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

Hendrik Wolff

Spatial distribution and leakage effects are of policy concern and increasingly discussed in the economics literature. We study Europe's most aggressive recent air pollution regulation: low-emission zones (LEZs) are areas in which vehicular access is allowed only to vehicles that emit low levels of PM_{10}. Using new administrative data sets from Germany, we assess the effect of LEZs on air pollution and the spatial substitution effects in green *versus* dirty vehicles. Back of the envelope calculations suggest that health benefits of roughly 2 billion dollars have come at a cost of 1 billion dollars for upgrading the fleet of vehicles.

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 μm – 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 (EU) 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[1] 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 (APs). While these APs 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).

Using new administrative data sets from Germany, this article assesses the distribution of air pollution and the spatial substitution effects in green *versus* dirty vehicles. We find that LEZs decrease PM_{10} by 9% while rejecting the hypotheses that dirty vehicles contribute to higher pollution levels by increasingly driving longer routes outside of the LEZ. 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.

In Germany, to deal with the large number of cities exceeding the EU threshold, the government has categorised vehicles into four mutually exclusive classes of PM_{10}

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[1] The European Commission is the executive body of the EU. It proposes, implements and enforces EU legislation for all of its 28 current member states.

emissions. All 46 million German cars, buses and trucks are required to display a coloured windscreen sticker indicating its PM_{10} pollution class. As of 2010, 41 German cities have implemented LEZs banning vehicles based on the colours 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.[2] According to a recent online survey, over 91% of Germans disapprove of LEZs, considering them too bureaucratic with likely having little effect (DSM, 2009). In an earlier survey, 70% 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 announced penalty for the city of Leipzig is 700,000 euro per day or 1,050,000 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 5 am and 10 pm one weekday per week based on the last digit of one's licence plate.[3] 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 LEZs (in Greater London's LEZ, larger vans and lorries pay a daily PM_{10} emission charge of £250–500 ($392–784) if they do not meet the Euro IV PM_{10} standard).[4] 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.[5]

Despite the widespread use of driving restrictions, the related empirical literature is sparse. In a recent study, Davis (2008) analyses the effect of Mexico City's HNC policy on

[2] Conversion to the next higher sticker costs 800–2,500 US Dollar (USD) for passenger cars and 7,000–22,000 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 Zeitung*, 2009).

[3] Similar licence plate programmes 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).

[4] In 2008, the Greater London Authority established one of the largest current LEZs in Europe, which roughly includes the area within the ring motorway 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 tonnes 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 Centre (Leape, 2006; TFL, 2008).

[5] Low-emission zones are particularly popular in Europe, licence plate programmes implemented in Latin America and congestion charging mostly considered in northern Europe and major Asian urban centres. 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 centre. While New York City's congestion fee stalled in the legislature, San Francisco is currently debating a $6 fee to drive through downtown. Milan has combined congestion pricing and LEZs with its Ecopass programme, 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).

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 behavioural response: drivers circumvented the restriction by buying older, more polluting second cars to have different licence plates.[6] 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 counter-productive results in Mexico City were due to the particular design of the HNC,[7] the German LEZ programme may be more successful because it includes a differentiation by emission level, creating an incentive to adopt cleaner technologies.[8] 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, 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 article is to estimate the causal effect of LEZs on PM_{10} levels using panel data of daily pollution and weather conditions across Germany from 2005 to 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} categorisation 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, this article studies changes in the composition of the vehicle fleet. Using a unique administrative panel data set of emission category and registration location of each vehicle from 2008 to 2010, we analyse the spatial substitution in vehicles' emission categories attributable to LEZs.

We find that the 'average' LEZ significantly decreases PM_{10} around 9% in traffic areas – ranging from an insignificant zero for smaller LEZs like Tübingen to a significant −15% in the case of the most populated LEZ of Berlin, inhabited by 1.1 million people. The 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, 2011) have shown that 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

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

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

[8] 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.

Neidell (2011) discuss settings in which the total welfare cost of air pollution is much larger due to avoidance behaviour. 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 centres, 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 2 billion dollars have come at a cost of just over 1 billion dollars for upgrading the fleet of vehicles.

Finally, this article 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 article proceeds as follows. Section 1 details the PM_{10} regulation and the implementation of LEZs. We describe our data in Section 2 and discuss the empirical strategy in Section 3. Section 4 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 5 combines these results in cost–benefit analysis and we conclude this article in Section 6.

1. Background

1.1. *Air Pollution Regulation in Europe*

Motor vehicle emission is the primary source of ambient PM_{10} in urban areas,[9] 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 online Appendix A). The main contributing factors are vehicle exhaust, resuspension of dust particles (caused by vehicles 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 8–23%.

In response to concerns about the health effects of PM_{10},[10] the EU Clean Air Directives[11] introduced in 2005 EU-wide limits on ambient PM_{10} such that the daily

[9] 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}.

[10] 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).

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

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 (μg/m³)	40	20
Daily average (24-h) limit (μg/m³)	50	50
Allowed number of exceeding days 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	26.2	23.1	21.2
	(5.2)	(5.5)	(5.3)	(4.9)
Mean number of days‡ above 50 μg/m³	19.6	26.8	16.2	11.6
	(20.9)	(21.1)	(15.8)	(12.9)
Cities in violation of 2005 standard	36	65	31	18
Cities in violation of 2010 standard	226	246	200	134

Notes. †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.

average does not exceed 50 μg/m³ on more than 35 days annually and the yearly average does not exceed 40 μg/m³. When any air pollution station exceeds the EU PM_{10} limit, the city is asked to develop a clean air AP. In the early years of the EU regulation, often cities did not comply with the timely delivery of their APs and the enforcement was lax. As a result, 70% of EU cities with a population greater than 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.[12] As a consequence, to enforce the legislation better, 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 formulae for the daily penalty payments is described in Wolff and Perry (2010). Furthermore, in January 2009, the European 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 APs from local authorities.

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

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

cities to meet; for example, we estimate that 285 German cities would have violated the 2010 limits based on 2005–8 emissions.[13] 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.

1.2. *Low-emission Zones in Germany*

Given the primacy of vehicle-based PM_{10}, clean air APs try to curtail emissions through:

(*i*) expanding public transportation;
(*ii*) utilising ring roads;
(*iii*) improving traffic flow; and
(*iv*) the implementation of an LEZ.

The fourth option, implementing an LEZ, has emerged as the most drastic and controversial element of the APs. The LEZs mostly cover city centres but vary considerably in size. In Berlin, for example, the LEZ covers 88 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 online 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 online Appendix Tables B1 and B2 list their characteristics.

Each German vehicle – as well as each visiting foreign vehicle – that wants to enter an LEZ must display a coloured windscreen 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 petrol 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 euro plus one driver's licence penalty point.[14] There are exceptions that allow certain emergency and other work-related vehicles to enter LEZs 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 1 January 2010. The LEZ of Dortmund (Brackler Strasse), on the other hand, has only permitted yellow and

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

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

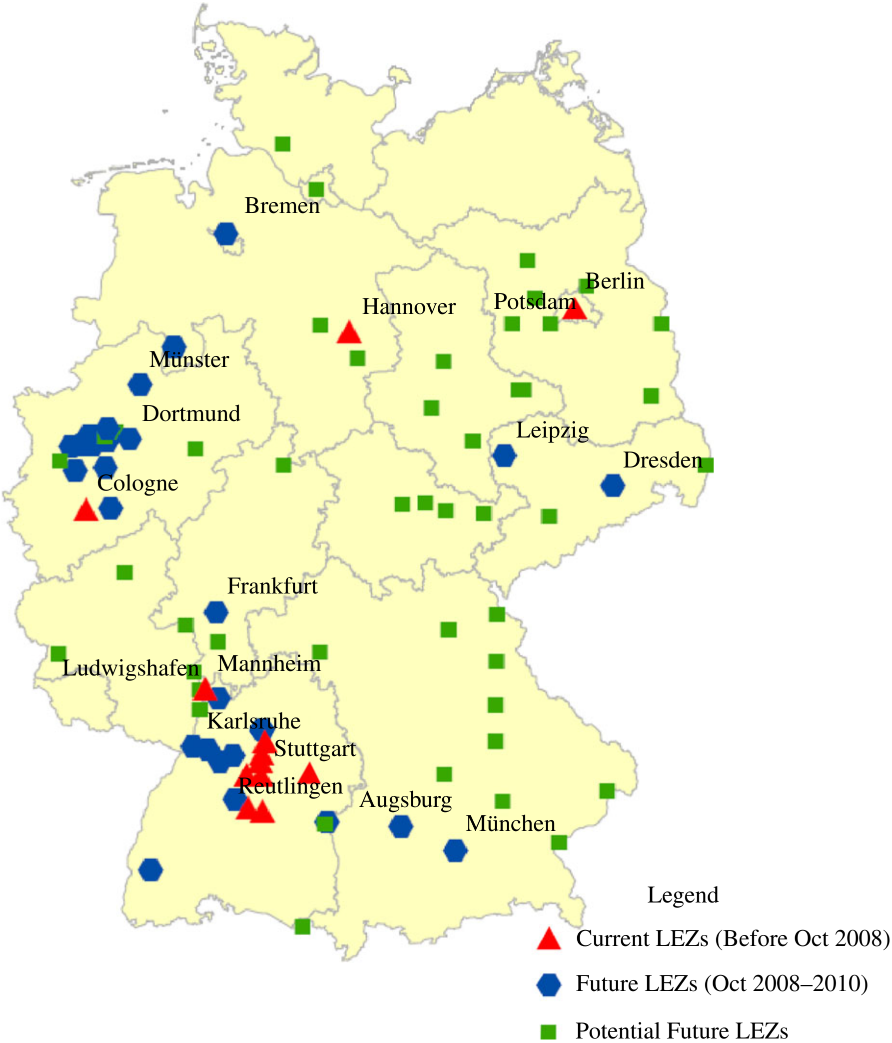


Fig. 1. *Current and Future German LEZs*

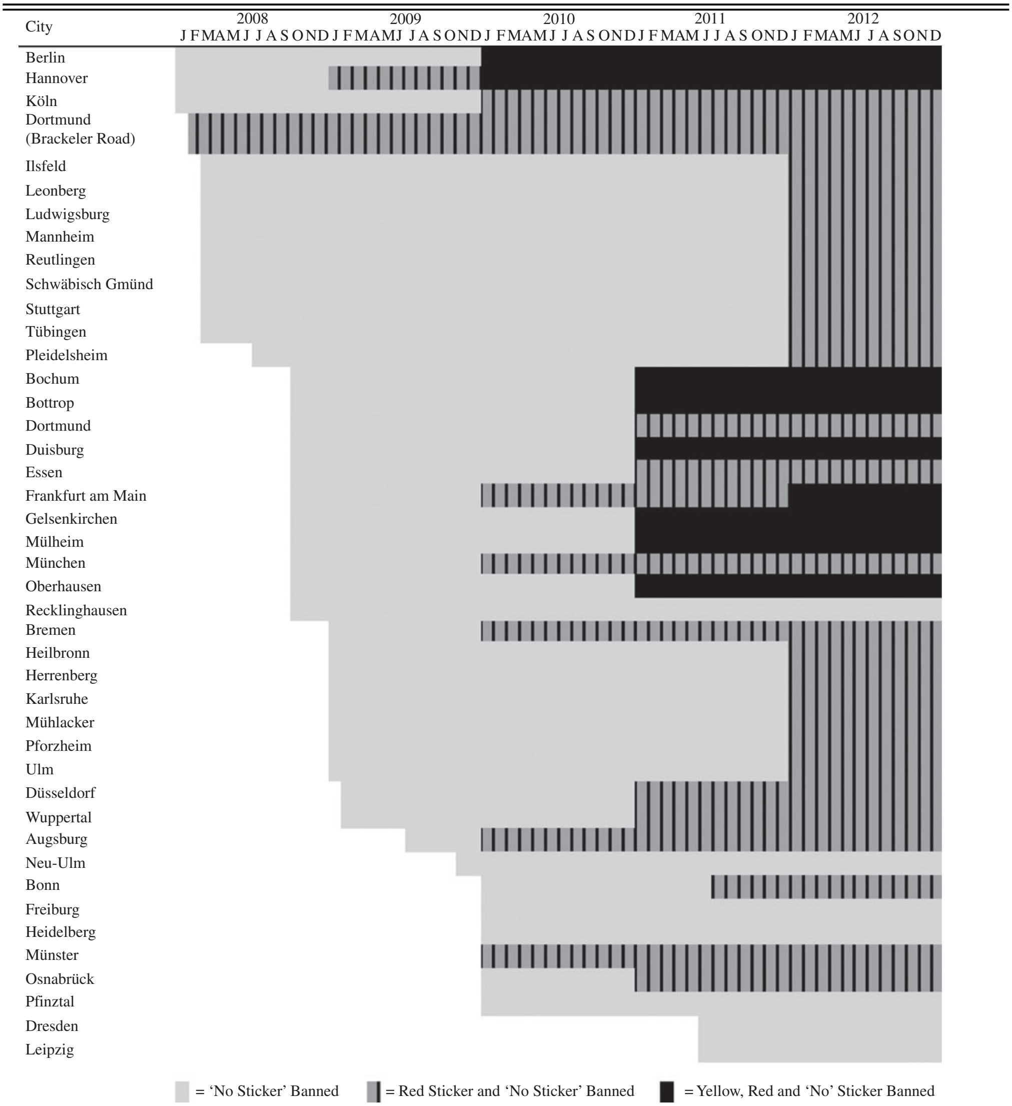
Table 2

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 2008–12



green sticker vehicles since January 2008. By 2012, more than 50% 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 categorise cities into various treatment groups based on this variation in implementation date and AP components. Figure 2 illustrates the classifications. First, we divide stations into two 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 AP) and 'non-attainment cities' that must develop an AP. Next, we divide the non-attainment cities into 'action plan only' (APO) cities, whose APs 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).[15]

2. Data

We collect a panel of air quality readings from January 2005 to 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 characterised 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 football fields. Using the co-ordinates for each station, we classify all stations as 'inside' or 'outside' of an LEZ.

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 20 μg/m³ to over 100 μg/m³ underscores the difficulty of modelling 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 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 geographical co-ordinates 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 km in distance and 300 m in altitude. The primary weather variables are summarised in Table 4. After calculating daily weather and PM_{10} readings

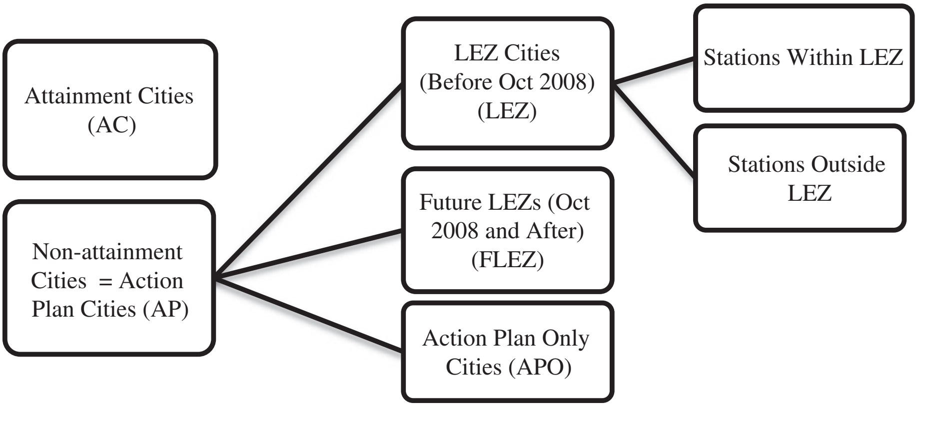


Fig. 2. *Classification of Cities Treatment Status*

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

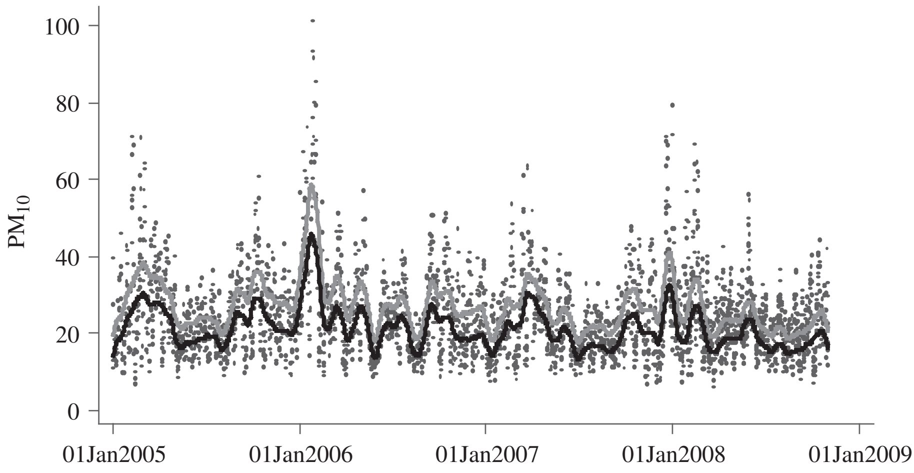


Fig. 3. *Average Daily PM_{10} Levels by Attainment Status*
Notes. Each dot represents the national average daily PM_{10} level. The light grey line displays average daily PM_{10} level for non-attainment cities and the black line the average daily PM_{10} level for attainment cities both estimated by the locally weighted scatterplot smoothing method with bandwidth of 0.03.

and handling missing values,[16] 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 100%, 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 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.[17]

[16] To calculate PM_{10} 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% of days with no readings. Among those stations reporting half-hourly and hourly data, less than 7% of days are missing observations for some hours, with over 70% 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 2005–7 if there are data for at least 340 of the 365 days of the year. Since we only have data up to October of 2008, a station has 'complete data' for 2008 if there are data for 280 of the 305 possible days. Finally, we studied the locations of all our stations in LEZ cities, on Google Maps. 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.

[17] 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.

Table 4
Summary of Weather Data

Weather variables	Unit	Mean	SD	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 average vapour pressure	1 hpa	9.9	4.1	0.2	26.9
Daily average air pressure	1 hpa	981	49	679	1,047
Daily average relative humidity	%	78.1	12.9	7	101
Daily average 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 average cloud cover	Tenths	7.1	1.3	0	9
Sun in day	1 h	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

3. Empirical Identification Strategy

3.1. *Difference-in-differences Approach*

To study the effect of LEZs on air quality, we use difference-in-differences (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 (1), where k indexes city, i indexes station and t indexes time

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

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 AP. $TreatLEZ_{k,t} = LEZ_k \times postLEZ_t$ 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,[18] 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 analyse 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 capture.

[18] Weather variables include daily values of mean temperature, mean temperature squared, maximum daily temperature, minimum daily temperature, one-day lag mean temperature and maximum temperature, mean relative humidity, mean relative humidity squared, one-day lag mean relative humidity, mean wind velocity interacted with whether it rained that day, maximum daily wind velocity, one-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, one-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.

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).[19]

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 APs. 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 APs with and without LEZs, we test the treatment of having an APO and having a FLEZ. We use (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.

3.2. *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 APs. 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 APs or LEZs.[20] 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 25–35 $\mu g/m^3$. We use the following rule for selecting this range. First, we calculated the 2005 median PM_{10} annual average among highest-polluting-stations, which equals to 30 $\mu g/m^3$, and then we add $\pm$ 5 $\mu g/m^3$ to obtain the range. We decided on the range of $\pm$ 5 $\mu g/m^3$ 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 online 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 APs exogenous.

Of these 73 cities, 22 cities that have never violated the PM_{10} limits and do not have an AP serve as our control AC. Another 22 cities have an AP but no LEZ (APO). We define these cities as APO cities if the first violation occurred in 2005 or in 2006. If the

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

[20] We acknowledge the limitation that we have no PM_{10} data prior to 2005 to detect potential pre-emptive behaviour 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 PM_{10} levels.

Table 5

Treatment and Control Characteristics

	Number of cities	2005 highest-polluting station average	Average number of exceedance days
Attainment cities	22	26.8	22.4
Action plan only cities	22	30.7	36.8
AP with LEZ after October 2008 (FLEZ)	7	30.0	34.7
AP with LEZ before October 2008 (LEZ)	4	28.9	28.9

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

violation occurred instead in 2007 (or later), we drop the city from the analysis. This is necessary because not enough time has passed between the date of the violation and the end of our data (October 2008) to be likely see an effect of the more long-term AP elements (*i*)–(*iii*). We also exclude 10 APO cities that developed an AP despite never violating the PM_{10} limit,[21] 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 exceeding days, with APO, FLEZ and LEZ cities exceeding the 50 $\mu g/m^3$ threshold on more than 35 days, and the attainment cities less than 35 days. In this sense, this first identification approach can also be 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.

3.3. *Geographical LEZ Approach*

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 that results are not 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 $\mu g/m^3$).[22] Having more cities also allows us to analyse the heterogeneity between LEZs of different sizes. We make use of the staggered introduction of LEZs by comparing cities

[21] Some cities preemptively implement APs 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, analyse Cologne separately below.

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

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.

3.4. *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 6(*a*) 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), panels 6(*b*) and (*c*) repeat the analysis using the years 2005 and 2006 as well as the changes in PM_{10} levels between years (panel (*d*)). Overall, the regression

Table 6

Effect of LEZ Start Date on 2007 PM_{10} Levels

	All stations (1)	Traffic stations (2)	Background stations (3)
Panel (*a*): Effect of LEZ start date on 2007 PM_{10} levels			
LEZ start date	−0.000173	−0.000225	0.0000811
	(0.000958)	(0.00117)	(0.000890)
Observations	24,942	15,478	9,464
Adjusted R^2	0.719	0.711	0.681
Panel (*b*): Effect of LEZ start date on 2005 PM_{10} levels			
LEZ start date	0.00137	0.00164	0.00167
	(0.00163)	(0.00112)	(0.00262)
Observations	19,409	10,757	8,652
Adjusted R^2	0.694	0.697	0.622
Panel (*c*): Effect of LEZ start date on 2006 PM_{10} levels			
LEZ start date	0.00282	0.00251	0.00386*
	(0.00193)	(0.00199)	(0.00205)
Observations	25,813	16,359	9,454
Adjusted R^2	0.717	0.718	0.672
Panel (*d*): Effect of LEZ start date on change in PM_{10} levels between 2006 and 2007			
LEZ start date	−0.00120	−0.00188	0.0000886
	(0.00118)	(0.00139)	(0.00231)
Observations	23,085	13,991	9,094
Adjusted R^2	0.469	0.478	0.467

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

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 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 summarise, 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 online Appendix C depict average daily PM_{10} levels over the entire sample period for treatment and control cities utilising each matching approach. These Figures visually illustrate that these groups of cities are not inherently different in terms of differential trends of PM_{10} levels and provides additional support to our identification strategies.

3.5. *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 data set 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 (2),

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

where $\Delta s_{icp} = s_{icp2010} - s_{icp2008}$ is the change in the share of vehicles with sticker colour 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 kilometres 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 colour 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}.

4. Results

This Section presents our results of estimating the effect of the clean air AP policies on air quality. The following two subsections 4.1 and 4.2 are based on the 'matching on PM_{10} in 2005' approach described in subsection 3.2, while subsection 4.3 presents our results based on the geographical matching approach.

4.1. *Effect of Non-attainment Status*

One challenge with evaluating Germanys LEZs is to disentangle the 'LEZ effect' from the other possible clean air AP instruments enacted simultaneously. To investigate this, first we test the overall effect of violating the PM_{10} standard by comparing cities that developed any type of AP to AC. Table 7 compares PM_{10} levels in 2005, the period

Table 7

Effect of Action Plans on Log PM_{10} (Matching Based on 2005 PM_{10} in Range 25–35)

	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	28,859	21,236	22,378	16,380	12,746	11,532
Adjusted R^2	0.657	0.618	0.656	0.622	0.604	0.608

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

before being found in non-attainment, to 2008, when cities violating the standard had at least two to three years to implement clean air APs.[23] 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 FLEZs. 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.

4.2. *Effect of LEZs*

In this subsection, we isolate the treatment of having LEZs as part of an AP as specified in (1). Table 8 compares the LEZs that began before October 2008 to the AC 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 use April through October data, since the Mannheim, Reutlingen and Leonberg LEZs did

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

Table 8

LEZ versus Attainment Cities (Matching Based on 2005 PM_{10} in Range 25–35)

	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	6,723	7,704	2,896	4,280
Adjusted R^2	0.657	0.591	0.653	0.653

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

not take effect until March 2008 and we are allowing a one month lag for cities to adjust to the LEZs.[24]

The main result of Table 8 is that LEZs on average over all cities have lowered PM_{10} levels by 9% (column 1) in urban traffic areas. This main result of this article will be tested below using alternative identification strategies below. To investigate the situation at background stations, columns 2 and 4 show statistically insignificant increases of 4–7%. Thus, the decrease in PM_{10} along major roads within the LEZ is not being realised 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.[25]

One concern with our 2005 matching identification strategy is that results depend on our fixed range of 25–35 $\mu g/m^3$ 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, +∞) $\mu g/m^3$. 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 25–35 emission range as our preferred matching strategy used in the

[24] 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).

[25] We expand on the analysis of background stations in the next subsections. Subsection 4.3 shows results of background stations that are located within an LEZ. In subsection 4.4, 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 behaviour.

Table 9

LEZ versus Attainment Cities: Sample Selection Effects

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
Matching based on 2005 PM_{10} in range 25–35				
LEZ treatment	−0.0910***	0.00724	−0.0686*	0.0448
	(0.0241)	(0.0285)	(0.0302)	(0.0354)
Observations	6,723	7,704	2,896	4,280
Adjusted R^2	0.657	0.591	0.653	0.653
Matching based on 2005 PM_{10} in range 23–37				
LEZ treatment	−0.0822***	0.00973	−0.0686*	0.0283
	(0.0203)	(0.0236)	(0.0302)	(0.0402)
Observations	7,977	11,984	2,896	5,992
Adjusted R^2	0.654	0.591	0.653	0.612
Matching based on 2005 PM_{10} in range 21–39				
LEZ treatment	−0.0486*	0.0249	−0.0362	0.0431
	(0.0272)	(0.0264)	(0.0346)	(0.0415)
Observations	10,942	17,974	5,861	9,842
Adjusted R^2	0.645	0.581	0.618	0.611
Matching based on 2005 PM_{10} in range 20–40				
LEZ treatment	−0.0486*	0.0228	−0.0362	0.0412
	(0.0272)	(0.0251)	(0.0346)	(0.0370)
Observations	10,942	19,686	5,861	10,698
Adjusted R^2	0.645	0.582	0.618	0.612
Matching based on 2005 PM_{10} No Range				
LEZ treatment	−0.0554**	0.0347	−0.0322	0.0477
	(0.0240)	(0.0290)	(0.0299)	(0.0376)
Observations	14,583	22,682	8,688	12,410
Adjusted R^2	0.669	0.587	0.661	0.618

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

manuscript. Before proceeding, we note that our results are robust to alternative specifications. In particular, whether to include weather covariates, holiday or population information does not change our overall treatment effect. Details on these robustness checks are provided in online Appendix D.

To investigate the heterogeneity between LEZs, Table 10 displays the treatment effects from regression each LEZ city separately to the same set of control cities. At traffic stations, PM_{10} decreases in the range of 5% in Cologne[26] to 13% in Mannheim. At background stations, again, none of the treatment effects is significantly different

[26] It is interesting to note that Cologne realised the lowest PM_{10} reduction (5%). Cologne is the only LEZ city that implemented an LEZ despite never violating the EC regulation. In Cologne it is not the police that are 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.

Table 10

Effect of Individual LEZ on log PM_{10} (Matching Based on 2005 PM_{10} in Range 25–35)

	All station types (1)	Traffic stations (2)	Background stations (3)
Mannheim LEZ			
LEZ treatment	−0.0837***	−0.132***	−0.0345
	(0.0182)	(0.0187)	(0.0263)
Observations	11,958	5,538	6,420
Adjusted R^2	0.592	0.618	0.578
Cologne LEZ			
LEZ treatment	−0.00605	−0.0475**	0.0132
	(0.0170)	(0.0192)	(0.0251)
Observations	12,412	5,564	6,848
Adjusted R^2	0.601	0.628	0.586
Reutlingen			
LEZ treatment	−0.0461**	−0.130***	0.0342
	(0.0206)	(0.0197)	(0.0271)
Observations	8,555	3,965	6,420
Adjusted R^2	0.632	0.658	0.592
Leonberg			
LEZ treatment	−0.0765***	−0.0693***	
	(0.0194)	(0.0187)	
Observations	11,531	5,539	
Adjusted R^2	0.601	0.631	

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

from zero. In summary, while there is some heterogeneity, all the LEZs are associated with significant decreases in PM_{10} at traffic stations.

4.3. *Geographical LEZ Results*

This subsection presents the results from our geographical identification strategy, which compares LEZ cities to nearby FLEZ. First, Table 11 displays the estimates from combining all the LEZs and their control cities. Across all traffic stations, column 1*a* shows that LEZs are associated with a 7.3% decrease in PM_{10} (which is qualitatively similar to the result of columns 1 and 3 of Table 8 in the previous Section). Auffhammer *et al.* (2009) show that within US counties that are not attaining 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 analyse PM_{10} pollution only at cities' dirtiest stations and find the treatment effect increases to −10.7% (column 2*a*).

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 3*a* of Table 11 shows that the treatment effect at stations inside LEZs is 8.6%, slightly larger than the average

Table 11

All Early LEZs versus Nearby FLEZs

	All stations	Dirtiest stations	Inside LEZ	Outside LEZ
	(1*a*)	(2*a*)	(3*a*)	(4*a*)
Traffic stations				
LEZ treatment	−0.0733**	−0.107**	−0.0862***	−0.0363
	(0.0319)	(0.0392)	(0.0289)	(0.0465)
Observations	15,794	7,849	14,156	10,885
Adjusted R^2	0.683	0.707	0.692	0.677
	(1*b*)	(2*b*)	(3*b*)	(4*b*)
Background stations				
LEZ treatment	0.0163	0.148	0.0145	0.0178
	(0.0381)	(0.0549)	(0.0643)	(0.0327)
Observations	9,842	1,284	6,848	8,130
Adjusted R^2	0.633	0.556	0.633	0.627

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

treatment effect. In comparison, at traffic stations outside of LEZs, PM_{10} decreases by a statistically insignificant 3.6% (column 4*a*). These results imply that the benefits of PM_{10} reduction within the zones are not fully carried over to the traffic 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 (1*b*)–(4*b*).

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 neighbouring FLEZ cities.[27] The cities in the figure are ranked in descending order by the number of inhabitants within the LEZ,[28] 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%, 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,

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

[28] 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.

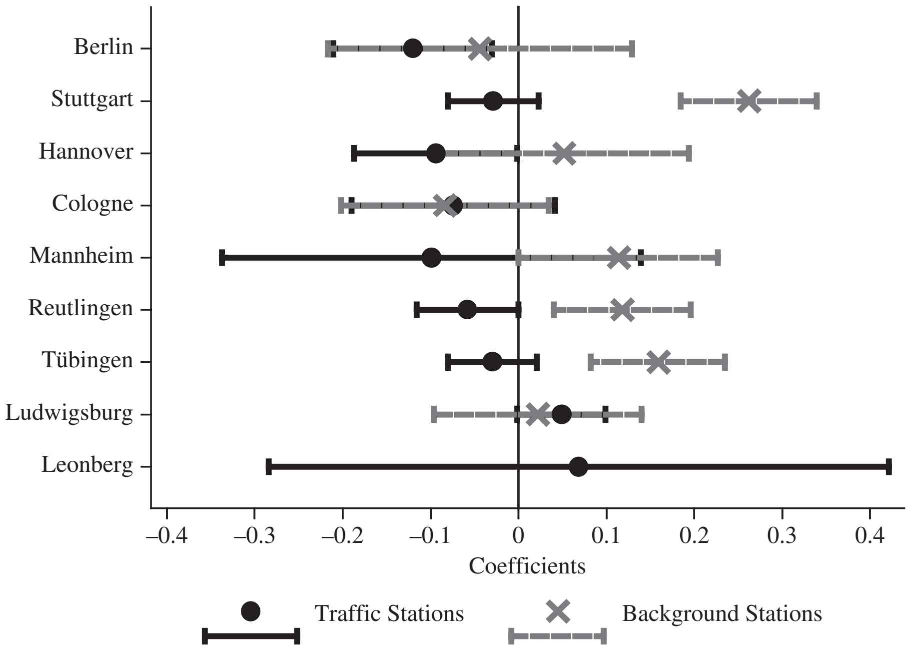


Fig. 4. *Treatment Effects of Individual LEZs Using Regional Approach*
Note. Plots include 95% confidence intervals of treatment effects.

Mannheim, Reutlingen and Tübingen, while the changes are insignificant for Berlin, Hannover, Cologne[29] and Ludwigsburg.[30]

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.[31] If cities are assigned into non-attainment 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 effect and hence overstate the true LEZ treatment effect. In following regressions of Tables 12 and 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.[32] We perform this placebo test for both:

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

[30] 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.

[31] Local construction sites, open coal barbeques or similar events can temporary drastically increase PM_{10} emissions. If PM_{10} exceeds 50 mg/m^3 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).

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

(*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 Tables 8 and 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 Tables 12 and 13 indicates that both of our matching strategies are robust to these tests of mean reversion.

Table 12

Placebo Regression: 2005 PM_{10} Matching Approach – Analogue to Table 8, but Using 2007 as the Placebo Treatment (LEZ versus Attainment Cities – 2006 versus 2007)

	All cities		Cities > 100,000	
	Traffic stations (1)	Background stations (2)	Traffic stations (3)	Background stations (4)
Placebo dummy	0.139	−0.0137	0.121	0.0191
	(0.144)	(0.0743)	(0.0953)	(0.0630)
Observations	6,420	8,132	2,896	4,280
Adjusted R^2	0.670	0.645	0.653	0.653

Notes. All regressions include year–month fixed effects, weather, holiday, station type and population covariates. Regressions include data for April to October 2006 *versus* 2007. Robust standard errors in parenthesis 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 versus Nearby FLEZs – 2006 versus 2007)

	All stations (1)	Dirtiest stations (2)	Inside LEZ (3)	Outside LEZ (4)
Traffic stations				
Placebo dummy	−0.0256	−0.0066	−0.0189	−0.0528
	(0.0405)	(0.0764)	(0.0470)	(0.0674)
Observations	17,110	7,271	15,612	11,332
Adjusted R^2	0.692	0.700	0.696	0.685
Background stations				
Placebo dummy	−0.0515	0.0376	0.0034	−0.0845
	(0.0443)	(0.100)	(0.0300)	(0.0555)
Observations	10,690	1,707	7,694	8,555
Adjusted R^2	0.656	0.622	0.650	0.647

Notes. All regressions include year–month fixed effects, weather, holiday, station type and population covariates. Regressions include data for April to October 2006 *versus* 2007. Robust standard errors in parenthesis 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	2,188	1,639	4,376	2,186
Adjusted R^2	0.599	0.615	0.591	0.591

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

4.4. *Spatial Spillover Effects: The LEZ of Berlin*

The LEZ policy of Berlin is of particular interest. It covers over 88 km^2 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 1 January 2010.[33] 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 analyse this city further.[34]

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% decrease in PM_{10} relative to traffic 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%, 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 the Berlin LEZ also reduce PM_{10}

[33] 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 from entering the city of Berlin since they do not have the green sticker. Furthermore, 13% of all privately used vehicles are non-green and hence are also excluded from entering the city of Berlin. See Table 15 for details.

[34] This Section uses 15 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.

levels by a significant 9.1%. Again, this is substantially larger than the (insignificant) average reduction of 3.6% for all German outside-LEZ traffic stations, as displayed in Table 11, column 4*a*. These results suggest that the benefits of adopting cleaner vehicles are also realised 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 that 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 −0.15 is exactly 0.06 larger compared to the 'outside LEZ' coefficient of −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.[35]

4.5. *Spatial Substitution Between Low and High-emission Vehicles*

One important argument for the four-tier PM_{10} categorisation 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, we construct an unique panel data set of German vehicles to analyse spatial substitution effects in purchasing new vehicles and retrofitting existing vehicles attributable to LEZs.

Data from the German Federal Motor Transport Authority (Kraftfahrtsbundesamt Flensburg) include 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 1 January of each year. Table 15 summarises 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% 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%, while red and no sticker vehicles decrease by 21% and 26% respectively. Because commercial vehicles are used for business activities and often rely on access to the city centre, 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.[36] The

[35] Also note that the same calculations hold for the background stations showing that the two (insignificant) treatment effects of −0.046 and −0.040 in column (4) are roughly equal to the (insignificant) treatment effect of −0.007 in column (2).
[36] We use 15 February 2009 to determine the status of the city whether it contains an LEZ or not.

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 1 September 2008. This date was then again postponed to be tentatively scheduled for

Table 15

Vehicle Registration by Emissions Sticker Category Private Vehicles

	2008	2009	2010	% change 2008 *versus* 2010
(*a*) *Private vehicles*				
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*				
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

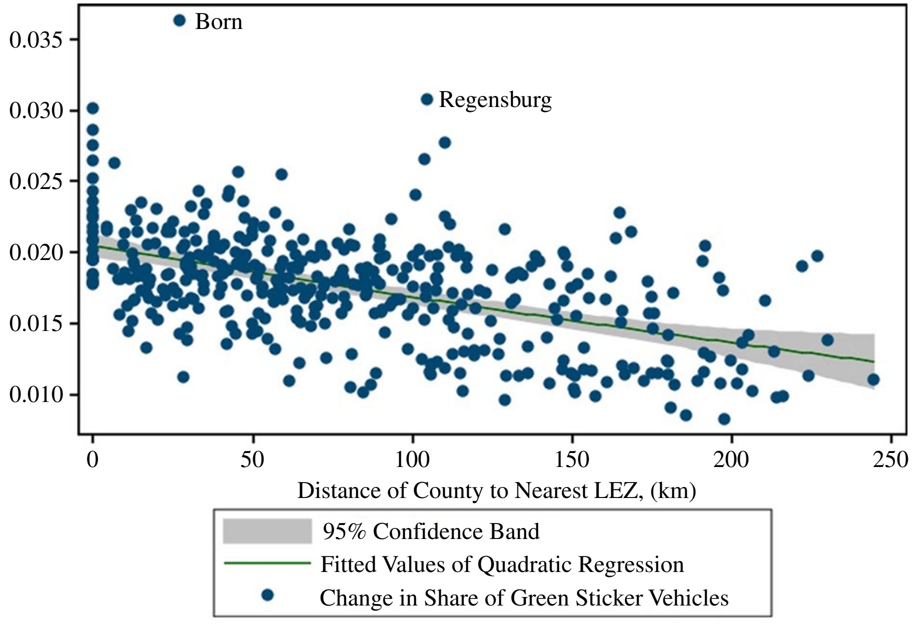


Fig. 5. *Change of Share of Green Sticker Vehicles 2008–9 as Function of Distance of the County to LEZ (Privately Owned Cars)*

January 2010 (Stadt Regensburg, 2008). The Regensburg LEZ has still not implemented.[37] 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 (1 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 largest drop. Similarly, Figures 7 and 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 kilometre closer a vehicle is to an LEZ, the incentive to upgrade to a green sticker increases by about 1% for

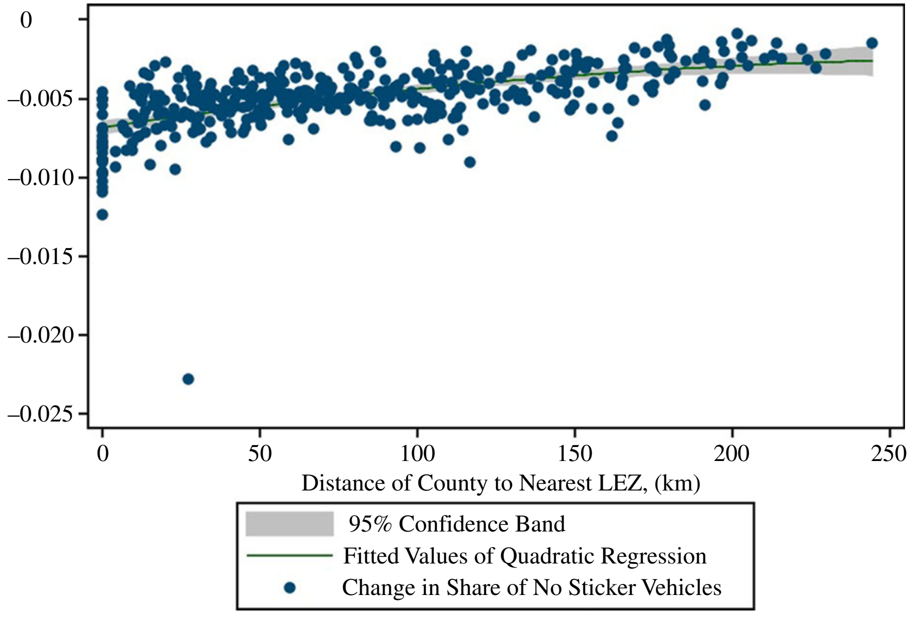


Fig. 6. *Change of Share of No Sticker Vehicles 2008–9 as Function of Distance of the County to LEZ (Privately Owned Cars)*

[37] See www.climate-company.de (last accessed 15 November 2013).

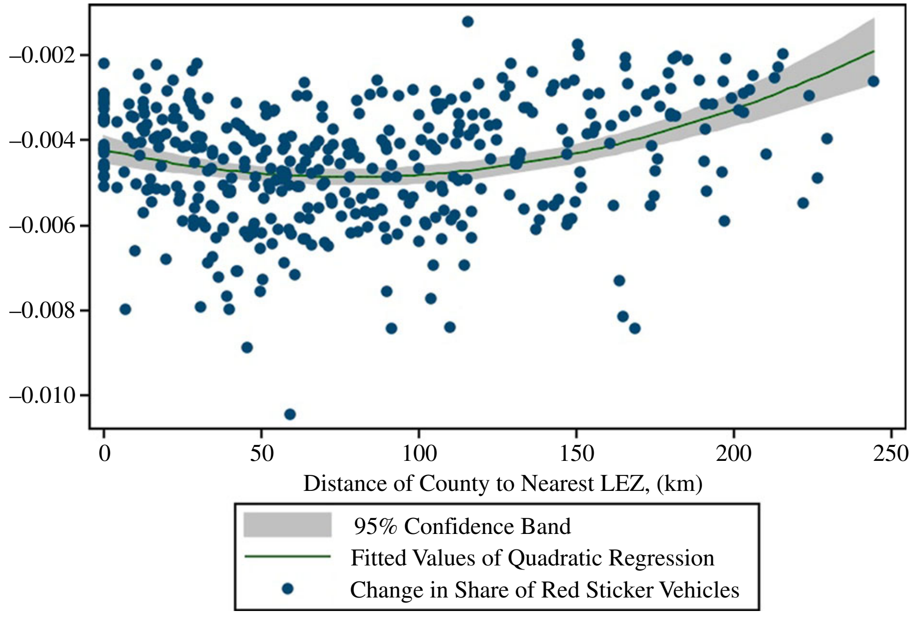


Fig. 7. *Change of Share of Red Sticker Vehicles 2008–9 as Function of Distance of the County to LEZ (Privately Owned Cars)*

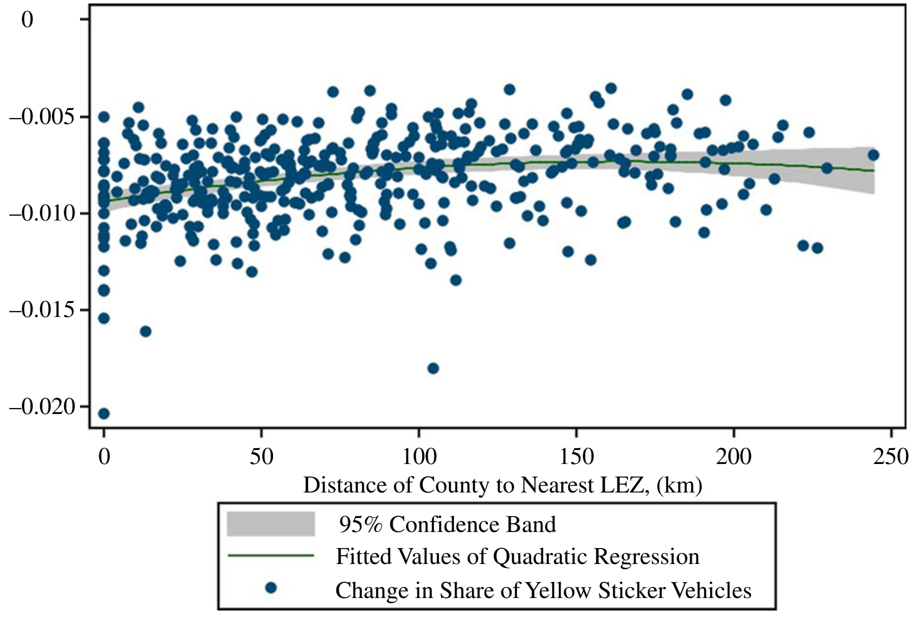


Fig. 8. *Change of Share of Yellow Sticker Vehicles 2008–9 as Function of Distance of the County to LEZ (Privately Owned Cars)*

Table 16

Effect of Distance From LEZ City on Green Technology Adoption

	Private vehicles	Commercial vehicles
Change in % of green sticker vehicles from 2008 to 2010		
Distance to nearest LEZ, km	−0.0061***	−0.0108***
	(0.0005)	(0.0025)
Observations	405	405
Adjusted R^2	0.265	0.042
Change in % of no sticker vehicles from 2008 to 2010		
Distance to nearest LEZ, km	0.0030***	0.0070***
	(0.00021)	(0.0012)
Observations	405	405
Adjusted R^2	0.333	0.080

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

commercial vehicles and 0.6% for private vehicles. Hence, again, the effect is larger for commercial vehicles, as these rely more on access to city centres 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 owners of commercial vehicles, who updated their fleet more aggressively due to the LEZs.

5. Cost–benefit Analysis

To obtain sense of LEZ's efficiency, we use our results to calculate back-of-the-envelope costs and benefits of LEZs.[38] 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 monetise these benefits (EPA, 2000). Using our city-specific estimates (from the geographical) approach of Section 4 and applying the reductions in PM_{10} to the exposure of the number of inhabitants residing within each LEZ, we monetise these health benefits to be 1.98 billion dollars.

These health benefits stand against the costs of the LEZ programme. 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 4. 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 the change in share of green stickers for the point furthest away from any LEZ as the baseline. For each location, we subtract this baseline from our

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

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

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 obtain the total cost of 1.09 billion dollars 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 the LEZ can be affected adversely or positively. 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 live strictly within the LEZ area. In the online 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, background stations were also 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 2 billion USD, which came at a cost of about 1 billion USD to upgrade the German vehicle fleet.

6. Conclusions

With over half of the world's population living in increasingly motorised 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 licence plate programme, permanent driving bans, congestion pricing, traffic cell architecture, temporary driving bans, the building of ring roads or the implementation of LEZs. Uncertainty about the effectiveness, however, creates difficulties in making informative decisions among policy options and in gaining public support by policy makers. As a result, often choices seem *ad hoc* and regionally clustered.

This article is the first to study the effect of LEZs, which is one of the most aggressive tools intended to decrease air pollutants rapidly, widely adopted across the EU but also existing in Asia (Tokyo) and variations of the programme are frequently discussed in combination with other traffic options, that is, to exclude traffic charges for low-emission vehicles in the US[40] and elsewhere.

[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 US cities are discussing similar programmes.

Our main findings are that LEZs reduce particulate emissions by 9%, whereas other air quality policies (which do not include a LEZ) surprisingly had no effect; avoidance behaviour of driving around the LEZ does not lead to significant spatial spillover effects; there is heterogeneity across zones, with larger LEZs having stronger impacts; and 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 one 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 article to assess this popular and rapidly growing policy. More studies of related policies (congestion charging, public transportation, etc.) are in order to inform this public policy debate better and to evaluate the relative efficiencies[41] of competing policies.

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Additional Supporting Information may be found in the online version of this article:

Appendix A. Comparative Results of Recent Urban PM_{10} Studies.
Appendix B. Characteristics of German Attainment Cities, Non-attainment Cities and LEZ.
Appendix C. Average Daily PM_{10} Level by LEZ Treatment Status.
Appendix D. Test of Alternative Specifications.
Appendix E. Sample Details on Geographical Matching Approach.
Appendix F. Cost–benefit Analysis.

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