The Impact of Low Emission Zones on Particulate Matter Concentration and Public Health

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ABSTRACT

A common policy for reducing particulate matter concentrations in the European Union is the introduction of Low Emission Zones (LEZs), which may only be entered by vehicles meeting predefined emission standards. This paper examines the effectiveness of LEZs for reducing PM_{10} levels in urban areas in Germany and quantifies the associated health impacts from reduced air pollution within the zones. We employ a fixed effects panel data model for daily observations of PM_{10} concentrations from 2000 to 2009 and control, inter alia, for local meteorological conditions and traffic volume. We apply the regression outputs to a concentration response function derived from the epidemiological literature to calculate associated health impacts of the introduction of LEZs in 25 German cities with a population of 3.96 Mio. Associated uncertainties are accounted for in Monte-Carlo simulations. It is found that the introduction of LEZs has significantly reduced inner city PM_{10} levels. We estimate the total mean health impact from reduced air pollution in 2010 due to the introduction of stage 1 zones to be ~700 Mio. EUR in the 25 LEZ-cities in the sample, whereas total mean health benefits are ~2.4 Billion EUR for the more stringent stage 2 zones when applied to the same cities.

Keywords: Environmental policy, Germany, low emission zones, road transport, particulate matter, health effects

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1 Introduction

While road transport contributes significantly to the growth and development of economies (Fernald 1999; Ozbay et al. 2007), this positive impact, simultaneously comes at an environmental cost. Externalities in relation to particulate matter (PM) emissions are currently one of the main concerns. Epidemiological literature shows that particulate matter has a significant negative impact on human health (Dockery et al. 1993; Ostro and Chestnut 1998; Chay and Greenstone 2003; Chay and Greenstone 2005; Anderson et al., 2004, Anderson 2009). Particulates contribute to premature mortality and morbidity, as they cause cardiovascular and respiratory diseases by penetrating the lungs and, depending on their size, by entering the blood system (Dockery et al. 1993; Hoffmann et al. 2009; Pope et al. 1995; 2002, 2011). Lahl and Steven (2005), for example, show that particulate matter emissions lead to a decrease in average life expectancy of more than 8 months in the EU 25. Annualized costs of premature mortality and morbidity due to particulate matter are estimated to amount to between 270 and 780 billion Euro across the EU 25 (Watkiss 2005).

Studies conducted in the EU show that the health impact of PM is linked primarily to exposure to particles stemming from road transport (Viana et al. 2008). Road transport adds to PM levels through exhaust emissions, break and tire abrasion, road wear and the resuspension of road dust and soil. High PM levels are found particularly within cities along busy roads, and traffic is found to be the prime contributor to anthropogenic inner city concentration of PM (Lenschow et al. 2001; Krzyzanowski et al. 2005; Diegmann et al. 2006; Jörß and Handke 2007; Umweltbundesamt 2011). At the same time, cities are densely populated and therefore, the number of people exposed to PM is high, which exacerbates the adverse health effects of PM emissions from road transport. Consequently, policies that mitigate the impact of particulate matter often focus on road transport in cities.

One recent policy for reducing PM concentrations in the EU is the introduction of Low Emission Zones (LEZs), which refer to certain geographical areas in urban agglomerations that may only be entered by vehicles meeting predefined emission standards. LEZs have been implemented for urban areas in several European countries (Low Emission Zone in Europe Network 2013), as well as in non-European cities such as Tokyo (Tokyo Metropolitan Government 2012), Beijing and Shanghai (Amin 2009). Note that Low Emission Zones set standards that are limited in geographical scope, namely to the zone in question, and do not impose any limits on overall traffic throughput within this zone.

The purpose of this paper is to investigate the effectiveness of Low Emission Zones for reducing PM levels in German cities and to calculate and monetize the associated health impacts. We focus on PM that are smaller than or equal to 10 microns in diameter (PM_{10}), as ambient air quality data for our observation period is often only available for PM_{10} on which there has been a generally stronger emphasis of EU regulation. We regard Germany as a particularly instructive sample case because of the widespread adoption of LEZs in German cities.

The contribution of the research is threefold. First, we add to the sparse literature on the evaluation of LEZs in Germany by using a particularly comprehensive dataset with respect to LEZs and cities considered (25 cities with Low Emission Zones, 112 cities without Low Emission Zones) and the temporal dimension (daily observations for the years 2000-2009). We also account for different stringencies of the Low Emission Zone introduced in a city. To date, to the best of our knowledge, there is only one archival publication by Wolff (2014) whose cross-sectional scope is limited to nine LEZs, and temporal dimension captures a maximum of ten months after a Low Emission Zone has been introduced.

Second, as traffic is a prime contributor to anthropogenic PM emissions (Viana et al. 2008), we use local information on traffic volume as an explanatory variable for particulate matter emissions. This approach has been omitted in previous research. By explicitly capturing changes in traffic volume, our analysis avoids bias that might stem from changes in PM_{10} levels being attributed to the introduction of LEZs, whereas they are actually caused by changes in traffic volume.

Third, we calculate the public health benefits of different stringencies of LEZs in terms of lower PM-attributable premature mortalities using a concentration response function obtained from the epidemiological literature and monetize the benefits using the value of a statistical life approach. Uncertainties in main parameters of the health impact calculation are propagated through the calculations in a Monte-Carlo framework, which gives a more complete picture on the monetized health benefits of LEZs than previously available.

The remainder of this paper is organized as follows. Section 2 gives a brief overview of LEZs in Germany. Section 3 shows the strategy for estimating the impact of Low Emission Zones on inner-city PM_{10} levels and Section 4 presents the data. In section 5 we present the results of the estimation and discuss them. Section 6 uses the estimation results in a Monte-Carlo framework to quantify and monetize the public health benefits of LEZs. The final section concludes.

2 Low Emission Zones in Germany

Low Emission Zones in Germany have been introduced to ensure compliance with binding PM_{10} limit values in ambient air as defined by the European Union in Council Directive 1999/30/EC (European Commission 1999). Starting from 1st January 2005, member states are obliged to implement provisions so that

(1) a 24 hour limit of 50 $\mu g/m^3$ PM_{10} is not exceeded on more than 35 days per calendar year and

(2) the annual average does not exceed 40 $\mu g/m^3$ PM_{10}.

Germany applied the European Directive to national law in 2002 through the 22nd "Ordinance of the Federal Immission Control Act" (Bundes-Immissionsschutzgesetz - BImSchG**).** A second national regulation, the 35th "Ordinance of Marking Vehicles with Low Emissions", which came into effect on March 1st 2007, gives cities and municipalities the right to define geographical areas as LEZs. Starting in January 2008 with just three cities, 47 LEZs covering 67 cities have since been introduced throughout Germany by July 2013 (Umweltbundesamt 2013a).

The "Ordinance of Marking Vehicles with Low Emissions" classifies vehicles according to emission classes. The system follows a simple color code (green, yellow, red). Vehicle owners can buy a colored sticker that shows the emission class the vehicle belongs to. As shown in Table 1, there are four different emission classifications, in which a vehicle will either not obtain a sticker because emissions are too high, or - in the order of decreasing emission thresholds - it will receive a red, yellow or green sticker. Requirements are different for diesel- and gasoline-powered vehicles.

Table 1 Vehicle Emission classifications system for Low Emission Zones

	Requirement for each sticker category			
	no sticker	**red sticker**	**yellow sticker**	**green sticker**
Diesel vehicles	Euro 1 or older	Euro 2 or Euro 1 + particle filter	Euro 3 or Euro 2 + particle filter	Euro 4 or better, or Euro 3 + particle filter
Gasoline vehicles	Without catalytic converter	--	--	Euro 1 with catalytic converter or better

Source: Based on 35. BImSchV.

Low emission zones are classified using the corresponding colors. They prohibit vehicles which do not meet a certain emission limit as indicated through the vehicle's emission classification from entering a specific geographical area. There are three stages of LEZ: Stage 1 LEZs only ban very high-emitting, non-sticker vehicles from entering the zone. Stage 2 LEZs ban non-sticker and red-sticker vehicles. Stage 3 LEZs only grant access to low-emitting vehicles with a green sticker. In all three stages of LEZs, certain exceptions apply, for example for vehicles on medical emergency calls, police and fire brigades. Vehicle owners who enter LEZs illegally are fined EUR 40 and, if they reside in Germany, receive a penalty point in the Central Register of Traffic Offenders.

Most LEZs in Germany were initially introduced as Stage 1 zones. If PM_{10} levels in a city remain above the limit values, LEZs can be made more stringent by moving to stage 2 or 3. Currently, 14 of 47 LEZs are designated as stage 2, and 34 LEZ have moved on to become stage 3 LEZs. 8 of the current stage 2 LEZs are scheduled to move to stage 3 in July 2014 (Umweltbundesamt 2013a).

The geographical scope of LEZs is designed to capture inner city areas with the highest PM_{10} exposure. In some cases, this area is large, as for the LEZ 'Ruhr', which was established in early 2012 by merging LEZs of 13 cities in the Ruhr area. It covers an area of 850 km^2 with 3.3 million citizens living within the zone. The second largest LEZ in terms of area is located in Stuttgart with 207 km^2 and 590,000 inhabitants. The geographical scope of Berlin's LEZ (88 km^2) is small compared to Stuttgart, but it encompasses 1.1 million inhabitants. On the other side of the spectrum, the smallest LEZs in Germany cover only 1 to 5 km^2 and a few thousand citizens.

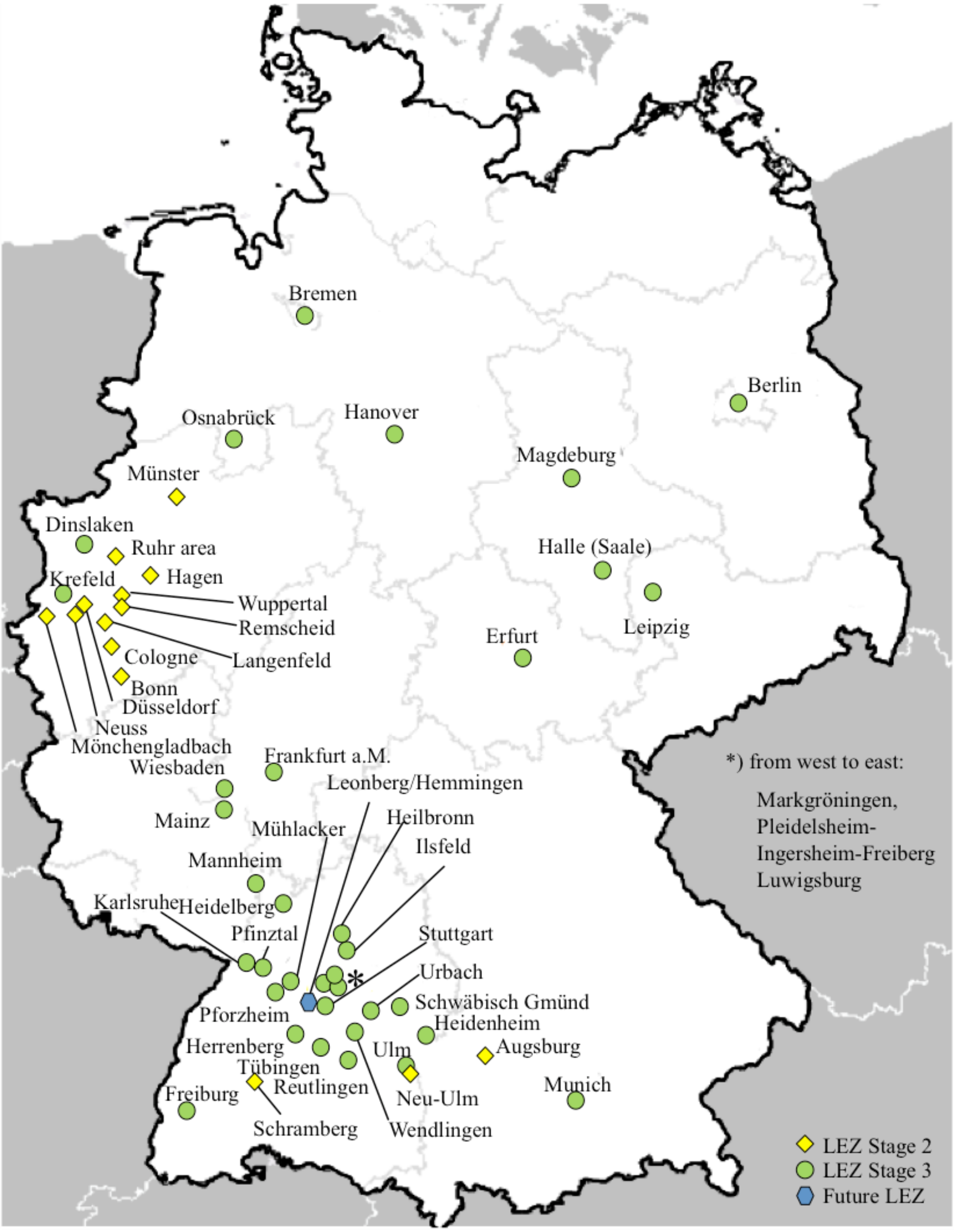


Fig 1 Spatial distribution and stage of LEZs in Germany as of July 2013.

Figure 1 shows that there is a spatial concentration of LEZs in the wider metropolitan region of Stuttgart in the southwest of Germany, which accounts for approximately half of all LEZs in the country. This area has high traffic volumes and unfavorable topographic conditions (mountain ridges), which exacerbate PM_{10} issues. Mountain ridges prevent the horizontal movement of pollutants out of the city, and therefore increase inner city PM_{10} levels (Davis

2008). A second cluster can be found in the west of Germany in the Rhine-Ruhr area (Ruhr, Cologne, Dusseldorf, and Bonn) which has high inner city traffic and is densely populated.

3 Methodology

In this section, we describe our econometric strategy for measuring the effects of Low Emission Zones on changes in PM_{10} levels. We assume that the PM_{10} level of monitor i on day t can be written as the following function:

$$PM10_{i,t} = f\left(LEZ_{j(i),t}, mv_{i,t}, dweek_t, \boldsymbol{W_{i,t}}, \boldsymbol{M_t}, \boldsymbol{Y_t}\right) \quad (1)$$

The daily PM_{10} level is assumed to depend on whether an LEZ has been implemented in the respective city ($LEZ_{j(i),t}$), based on the road traffic volume in the city ($mv_{i,t}$), on weekdays versus weekends ($dweek_t$), on local meteorological conditions ($\boldsymbol{W_{i,t}}$), on the month ($\boldsymbol{M_t}$) and on annual fixed effects impacting on PM_{10} ($\boldsymbol{Y_t}$).

In order to quantity the effects of LEZs on PM_{10} values, $LEZ_{j(i),t}$ indicates whether city *j* has implemented an LEZ on day t. For the econometric model, this variable will be further divided into the different implementation stages.

We include the road traffic volume $mv_{i,t}$, as numerous studies have shown that PM_{10} levels in urban areas are influenced substantially by road transport (e.g. the meta-analysis of Viana et al. 2008; Fuller and Green 2006; Charron et al. 2007; Byrd et al. 2010; Juda-Retzler et al. 2011; Lonati et al. 2006; Lenschow et al. 2001). Traffic volume can also, to a certain extent, control for different emission sources from road transport (exhaust emissions, break and tire abrasion, road wear and resuspension of road dust and soil), as they all vary with the volume of traffic.

We also assume that the PM_{10} level of monitor i on day t depends on whether the day of observation is a weekday ($dweek_t$) or a weekend. This enables us to control for variations in driving behaviour and in the composition of the vehicle fleet on the roads on weekdays and weekends, as applied in related research (Davis 2008; Klingner and Sähn 2008; Charron et al. 2007; Lonati et al. 2006; Qin et al. 2004; Morawska et al. 2002; Motabelli 2003; Blanchard and Tanenbaum 2003).

Furthermore, we include $\boldsymbol{W_{i,t}}$, which is a vector of explanatory meteorological variables varying over time at the monitor level, as there is considerable evidence of a causal relationship between PM_{10} levels and meteorological conditions (Viana et al. 2008; Vardoulakis and Kassomenos 2008; Juda-Rezler 2011; Beevers and Carslaw 2005). It was found that ambient PM_{10} concentrations are impacted by temperature, precipitation, humidity, sunshine, wind, air pressure, snow and vapour pressure (Klingner and Sähn 2008; Baklanov et al. 2010; Bauer et al. 2007; Holst et al. 2008, Vardoulakis and Kassomenos 2008). Regarding our model, we therefore include values for mean temperature (TMK), total precipitation (RSK), mean relative humidity (UPM), total sunshine duration in hours (SDK), mean wind force (FM), maximum wind speed (FX)**,** mean air pressure (APM), Snow depth (SHK) and mean vapor pressure (VPM).

In addition to the climate data, certain weather phenomena have been shown to contribute to high PM_{10} episodes. The less the atmosphere in the boundary layer can mix, the more it accumulates locally emitted particles, as they are not dispersed through air movement (Bauer et al. 2007). In relation to high PM_{10} episodes, there are two key meteorological phenomena which cause stagnant air, thus hindering vertical air flows and therefore mixing. Firstly, there are inversions near the surface, where a warmer air layer above encloses a colder air layer underneath, and secondly, stable atmospheric stratification, where the lower atmosphere displays almost isothermal vertical temperature profiles (Baklanov et al. 2010; Klingner and Sähn 2008; Holst et al. 2008; Bauer et al. 2007, Kukkonen et al. 2005). These phenomena are often associated with high atmospheric pressure and sometimes low wind speed (Baklanov et al. 2010; Bauer et al. 2007, Kukkonen et al. 2005). In a wide-ranging study of European high-pollution episodes, Baklanov et al. (2010) find that, in northern Europe, conditions that hinder mixing often occur in winter. Bauer et al. (2007), Klingner and Sähn (2008) and Holst et al. (2008) show that a lack of precipitation, in combination with sunny and dry weather conditions, ceteris paribus, also increase PM_{10} levels.

As we cannot include these weather phenomena directly in our model due to a lack of data, we approximate them by using interaction terms of measured meteorological variables. We define the following meteorological dummy variables and interaction terms, listed in Table 2 below:

Table 2 Meteorological dummy variables and interaction terms

Configuration	Notation
Meteorological dummy variables	
dummy variable that is equal to 1 when RSK = 0	NORAIN
dummy variable that is equal to 1 when TMK < 0	COLDDAY
dummy variable that is equal to 1 when FM < 3.4	LOWWIND
Interaction terms	
days without precipitation in combination with mean air pressure	NORAINAPM
days without precipitation in combination with cold temperatures	COLDDAYNORAIN
days with low temperature in combination with mean air pressure	COLDDAYAMP
days with low mean wind force in combination with mean air pressure	LOWWINDAPM
daily mean temperature in combination with daily mean relative humidity	TKMUPM
daily mean temperature in combination with daily total sunshine duration hours	TMKSDK
the difference between daily maximum temperature (TXK) and daily minimum temperature (TNK) to reflect extreme temperature variation throughout the day	TXK-TNK

Moreover, dummy variables for each month ($\boldsymbol{M_t}$) are part of our function, so as to account for seasonal climatic conditions and large-scale weather phenomena which are not described by the meteorological variables.

Finally, dummy variables for each year ($\boldsymbol{Y_t}$) capture macroeconomic factors that vary over time, for example regulatory measures such as the introduction of the German car scrapping scheme and the European Emission Standards Euro 5/Euro 6, fuel price cycles or the financial crisis.

We assume a linear relationship between PM_{10} emissions and our explanatory variables and make a choice between a fixed effects and a random effects panel data model. A Hausman test is employed to find the preferred method. The test leads us to reject the null hypothesis of no correlation between individual effects and other regressors in the model, which indicates that a fixed effects model is appropriate. According to the Fisher-ADF and Fisher-PP unit root tests for unbalanced panels, the null hypothesis of nonstationarity can be rejected. A White Test is executed to test for heteroscedasticity. The null hypothesis of homoscedasticity is rejected. Furthermore, we employ the Wooldridge test for serial correlation in panel data with the null hypothesis of no first-order correlation. We reject the null hypothesis and conclude that there is serial correlation. As a consequence, we estimate a robust fixed effects model to control for heteroscedasticity and autocorrelation (Baltagi 2008).

Our econometric model of equation (1) is given by:

$$PM10_{i,t} = \beta_0 + \beta_1 LEZ_{j(i),t} + \beta_2 LEZ2_{j(i),t} + \beta_3 mv_{i,t} + \beta_4 dweek_t + \boldsymbol{\gamma W_{i,t}} + \boldsymbol{\varepsilon M_t} + \boldsymbol{\theta Y_t} + \tau_i + v_{it} \quad (2)$$

Let $LEZ_{j(i),t}$ be a dummy variable that is equal to 1 when city *j* has implemented an LEZ, irrespective of stage, on day *t*. The index *j(i)* indicates the city *j* to which monitor *i* is linked. $LEZ2_{j(i),t}$ is a dummy variable that takes the value of 1 when city *j* has a stage 2 LEZ on day *t*. β_1 and β_2 are the parameters of interest. β_1 measures the difference in PM_{10} levels between LEZ and non-LEZ cities. β_2 measures the difference in impact between LEZs in general and stage 2 LEZs.

Contrary to other studies, which use only proxy variables to account for the impact of road transport, we explicitly integrate the daily local road traffic volume of motor vehicles $mv_{i,t}$ into our model. The number of motor vehicles varies over time at the monitor level, and β_3 shows the influence of traffic volume on PM_{10} levels. $dweek_t$ is a binary dummy variable that equals 1 when the time variable refers to a weekday (Monday to Friday).

Using meteorological variables and interaction terms, we obtain vector $\boldsymbol{W_{i,t}}$:

$$W_{i,t} = (TMK_{i,t}, RSK_{i,t}, UPM_{i,t}, SDK_{i,t}, FM_{i,t}, FX_{i,t}, APM_{i,t}, SHK_{i,t}, VPM_{i,t}, (TXK - TNK)_{i,t}, COLDDAYAPM_{i,t}, LOWWINDAPM_{i,t}, NORAINAPM_{i,t}, COLDDAYNORAIN_{i,t}, TMKUPM_{i,t}, TMKSDK_{i,t})^T \quad (3)$$

To control for seasonal climatic conditions, $\boldsymbol{M_t}$ is a vector of dummy variables for each month that equals 1 when the time variable defines any day of the respective month. $\boldsymbol{Y_t}$ is a vector of dummy variables, that captures yearly fixed effects. τ_i is the unobserved time-invariant monitor specific fixed effect and v_{it} is the idiosyncratic unobserved error component.

4 Data

We obtained a data set of aggregated daily means of the PM_{10} level at all German PM_{10} monitoring stations from the German Federal Environment Agency (Umweltbundesamt). For our research, we used data from monitoring stations, whose PM_{10} levels are predominantly influenced by traffic, since the policy measure being assessed in this paper is directed toward road transport. Daily PM_{10} levels are measured by gravimetric and continuous measurement. We used gravimetric measurements whenever they are available, as this is the Europe-wide reference method (Umweltbundesamt, 2012).

We collected daily meteorological data from 74 monitoring stations from the German National Meteorological Service (Deutscher Wetterdienst, DWD). As air quality and weather monitoring stations are not at the same location, we matched air quality stations with the adjacent meteorological stations within a 50 km radius. PM_{10} monitors whose distance to the nearest meteorological station exceeds 50 km are removed from the analysis, as the actual meteorological conditions at the air quality monitor would not be captured effectively by distant stations. In order to determine one indicator per air quality measuring station that captures the local meteorological conditions, the mean value across all assigned meteorological stations is calculated.

We obtained daily road traffic volume data for selected counting stations from the Federal Highway Research Institute (Bundesanstalt für Straßenwesen, BASt) for January 2000 through to December 2009. To match counting stations with PM_{10} monitors, we examined all counting stations in proximity to each PM_{10} monitor. A counting station is assigned to the PM_{10} monitor if the street on which the count is taken leads toward the PM_{10} monitoring station. If more than one counting station fits this criterion, we calculated the average traffic volume from the assigned counting stations and used this average as traffic volume at the corresponding PM_{10} monitor.

Table 3 provides summary statistics for meteorological and traffic variables.

Information on previous and current stages of LEZs is available from the German Federal Environment Agency. Different start dates and stage evolutions are taken into account in the time dimension. We defined three implementation groups: cities without LEZ, cities with stage 1 LEZ and cities with stage 2 LEZ. We did not include stage 3 LEZs, as the first of these zones were only introduced in 2010. Finally, we follow the criterion in Annex 11 of the

BImSchV (Federal Emission Control Regulation) for the representativeness of monitoring stations and drop stations, which record data on less than 90 per cent of all days within an observation year. Overall, we obtained an unbalanced panel with data for PM_{10} levels, meteorology and traffic volume for 232 stations, covering 137 cities from January 2000 through to December 2009.

Table 3 Summary statistics of meteorological and traffic variables

	Unit	Mean	St. Dev.	Min	Max
Meteorological Variables					
Daily mean temp. 2 m above ground (TMK)	°C	9.822418	7.536171	-19.3	30.6
Daily min temp. 2 m above ground (TNK)	°C	5.564815	6.733873	-25.1	23.5
Daily max temp. 2 m above ground (TXK)	°C	14.12986	8.81725	-17.3	40.2
Daily mean relative humidity (UPM)	%	77.66383	12.54398	7	100
Daily mean wind force (FM)	m/sec	3.672707	2.089523	0.1	25.2
Daily maximum wind speed(FX)	m/sec	10.48599	4.424542	0.7	54
Daily total sunshine duration hours (SDK)	hours	4.77476	4.40869	0	16.7
Daily total precipitation (RSK)	mm	1.982115	4.354956	0	158
Daily mean air pressure (APM)	hpa	985.7855	29.91497	819.6	1045.3
Daily mean vapor pressure (VPM)	hpa	9.893972	4.036125	0.5	24.5
Snow depth (SHK)	cm	1.455802	9.480786	0	250
Traffic variable					
Traffic volume of all motor vehicles (MV)	mv/day	41504.63	28069.24	0	211666.5

Figure 2 plots daily average PM_{10} levels within the study period for all traffic stations in cities without LEZs and for all traffic stations in cities that implemented LEZs in 2008 or 2009.

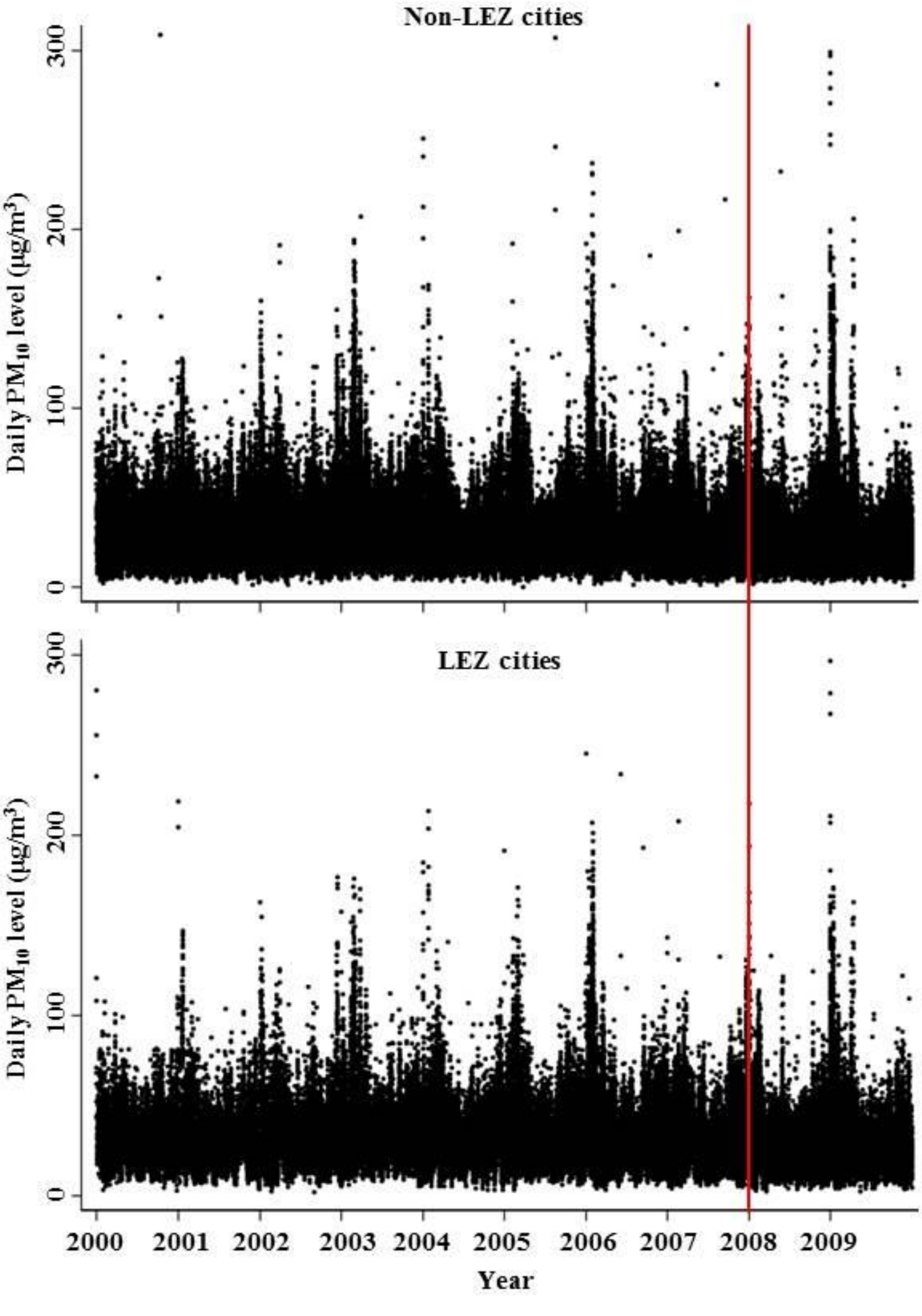


Fig 2 Daily average PM_{10} levels at traffic measuring stations (2000 - 2009).

Table 4 summarizes the PM_{10} levels between 2000 and 2009, as well as annual summary information for the monitors included in our analysis. Daily PM_{10} levels vary widely across days and monitoring stations. They range from below 1 μg/m³ to over 200 μg/m³. During the observation period, the limit value not to exceed a 24 hour average of 50 μg/m³ PM_{10} on more than 35 days per calendar year is violated by 87 cities in our dataset, in one or more years. The annual average of PM_{10} concentrations range from 11.22 μg/m^3 in Gittrup in 2001 to 68.24 μg/m^3 in Erfurt in 2000. Overall, 27 German cities exceed the limit of the annual average of 40 μg/m^3 in one or more years between 2000 and 2009.

Table 4 Summary statistics of PM_{10} variables (2000-2009)

Year	Number of monitors	Number of cities	Number of monitored LEZ cities	Mean annual PM_{10} level	Standard deviation	Min	Max
2000	75	54	N/A	29.75346	14.6307	1.8	308.51
2001	81	56	N/A	29.11361	15.46325	1	218.92
2002	85	58	N/A	31.23099	17.48293	1	190.81
2003	101	74	N/A	33.95486	19.09845	3.6	207
2004	103	73	N/A	28.74643	15.43109	3	250.8
2005	125	82	N/A	30.25702	15.55592	0	307.16
2006	153	97	N/A	31.55879	18.60057	1	245.42
2007	164	107	N/A	27.12918	14.90676	1	280.94
2008	156	110	14	25.92971	13.76578	1.7	232
2009	145	103	25	27.34751	17.01733	0.7	298.88

Figure 3 plots the annual number of cities in which the daily average of 50 μg/m^3 PM_{10} is exceeded on more than 35 days per calendar year and the annual number of cities in which the annual average exceeds 40 μg/m^3 PM_{10}.

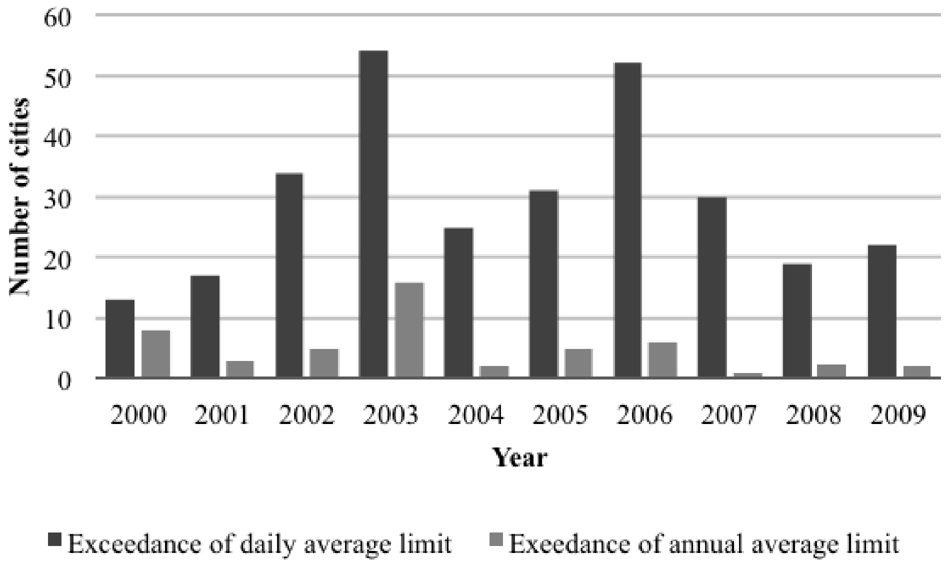


Fig 3 Number of German cities exceeding EU PM_{10} limits.

At this aggregated level we cannot identify any substantial long-term pattern, nor a visible decrease in PM_{10} emissions that coincides with the implementation of LEZs.

5 Results and Interpretation

We estimate our model using STATA 12.1. Table 5 displays the main estimation results. The entries depict the parameter estimates, and their estimated robust standard errors are in parentheses.

The key finding is that, after controlling for meteorological conditions, traffic volume and time and seasonal variations, as well as the time invariant unobservables at the monitor level, the implementation of LEZs explains a statistically significant share of the variation in PM_{10} levels in urban traffic areas. The estimated coefficient β_1 is negative and statistically different from zero at the 1 per cent level. The parameter describes a decrease in daily average PM_{10} concentration of 2.19 $\mu g/m^3$, due to the introduction of LEZs in general. β_2 is also significantly different from zero at the 1 per cent level. Therefore, the estimate presents evidence of a significant difference in the impact of LEZs in general and of stage 2 LEZs on PM_{10} levels. The negative parameter indicates that stage 2 LEZs reduce PM_{10} levels by an additional 5.28 $\mu g/m^3$, compared to stage 1 LEZs, for a total of 7.47 $\mu g/m^3$ reduction. These results give some support to results obtained from ex-ante modeling of emissions prior to LEZ introduction for selected cities, which estimated that mean daily PM_{10} concentration could be reduced by up 13 per cent (~5 μg/m^3 based on a 40 μg/m^3 daily average) (Umweltbundesamt 2007).

The coefficients of the meteorological control variables are statistically significant at the 1 per cent level. This supports previous findings referenced in Section 3 of this paper that local meteorological conditions exert a significant influence on daily average PM_{10} levels.

The coefficient β_3 for the traffic volume of motor vehicles is significantly different from zero at the 1 per cent level. The daily number of motor vehicles in urban areas has a positive influence on PM_{10} emissions, which means that PM_{10} levels increase with the throughput of these vehicles.

The estimated coefficient for 'the monitoring day is a weekday' (β_4) is positive and significantly different from zero at the 1 per cent level. According to the parameter, PM_{10} levels at weekdays are 4.19 μg/m^3 higher than at weekends. This cannot be explained by less traffic activity at weekends due to lower levels of commuter and commercial traffic, since this is already captured by the traffic-volume variables. The increase in emissions at weekdays might be attributed to the composition of the vehicle fleet, as there is more heavy duty traffic on working days than at weekends. At weekends, the number of heavy duty vehicles decreases by 63.5 per cent compared to weekdays, while the number of personal motor vehicles only decreases by 33.4 per cent in Germany (BMVBS 2012). Additionally, there is some empirical evidence that drivers on weekends, on average, drive less aggressively (Shinar and Compton 2004), which reduces acceleration and might also contribute to lower PM_{10} levels compared to weekdays.

Table 5 Fixed effects regression results (392,078 observations; 232 groups)

Parameter	**Description**	**Estimates (standard error in parenthesis)**
β_1	LEZ	-2.193365* (0.5202758)
β_2	LEZ2	-5.284499* (0.4589875)
γ_1	TMK	0.4315875* (0.1549993)
γ_2	RSK	-0.0312807* (0.0118924)
γ_3	UPM	-0.1942573* (0.0247699)
γ_4	SDK	0.1313974* (0.0485326)
γ_5	FM	-1.109957* (0.1871431)
γ_6	FX	-0.6965697* (0.0078178)
γ_7	APM	0.1243186* (0.0080545)
γ_8	SHK	-0.045808* (0.0094424)
γ_9	VPM	4.031473* (0.1197419)
γ_{10}	TXK-TNK	0.8670578* (0.0313878)
γ_{11}	COLDDAYAPM	0.000793* (0.0002666)
γ_{12}	LOWWINDAPM	0.0016181* (0.0003442)
γ_{13}	NORAINAPM	0.0018624* (0.0000917)
γ_{14}	COLDDAYNORAIN	4.239301* (0.3544246)
γ_{15}	TMKUPM	-0.0312226* (0.0026796)
γ_{16}	TMKSDK	-0.0412323* (0.0037086)
β_3	MV	0.0000235* (0.00000803)
β_4	Dweek	4.194023* (0.1699373)
β_0	Constant	-88.24446* (7.485267)
	R^2 (within)	0.3727

Notes: * Significant at 1 per cent level.

6 Public health impacts of Low Emission Zones

We calculate the public health impacts of the introduction of LEZs using changes in all-cause premature mortalities due to LEZ-attributable changes in long-term exposure to $PM_{2.5}$, as metric recommended by the World Health Organization (WHO Regional Office for Europe 2013). The base year of the calculation is 2010. All values are directly obtained for this base year, unless otherwise noted as adjusted to 2010.

We map changes in $PM_{2.5}$ to changes in premature mortalities using a linear concentration response function (CRF) derived in a meta-regression analysis (Hoek et al. 2013). The CRF obtained yields a mean change in all-cause mortality of the exposed adult population (>30 years) of 0.62 per cent for a 1 $\mu g/m^3$ change in $PM_{2.5}$. Since our regression was based on PM_{10} as pollutant of interest in the EU regulation and pollutant measured at the monitoring stations, we use a most-likely $PM_{2.5}/PM_{10}$ ratio of 0.65 as recommended by WHO (WHO Regional Office for Europe 2013) to establish a relationship between changes in PM_{10} and changes in all-cause mortality. We apply this CRF using parameters β_1 and β_2 (for LEZ 1 and LEZ 2) from our regression to the adult population living in Low Emission Zones using the German average mortality rate in this age group of 0.0155 mortalities per capita and year (WHO 2014). See Annex 1 for the population estimates for the 25 LEZs in the sample. We calculate premature mortalities for two cases. In case 1 it is assumed that all 25 LEZ cities in the saple have introduced stage 1 zones. In case 2 it is assumed that all 25 cities have introduced stage 2 zones.

We monetize the change in premature mortalities attributable to the introduction of LEZ 1 and LEZ 2 using the value of a statistical life (VSL). The mean VSL estimate of 2.0 million EUR is taken from a German labor market study that quantifies a 2008 VSL using job-changer data (Schaffner and Spengler, 2010). It is adjusted to 2010 levels using the development of the German consumer price index (CPI).

Overall, this yields the following equations for the monetized health impact of LEZ 1 (equation 4a) and LEZ 2 (equation 4b):

$$PHB_{LEZ\,1} = \sum_{r=1}^{25} Pop_{LEZ_r} * adshare * mort_{base} * CRF_{PM_{2.5}} * PMratio * \beta_1 * VSL \tag{4a}$$

$$PHB_{LEZ\,2} = \sum_{r=1}^{25} Pop_{LEZ_r} * adshare * mort_{base} * CRF_{PM_{2.5}} * \tag{4b}$$

$$PMratio * (\beta_1 + \beta_2) * VSL$$

with *PHB* as Public Health Benefit in EUR, Pop_{LEZr} as population living in Low Emission Zone *r*, *adshare* as share of adults (>30 years) in population, $mort_{base}$ as all-cause baseline mortality of the population, *CRF* as concentration response function applied, $PMratio$ as ratio of $PM_{2.5}$ to PM_{10}, and β_1 and β_2 as parameters obtained in the regression for the change in PM_{10} levels associated with the introduction of LEZ 1 (β_1), and respectively associated with incrementally changing the stringency of regulation from LEZ 1 to LEZ 2 (β_2), and *VSL* as value of a statistical life.

Note that equation (4b) calculates the total monetized health impact of introducing a stage 2 zone compared to no emission zone, instead of the incremental impact of going from LEZ 1 to LEZ 2.

We capture uncertainties associated with the impact of LEZs on PM_{10} levels, with the $PM_{2.5}/PM_{10}$ ratio, the value of a statistical life and the concentration response function, which we propagate through our calculations using Monte-Carlo simulations. All remaining parameters of equations (4a) and (4b) are treated as deterministic. Table 6 provides descriptive statistics for the parameters used in the health benefit calculation.

Table 6 Descriptive statistics and data sources for health benefit calculation

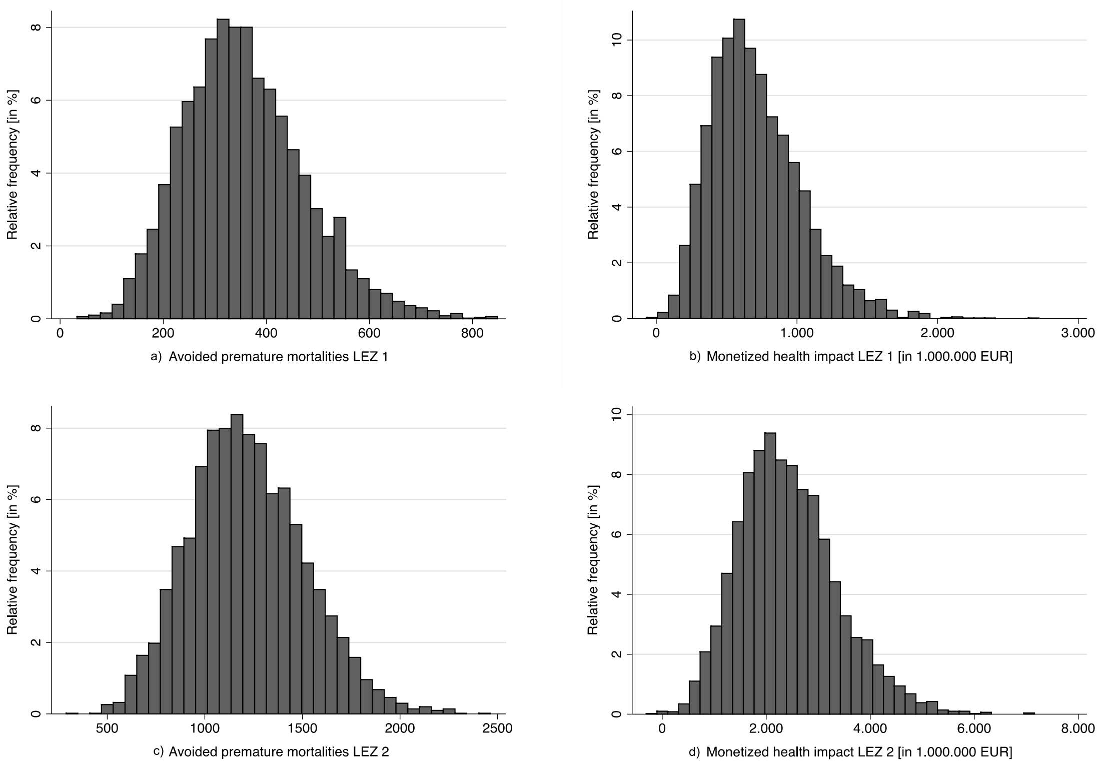
Parameter	Distribution (mean; standard error) or value	Data source and comments
Stochastic		
Change in adult mortality rate in % per 1 μg/m^3 of $PM_{2.5}$ (Concentration response function); $CRF_{PM2.5}$	$CRF_{PM2.5}$ ~ N (0.62, 0.1096939)	Hoek et al. 2013
$PM_{2.5}$/ PM_{10} ratio; *PMratio*	*PMratio* ~ Triangular (0.4,0.8,0.65)	WHO Regional Office for Europe 2013
Reduction in PM_{10} levels in μg/m^3 associated with the introduction of LEZ 1; $\boldsymbol{\beta_1}$	β_1 ~N (2.193365, 0.5202758)	Own calculation
Reduction in PM_{10} levels in μg/m^3 associated with the introduction of LEZ 2; $\boldsymbol{\beta_2}$	β_2 ~ N (5.284499, 0.4589875)	Own calculation
Value of a statistical life in EUR; *VSL*	*VSL* ~ N (2000430, 593877.86)	Schaffner and Spengler 2010
Deterministic		
Total Population in Low Emission Zones; $\sum_{r=1}^{25} \boldsymbol{Pop_{LEZr}}$	3,960,771	See Annex 1
Share of adult population (>30 years) at total popualtio;; *adshare*	0.6925	Federal German Statistical Office
Baseline adult mortality rate per capita; $mort_{base}$	0.0155	WHO 2014

Relying on the parameters and distributions from Table 6, we conduct 5,000 Monte-Carlo runs using Microsoft Excel using the SIMTOOL add-in (version 3.3) from the University of Chicago. The mean health benefit of LEZ 1 in all 25 cities in our sample that have introduced a Low Emission Zone is found to amount to ~710 Mio. EUR, following from a mean decrease in premature mortalities by ~357 incidents. If all cities in the sample increase the stringency of the Low Emission Zone from stage 1 to stage 2, then premature mortalities are further decreased by ~861 at the mean, for a total of 1,217 incidents compared to a situation without an LEZ. This yields mean total monetized health benefits associated with the introduction of LEZ 2 of ~2,421 Mio. EUR. Uncertainty on the actual magnitude of the health effects are considerable, with, for example, the 5% percentile for the total effect of LEZ 2 being around 1.03 Billion EUR while the 95% percentile amounting to 4.14 Billion EUR. The main Monte-Carlo results are summarized in Table 7, while histograms of the LEZ-attributable changes in premature mortalities and associated monetized impacts are presented in Figures 4a to 4d.

Table 7 Main results of Monte-Carlo simulation

	Avoided premature mortalities			Monetized health benefit in EUR		
	LEZ 1	LEZ 2 incremental	LEZ 2 total	LEZ 1	LEZ 2 incremental	LEZ 2 total
Mean	356.7	860.4	1,217.1	709,180,804	1,710,257,057	2,419,362,869
Min	32.6	224.5	289	-68,825,930	-239,381,920	-308,207,850
5% Percentile	183.1	544.4	762.5	261,222,021	730,903,222	1,032,677,903
Median	346.1	846.2	1,198.0	661,534,790.5	1,644,847,434	2,321,979,682
95% Percentile	563.1	1,212.30	1,722.1	1,308,037,888	2,932,495,429	4,139,593,737
Max	848.8	1,674.0	2,462.6	2,720,846,614	4,748,467,151	7,159,143,694

Notes: Negative monetized health benefits are a result of VSL being negative with ~0.04 per cent probability.



Note that the LEZ 2 results are shown compared to a situation without zone.

Fig 4: Histogram of Monte-Carlo results for changes in premature mortalities and monetized health impacts of stage 1 and 2 LEZs.

7 Conclusions

The key finding of the paper is a decrease in urban PM_{10} levels that can be attributed to the introduction of LEZs. We also find that more stringent zones (stage 2 zones) reduce PM_{10} concentrations more than three times as much as stage 1 zones. We translate these changes in PM_{10} levels into health impacts using a concentration response function, which we apply to the 3.96 Mio. inhabitants of the 25 LEZ-cities of our sample. The mean health benefits amount to ~700 Mio. EUR in the year 2010 if all cities are assumed to use stage 1 zones, whereas total mean health benefits are 2.4 Billion EUR for the more stringent stage 2 zones, if assumed to be applied in all 25 cities. To put these results into perspective: total health impacts from road transport emissions amount to 15 Billion EUR in Germany in 2010, if VSL-adjusted values are applied to a study on the external costs of transport (Infras 2007). Based on these numbers, introducing stage 1 zones in all 25 sample LEZ-cities reduces total health impacts from road transport in Germany by 4.7 per cent percent, while introducing stage 2 zones reduces them by 16.1 per cent. We also compare our results to health benefits obtained by Wolff (2014), who estimates health benefits of 1.93 Billion USD (1.47 Billion EUR at OECD 2010 purchasing power parity value of 1.31 USD/EUR) associated with the introduction of stage 1 zones in an area encompassing a total population of 2.6 Mio. Scaling the results of Wolf (2014) to the population considered in our paper (3.96 Mio.) would yield a total health benefit of 2.25 Billion EUR, which is more than three times higher than our estimate for stage 1 zones. This can largely be explained with Wolff (2014) using a U.S.-specific value of a statistical life, which is set to 7.8 Mio. USD (5.95 Mio. EUR at 1.31 USD/EUR).

While we find that the total health impact of Low Emission Zones – especially in case of stage 2 zones – can significantly reduce total road-transport related air quality impacts, it is important to note that the city-specific effect of the implementation of a LEZ on the actual compliance with European PM_{10} regulation is dependent on the local situation. If a city generally exceeds the daily limit value of 50 $\mu g/m^3$ by only a small amount, the average reduction of approximately 2 $\mu g/m^3$ through Stage 1 LEZs or approximately 7 $\mu g/m^3$ through stage 2 LEZs, as calculated in our estimation, might be sufficient to lead to regulatory compliance. If PM_{10} levels are far above the limits, there might be a need for more stringent zones or additional mitigation strategies.

We close by noting three caveats. First, the analysis presented in this paper has assumed that the reduction in PM_{10} concentration estimated for measuring stations within an LEZ applies to all locations within the zone, whereas no reduction is assumed to happen outside of the zone. In order to move beyond this simplified approach and to gain a more detailed understanding about the spatial distribution of PM_{10} concentration changes and, consequently, the size of affected population, one would need to conduct detailed atmospheric dispersion modeling which is beyond the scope of this paper.

Second, we emphasize that cities are increasingly transitioning to the most stringent stage 3 zone, so that the actual total health impact of LEZs might already go beyond stage 1 and stage 2. Consequently, it would be useful to investigate the incremental emissions and health impact of this move, once the necessary data is available.

Third, even though it is found that LEZs in Germany have led to a significant reduction in PM_{10} levels with corresponding health benefits, this does not imply that the introduction was net beneficial from a societal perspective. In order to analyze the net economic gain, one would have to compare the benefits to the costs of the policy, which, inter alia, arise on the side of the vehicle owners in the form of sticker acquisition and potential vehicle upgrading, and on the administrative side in the form of signage and policy enforcement. To date, there exists only an estimate for vehicle upgrading and this estimate is to be regarded – as acknowledged by the study itself – as “back of the envelope” (Wolf 2014). We conclude that the costs of a Low Emission Zone policy is an interesting avenue for further research.

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Annex 1: Estimates for population in Low Emission Zones in Germany in 2010

LEZ-cities in sample	Population estimate	Source
Augsburg	40,000	1
Berlin	1,000,000	1
Bremen	56,000	1
Duisburg	123,201	2
Düsseldorf	131,838	2
Essen/Gelsenkirchen	226,380	2
Frankfurt	170,610	2
Hanover	220,000	6
Heilbronn	114,879	3
Herrenberg	14,975	3
Ilsfeld	5,393	3
Cologne	147,000	1
Leonberg	39,453	3
Ludwigsburg	75,272	3
Mannheim	100,928	3
Mühlacker	7,094	3
Munich	420,000	7
Pforzheim	93,366	3
Pleidelsheim	6,223	4
Recklinghausen	1,672	5
Reutlingen	32,176	5
Stuttgart	592,915	4
Tübingen	71,842	3
Ulm	75,553	3
Wuppertal	194,000	1
Sum	**3,960,771**	

Notes: 1: Official city estimate, 2: Own estimate based on size of LEZ and city-specific population density; 3: Own estimate based on population data for neighborhoods that are part of LEZ; 4: LEZ encompasses whole city, therefore population data for whole city is used; 5: Own estimate based on size of LEZ and neighborhood-specific population density; 6: Eltis 2014; 7: Wichmann 2011.