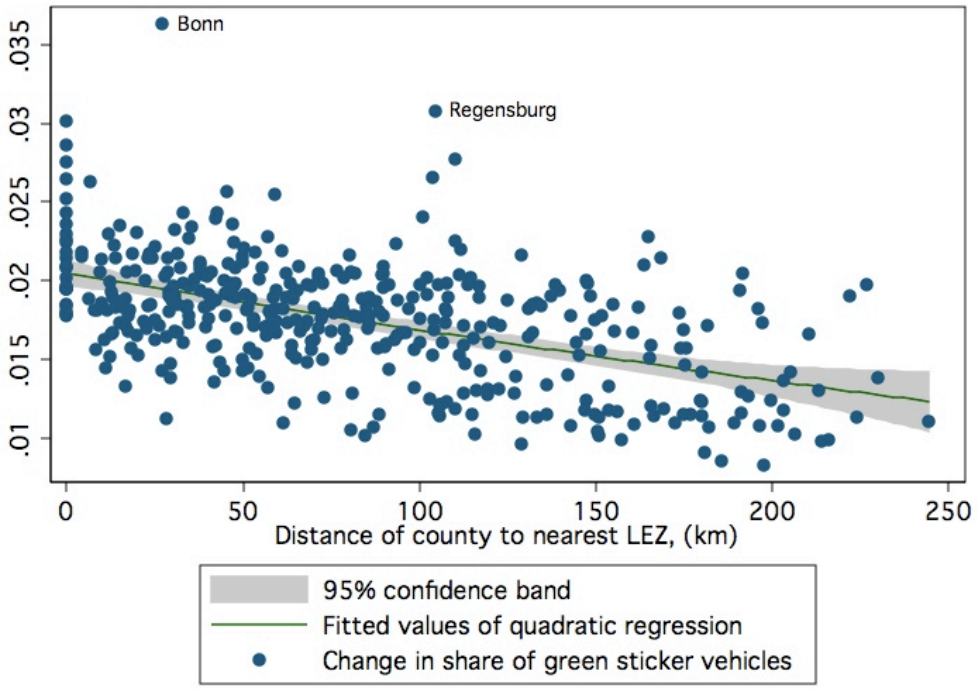


Figure 6: Change of share of no sticker vehicles 2008 to 2009 as function of distance of the county to LEZ (privately owned cars)

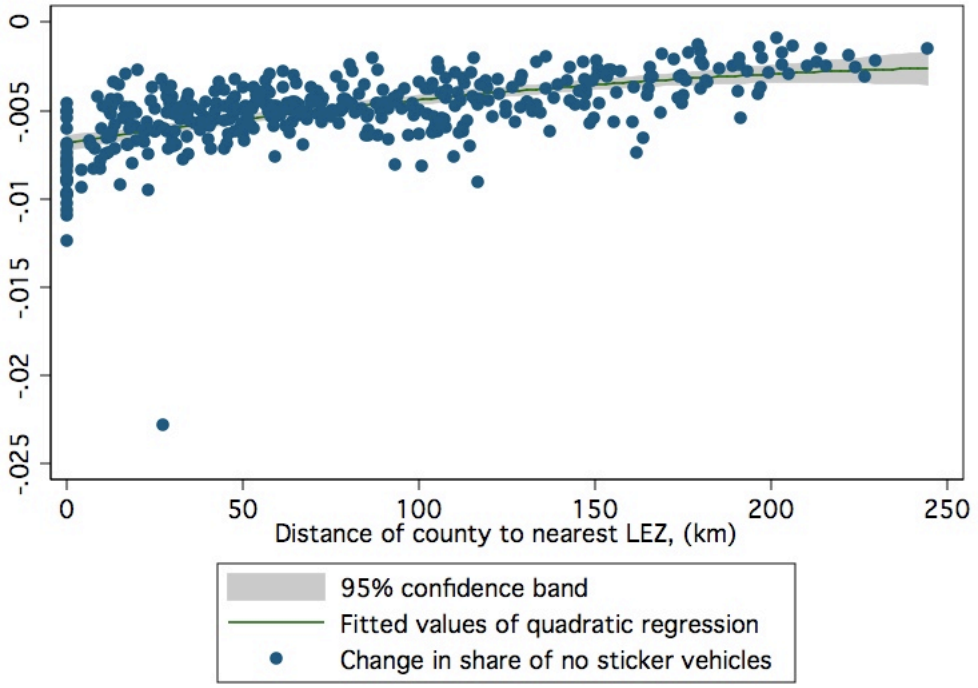


Figure 7: Change of share of red sticker vehicles 2008 to 2009 as function of distance of the county to LEZ (privately owned cars)

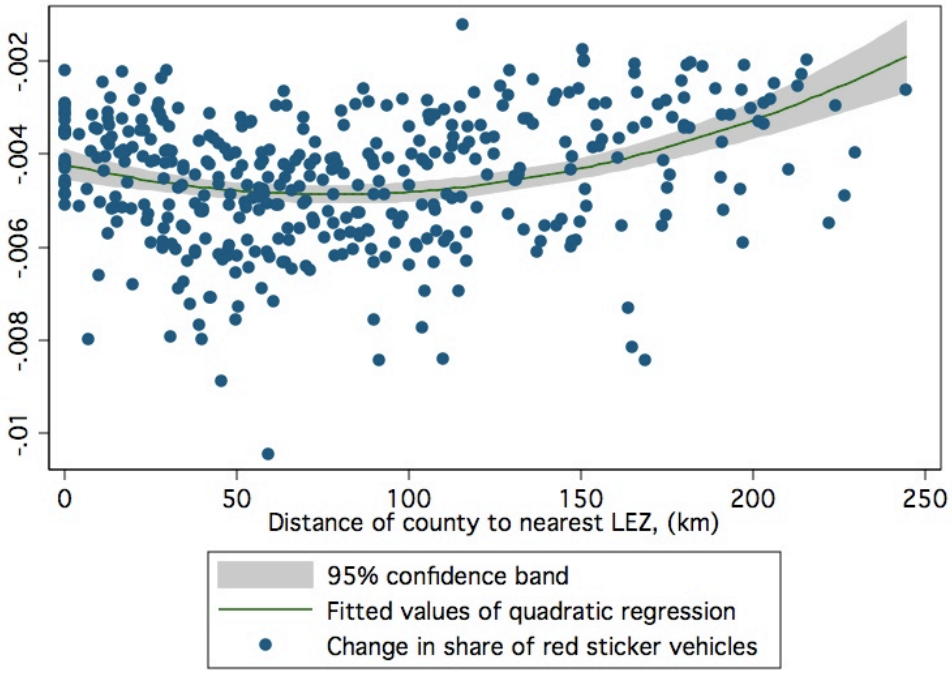
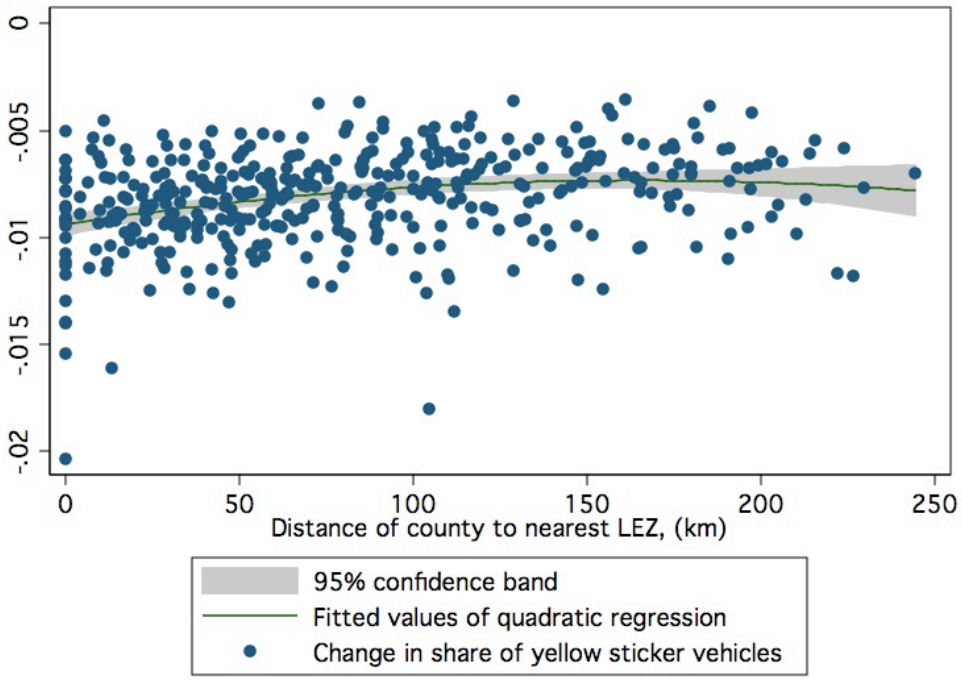


Figure 8: Change of share of yellow sticker vehicles 2008 to 2009 as function of distance of the county to LEZ (privately owned cars)



Technical Appendix to

KEEP YOUR CLUNKER IN THE SUBURB: LOW EMISSION ZONES AND ADOPTION OF GREEN VEHICLES

Hendrik Wolff

This is the web based online supplemental Appendix of the main article and consists of the following six sections:

Appendix A: Comparative Results of Recent Urban PM10 Studies

Appendix B: Characteristics of German Attainment Cities, Nonattainment Cities and LEZ

Appendix C: Average daily PM10 level by LEZ Treatment Status

Appendix D: Test of Alternative Specifications:

Appendix E: Sample Details on Geographical Matching Approach

Appendix F: Cost Benefit Analysis

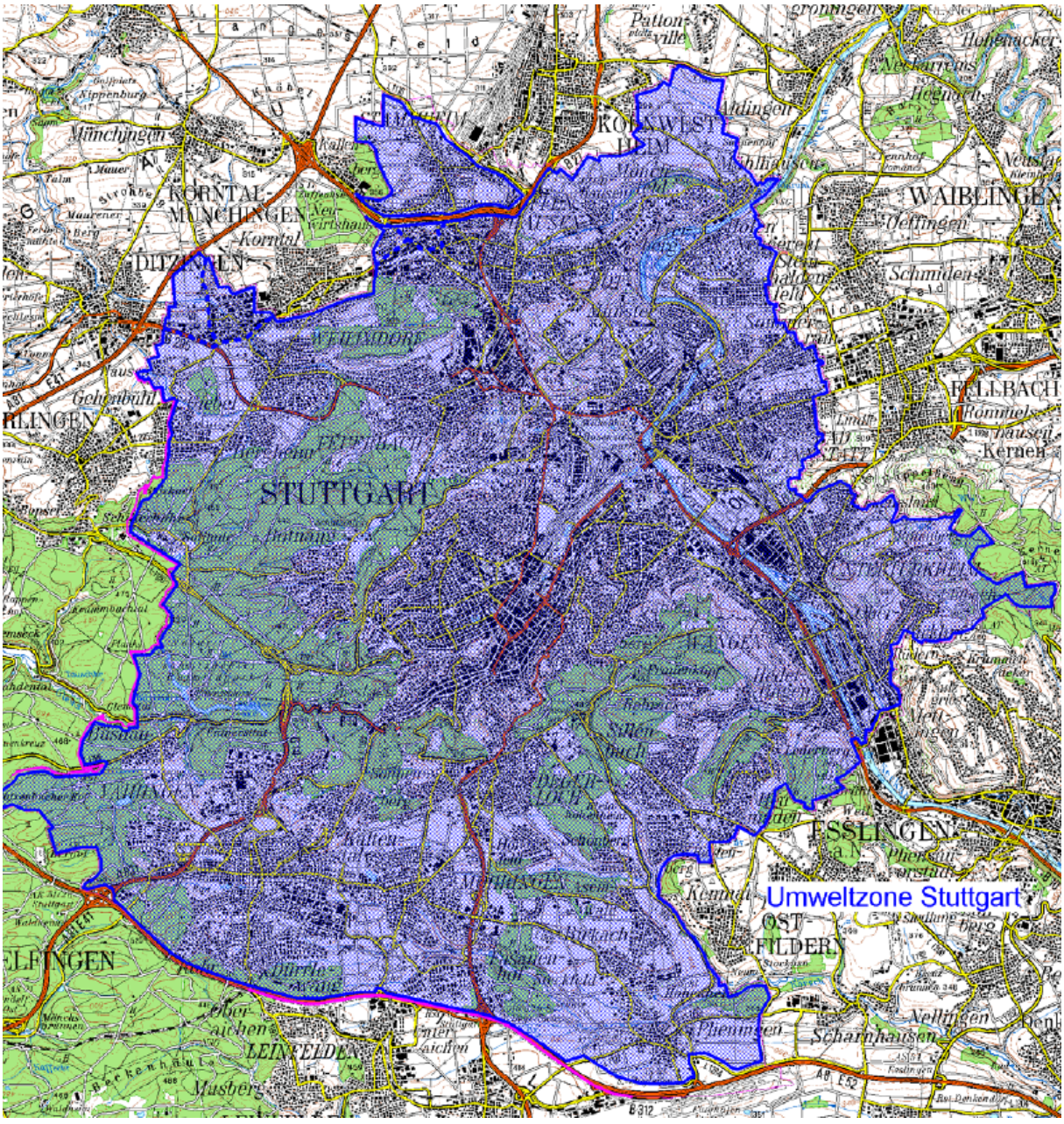
Table A.1: Comparative Results of Recent Urban PM10 Studies

Study	Country	Station Type	PM 10 Sources				
			Motor Vehicle Exhaust	Resuspension (Dust)	Combustion (Industry and Individual)	Natural Sources	Other
Lenschow et al. (2001)	Germany (Berlin)	Traffic	38%	12%[1]	24%	12%[2]	NA
		Background	23%	8%[3]	33%	14%[2]	NA
Querol et al. (2004)	EU	Traffic	35-55%	NA	15-25%	17-24%	NA
Querol et al. (2001)	Spain	Traffic	54%	NA	NA	30%	17%[4]
Ferusjo et al. (2007)	Sweden	Traffic	36%	23%	14%	NA	26%[5]
		Background	13%	23%	19%	NA	34%[5]
Rodriquez et al. (2003)	Spain	Traffic	25%	33%	16%	11%[6]	NA
		Background	8%	42%	20%	11%[6]	NA
Chow et al. (1996)	USA (CA)	Traffic	30-42%	25-37%	NA	18-23%[6]	NA
Harrison et al. (1997)	UK	Traffic	32%	50%	NA	NA	18%[7]

[1]The authors attribute 50% of PM10 levels to motor vehicles and then split this into 38% from emissions/tire abrasion and 12% from the resuspension of dust caused by traffic.
[2]The residual is attributed to natural sources such as pollen and wind-borne soil.
[3]The authors attribute 31% of PM10 levels to traffic and then split this into 23% from emissions/tire abrasion effect on background levels and 8% from resuspension of dust.
[4] Source is undetermined.
[5]Long range transport of pollution or dust particles from outside of Sweden.
[6]The specific natural source is marine aerosol.
[7]They identify the residual as secondary ammonium salts and are unable to determine whether these arise from combustion or are the effect of marine air.

Appendix B: Characteristics of German Attainment Cities, Nonattainment Cities and LEZ

Figure B.1: The LEZ of Stuttgart



Copyright: Landesvermessungsamt Baden-Württemberg, Bundesamt für Kartographie und Geodäsie 2003. The English term “Low Emission Zones” is commonly known in German as *Umweltzone* (Environmental Zone).

Table B1: Current and Future German LEZs

City	Start date	Excluded vehicles	Size of LEZ: new	Inhabitants that live within the LEZ	Dates of future restrictions (2nd, 3rd round)	Future excluded vehicles (2nd, 3rd round)
Berlin	1/1/2008	no sticker	88 km^2	1.1 mill	1/1/2010	red + yellow
Cologne	1/1/2008	no sticker	16 km^2	130,000	1/1/2010	red
Hannover	1/1/2008	no sticker	50 km^2	218,000	01/01/09, 01/01/10	red, yellow
Dortmund (Brackeler Road)	1/12/2008	no sticker + red	< 0.1 km^2	300	1/1/2010	not yet planned
Ilsfeld	3/1/2008	no sticker	2.5 km^2	4,000	1/1/2012	red
Leonberg	3/1/2008	no sticker	30 km^2	40,000	1/1/2012	red
Ludwigsburg	3/1/2008	no sticker	30 km^2	55,000	1/1/2012	red
Mannheim	3/1/2008	no sticker	7.5 km^2	93,900	1/1/2012	red
Reutlingen	3/1/2008	no sticker	<10 km^2	Unknown	1/1/2012	red
Schwäbisch Gmünd	3/1/2008	no sticker	5 km^2	20,000	1/1/2012	red
Stuttgart	3/1/2008	no sticker	207 km^2	590,000	1/1/2012	red
Tübingen	3/1/2008	no sticker	≈13 km^2	Unknown	1/1/2012	red
Pleidelsheim	7/1/2008	no sticker	7 km^2	7,000	1/1/2012	red
Bochum	10/1/2008	no sticker	58.1 km^2	150,000	end of 2010	red + yellow
Bottrop	10/1/2008	no sticker	≈25 km^2	Unknown	end of 2010	red + yellow
Dortmund	10/1/2008	no sticker	19.1 km^2	587,137	1/1/2011	red
Duisburg	10/1/2008	no sticker	≈43 km^2	Unknown	end of 2010	red + yellow
Essen	10/1/2008	no sticker	140 km^2	14,000	1/1/2011	red
Frankfurt	10/1/2008	no sticker	110 km^2	Unknown	01/01/10, 01/01/12	red, yellow
Gelsenkirchen	10/1/2008	no sticker	20 km^2	Unknown	end of 2010	red + yellow
Mülheim	10/1/2008	no sticker	≈14.2 km^2	Unknown	end of 2010	red + yellow
München	10/1/2008	no sticker	44 km^2	431,000	1/1/2010	red
Oberhausen	10/1/2008	no sticker	23.8 km^2	91,000	end of 2010	red + yellow
Recklinghausen	10/1/2008	no sticker	<20 km^2	Unknown	Unknown	Unknown
Bremen	1/1/2009	no sticker	7 km^2	56,000	1/1/2010	red
Heilbronn	1/1/2009	no sticker	≈22.5 km^2	Unknown	1/1/2012	red
Herrenberg	1/1/2009	no sticker	≈4 km^2	28,000	1/1/2012	red
Karlsruhe	1/1/2009	no sticker	≈ 12 km^2	Unknown	1/1/2012	red
Mühlacker	1/1/2009	no sticker	≈ 1.5 km^2	Unknown	2012	red
Pforzheim	1/1/2009	no sticker	≈ 2 km^2	Unknown	1/1/2012	red
Ulm	1/1/2009	no sticker	≈ 27 km^2	Unknown	1/1/2012	red
Düsseldorf	2/15/2009	no sticker	13.8 km^2	36,500	1/1/2011	red
Wuppertal	2/15/2009	no sticker	≈ 15 km^2	Unknown	1/1/2011	red
Augsburg	7/1/2009	no sticker	5.2 km^2	Unknown	1/1/2010	red
Neu-Ulm	11/1/2009	no sticker	≈ 2.7 km^2	Unknown	1/1/2012	red
Bonn	1/1/2010	no sticker	≈ 5 km^2	Unknown	7/1/2011	red + yellow
Freiburg	1/1/2010	no sticker	28 km^2	120,000	1/1/2012	red + yellow
Heidelberg	1/1/2010	no sticker	10.3 km^2	170,000	1/1/2012	red
Münster	1/1/2010	no sticker + red	≈ 1.5 km^2	Unknown	Unknown	Unknown
Osnabrück	1/4/2010	no sticker	14 km^2	7,000	1/4/2011	red
Pfinztal	1/1/2010	no sticker	31 km^2	18,000	1/1/2012	red
Dresden	2012	no sticker	4.2 km^2	6,500	Unknown	Unknown
Leipzig	1/1/2011	no sticker-yellow	≈ 239 km^2	Unknown	Unknown	Unknown

Cities with proposed LEZs (no final start date yet): Arnsbach, Arzberg, Aschersleben, Bayreuth, Bernau, Brandenburg an der Havel, Braunschweig, Burgdorf, Burghausen, Castrop-Rauxel, Chemnitz, Cottbus, Darmstadt, Eberswalde, Erfurt, Erwitte, Frankfurt an der Oder, Gera, Görlitz, Halle (Saale), Hambach, Hamburg, Ingolstadt, Itzehoe, Jena, Kassel, Krefeld, Lahn-Dill, Landshut, Lindau, Ludwigshafen, Lutherstadt Wittenberg, Mainz, Magdeburg, Mühlheim an der Ruhr, Nauen, Neuruppin, Neuwied, Neuss, Passau, Potsdam, Regensburg, Rhein-Main, Schwandorf, Speyer, Trier, Warstein, Weiden, Weimar, Worms, Wuppertal, Würzburg

Table B2: Characteristics of all Attainment and Nonattainment Cities

City	Avg. 2005 PM_{10} at highest polluting station	2005 Exceed-ance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Wascheid	12.0	0	0	Attainment		
Netphen	12.6	0	0	Attainment		
Neuglobsow	13.8	3	0	Attainment		
Simmerath	14.0	0	0	Attainment		
Welzheim	16.2	4	0	Attainment		
Andechs, Gde.teil Rothenfeld	16.5	4	0	Attainment		3,237
Dunzweiler	16.6	2	0	Attainment		974
Hummelshain	16.6	1	0	Attainment		641
Bad Arolsen/Kohlgrund	17.0	5	0	Attainment		
Wittenberge	17.3	2	0	Attainment		
Dreißigacker	17.5	0	0	Attainment		
Rehlingen-Siersburg	17.7	3	0	Attainment		15,805
Klötze	17.8	2	0	Attainment		5,243
Kiel	18.7	5	0	APO-no violation		234,470
Güstrow	19.4	4	0	Attainment		105,071
Saarlouis	19.6	3	0	Attainment		209,719
Westerland	19.6	7	0	Attainment		
Kempten (Allgäu)	19.7	8	0	Attainment		61,442
Pfullendorf	20.1	8	0	Attainment		
Soest	20.4	6	0	Attainment		308,211
Wörth	20.5	8	0	Attainment		17,500
Tauberbischofsheim	20.5	13	0	Attainment		
Gülzow	20.6	9	0	Attainment		1,288
Wilhelmshaven	20.8	11	0	Attainment		83,245
Ratingen	20.8	5	0	Attainment		
Leverkusen	20.8	2	0	Attainment		161,030
Zarrentin	20.8	9	0	Attainment		4,672
Solingen	20.9	7	0	Attainment		163,291
Naila	21.1	7	0	Attainment		8,305
Walsrode	21.1	8	0	Attainment		
Michelstadt	21.2	7	0	Attainment		
Zella-Mehlis	21.3	4	0	Attainment		12,245
Göhlen	21.3	11	0	Attainment		407
Tübingen	21.6	9	1	LEZ	3/1/2008	216,616
Biberach	21.6	13	0	Attainment		188,693
Klingenthal	21.6	9	0	Attainment		8,831
Pforzheim	21.7	13	1	'Future' LEZ	1/1/2009	119,168
Eisenach	21.8	10	0	Attainment		43,703
Jork	21.8	11	0	Attainment		
Völklingen	21.9	3	0	Attainment		40,794
Nettetal	22.1	8	0	Attainment		
Reidstadt	22.2	9	0	Attainment		
Eggenstein	22.3	10	0	Attainment		
Neuruppin	22.4	13	0	APO-no violation		
Wiesloch	22.4	12	0	Attainment		

Appendix B (cont.) City	Avg. 2005 PM_{10} at highest polluting station	2005 Exceed-ance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Dillingen	22.5	4	0	Attainment		21,431
Friedrichshafen	22.5	14	0	Attainment		
Kleinwallstadt	22.6	9	0	Attainment		5,823
Fulda	22.7	7	0	Attainment		219,600
Neu Zauche	22.7	16	0	Attainment		
Aalen	22.8	16	0	Attainment		
Bonn	22.9	4	0	'Future' LEZ -no violation	1/1/2010	313,291
Raunheim	23.1	12	0	Attainment		
Zeitz	23.1	16	0	Attainment		31,045
Hattingen	23.2	7	0	Attainment		
Wesel	23.2	15	0	Attainment		475,923
Radebeul	23.2	14	0	Attainment		33,091
Greiz	23.2	16	0	Attainment		115,387
Waiblingen	23.3	13	0	Attainment		
Bebra	23.3	10	0	Attainment		
Neustadt a.d. Donau	23.3	14	0	Attainment		12,738
Schwerte	23.5	9	0	Attainment		
Lünen	23.5	11	0	Attainment		
Osnabrück	23.6	13	1	'Future' LEZ -no violation	1/4/2010	163,330
Konstanz	23.6	18	0	Attainment		274,571
Plochingen	23.6	13	0	Attainment		
Delitzsch	23.7	12	0	Attainment		122,500
Buckow	23.8	21	0	Attainment		
Schwäbisch Hall	23.9	13	0	Attainment		189,579
Saalfeld	24.0	16	0	Attainment		27,861
Heidelberg	24.0	11	0	'Future' LEZ -no violation	1/1/2010	143,897
Burg	24.0	6	0	Attainment		25,000
Lingen	24.4	21	0	Attainment		
Meiningen	24.4	10	0	Attainment		21,448
Hof	24.4	21	0	Attainment		48,443
Hoyerswerda	24.4	20	0	Attainment		42,048
Bernburg	24.4	9	0	Attainment		64,860
Rostock	24.7	15	0	APO-no violation		199,325
Zwickau	24.7	18	0	Attainment		97,296
Hürth	24.7	8	0	Attainment		
Suhl	24.8	2	0	Attainment		42,283
Speyer	24.8	18	0	APO-no violation		50,567
Kulmbach	24.9	12	0	Attainment		76,890
Mönchengladbach	25.0	24	0	Attainment		261,216
Ulm	25.1	18	1	'Future' LEZ	1/1/2009	120,748
Schweinfurt	25.1	14	0	Attainment		54,097
Altenburg	25.2	27	0	Attainment		37,236
Coburg	25.4	15	0	Attainment		41,768
Aschaffenburg	25.6	12	0	Attainment		68,645
Wiesbaden	25.8	18	0	Attainment		275,085
Bernhausen	25.9	21	1	APO		13,216

Appendix B (cont.) City	Avg. 2005 PM_{10} at highest polluting station	2005 Exceed-ance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Bautzen	25.9	20	0	Attainment		148,945
Stralsund	26.2	22	0	Attainment		58,563
Heilbronn	26.2	22	1	'Future' LEZ	1/1/2009	121,498
Lindau (Bodensee)	26.3	28	1	APO		79,636
Emden	26.3	20	0	Attainment		51,666
Nauen	26.4	25	0	APO-no violation		16,674
Hanau	26.5	20	0	Attainment		88,251
Königs Wusterhausen	26.5	20	0	Attainment		33,201
Weißenfels	26.6	32	0	Attainment		73,624
Pirmasens	26.6	16	0	Attainment		42,761
Bamberg	26.7	20	0	Attainment		69,746
Freiberg	26.7	33	0	Attainment		144,094
Leonberg	26.8	16	1	LEZ	3/1/2008	45,537
Stendal	26.9	18	0	Attainment		130,436
Gelsenkirchen	27.0	24	0	'Future' LEZ	10/1/2008	267,418
Cologne	27.0	14	0	LEZ-no violation	1/1/2008	986,317
Mülheim	27.0	21	0	'Future' LEZ-no violation	10/1/2008	169,651
Zittau	27.0	31	0	Attainment		29,898
Arzberg	27.0	24	0	APO-no violation		5,893
Itzehoe	27.1	21	0	APO-no violation		33,800
Dessau	27.2	18	0	Attainment		77,914
Schwandorf	27.3	30	0	APO-no violation		144,644
Worms	27.5	27	1	APO		81,984
Würzburg	27.7	30	0	APO-no violation		134,080
Glauchau	27.8	24	0	Attainment		25,760
Norderney	27.8	17	0	Attainment		5,986
Aachen	28.0	18	0	APO		258,055
Wuppertal	28.0	20	0	'Future' LEZ	2/15/2009	358,813
Plauen	28.1	33	1	APO		68,614
Magdeburg	28.3	22	1	APO		229,344
Erlangen	28.3	22	0	APO		103,469
Gera	28.4	31	1	APO		103,446
Reutlingen	28.5	17	1	LEZ	3/1/2008	281,933
Saarbrücken	28.5	18	0	Attainment		340,702
Ratzeburg	28.8	28	0	APO-no violation		13,671
Datteln	29.0	30	0	Attainment		36,297
Krefeld	29.0	24	1	APO		237,336
Borna	29.1	31	0	Attainment		22,561
Neu-Ulm	29.1	34	1	'Future' LEZ	11/1/2009	163,477
Jena	29.6	29	1	APO		102,291
Landshut	29.7	39	1	APO		61,757
Nürnberg	29.7	33	0	APO-no violation		498,936
Weimar	29.8	35	1	APO		64,541
Trier	29.9	26	0	APO-no violation		100,198
Karlsruhe	29.9	22	1	'Future' LEZ	1/1/2009	285,756
Bottrop	30.0	33	0	'Future' LEZ	10/1/2008	119,195

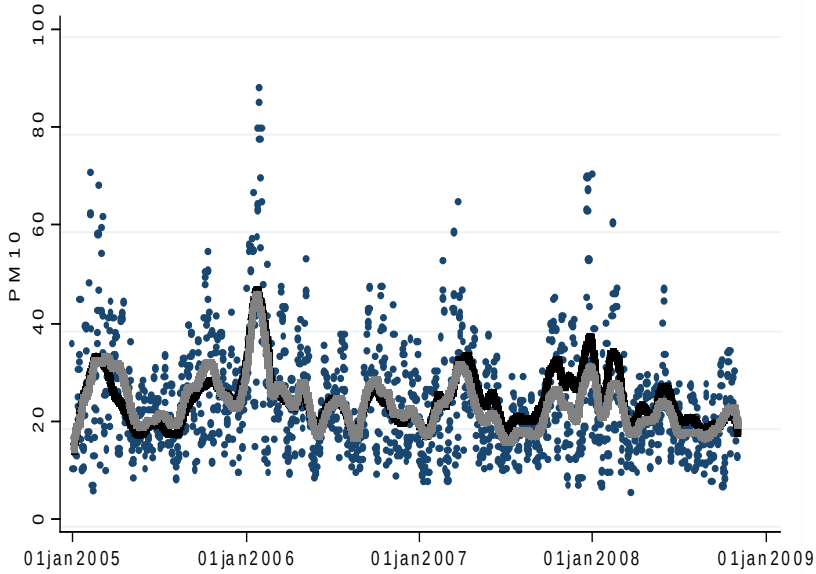
Appendix B (cont.) City	Avg. 2005 PM_{10} at highest polluting station	2005 Exceed-ance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Fürth	30.1	30	0	Attainment		113,596
Ansbach	30.2	29	1	APO		40,531
Regensburg	31.6	37	1	APO		130,153
Ludwigshafen	31.7	37	1	APO		163,536
Görlitz	31.8	42	1	APO		57,418
Hagen	32.0	27	1	APO		196,295
Halle/Saale	32.2	51	1	APO		236,576
Kassel	32.2	48	1	APO		193,842
Aschersleben	32.2	38	1	APO		31,717
Freiburg	32.5	21	1	'Future' LEZ	1/1/2010	216,448
Münster	32.5	33	0	'Future' LEZ-no violation	1/1/2010	271,404
Frankfurt	32.5	48	1	'Future' LEZ	10/1/2008	648,925
Mannheim	33.4	43	1	LEZ	3/1/2008	307,847
Mainz	33.7	47	1	APO		195,178
Hamburg	33.7	46	1	APO		1,748,544
Darmstadt	34.0	42	1	APO		140,366
Erfurt	34.3	49	1	APO		202,723
Bayreuth	34.9	54	1	APO		73,617
Dresden	34.9	78	1	'Future' LEZ	2011	500,471
Potsdam	35.2	55	1	APO		148,126
Pleidelsheim	35.6	55	1	LEZ	7/1/2008	6,239
Essen	35.9	61	1	'Future' LEZ	10/1/2008	584,136
Frankfurt (Oder)	36.9	65	1	APO		63,177
Augsburg	37.1	61	1	'Future' LEZ	7/1/2009	262,492
Hannover	37.5	63	1	LEZ	1/1/2008	515,559
Düsseldorf	38.0	69	1	'Future' LEZ	2/15/2009	576,090
Berlin	38.1	74	1	LEZ	1/1/2008	3,399,896
Leipzig	38.2	75	1	'Future' LEZ	1/1/2011	504,798
Dortmund	39.5	82	1	'Future' LEZ	10/1/2008	587,870
Duisburg	40.0	83	1	'Future' LEZ	10/1/2008	500,217
Ludwigsburg	41.1	78	1	LEZ	3/1/2008	513,799
München	44.8	107	1	'Future' LEZ	10/1/2008	1,278,559
Stuttgart	54.5	187	1	LEZ	3/1/2008	593,244
Berghausen	NA	NA	1	APO		
Bernau	NA	NA	0	APO-no violation		
Burgdorf	NA	NA	0	APO-no violation		
Edertal-Hemfurth	NA	NA	0	Attainment		
Flensburg	NA	NA	0	Attainment		86,365
Heidenheim	NA	NA	0	Attainment		134,722
Heppenheim	NA	NA	0	Attainment		
Herrenberg	NA	NA	1	'Future' LEZ	1/1/2009	
Ilsfeld	NA	NA	1	LEZ	3/1/2008	8,307
Markgröningen	NA	NA	0	Attainment		
Mühlacker	NA	NA	1	'Future' LEZ	1/1/2009	
Possen	NA	NA	0	Attainment		
Sproitz	NA	NA	0	Attainment		

Appendix B (cont.) City	Avg. 2005 PM_{10} at highest polluting station	2005 Exceed-ance days	Violate limit in 2005-06	Treatment status	LEZ start date	Population
Wlzbachtal-Jöhlingen	NA	NA	0	Attainment		

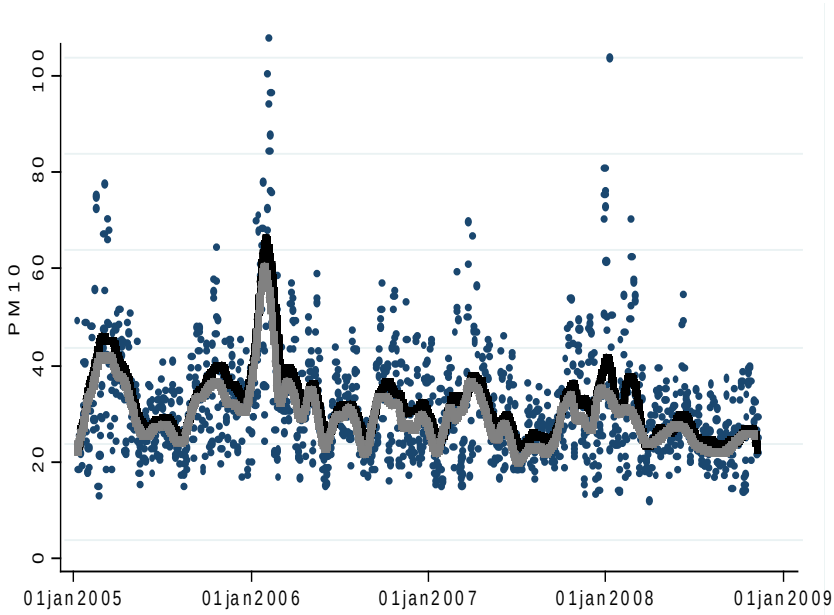
Notes: Shaded area used in PM_{10} matching analysis. List only includes stations with sufficient data. 'Future' LEZs came into effect on or after 10/1/2008. 'No violation' refers to cities with APs despite not violating the PM_{10} standard.

Appendix C
Figure: Average daily PM10 level by LEZ Treatment Status

Panel a: 2005 PM10 Matching Approach



Panel b: Geographical Matching Approach



Note: Each dot represents the average daily PM10 level of the samples described under each of the two approaches. (The sample of the 2005 matching approach is described in Section 4.2 and the sample of the Geographical approach is described in Section 4.3). The bold light grey line displays average daily PM10 level for control cities and the black bold black line the average daily PM10 level for treatment cities both estimated by the locally weighted scatterplot smoothing method with bandwidth of 0.04.

Appendix D: Test of Alternative Specifications:

With respect to robustness in covariates, the table below lists the effects of including/omitting the following set of regressors:

- Original regression including all covariates
- Without any weather covariates
- Without Holiday covariates
- Without Population covariates
- Without any covariate, except the necessary dummies to identify the Differences-in-Differences treatment effects,

Table: LEZ vs. Attainment cities – All Cities

Matching based on 2005 PM_{10} in range 25 to 35

	With All Covariates		**Without Weather Covariates**		**Without Holiday Covariates**	
	Traffic stations	Background stations	Traffic stations	Background stations	Traffic stations	Background stations
	(1)	(2)	(3)	(4)	(5)	(6)
LEZ treatment	-0.0910***	0.00724	-0.105***	0.0100	-0.0912***	0.00722
	[0.0241]	[0.0285]	[0.0244]	[0.209]	[0.0247]	[0.0287]
Observations	6723	7704	6723	7704	6723	7704
Adj. R-squared	0.657	0.591	0.314	0.197	0.649	0.558

LEZ vs. Attainment cities – Cities > 100,000

Matching based on 2005 PM_{10} in range 25 to 35

	With All Covariates		**Without Weather Covariates**		**Without Holiday Covariates**	
	Traffic stations	Background stations	Traffic stations	Background stations	Traffic stations	Background stations
	(1)	(2)	(3)	(4)	(5)	(6)
LEZ treatment	-0.0686*	0.0448	-0.0663*	0.0559*	-0.0685*	0.0454
	[0.0302]	[0.0354]	[0.0307]	[0.0265]	[0.0310]	[0.0357]
Observations	2896	4280	2896	4280	2896	4280
Adj. R-squared	0.653	0.612	0.300	0.193	0.641	0.608

Table: LEZ vs. Attainment cities – All Cities

Matching based on 2005 PM_{10} in range 25 to 35

	With All Covariates		Without Population Covariates		Without Any Covariates	
	Traffic stations	Background stations	Traffic stations	Background stations	Traffic stations	Background stations
	(1)	(2)	(3)	(4)	(5)	(6)
LEZ treatment	-0.0910***	0.00724	-0.0910***	0.00724	-0.106***	0.0102
	[0.0241]	[0.0285]	[0.0241]	[0.0285]	[0.0248]	[0.209]
Observations	6723	7704	6723	7704	6723	7704
Adj. R-squared	0.657	0.591	0.657	0.591	0.299	0.187

LEZ vs. Attainment cities – Cities > 100,000

Matching based on 2005 PM_{10} in range 25 to 35

	With All Covariates		Without Population Covariates		Without Any Covariates	
	Traffic stations	Background stations	Traffic stations	Background stations	Traffic stations	Background stations
	(1)	(2)	(3)	(4)	(5)	(6)
LEZ treatment	-0.0686*	0.0448	-0.0686*	0.0448	-0.0669*	0.0564*
	[0.0302]	[0.0354]	[0.0302]	[0.0354]	[0.0313]	[0.0265]
Observations	2896	4280	2896	4280	2896	4280
Adj. R-squared	0.653	0.612	0.653	0.612	0.283	0.181

Except where indicated in the column header, all regressions include year-month fixed effects, weather, holiday, station type and population covariates.
Regressions include data for April-October 2007 vs. 2008.
Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1.

These alternative specifications of Table 8 show that our results are overall qualitatively similar to those when all covariates are included.

Appendix E: Sample Details on Geographical Matching Approach

For the regional regressions, the following control cities are used for each LEZ city:

Table E1: Control Cities for Individual LEZ Regressions

Stuttgart, Tübingen, Reutlingen & Ludwigsburg	Leonberg	Mannheim	Cologne	Hannover	Berlin
Heidelberg	Herrenberg	Heidelberg	Essen	Bremen	Leipzig
Karlsruhe	Mühlacker	Karlsruhe	Dortmund	Osnabruck	Dresden
Pforzheim			Dusseldorf	Göttingen	
Ulm			Duisburg	Braunschweig	
Heilbronn					
Freiburg					
Herrenberg					
Mühlacker					

Table E2: Effect of individual LEZs on log PM_{10}

Matching based on regional approach

	Berlin	**Stuttgart**	**Hannover**	**Cologne**	**Mannheim**	**Reutlingen**	**Tubingen**	**Ludwigsburg**	**Leonberg**
					Traffic stations				
	(1a)	(2a)	(3a)	(4a)	(5a)	(6a)	(7a)	(8a)	(9a)
LEZ treatment	-0.120***	-0.0288	-0.0939**	-0.0742	-0.0992	-0.0582**	-0.0296	0.0489*	0.0687
	[0.0352]	[0.0218]	[0.0215]	[0.0416]	[0.0553]	[0.0246]	[0.0213]	[0.0212]	[0.0819]
Observations	4376	6507	2188	2996	2050	4836	4879	4880	1202
Adj. R-squared	0.59	0.712	0.579	0.685	0.633	0.667	0.647	0.668	0.436
					Background stations				
	(1b)	(2b)	(3b)	(4b)	(5b)	(6b)	(7b)	(8b)	(9b)
LEZ treatment	-0.0442	0.262***	0.0516	-0.0837	0.114*	0.118**	0.159***	0.0217	
	[0.0494]	[0.0243]	[0.0330]	[0.0425]	[0.00894]	[0.0244]	[0.0240]	[0.0370]	
Observations	2186	1712	2735	2568	856	1712	1712	1712	
Adj. R-squared	0.591	0.619	0.461	0.612	0.639	0.596	0.591	0.593	

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

Robust standard errors in brackets are clustered by city, *** p<0.01, ** p<0.05, * p<0.1

Appendix F: Cost Benefit Analysis

F.1 Benefits

We use improvements in long-term mortality attributable to the decreased PM_{10} in LEZs as our measure of benefits. Long-term mortality measures the decrease in life expectancy caused by long-term exposure to PM_{10}. We ignore acute mortality, or the increase in mortality due to a short-term increase in PM_{10}, since this may just be measuring the 'harvesting' effect where people who were near death die a few days or weeks earlier. To calculate the effect of PM_{10} on long-term mortality, we use estimates of the link between PM_{10} and mortality and morbidity in France, Switzerland and Austria. These estimates were derived by the World Health Organization (WHO) and have been used extensively in the epidemiology literature, i.e. in Medina *et al.* (2004), Kunzli *et al.* (2000), Seethaler (1999), van Zelm (2008).[1] Specifically, the WHO study found that for every one million residents in Switzerland and France, each 10 $\mu g/m^3$ increase in PM_{10} is associated with an additional 340 premature mortalities. Since these studies find that the effect of PM_{10} on mortality is close to linear over the relevant range of PM_{10}, this means that each 1 $\mu g/m^3$ increase in PM_{10} is associated with 34 deaths per million residents. From these numbers using procedure described in section 7, we calculate the number of lives saved by each LEZ using the number of inhabitants within each LEZ. We multiply this by the EPA's value of statistical life (VSL) of \$7,900,000 (2008\$)[2] to monetize these benefits (EPA 2000). Using this method, as summarized in Table A1 we find that the benefit from LEZs is approximately \$1.98 billion (\$1,978,395,825).

[1] These estimates are based on two cohort studies, Pope, et al. (1995) and Dockery, et al. (1993), as re-estimated by Krewski, et al. (2000). In their extensive review of the literature, the EPA singled out these two as the best studies for their cost-benefit analysis of the Clean Air Act Amendments (EPA 1999).

[2] This value has been adjusted to 2008 dollars from the value for 1999 specified in the cited report. Kiesner *et al.* (2012) estimate a range of VSL from 7 to 12 million.

Table F1: Value of mortality benefits from decreased PM_{10}

Fixed baseline mortality increment per 10 μg/m³ PM_{10} and 1 million inhabitants	340
Deaths per person per 1 μg/m³	0.000034

City	Traffic station coefficient	Avg 2007 Traffic station PM_{10}	Amount PM_{10} decreases in 2008	Inhabitants of LEZ	Number of lives saved
Berlin	-0.1500[3]	28.86	4.33	1,300,000	191.33
Ludwigsburg	0.0489	34.65	-1.69	55,000	-3.17
Tubingen	-0.0296	31.26	0.93	78300	2.46
Reutlingen	-0.0582	38.12	2.22	78523.2	5.92
Stuttgart	-0.0288	33.01	0.95	590,000	19.07
Hannover	-0.0939	26.02	2.44	218,000	18.11
Leonberg	0.0687	33.42	-2.30	40,000	-3.12
Koln	-0.0742	32.98	2.45	130,000	10.82
Mannheim	-0.0992	28.43	2.82	93,900	9.00

Total number of lives saved	250

	EPA Estimate
Value of statistical life	$7,800,000
Value of lives saved	$1,953,352,840

This estimate of benefits is conservative for many reasons. First, we only count the improvement in mortality amongst people who reside within the LEZs studied. As our results show, however, PM_{10} also decreased in traffic areas outside of LEZs, most likely because of the adoption of cleaner vehicles, so if these areas were also included the number of lives saved would be higher. If each city's entire population was used instead of just inhabitants of the LEZ, the benefits would jump to $5.22 billion ($5,217,522,677).

The second way in which our estimates are conservative is that we only consider long-term mortality. PM_{10} is also associated with non-lethal morbidity, however. In the above studies, also health effects from respiratory hospital admissions, cardiovascular hospital admissions, adult chronic bronchitis, child bronchitis and adult and child asthmatic attacks are considered. If these conditions and parameters are included in our benefits calculation in the same manner as above,[4] then Table A2 shows how our measure of the benefits increases by $13,661,332.

F.2 Costs

[3] This estimate is derived from the stations that reside inside of the LEZ of Berlin (column 3 of Table 14).

[4] For the conditions that differentiate between adults and children, we adjust the population numbers, using 14% as the proportion of children under 14 in Germany.
http://www.countryreports.org/people/ageStructure.aspx?countryid=91&countryname=

To measure the costs LEZs have imposed on Germans, we estimate the total cost of upgrading vehicles to be able to enter the LEZs. Since we measure the health benefits realized between 2007 and 2008, we also look at the costs of upgrading vehicles over this time period. To do this, we use our spatial vehicle registration data to fit regressions of the change in share of green-sticker cars and trucks from 2008 to 2009 on distance from an LEZ. Since we don't want to count vehicles that would have switched to green sticker vehicles in the absence of the LEZ regulation, we use the change in share of green stickers for the point furthest away from an LEZ (0.0110 and 0.0828 at 244 km from an LEZ for cars and trucks, respectively) as the baseline change in share of green stickers. For each location, we subtract this 0.0110 (0.0828) from our regression's predicted change in share of green stickered cars (trucks). This is the change in share of green stickers due to the LEZ, which we then multiply by the number of cars (trucks) for that location in 2008 to get the number of new green cars attributable to LEZs. We sum these numbers for all locations to get the total number of new cars and trucks due to the LEZ and multiply this by the average cost for upgrading a vehicle ($1,650 for cars, $14,500 for trucks) to get the total cost of upgrading cars and trucks because of LEZs. In other words, we estimate cost using the following formula

$$Total\ Cost = \sum_{i=cars,trucks} p_i \sum_{j=1}^{J} N_{ij}(\widehat{C_{ij}} - C_{i0})$$

where *i* represents cars and trucks, *j* indexes counties, *N* is the number of vehicles in 2008, $\widehat{C_{ij}}$ is fitted value of change in share of green cars, C_{i0} is the baseline change in share of green vehicles, and *p* equals the cost of upgrading each vehicle type.

We find that the total cost of upgrading cars is $475,185,312 and the total cost of upgrading trucks is $618,133,842. The combined total cost is $1,093,319,154. This cost is nearly half of our primary measure of benefits, $1,978,395,825. If one considers the benefits for those who live close to but outside of an LEZ, as well as morbidity benefits, then the benefits of LEZs will exceed the costs by even more.

Table F2: Value of morbidity benefits from decreased PM_{10}

Condition	Fixed baseline mortality increment per 10 μg/m³ PM_{10} and 1 million inhabitants cases	Deaths per person per 1 μg/m³	Willingness to Pay to avoid condition (1996 Euros)
Respiratory Hospital Admission	140	0.000014	$7,870.00
Cardiovascular Hospital Admissions	255	0.0000255	$7,870.00
Chronic Bronchitis Incidence (adult)	410	0.000041	$20,900.00
Bronchitis (child)	4725	0.0004725	$131.00
Asthmatic Attacks (children)	2500	0.00025	$31.00
Asthmatic Attacks (adult)	6280	0.000628	$31.00

						Number of incidents avoided			
City	Traffic station coefficient	Avg 2007 Traffic station PM_{10}	Amount PM_{10} decreases in 2008	Inhabitants of LEZ	Respiratory Hospital Admission	Cardiovascular Hospital Admissions	Chronic Bronchitis Incidence (adult)	Bronchitis (child)	Asthmatic Attacks (adult)	Asthmatic Attacks (children)
Berlin	-0.15	28.86	4.33	1,300,000	78.78	143.50	198.42	372.25	3039.26	196.96
Ludwigsburg	0.0489	34.65	-1.69	55,000	-1.30	-2.38	-3.29	-6.17	-50.34	-3.26
Tubingen	-0.0296	31.26	0.93	78300	1.01	1.85	2.55	4.79	39.13	2.54
Reutlingen	-0.0582	38.12	2.22	78523	2.44	4.44	6.14	11.52	94.09	6.10
Stuttgart	-0.0288	33.01	0.95	590,000	7.85	14.30	19.78	37.10	302.92	19.63
Hannover	-0.0939	26.02	2.44	218,000	7.46	13.58	18.78	35.24	287.69	18.64
Leonberg	0.0687	33.42	-2.30	40,000	-1.29	-2.34	-3.24	-6.07	-49.60	-3.21
Koln	-0.0742	32.98	2.45	130,000	4.45	8.11	11.22	21.05	171.83	11.14
Mannheim	-0.0992	28.43	2.82	93,900	3.71	6.75	9.34	17.52	143.03	9.27
Total incidents avoided					103.12	187.82	259.71	487.23	3978.00	257.80
Willingness to pay (1996 Euros)					$811,540	$1,478,162	$5,427,949	$63,828	$123,318	$7,992

Willingness to pay total (1996 Euros)	$7,912,789
Willingness to pay total (2008 USD)	$13,661,332

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