Low Emission Zones - A Policy Revisited

Review of the Effectiveness of Low Emission Zones in 63 German Cities

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Abstract

This paper investigates the impact of low emission zones (LEZ) on the particulate matter concentration in Germany. The exploration of measurement data by over 500 monitoring stations between 2007 and 2017 allows me to evaluate effects within and around the perimeter of LEZs. I distinguish between restriction level Euro 2, Euro 3 and Euro 4 as well as between a *staggered* and an *at once* implementation of the policy. Whereas staggered stands for a start at Euro 2 and a subsequent upgrade to Euro 3 and 4, the at once procedure implies skipping lower levels. The results show that the highest restriction level (Euro 4) is associated with a decreased concentration level of about 4 percent, if the implementation is staggered. Starting at restriction level Euro 4 without any preceding treatment is not related to a reduction of particulate matter. Furthermore, I find indications for increased pollution levels within the radius of 20km of an LEZ after the initial introduction.

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List of Abbreviations

ADAC	Automobile Club Germany (Allg. Deutscher Automobil Club)
BImSchG	Clean Air Act (Bundesimmissionsschutzgesetz)
DUH	German Environmental Relief (Deutsche Umwelthilfe)
ECJ	European Court of Justice
EPA	Environmental Protection Agency
kt	Kilo tonnes
LEZ	Low Emission Zone
LDV	Lagged Dependent Variable
$\mu m/m^3$	Microns per cubic metre
PM_{10}	Particulate Matter with diameter <10 microns
UBA	Federal Environmental Agency (Umweltbundesamt)

1 Introduction

A spectre is haunting European cities - the spectre of air pollution caused by diesel-powered vehicles. Since September 2015, especially German diesel-powered vehicles have fallen into disrepute. After the revelations by the United States Environmental Protection Agency (EPA) and following prosecution, German vehicle manufactures admitted they intentionally manipulated their cars' software in order to meet the internationally required emission standards. Furthermore, in May 2017, the European Court of Justice (ECJ) announced to file lawsuits against member states, for not complying with the Air Quality Framework Directive which was passed in 2008. The responsible governments quickly agreed on a universal scapegoat: Diesel-powered vehicles. Their proposed solution is to steadily ban diesel cars from European cities.

However, this idea is nothing new. The EU commission passed the Air Quality Framework Directive in 2008, which includes legal thresholds for particulate matter (PM_{10}). According to this directive, member states have to ensure, the measured PM_{10} concentration does not exceed 50 $\mu m/m^3$ on more than 35 days per year. In response to the legal thresholds, so-called Low Emission Zones (LEZs) were introduced in those European cities which were particularly affected by air pollution. Within the framework of LEZs, a categorisation system for vehicles regarding their emitted pollutions was developed. In 2008, four categories, Euro 1, Euro 2, Euro 3 and Euro 4 where introduced, whereas a higher number represents higher requirements the vehicle has to meet. Later, categories Euro 5 and Euro 6 followed and further increased the demands. The application of the policy is simple, a Euro 3 LEZ, for instance, restricts all vehicles from entering which do not at least comply with the Euro 3 emission standard. Generally, an LEZ starts at restriction level Euro 2 and introduces higher levels in the years to follow. Legitimately, the developments and the political debate in 2018 on the ban of diesel cars feel like a déjà vu: The initial LEZs in 2008 (Euro 2 or Euro 3) only restricted diesel-powered vehicles from entering since gasoline cars are generally granted the Euro 4 status.

In the beginning of 2018 in Germany, the highest introduced restriction level corresponds to the Euro 4 norm but the diesel's negative publicity and the lawsuits by the ECJ induced the federal government to react. The responsible ministry intends to expand the LEZ policy by further increasing the restriction level to Euro 5 or Euro 6 in 2018. The expansion implies the establishment of new LEZs with restriction level Euro 5 or Euro 6 or the upgrade of already existing zones. Both measures would restrict the vast majority of diesel-powered vehicles in the respective regions. This initiative, publicly referred to as the general ban on diesel cars, reignited an old political and public debate.

Initially, the debate started after the establishment of the first Germany LEZs in 2008, with clear opinions on both sides. Whereas the German Automobile Association (ADAC), the general public and some state governments condemn the policy's disproportion and doubt that the concept of LEZs actually reduces air pollution, the federal government maintains its view and defends the new policy. In the following years, studies supporting both opinions were published. On the one hand, investigations by Laberer and Niedermeier (2009), Morfeld et al. (2013) or Löschau et al. (2013) state that LEZs do not decrease the measured PM_{10} concentration. On the other hand, Cyrys et al. (2009), Lutz et al. (2009) or Qadir et al. (2013) find reductions of over 15%. All of these studies are based on short-term observations in one to four cities and apply mostly simple econometric approaches. For instance, Laberer and Niedermeier (2009) rely on results obtained by a pooled-OLS model, based twelve months observations in four cities, Cyrys et al. (2009) only account for the city of Munich with the same empirical approach. Additionally, several municipalities have commissioned independent reports on their own LEZs with overall conflicting results (Gehrsitz, 2017). The most credible assessments on the efficacy of LEZs are conducted by Wolff (2014) and Gehrsitz (2017). Both authors find a significant reduction of PM_{10} levels within the nine and 25 observed cities, using a difference-in-difference approach. Unfortunately, no studies include observations after the year 2012 and therefore omit most of the Euro 4 LEZs. Gehrsitz (2017) for instance combines Euro 3 and Euro 4 due to a lack of observations. After 2012, however, the LEZ regulation was amended to the extent that no further Euro 2 or Euro 3 LEZs will be established. After that, any newly introduced zone started immediately at the restriction level Euro 4.

The situation in 2018 is similar. The law on a new ban on diesel vehicles is passed and is about to be implemented, the public opinion is outraged, the chief minister of Hesse, Volker Bouffier announced to appeal the judgement, whereas the federal government defends its decision. Yet, an overall and independent performance evaluation of LEZs does not exist.

This study attempts to close this gap and provides a comprehensive assessment of the effectiveness of LEZs in over 60 German cities between 2007 and 2017 with respect to PM_{10} pollution. To evaluate the performance of the different restriction levels Euro 2, Euro 3 and Euro 4, I created a unique panel data set including the daily mean PM_{10} concentrations of more than 500 monitoring stations within eleven years. Beyond that, this paper is the first to address the policy change after 2012/2013 and considers potential difficulties related to the new implementation method. Furthermore, it investigates whether regions close to established LEZs are adversely affected or benefit from the policy. The findings shed light on the question whether LEZs are an appropriate measure to a) Reduce PM_{10} pollution in general, and b) Reduce the number of days the legal maximum is exceeded. Moreover, the empirical strategy allows for evaluating whether pollution was actually decreased or just a reallocated to neighbouring regions. Therefore, the results indicate whether the previous ban of diesel-powered vehicles was a success and may give implications regarding the next step of the LEZ policy in 2018.

I find that the average LEZ significantly decreases the PM_{10} concentration by around 4% and has no persistent adverse effects. Furthermore, the number of exceedance days is significantly reduced after the establishment of an LEZ. However, the efficacy depends on the implementation method. Whereas the staggered method, starting at Euro 2 and introducing Euro 3 and Euro 4 later, implies a reduction, the immediate start at restriction level Euro 4 is not related to a significant alteration in the PM_{10} concentration. Furthermore, my findings suggest that adverse treatments effects are mainly present in the period following the initial introduction of the policy. However, whereas an increased pollution level in regions close to Euro 2 zones scatters within the first years, the adverse effects related to zones which immediately start at the Euro 4 level are more persistent. Within the timeframe of this study, I do not observe decreasing adverse treatment effects regarding zones affected by the policy change in 2012/2013.

The significant reduction of PM_{10} levels, associated with the average LEZ is in line with my predictions and the findings of other relevant literature. My empirical strategy is comparable to the one applied by Wolff (2014) and Gehrsitz (2017), who both find decreased pollution within the observed cities. This also applies for the determined decrease regarding the number of annual exceedance days. Thus, it is all the more surprising that I do not find a significant effect of LEZs which immediately start at restriction level Euro 4. Furthermore, I expected adverse effects to be present for a short time in the initial stages, during a ‘familiarisation period’. This was only very partially confirmed by my findings since some regions experience an increased PM_{10} level for more than four years after an LEZ was established nearby.

The remainder of this paper is structured as follows: Section 2 provides background information on PM_{10} and on the general concept of Germany LEZs. Section 3 describes the data sources, explains the different treatments and gives insights into the general implementation. Section 4 introduces the econometric strategy and presents the regression results which are in detail discussed in the following Section 5. Section 6 concludes.

2 Particulate Matter and Low Emission Zones

In this chapter, I will introduce PM_{10}, illustrate its main emission sources in Germany and briefly explain why it is hazardous to the human health. Furthermore, I will present the concepts of LEZs and elaborate on how they are designed to reduce PM_{10} concentrations.

2.1 Particulate Matter: PM_{10}

PM_{10} comprises all parts of airborne dust with a diameter between 2.5 and 10 micrometres. Its aerial concentration is measured and recorded by the UBA with dedicated monitoring stations. The majority of particulate matter originates from human activity such as emissions by motor vehicles, power plants or stoves and heaters in residential buildings.

Figure 1 shows the trends of five major sources for human-caused PM_{10} pollution in Germany between 2005 and 2015. The relative share of each source is shown in the appendix (Figure A1).

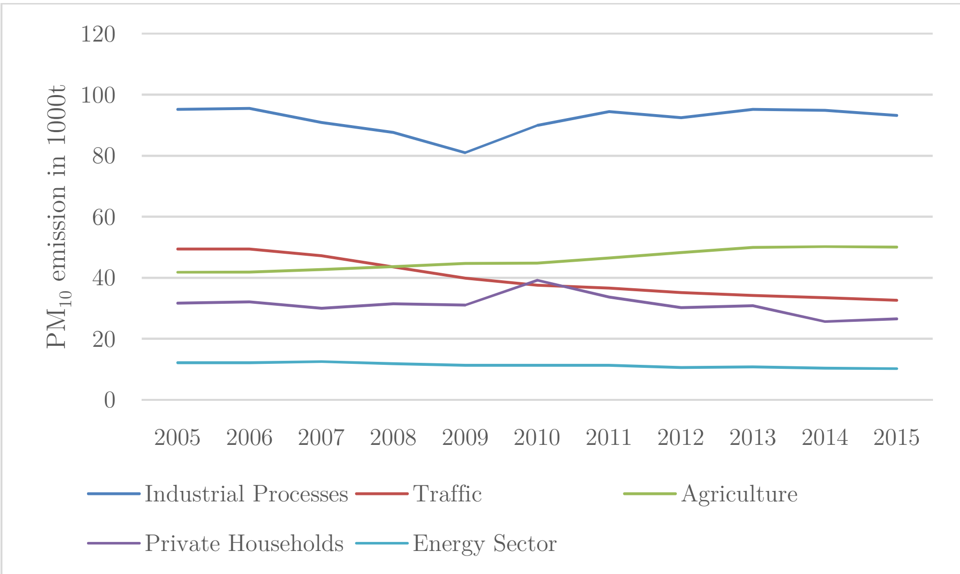

Figure 1: Human-Caused Sources for PM_{10} Emissions in Germany (UBA, 2017)

The largest share (Ø 92.5 kt/year) is caused by industrial processes and manufacturing whereas the smallest (Ø 11.3 kt/year) originates from the energy sector. The drop in total emissions for industrial processes around 2009 can be partly explained by the financial crises which forced many manufacturing companies to reduce their output, which in turn resulted in reduced emissions. Emissions caused by the energy sector have slowly but steadily decreased in the past ten years as they originate mainly from coal power stations for which the demand has declined. Traffic (Ø 39.9 kt/year) and agriculture (Ø 45.9 kt/year) switch their ranks in 2008. The explanation for the decrease in traffic induced PM_{10} emissions will be elaborated in the following sections of this study. Private households account on average for about 31.2 kt annually.

For vehicles, besides the combustion process in the engine, brake abrasion and road dust resuspension play a significant role in the formation of PM_{10}, especially in urban areas with a high traffic density (Kerschbaumer et al., 2008). The pollution factors 'dust resuspension' and 'brake abrasion' were recently getting additional public attention as those cannot be reduced by for instance restricting diesel-powered vehicles.

Besides human-caused pollution, PM_{10} also has natural origins, for example, soil erosion, forest fires or volcanos (Cyrys et al., 2017). The extent of the natural contribution to local PM_{10} concentrations depends severely on weather, climate as well as on geographic conditions. Additionally, the same factors influence the dispersion of human-caused PM_{10} pollution, wherefore disentangling natural and anthropogenic sources not always precise or persistent (Bruggemann et al., 2009; Schauer et al., 2001).

The number of studies assessing the impact of PM_{10} on the human health has increased significantly in recent years, which explains the increased public and political attention regarding this subject (Biancofiore et al., 2009), Particulate matter penetrates the respiratory tract where it can harm the nasal mucosa, the throat area, and the lung tissue. The Federal German Environmental Agency (2009) states that even a short-term increase of PM_{10} concentration is connected to a growing number of hospitalizations due to respiratory diseases. According to estimates of the World Health Organization (WHO), particulate matter is associated with 800.000 premature deaths worldwide (Riediker et al., 2004). Compared to other pollutants like Sulphur or Carbon Monoxide, there is no threshold under which PM_{10} concentrations are considered harmless since even the smallest amount of particulate matter has adverse effects (UBA, 2009). This implies that especially long-term exposure, even below the legal maximum, is damaging the organism (Turner et al., 2011).

In response to these health risks, the European Parliament and Council introduced the directive 2008/50/EG (Air Quality Framework Directive), which includes, inter alia, the specification of legal threshold values for PM_{10}. Accordingly, an annual mean of 40 $\mu m/m^3$ is not to be exceeded and furthermore, a daily mean of 50 $\mu m/m^3$ is not to be exceeded on more than 35 days per year. Throughout the study, I will refer to the latter as *exceedance days*. Authorities of districts not complying with these directives are obligated to take appropriate mitigating measures to reduce local air pollution. These measures involve a variety of short- and long-term actions including, among others, the encouragement of residents to use the bike more frequently by further developing cycle tracks, the introduction of speed limits, the ban of trucks within the city centre, or the establishment of LEZs (Wolff, 2014).

2.2 Low Emission Zones

An LEZ is a defined area which restricts entry to vehicles that are not complying with the required emission standard. The motivation behind LEZs is to reduce emission concentration as well as to lower the number of annual exceedance days. Within the timeframe of this study, three levels of LEZs have been established: Euro 2, Euro 3 and Euro 4. Euro 1 comprises all regions that are not within an LEZ. A higher number indicates stricter requirements, a car has to meet with respect to the emission exhaust. Whereas Euro 2 and Euro 3 only restrict diesel-powered vehicles without particulate filters, Euro 4 also places requirements on gasoline-powered cars (Cyrys et al., 2017).

Vehicle owners in Germany are obligated to place coloured windscreen badges, indicating the car's fulfilled level of the European emission standard (Table 1). For example, a vehicle with the red Euro 2 sticker is not allowed to drive in a zone indicated as Euro 3.

Table 1: Low Emission Zones Windshield Batches

Emission Group	Euro 1	Euro 2	Euro 3	Euro 4
Sticker	No sticker			

The entrance into an LEZ is marked by street signs displaying which windshield badge is required for all vehicles, including cars that are not registered in Germany. However, derogations exist for instance for working machines, ambulances or old-timers (Cyrys et al., 2017). It is the task of the local police and the public order office to actively check the validity of windshield badges in parking and driving vehicles. Not complying with the postulated emission standard is a misdemeanour and is fined with at least 80 Euros. For instance, in 2016, the city of Berlin alone collected over 5 million Euros in fines, which corresponds to about 65.000 infringements (DPA, 2018). However, surveys reveal that regular controls only occur in 11% of the cities (DUH, 2011).

Pattern and Timing of the LEZ Establishment

The first German LEZs with the emission standard Euro 2 were introduced on January 1st, 2008. LEZs with restriction level Euro 3 and 4 followed in the two consecutive years. Between 2008 and 2017, a total of 56 LEZs were implemented in 82 cities in eleven states, whereas most zones are located in the southwest (Figure A2). Detailed maps of all zones are available, precisely showing their extent and borders. Their catchment area reaches from parts of the city centre to entire regions (Figure A3, Figure A4). The shape of each individual zone depends on the respective road network and there exists no consistent pattern. As LEZs are primarily designed to reduce pollution by restricting vehicles or traffic, they are exclusively set up in urban and suburban areas.

In general, LEZs were established in two different manners, either staggered or at once. The staggered zones usually start at level Euro 2 and introduce Euro 3 and Euro 4 standards at a later stage, whereas 'at once' implies an immediate start with a higher level.

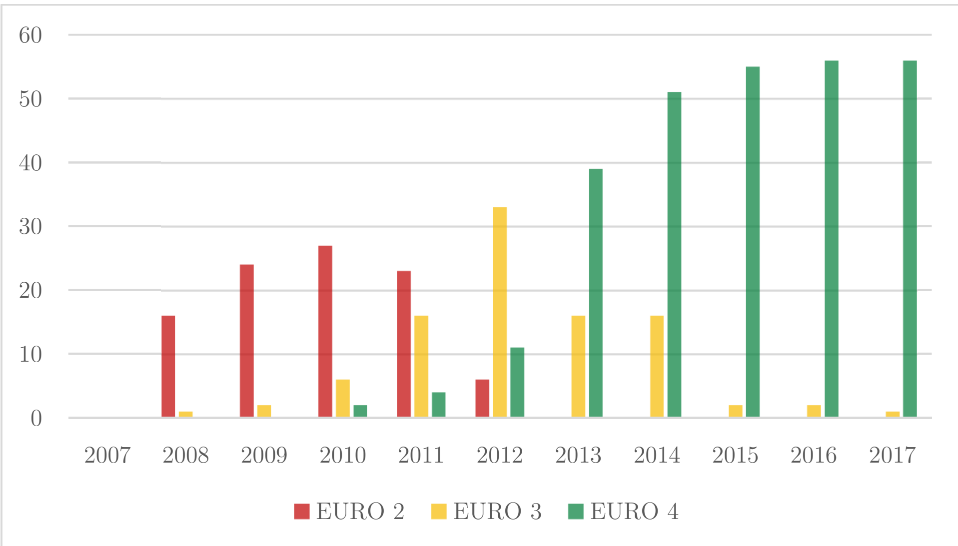

Figure 2: Number of Active LEZs per Year

Figure 2 shows the total number of active LEZs by level and year. A restriction level is active until it is replaced by a higher one and no LEZ was removed after once being established. The coloured bars indicate the total number of active LEZs per year. Between 2010 and 2012, three different levels of LEZs where active simultaneously across Germany. The last Euro 2 LEZ was transformed into a higher restriction level in 2013, and after 2016, all but one Euro 3 LEZ were upgraded to Euro 4.

A popular starting date for LEZs is January 1st; however, a variety of further initial dates exist. Figure A5 shows the relative occurrence of treatment starting months over the past eleven years. Furthermore, the time span between the initial introduction and the change to a higher level is not unified and reaches from six to up to 72 months.

To sum it up, LEZs differ in size, shape and with respect to their implementation dates. They do occur in areas where similar policies have been implemented as well as isolated.

3 Data, Treatments, Implementation

Section three contains a description of the data source, followed by an explanation of the individual treatments as well as a discussion about whether the selection into treatment can be considered random. Note that neither the type of treatment nor the number of observations within a treatment group lies in my power. The last part, section 3.3, covers the general implementation and introduces the applied control variables of the subsequent empirical analysis.

3.1 Data

To construct the sample, I obtain measurement data from air pollution monitoring stations all over Germany, provided by the German Federal Environment Agency. Besides pollutant concentration, the data gives insight into the location (coordinates), the type of measurement (background, industry or traffic) as well as the start and end date for each monitoring station. Stations differ with respect to their measuring interval ranging from hourly to yearly mean PM_{10} concentrations.

A substantial part of the analysis covers the question of whether LEZs are an appropriate measure to meet the legal demands of the EU regulation. The legal provision involves the reduction of days per year on which the measured PM_{10} concentration exceeds 50 $\mu m/m^3$. Since the generation of a variable that counts daily mean exceedances requires hourly or daily data, I exclude all stations not recording in this interval. Schauer et al. (2001) raise the concern that some applied measurement techniques, especially those involving mean values, are prone to errors and outliers. For instance, unusual high traffic densities, construction works, fires or parades can bias the evaluation. Unfortunately, it is not possible to obtain daily median values from monitoring stations designed to log daily means, which would be more robust to these outliers. Even though including these stations would lead to more observations, I would lose the robustness and control mechanism provided by hourly data as these stations allow for the creation of daily means and medians. Therefore, I exclude stations which exclusively record daily mean concentrations.

The final dataset contains 507 monitoring stations, of which 104 are placed in LEZs. During the observed eleven years (2007 - 2017), the included stations have submitted more than 30 million hourly PM_{10} concentration values.[1] The year 2007 serves as a

[1] Within the observed eleven years, not all 507 stations were active every day, resulting in an unbalanced panel of PM_{10} concentration values from 1,28 million days.

baseline since the first LEZs where introduced in 2008. Given the previously explained requirements for stations, the study covers a total of 34 LEZs[2] in 63 cities. Unfortunately, the remaining zones either do not have a dedicated monitoring station or the available one(s) do not meet the requirements.

3.2 Treatments

The main objective of the analysis is to determine whether the local PM_{10} concentration experiences an alteration after an LEZ is introduced (henceforth referred to as "treatment"). A monitoring station and thus its surrounding area is referred to as being treated if its location is classified as an LEZ between 2008 and 2017, which accounts for a total of 104 facilities.

Table 2: Overview Treatments

#	Treatment	Description			# LEZs	# Stations
1	Euro 2	No LEZ	→		23	61
2	Euro 3		→		20	49
3	Euro 4		→		24	54
4	Euro 3*	No LEZ	→		4	8
5	Euro 4*	No LEZ	→		8	18
6	Euro 4** (Berlin)		→		1	6

LEZs is the total number of LEZs within a treatment group. The outline counts all zones which were merged together as one LEZ. # Stations specifies the number of monitoring stations per treatment group.

[2] The total of 34 LEZs corresponds to the official classification of the UBA. In recent years, 32 individual zones were merged together, resulting in three large areas. However, within these merged zones the starting dates are not consistent. Therefore, I distinguish between 63 LEZs throughout the study.

Table 2 labels and describes all applied treatments. As introduced in section 2.2, I distinguish between phased and at once. The reasoning behind the differentiation depending on previous treatments will be discussed after a brief description of the treatments. As illustrated in column three, treatment Euro 2 implies the initial establishment of an LEZ at the lowest level, restricting all vehicles that do not qualify for at least a red windshield batch (Table 1). The Euro 3 treatment only refers to zones which have been previously treated by Euro 2, and the Euro 4 treatment requires a preceding treatment of Euro 3. Euro 3* treatment only skips the lowest level, whereas Euro 4* bypasses both predecessors by transforming an initially unregulated area into the highest-level LEZ. The special case Euro 4** has only been carried out in the city of Berlin and bypasses restriction level Euro 3, by moving from Euro 2 to Euro 4.

Column four shows the total number of LEZs within one treatment group. The prevalent occurrence of an LEZ is the consecutive increase of the restriction level, starting at Euro 2, then turning into Euro 3 and later into Euro 4. Treatment Euro 4* is applied exclusively after 2012 but will be the benchmark for any future LEZs since a start at a lower level no longer takes place after 2014. Column five shows the number of monitoring stations within a treatment group.

Division of the Treatments

Despite similar legal provisions for identical LEZ restriction levels, I decided to subdivide the treatments depending on previously applied treatments. Ignoring preceding treatments and solely differentiating according to the restriction level could lead to biased results for the following reasons.

A bias could occur due to a potential adaption process of the population. A gradual increase of the restriction level offers more time to adjust, whereas the start at the highest restriction level might be perceived as a more severe interference and could therefore encounter more resistance from the population. Assume the presence of a familiarisation process. This process is expected to adversely affect the LEZ's efficacy after its initial establishment, for a limited time. In the beginning, for instance, people might forget about the LEZ, drive through the restricted area on purpose, or PM_{10} that has been previously emitted by strongly polluting cars may still be on the road and then be stirred up by other vehicles.[3] The Euro 4 treatment is always applied to previously treated areas which means that the familiarisation period is already over. In the

[3] Road dust and its resuspension in general is identified as a main source for PM_{10} pollution. Therefore, municipalities increase the road cleaning as an urgent measure to reduce the exposure.

case of Euro 4*, however, a potential familiarisation process starts with the initial establishment of the LEZ and is afterwards present for many years as the Euro 4* treatment is applied between 2012 and 2017. Now, let us assume a combination of the treatments Euro 4 and Euro 4*. Whereas treatment Euro 4 has already overcome potential starting difficulties, observations of the Euro 4* treatment might still be prone to them. This would at least increase the standard errors of a combined treatment coefficient or lead to an underestimation of the treatment effect.

Furthermore, an overestimation of the treatment effect is also conceivable if the treatments are not differentiated. One aspect the LEZ policy relies on is the gradual renewal of the vehicle fleet towards a composition with lower emissions (Diegmann & Pfäfflin, 2015). Ceteris paribus, every introduced restriction level implies the same expected efficacy, given a similar distribution of vehicle types across the country. Consequently, every restriction level 2, 3 and 4 has some potential to reduce the local PM_{10} concentration. If every treatment does indeed have its desired effect, it follows that the Euro 4 treatment is implemented in areas where the PM_{10} concentration is already reduced by preceding Euro 2 and Euro 3 treatments. In contrast, Euro 4* is always facing unaffected regions. Obviously, I cannot foresee the efficacy of every treatment before executing the empirical analysis, wherefore I have to consider several possibilities. Assume, for instance the step from Euro 2 to Euro 3 results in a large reduction of the PM_{10} concentration, whereas the step from Euro 3 to Euro 4 is only marginal. Now, without differentiating the treatments Euro 4 and Euro 4*, the experienced effect of a combined treatment would be overestimated since the Euro 4* treatment regions occupy the strong effect of the Euro 3 treatment and therefore bias the combined coefficient.

The previously listed concerns of heterogeneous treatments were established in an early stage of the analysis, wherefore I decided to initially separate the treatments as illustrated in Table 2. If treatments turned out to be similar, regardless of the preceding treatment, I could re-combine them with respect to the restriction level only. However, the following analysis shows that the role of an adaption process, the altered composition and the potentially previously reduced PM_{10} concentration should not be underestimated as there are differences in treatments despite similar legal restrictions which will be shown in Section 4.2. The separate review of treatment Euro 4** in Berlin is not based on the aforementioned concerns as it is quite similar to Euro 4, with the only difference of skipping Euro 3. Nevertheless, as it is unique in its implementation, I decided to segregate it.

Which Areas are Treated?

To avoid legal steps involving high penalties on the part of the EU, Germany as a country is responsible for the compliance with legal requirements regarding PM_{10} emissions. The federal government assigns this task to local authorities who are obligated to develop appropriate measures if the guidelines are not met within their administrative district (§ 40, BlmSchG). Accordingly, all regions with an annual mean concentration of more than 40 $\mu m/m^3$, or regions in which the PM_{10} concentration exceeds a daily mean of 50 $\mu m/m^3$ on more than 35 days a year, are legally bound to act.

However, this is not always the case. Over the past eleven years, 64 individual monitoring stations have reported a violation of the 35-days rule in at least one year. The areas around 31 of these stations eventually became an LEZ and other measures to reduce the pollution were applied in the surroundings of 20 further stations. For regions surrounding the remaining 13 monitoring stations, no action has been taken although some of them record violations in four consecutive years. In contrast to that, multiple areas have become LEZs even though the local monitoring stations reported values not even close to the legal limit of 35 days. One example is the LEZ in the city of Aachen which contains two monitoring stations placed in different parts of the city. In 2013, one of them indicated a violation with 40 days over the legal maximum, whereas the other station reported an exceedance on only eight days. Based on these readings, an LEZ was established in 2016 despite the fact that the number of exceedance days has previously dropped to eleven and three without any treatment or other measures.

This example is not an isolated incidence as similar patterns occur in other cities too. Besides, it appears that some LEZs are planned and established as a matter of precaution based on outliers in a given year. The authorities' individual motivation can only be assumed and might range from political reasons to unawareness or simply uncertainty about the future development of the local PM_{10} concentration, which is susceptible to fluctuations (Figure A6).

Obviously, randomly allocating the treatment is not in the sense of the policy. However, the data shows that there are highly polluted areas that are not within an LEZ as well as mildly polluted areas that become an LEZ. Figure A9 shows distributions of daily mean PM_{10} concentrations. I distinguish between areas that become an LEZ in the indicated year (blue) and the corresponding control group[4] in the same time period (green). The concentration distribution is similar in both groups during all observed

[4] The control group consists of all areas that have not received treatment so far which means that areas that become an LEZ at a later stage are also included.

years but the PM_{10} concentrations in areas that receive treatment are slightly higher in some years. However, this difference is not substantial. Beyond that, Figure A6, Figure A7 and Figure A8 show that treated and untreated regions follow a common trend. Figure A6 distinguishes between LEZ and no LEZ regions, thus all monitoring stations that are eventually treated and those that are never treated. Figure A7 distinguishes between currently treated and areas which eventually become an LEZ, combined with those regions that never adopt the policy (dynamic control group). Figure A8 only includes observations from monitoring stations within an LEZ and distinguishes between already and soon to be treated areas.

One potential explanation why mildly polluted areas eventually become LEZs refers to the inertia of bureaucracy which was illustrated by the previous example. In the case of Aachen, several years have passed between the political decision and the actual establishment. Within this period, conditions have changed, rendering the LEZ unnecessary with respect to the legal requirements. The previous process which is equal to the treatment of a low-pollution area. This inertia occurs in every LEZ as there is always a time lag between the violation of the law, the political decision and the implementation. This delay and the fact that some LEZs were established based on false projections leads to the appearance of mildly polluted areas in the treatment group.

By contrast, how can severely polluted regions in the control group be explained? Again, I can only speculate and one potential reason for this might be the EU's lax enforcement or punishment of pollution violations in recent years. The first lawsuits by the EU Commission against member states for not complying with the Air Quality Framework Directive were filed in 2017, ten years after the directive was adopted (Gökkaya, 2018). Thus, within the time of the study, actual legal pressure on the part of the EU Commission was absent. This implies that local authorities had more political leeway in pollution matters and therefore more options to respond to the public opinion, which was mostly not in favour of LEZs.

Concluding, PM_{10} concentrations are on average slightly higher in areas where either LEZs or other measures have been established, which implies that less polluted regions are more prevalent in the control group. However, treatments are not exclusively applied in regions with PM_{10} values that go beyond the legal threshold and both groups follow the same trend. To address these differences, I perform multiple robustness tests in the analytical part.

3.3 Implementation

The appraisal of potential effects on the local PM_{10} concentration, caused by the introduction of LEZs, requires identifying whether and since when a monitoring station is placed within the catchment area of an LEZ. Therefore, as a first step the coordinates of every station are checked against the geographical extent of every LEZ and marked as lying either *inside* or *outside*. Afterwards, each station previously identified as *inside* is matched with the individual time horizon (treatment period) of the corresponding LEZ. For example, the LEZ in the city of Augsburg was initially established on July 1st, 2009, restricting all cars not complying with the Euro 2 emission standard. Thus, every monitoring station within the delimited area is specified accordingly as of this date. On January 1st, 2011, restrictions were tightened by additionally banning cars not complying with the Euro 2 or Euro 3 standard, meaning that the Euro 2 treatment ends on December 31st in 2010 and that the Euro 3 treatment begins the day after. The same applies for the introduction of the Euro 4 treatment on June 1st, 2016 which appropriately represents the end of Euro 3 on the day before. This procedure was executed separately for every LEZ and the corresponding monitoring station(s) as the starting dates and the treatment duration differ throughout.

Controls 1: Proximity to LEZs

Given the nature of this study, I cannot rule out the occurrence of treatment spillovers for several reasons.

The first one pertains the observed object's condition. The prevalence of aerial pollutants depends on thermodynamic conditions in the near-earth air layers which can either intensify or reduce the PM_{10} concentration or its dispersion (Marcazzan, 2001). For instance, whereas fog restrains the potential travel distance of the particles, dry air and wind have opposite effects and increase the distance PM_{10} is able to cover by air (Giuliacci, 1988). In general, wind can carry fine particles hundreds of kilometres but as this study focuses on pollution caused by cars which emit particles close to the ground, the average distance is much lower (Schmidt et al, 2010). As LEZs are not sealed off, a change in the PM_{10} concentration within an LEZ can also affect surrounding areas which will then be detected by their located monitoring stations.

The second reason for potential spillovers lies in the very nature of the legal regulation. Restricting certain types of automobiles will not lead to their immediate replacements or their equipment with particle filters but might initiate adverse behaviour. For instance, some vehicle owners might bypass the LEZs, causing additional pollution in neighbouring regions. Some navigation systems (e.g. Becker) even offer routing options that specifically avoid LEZs. Depending on the occurrence of the described phenomenon, adverse effects, not only for surrounding regions but also for the LEZ itself, cannot be ruled out. If highly polluting vehicles are obliged to drive longer distances in order to avoid LEZs, the treatment itself might even backfire as the additional traffic is causing more emissions.

Whereas other studies intentionally excluded monitoring stations close to LEZs in order to avoid distorted results, I decided to retain them. Keeping these stations provides me with more observations and furthermore gives insights into potential adverse treatment effects. Therefore, I identify monitoring stations which are not placed inside but within a certain radius[5] of an LEZ. This process again involves a differentiation according to the treatments and their respective schedule. For example, a monitoring station within the radius of an LEZ which undergoes the Euro 2 treatment is indicated as *Near Euro 2* on the same day the treatment begins. This is applied for all six treatments and is performed separately for radii of 10 km, 15 km and 20 km. This identification allows me to not only address the concern for spillovers but also to possibly capture their direction and size.

Table 3 provides information about the number of monitoring stations that are affected by the establishment of an LEZ, classified by treatment and radius. Naturally, the number of stations increases as the radius is enlarged.

Table 3: Classifications of Monitoring Stations in Proximity to an LEZ.

	10 km		15 km		20 km	
	Obs.	Stations	Obs.	Stations	Obs.	Stations
Near Euro 2	27,832	32	39,666	49	47,839	59
Near Euro 3	13,173	25	22,928	40	27,990	48
Near Euro 4	43,722	32	59,407	46	69,964	51
Near Euro 3*	3,548	7	5,274	12	5,895	14
Near Euro 4*	1,407	2	8,590	8	14,153	13
Near Euro 4**	14,288	6	22,068	9	22,068	9

The first column contains a monitoring station's classification, separated according to the treatment the nearby LEZ receives. Column 2 & 3 show the number of observations and the number of stations within a radius of 10 km of an LEZ. Column 4 & 5 and column 6 & 7 indicate these values for 15 and 20 km respectively.

[5] The choice of these distances is arbitrary as the potential travel distance of PM_{10} in every region for every day is not ascertainable. However, my findings are robust to the distance.

A larger radius provides on the one hand for more - but on the other hand for more distorted information as the emitted PM_{10} concentration is dispersing in the distance (Giuliacci, 1988). Furthermore, an adverse treatment effect, which emerges due to people simply circumventing LEZs, is expected to be less prevalent for distances beyond 20km. Other studies (Wolff, 2014; Gehrsitz 2017) investigated potential spillover for radii of 50 and 100km but did not find a significant effect.

As mentioned in the previous section, not all LEZs contain a dedicated monitoring station that meets the requirements of this study. However, the proximity variables are generated for these zones as well.

Controls 2: Additional Measures to Reduce Pollution

As referenced in section 2.1, LEZs are not the only measures (action plans) which were established to counter PM_{10}. Numerous action plans were implemented nationwide, with the aim of reducing the exposure to pollutants. These measures include for instance the establishment of parking guidance systems in order to reduce the time spent looking for a parking spot, lower-priced public transportation or providing additional green spaces which are supposed to serve as a dust filter. Compared to LEZs, the particular impacts of these measures are difficult to estimate since their efficiency range is not as explicit as the one of LEZs. Whereas the LEZ policy restricts certain vehicles in a determined area after a defined day, most other measures are rather vague in this matter. With the available data, I cannot distinguish between every action plan and the respective time horizon. The vast majority of these action plans is implemented outside of LEZs, wherefore primary the control group is affected by them. Nevertheless, the isolation of the impact by LEZs requires the identification of monitoring stations which might be influenced by other mitigation measures. Therefore, I label all monitoring stations within cities that introduced action plans. Since I cannot distinguish between the different measures I indicate the corresponding starting date only.

Compared to the permanently established LEZs, some interventions are rather short-term or only applied if needed. Authorities in the city of Trier, for instance, agreed on the application of pre-wetted road salt instead of using the usual de-icing road salt to reduce dust dispersal by cars (Hermann & Zemke, 2006). Naturally, this was only applied on some days during the winter. As I cannot assess the long-term effect of these short-term measures, I assume every measure to be permanent after being established. The attempt to determine the effect duration of every executed action plan would not only go beyond the scope of this study but is also not considered necessary, since many districts that carry out seasonal mitigating measures introduce equivalent plans for every season.

The control mechanism for action plans or other measures besides LEZs is rather imprecise. Therefore, I present the regression results shown in section 4 without monitoring stations affected by action plans in Table A1. Furthermore, I illustrate how the treatment coefficients change after controlling for action plans as well as the other control variables in Table A2. The regression results in Table A1 and A2 match closely with those obtained in section 4.

Controls 3: Meteorological Data

PM_{10} concentrations are impacted by prevalent meteorological conditions including for instance temperature, humidity, wind or vapor pressure (Vardoulakis & Kassemenos, 2008). Therefore, I follow the example of Malina and Scheffler (2015) and include twelve meteorological variables in the regression analysis to control for variance in the PM_{10} concentration caused by the weather (Table A3). These are provided by the Germany Meteorological Service (DWD) and are aggregated on daily mean values across all German administrative districts. Therefore, they vary across days and LEZs.

4 Methodology and Results

In section 4.1, I present the econometric strategy to estimate the impact of LEZs on either the local PM_{10} concentration or the total number of annual exceedance days. Section 4.2 illustrates the regression results.

4.1 Methodology

Equation (1) is designed to estimate the effect the introduction of an LEZ has on the measured PM_{10} concentration.

$$\ln(1 + PM10_{t,s}) = \beta_i EURO_{i,t,s} + \alpha_i \, NearEuro_{i,t,s} + \theta APC_{t,s} + \omega_{t,s} + \alpha_s + \delta_t \quad (1)$$

The dependent variable is the daily mean PM_{10} concentration measured by a station *s* on day *t*. $EURO_{i,t,s}$ is a dummy variable that is equal to 1 if station *s* is located within an LEZ with restriction level *i* on day *t*. Therefore, coefficient β_i measures the impact of every treatment $i \in \{2, 3, 4, 3^*, 4^*, 4^{**}\}$ separately. Let $NearEuro_{i,t,s}$ be a dummy variable taking the value of 1, if a monitoring station *s* at day *t* is within a certain radius (10km, 15km or 20km) around an LEZ of stage *i*. Coefficient α_i then indicates changes in the PM_{10} concentration after an LEZ with emission standard Euro *i* was established nearby. $APC_{t,s}$ is a binary variable indicating whether a station *s* at time *t* is affected by other air pollution control measures besides LEZs. $\omega_{t,s}$ is a vector of twelve meteorological variables which controls for weather conditions on day *t* around station *s*. Each variable within $\omega_{t,s}$ varies over time and administrative district. Station and day fixed effects are represented by α_s and δ_t respectively. Compared to week, month or year fixed effects, the application of day fixed effects is the most appropriate since I assume traffic volume to be higher on weekdays than weekends. Furthermore, day fixed effects capture time-varying macroeconomic factors which affect every station similarly like, for instance, fuel prices, the financial crisis or the scrappage premium for old diesel vehicles after 2009 (Malina & Scheffler, 2015).

In Equation (2), the dependent variable is the number of annual exceedance days. Recall, an exceedance day implies a mean daily PM_{10} concentration of over 50 $\mu m/m^3$. Overstepping this limit on more than 35 days in one calendar year implies a violation of the law. Naturally, the dependent variable is not changing throughout a year which reduces the number of actual observations.

Changing the observation level from daily to annually also implies a loss in precision regarding the treatment period as not all treatments start on the 1st of January. Therefore, the $EURO_{i,t,s}$ or the $NearEuro_{i,t,s}$ dummies take the value one if station *s* is within or nearby an LEZ in year *t*. Weather controls $\omega_{t,s}$ are aggregated over twelve months, and station as well as year fixed effects are represented by α_s and δ_t.

$$\#\, exceedance\ days_{i,t} = \beta_i EURO_{\,i,t,s} + \alpha_i\, NearEuro_{i,t,s} + \theta APC_{t,s} + \omega_{t,s} + \alpha_s + \delta_t \qquad (2)$$

Additionally, I perform the Woolridge test for serial auto correlation for both specifications and strongly reject the null hypothesis of no serial correlation. Therefore, I apply clustered standard errors on the monitoring station level (Bertrand et al., 2004; Baltagi, 2008).

Summary statistics of the mean and median PM_{10} concentration as well as of the number of annual exceedance days are shown in Table 4.

Table 4: Summary Statistics Dependent Variables

	Mean	Sd	Min	Max
Mean PM_{10} $(\mu m/m^3)$	20.75	13.62	0	1866.61
Median PM_{10} $(\mu m/m^3)$	19.84	13.20	0	353.02
# Exceedance Days	11.90	10.13	0	76

Lagged Dependent Variable

It can be tentatively assumed that the mean PM_{10} concentration on day *t* is somehow correlated to the PM_{10} concentration on day *t-1* since pollution is not reset at midnight. As previously mentioned, the Woolridge test for serial correlation confirmed the assumption of prevalent autoregression. This finding combined with a Fisher-type unit root test, which showed that the data generating process is stationary, justifies the introduction of a lagged dependent variable (LDV) in the regression specification. However, the application of an LDV is no magic bullet in order to get consistent and unbiased estimates.

One problem occurs when controlling for unobserved heterogeneity via the inclusion of fixed effects. For the purpose of this study, individual fixed effects are crucial as they capture factors which do not change over time like the permanently present background pollution or other location-specific factors. In general, the combination of fixed effects and an LDV gives rise to further potential inconsistencies like the Nickell's Bias. This bias is particularly strong if the panel contains only a few periods (T) and many individuals (N) but is still persistent when increasing T, and never mitigated by increasing N (Nickell, 1981). Furthermore, the bias is always negative and theoretically only affects the coefficient of the LDV. If other independent variables, however, are correlated with the LDV, their coefficients might be biased as well. The panel applied in the first regression specification contains T=4015 and N=507, whereas T is drastically reduced to eleven in the second specification which means that the concern of biased results is more prevalent when estimating the impact of LEZs on the number of exceedance days.

As pointed out, the Nickell's bias does not decrease in the number of observations. At the same time, without an LDV, Hansen (2007) notes that serial correlation is a minor concern if the number of observed groups is sufficiently large. The general rule states that approximately 42 groups/clusters are required in order to attain reliable standard errors and estimates (Angrist & Pischke, 2008). Since I cluster observations on the individual monitoring station level, I am well above this value.

As I cannot say with certainty whether the fixed effects regression with clustered standard errors or the introduction of an LDV will produce better, less biased or more efficient estimates, I will present results of both the static as well as the dynamic approach in section 4.2. For equation (1), the LDV is represented by the PM_{10} concentration on day_{t-1}, and in equation (2), it is represented by the number of exceedance days in the previous year.

Control Group

The inclusion of all treatment and all spillover dummy variables in one specification should be briefly discussed. Given the dynamic nature of treatment periods, the control group in specification (1) and (2) is also dynamic. In simple terms, this means that every treatment is not only compared to those areas which have never become an LEZ but also to those regions that are currently no LEZ or experience a different treatment in the same time. This occurs more frequently between 2010 and 2013, where the count of simultaneously active treatment is highest and is less prevalent in later periods (Figure 2). One advantage of this approach is the provision of a natural control group, namely all cities which have not yet implemented their LEZ but will in the future. An alternative approach would be to define a control group and run regressions separately for every treatment. The control group can either contain all monitoring stations that have not been treated so far or, alternatively, comprise a representative group of monitoring stations that are never in the catchment area of an LEZ. The advantage of the two alternative approaches might potentially be the obtainment of more precise coefficients with regard to the question of an actual treatment effect. However, as my intent is not to show causality, the advantage of additionally being able to differentiate between treatments as illustrated in equation (1) and (2) outweighs the benefits of isolating the treatments. As described in section 3.2, I am particularly interested in the differences between LEZs which are established gradually and LEZs that start at the highest restriction level. Furthermore, this method significantly increases the underlying variance due to additional observations and was similarly implemented by Malina and Scheffler (2015).

Treatment coefficients of the alternative approaches indicate similar effects and are summarized in the appendix (Table A5, Table A6).

4.2 Results

PM_{10} Concentration

Table 5 presents the regression results of equation (1) with the PM_{10} concentration as the dependent variable. Column (1) contains the main regression specification, whereas column (2), (3) and (4) comprise the according robustness checks. The applied model in column (3) and (4) is similar to the model in (1) and (2), but additionally controls for the measured PM_{10} concentration on the previous day (t-1). The spillover radius for the *Near Treatment* is 15km[6]. The basic model includes all urban and sub-urban areas, whereas 'No Industry' excludes monitoring stations that were established to measure pollution by industrial processes. Thus, only background- and traffic monitoring stations remain. However, as some of the industry monitoring stations are placed within LEZs, I do not regard a general exclusion of these as reasonable.

In general, and independent of the model, all but Euro 4* treatment coefficients are negative and indicate a reduced PM_{10} concentration of about 0.4 - 4.5%. In the basic model, the gradually applied treatments (Euro 2, Euro 3, Euro 4) show a reduced pollution of up to 4.5%. The coefficients might appear small but considering road transport only accounts for less than 20% of overall PM_{10} emissions (Figure A1), this reduction is not trivial. The same applies to the Euro 3* treatment which also shows a significant decrease. The Euro 4* treatment, in which an LEZ with the highest restriction level is established without any preceding treatment, appears to have no effect on the local pollution concentration. Along with the large standard error, the small coefficient creates the impression that the impact of the treatment is negligible. The efficacy of the established LEZ in the city of Berlin (Euro 4**) is also equivocal. Even though the coefficient and the standard error are more favourable compared to the Euro 4* treatment, the confidence interval casts doubt on whether an actual change in the pollution concentration can be attributed to the LEZ.

The impact of an LEZ on surrounding areas varies widely depending on the applied treatment and reaches from insignificant reductions to mild and severe increases of the PM_{10} concentration. Regions close to LEZs undergoing the Euro 2 treatment (Near Euro 2) initially experience an increase in emissions. However, this increase is only temporary as all Euro 2 zones undergo the Euro 3 and Euro 4 treatment in the following years.

[6] Table A4 in the appendix shows that the actual treatment is robust to the radius. However, the coefficients of the spillover variables, decrease in the distance, and/or their standard errors increase. This is in line with the hypothesis that the effect an LEZ has on nearby areas vanishes in the distance.

Table 5: Regression Results Equation (1), 15km

VARIABLES	(1) Basic	(2) No Industry	(3) Basic (lagged)	(4) No Industry (lagged)
Euro 2	-0.0172	-0.0122	-0.0118*	-0.00863
	(0.0112)	(0.0113)	(0.00667)	(0.00674)
Euro 3	-0.0441***	-0.0381**	-0.0259***	-0.0226**
	(0.0148)	(0.0151)	(0.00892)	(0.00912)
Euro 4	-0.0420**	-0.0376**	-0.0234**	-0.0212**
	(0.0167)	(0.0171)	(0.00980)	(0.0101)
Euro 3*	-0.0384**	-0.0360**	-0.0245***	-0.0233***
	(0.0150)	(0.0151)	(0.00890)	(0.00895)
Euro 4*	0.00184	0.00287	0.00432	0.00481
	(0.0225)	(0.0225)	(0.0137)	(0.0137)
Euro 4** (B)	-0.00815	-0.00414	-0.00684	-0.00444
	(0.0174)	(0.0176)	(0.0107)	(0.0108)
Near Euro 2	0.0134	0.0209**	0.00890	0.0131**
	(0.0108)	(0.0100)	(0.00637)	(0.00607)
Near Euro 3	-0.00992	-0.00763	-0.00349	-0.00266
	(0.0143)	(0.0144)	(0.00868)	(0.00888)
Near Euro 4	-0.00190	0.00251	0.00130	0.00350
	(0.0162)	(0.0163)	(0.00977)	(0.00997)
Near Euro 3*	0.0369**	0.0470***	0.0251**	0.0307***
	(0.0181)	(0.0174)	(0.0113)	(0.0112)
Near Euro 4*	0.100***	0.101***	0.0629***	0.0633***
	(0.0235)	(0.0238)	(0.0150)	(0.0151)
Near Euro 4** (B)	0.0286	0.0347	0.0165	0.0198
	(0.0226)	(0.0223)	(0.0131)	(0.0130)
Other Measures	-0.0341***	-0.0316**	-0.0194***	-0.0186**
	(0.0127)	(0.0133)	(0.00744)	(0.00781)
Observations	1,005,820	939,922	1,005,407	939,543
R-squared	0.711	0.714	0.770	0.772
Weather Controls	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes
Day FE	Yes	Yes	Yes	Yes

The dependent variable in all columns is the natural logarithm of the measured PM_{10} concentration. One observation represents 24 hourly values at one monitoring station. All weather controls are significant at the 1% level. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

The coefficients of Near Euro 3 and Near Euro 4 either indicate a mildly reduced PM_{10} concentration or no effect at all given the large standard errors. The Near Euro 3* coefficient indicates an increased pollution concentration of about 3.7% which later disperses after the Euro 4 treatment has been introduced. The largest and statistically most significant increase of PM_{10} pollution is registered in areas around Euro 4* LEZs. The indicated rise of 10% remains persistent until the end of 2017. The coefficient of Near Euro 4**, which represents monitoring stations around the LEZ in Berlin, suggests an increased PM_{10} exposure even after upgrading the LEZ to the highest level. From an econometric perspective, the 95% confidence interval [-0.0159; 0.0731] of this coefficient does not permit a clear conclusion. The following discussion, however, shows that an increased pollution level is more likely than a reduced.

Other measures besides LEZ indicate a consistent reduction of measured pollution of about 3.4%.

The exclusion of industry monitoring stations (column 2 & column 4) does not substantially alter the estimated coefficients. Furthermore, most coefficients in the dynamic approach are smaller compared to the static model, but yet similar with respect to their sign.

Number of Exceedance Days

This section explores whether LEZs are an appropriate measure to reduce the total number of annual exceedance days, as required by the EU regulation. The results in Table 6 show a significant decrease in exceedance days for most LEZs and are in line with those shown in Table 5. Again, column (1) contains results of the main regression, whereas the other three represent robustness checks.

The coefficients of the Euro 2, Euro 3, Euro 4 and Euro 3* dummies indicate a significant decrease of exceedance days. Monitoring stations within these LEZs record on average five to seven days less on which the PM_{10} concentration exceeded 50 $\mu m/m^3$. Similar to the results in Table 6, the impact of Euro 4* appears to be minor, whereas Euro 4** is related to a significant increase of over four days on average.

The impact of the Euro 2 or Euro 4 treatment on its surrounding regions is limited. In fact, all columns suggest a minor decrease of about half a day, although this effect might also be non-existent given the large standard errors. Areas close to Euro 3 zones experience two to three fewer exceedance days, whereas the Near Euro 3* coefficient demonstrates an increase. Similar to the results of Table 4, regions near Euro 4 or Euro 4** are most adversely affected by the policy. Again, the results of the dynamic model are not substantially different to the static approach and inspire confidence in the robustness of the results.

Table 6: Regression Results Equation (2), 15km

VARIABLES	(1) Basic	(2) No Industry	(3) Basic (lagged)	(4) No Industry (lagged)
Euro 2	-4.018***	-3.736***	-1.641	-1.858
	(1.055)	(1.085)	(1.337)	(1.394)
Euro 3	-7.541***	-7.043***	-4.450***	-4.375***
	(1.270)	(1.302)	(1.366)	(1.419)
Euro 4	-7.514***	-7.130***	-4.707***	-4.703***
	(1.372)	(1.405)	(1.304)	(1.343)
Euro 3*	-5.224***	-5.007***	-4.546***	-4.598***
	(1.079)	(1.088)	(0.958)	(0.986)
Euro 4*	-0.762	-0.579	-0.0554	0.0814
	(1.138)	(1.140)	(1.106)	(1.108)
Euro 4** (B)	4.718***	5.149***	4.417**	4.411**
	(1.503)	(1.511)	(2.132)	(2.173)
Near Euro 2	-0.525	-0.0783	-0.547	-0.484
	(0.649)	(0.628)	(0.893)	(0.954)
Near Euro 3	-2.963***	-2.420***	-2.146**	-1.975*
	(1.005)	(0.883)	(1.005)	(1.070)
Near Euro 4	-0.424	-0.379	-0.123	-0.255
	(0.842)	(0.770)	(1.022)	(1.106)
Near Euro 3*	1.148	2.203**	0.769	1.257
	(1.279)	(1.078)	(0.935)	(0.958)
Near Euro 4*	3.588***	3.620***	4.204***	4.262***
	(0.962)	(1.033)	(0.846)	(0.889)
Near Euro 4** (B)	2.031	2.613	4.956***	5.243***
	(4.189)	(4.146)	(1.448)	(1.500)
Other Measures	-1.444	-1.397	-1.136	-1.166
	(0.943)	(0.988)	(0.839)	(0.881)
Observations	3,192	2,975	2,783	2,594
R-squared	0.719	0.719	0.746	0.745
Weather Controls	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

The dependent variable in each column is the number of annual exceedance days per monitoring station. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Summarizing Patterns

In sum, the results show that LEZs are an appropriate measure to reduce local pollution and the number of exceedance days. However, the applied establishment method seems to determine their efficacy. Gradually increasing the restriction level is more effective and has less adverse effects on its surrounding areas compared to immediately starting at the highest restriction level. Furthermore, there are consistent adverse effects on surrounding regions after initial establishments of LEZs. Treatment Euro 2, Euro 3* and Euro 4* are applied in regions with no preceding LEZ (Table 2). The respective coefficients of Near Euro 2, Near Euro 3* and Near Euro 4* are consistently positive and furthermore increase according to the applied restriction level. Whereas the coefficient of Near Euro 2 suggests an increased concentration of 1 - 2%, Near Euro 3* already indicates a plus of 2.5 - 4.7%. The highest adverse treatment effects, with an increase of around 10%, are measured by monitoring stations close to the Euro 4* treatment. This pattern is in line with a familiarisation period as the adverse effects are always persistent in the initial phases of LEZs. The adverse effects appear to be increasing with the applied restriction level.

The LEZ in the city of Berlin appears to have failed as it did not reduce PM_{10} concentration levels within the appropriate area but further caused additional pollution in surrounding areas.

The results have shown that there is heterogeneity in treatments regardless of similar legal provisions. Even though Euro 4, Euro 4* and Euro 4** are based on the same regulation, they provide very different results. All results are robust to the applied model as well as to the implementation of alternative control groups (Table A5, Table A6).

5 Discussion

What can explain the differences in LEZ efficacy regarding Euro 4, Euro 4* and Euro 4** and their associated effect on surrounding regions despite similar legal provisions? In this section, I assess possible explanations for the discovered patterns. Initially, differences between Euro 4 and Euro 4* will be looked at, followed by a potential explanation of why the Euro 4** treatment in the city of Berlin might have failed.

Familiarisation Effect

Perhaps vehicle owners or others affected by LEZs need time to adjust to the restriction and the related consequences. Even though LEZs are usually announced one year in advance, residents or companies might start considering alternatives after the establishment and for instance initially bypass the LEZ. The fact that some car navigation systems even offer the function of showing alternative routes indicates that there is indeed a demand for bypassing. Additionally, Euro 4* zones are the most recent ones and some of them were introduced after 2015. This means that they had less time to gain traction compared to Euro 4 LEZs which all had preceding treatment periods. A familiarisation period could explain the insignificant Euro 4* coefficient and the large and positive coefficient of the Near Euro 4* dummy. If the so far most efficient route for vehicle owners is now restricted due to an LEZ, individuals need to take less efficient roads, causing additional traffic and pollution in surrounding areas which is in line with the positive Near Euro 4* coefficient. As PM_{10} travels through the air, this additional pollution can also adversely affect the LEZ itself which could explain the insignificant Euro 4* treatment dummy. I assume this effect to be temporary since the results so far show that regions near LEZs experience an increase in pollution in the initial phase of a newly established LEZ which is also represented by the significant and positive coefficients of Near Euro 2 and Near Euro 3* as illustrated in table 5. To further evaluate their behaviour of treatment over time and to see whether their pattern is in line with a familiarisation effect, I interact all treatment and proximity variables with year dummies. The results are presented in Table A7 and Table A8. The Near Euro 2 coefficients in column (2) of Table A8 indicate, that regions close to LEZs experience increased PM_{10} concentration in all years. Comparing the coefficients of column (2) and column (3) in the year 2009 shows that while Near Euro 2 is still positive, the Near Euro 3 coefficient has a negative sign. This implies that the adverse treatment effect of Euro 2 was only present for one year and vanished after the introduction of Euro 3. It is unlikely that this pattern can be explained by the applied restriction level itself. Near Euro 3* (column (4)) basically corresponds to the same policy as Near Euro 3 (column (2)) but the coefficients have different signs in 2009. Whereas Near Euro 3* regions, which relate to initial established LEZs experience an increase PM_{10} concentration, Near Euro 3 regions, which correspond to previously treated regions experience decreased pollution. This supports the assumption, that the region around a recently established LEZ is negatively affected by the treatment during its early stages. This pattern is independent of the applied restriction level and appears to be solely related to initial establishments.

To investigate the possibility of a familiarisation effect regarding the Euro 4* treatment, I return to equation (1) and perform a similar regression. However, I exclude LEZs that were initially established in 2016 or 2017 and disregard all of their associated monitoring stations nearby. This guarantees that every remaining LEZ has been active for at least two years and that people who were affected have had time to adapt. To investigate further and evaluate the duration of this effect, I additionally exclude LEZs which were established before 2015 and 2014 respectively. Therefore, if there is indeed a familiarisation effect regarding the Euro 4* treatment, the coefficients should experience at least one of the following changes after excluding the most recent observations: 1) A negative sign for Euro 4*, showing that the treatment now has the desired effect and is similar to Euro 4; 2) A decreasing or even negative Near Euro 4* coefficient, implying that the adverse treatment effect is only temporarily.: Or 3) A Larger standard error of the Near Euro 4* coefficient. The latter would indicate that the adverse treatment effect on surrounding areas is diminishing over time. The described changes correspond to the observations made in the previous section with respect to Euro 2 and Euro 3*. As I assume the presence of a transition period for these treatments, a similar pattern for the Euro 4*, after excluding recent LEZs, could confirm the existence of a transition period.

Table A9 contains results of the described specification. Column (1) excludes LEZs established in 2016 or 2017; in column (2) and (3) I additionally exclude the years 2015 and 2014. This implies that every observed LEZ is active for at least two, three or four years. However, the overall regression results contradict the hypothesis of a familiarisation effect with respect to the Euro 4* treatment as I do not observe any of the above-mentioned changes. Regardless of the observed timeframe, the Euro 4* treatment coefficient stays small and statistically insignificant, whereas the Near Euro 4* coefficient is consistently large, positive and statistically significant at the 1%-level. It gets even greater in column (3) where all LEZs are active for at least four years. Compared to Euro 2 and Euro 3*, their transition period did not exceed four years on average since all eligible LEZs were earlier upgraded to a higher restriction level which no longer indicates an adverse effect. Even though it is possible that four years are not enough for a Euro 4* LEZ to overcome the familiarisation period, going further back would drastically reduce observations of the Euro 4* treatment and would therefore not offer reliable results.

In summary, I cannot generally rule out the presence of a familiarisation process for the Euro 4* treatment as the observed patterns regarding Euro 2 and Euro 3* are strongly in favour of this hypothesis. Regression results in section 4.2 show that the adverse effects are increasing in the treatment intensity, thus, the transition period for Euro 4* may last longer compared to the less restrictive policies. If these results can be applied to other regions, the planned Euro 5* LEZs (implementing Euro 5 emission standard without any preceding LEZ) are expected to have similar or even stronger adverse effects as well as an even longer transition phase. Concluding, a familiarisation process can neither be confirmed nor rejected for Euro 4* and Near Euro 4* as further years of observation are required to reach a final statement.

The Effectiveness of LEZs can Already be Fully Exploited (Saturation Effect)

The LEZ policy is designed to induce the general public to reduce PM_{10} pollution through either switching to more environmental-friendly cars or through equipping their vehicles with particulate filters. The effectiveness of the policy is fully exploited if every vehicle meets the Euro 4 standard which implies that no further change in the PM_{10} concentration can be expected since no more vehicles can be restricted. In 2015, a study ADAC states that already 89% of the registered passenger cars complies with the Euro 4 norm and urges that further expanding LEZs in their current form is socially inefficient. Whilst a saturation of the policy can explain the small and insignificant coefficient of the Euro 4* treatment, the pattern for Near Euro 4* coefficient is not consistent with this hypothesis. An increased pollution in regions induced by the establishment of an LEZ cannot occur if all cars are already complying with the regulation. Furthermore, if the effectiveness of LEZs was already fully exploited somewhen before 2017, the Euro 4 treatment should be affected in a similar way.

Even though my findings are not fully in line with the hypothesis of a saturation effect, the statement of the ADAC is worth investigating as the outcome bears important policy implications for future LEZs. To test if the treatment effect has decreased or has become insignificant in recent years, or more precisely after a given year, I go back to the results of Table A7. The treatment and year interaction terms allow me to evaluate the treatment performance in a given year. The coefficients of the Euro 4 treatment in column (3) do indeed steadily decrease and become insignificant after 2014 which is consistent with a saturation effect, whereas the Euro 4* coefficients do not allow for a clear interpretation.

It still remains open what explains the increased pollution despite a vehicle fleet in which around 90% fulfil the Euro 4 norm? Is it possible that the remaining 10% are responsible for the additional particulate matter? Further investigating this question leads to a possible explanation which unfortunately cannot be shown with the available data. Perhaps the increase is mainly due to pollution caused by commercial vehicles and trucks. The number of cars complying with the Euro 4 norm refers to passenger cars only according to a study published by the ADAC in 2015. On the other side, a study of the UBA (2015) determined that 40 to 50% of commercial vehicles and trucks do not have a green windshield batch. This number only accounts for vehicles registered in Germany and the actual number of trucks not complying with the Euro 4 norm on German roads might be even larger. In addition, the German ministry for traffic and digital infrastructure (2014) predicted an annual growth in freight traffic of at least 2%. A closer look at the geographical characteristics reveals that five of eight monitoring stations around Euro 4* treatment areas are in the immediate proximity of a highway (Figure A10). Therefore, it is possible that the additional road transport, the restricted areas and a large share of commercial vehicles affected by the restriction can explain the observed pattern for Near Euro 4* and Euro 4*. This would imply that vehicle owners in the commercial sector are induced to bypass LEZs on these highways instead of complying with the norm.

If the numbers are accurate, it is true that most passenger cars registered in Germany are no longer restricted by the LEZ policy by the end of 2017 which means the policy is saturated in this section. However, commercial and foreign vehicles are still affected and might be responsible for the observed collateral pollution. The federal government is already taking steps regarding the large compliance rate of passenger cars and plans to introduce the first Euro 5 zones in 2018, which will further raise the requirements a car has to meet. This is expected to positively influence the composition of the vehicle fleet in general. However, if the explanation for the observed pattern is true, this stricter policy will not solve the issue of adverse treatment effects. Currently, no highways are within the catchment area of an LEZ which diminishes the incentives for switching to a less polluting car. The question if commercial cars are indeed responsible for the additional pollution around LEZs can only be answered by targeted traffic counts. If the assumption was confirmed, adding highways to LEZs should significantly increase their efficacy as well as reduce their adverse effects.

Infringements and Isolated LEZs

So far, I discussed potential explanations accounting for the observed differences between Euro 4 and Euro 4*. The reasons why these explanations do not apply for the LEZ in the city of Berlin (Euro 4**) will be discussed below. In the case of Euro 4**, the regression analysis shows, on the one hand, an insignificant correlation with the pollution concentration, and, on the other hand, a significant and positive correlation with the number of exceedance days. Both results indicate a failure of the policy.

An important criterion for the efficiency of an LEZ is the compliance rate regarding the policy. According to the German Environmental Relief (DUH), only 11% of the municipalities regularly check the windshield batches of both parking and driving cars within the zones. Infringements are punished with a fine of at least 80 Euros (DUH, 2013; Diegmann et al., 2014). LEZs generally encounter little agreement from the general population. In Berlin, public complaints, citizens' initiatives and legal actions against the planned LEZ occurred frequently. However, the appeals have failed, and the LEZ was nonetheless introduced in 2008 (Radke & Jacobs, 2009).

Since the introduction of the zone, Berlin has by far the highest number of punished infringements with over 65.000 cases in 2017 and this number has greatly increased over the years (DPA, 2018). Whereas officials report 5.600 label infringements in 2008, this number already doubled in 2011 (Diegmann et al., 2014). In comparison, the second and third largest amount of violations in 2017 were reported in Aachen and Cologne with 29.000 and 11.000, respectively (DPA, 2018). It is possible, even likely, that this enormous number of infringements renders the LEZ in Berlin ineffective.

The public order office in Berlin reported that the majority of infringements were committed by vehicles which are not registered in Berlin but in the surrounding regions. As illustrated in Figure A2, the LEZ in Berlin is the only zone within a radius of over 100km. This implies that the incentive to upgrade the car or to simply get the green sticker in areas with only a few LEZs is lower compared to regions with a higher number of LEZs. For instance, in the southwestern regions of Germany almost every city is restricted for cars not complying with the Euro 4 norm, whereas in the northeast of Germany, the city centre of Berlin is the only LEZ.

Berlin was originally evaluated separately due to its unique treatment structure, moving directly from Euro 2 to Euro 4. Perhaps the pattern observed in Berlin is independent of this treatment structure but can be associated with the LEZ's remote location which implies that similarly isolated LEZs with other treatment structures might experience the same. Compared to Euro 4**, other treatments are always implemented in more than one city and thus the results in the regression tables are mean values. This suggests the possibility that the actual inefficiency of the few isolated LEZs is blurred by other observations. Unfortunately, no detailed data on infringements is available. However, the hypothesis that isolated zones tend to struggle more, as the incentives to comply are lower, can be tested. If the channel for infringements or other inefficiencies were connected to the number of LEZs in a given region, the same pattern as in the case of Berlin should occur in other isolated zones. A confirmation or rejection of this hypothesis holds valuable information for future LEZs and their expected suitability. Therefore, I identify nine further isolated LEZs and implement regression specification (1) and (2) for these LEZs separately. An LEZ qualifies as isolated if no other zone is within a radius of 50km. All regressions are executed with the similar (static)[7] control group. Additionally, I add Aachen and Cologne since the number of reported violations in these LEZs is high as well.

Table 7 summarizes the individual regression results. Whereas column (2) illustrates the rounded coefficients of the highest applied treatment regarding the pollution concentration, column (4) outlines the rounded treatment effect on the number of exceedance days. Column (3) and (5) show the corresponding 95% confidence intervals. Four out of ten LEZs indicate a significant reduction of PM_{10} exposure and this reduction is even larger compared to the average. Additionally, four further cities have a negative yet statistically insignificant coefficient. Berlin and Osnabrück are the sole LEZs associated with an increased exposure. These results imply that the hypothesis of isolated LEZs generally experiencing difficulties can be rejected.

Furthermore, it is not possible to provide an accurate statement regarding the relation of violations and LEZ performance. In the case of Aachen, the treatment is indeed not significant but still negative. I previously mentioned the city of Aachen in section 03.2 as a negative example of an imprudent established LEZ which can also explain its insignificance, besides the infringements. The LEZ in Cologne is associated with a significant decrease, despite the number of breaches. However, the reported infringements in Cologne only account for one-sixth of those in Berlin.

[7] The definition of a static control group can be found in the appendix.

Table 7: Summary Regression Results, Isolated LEZs

City	Impact on Concentration	95% Confidence Interval (in %)	Impact on Exceedance Days	95% Confidence Interval (in days)
Berlin	+0.34%	(−2.71, 3.50)	+8	(5.7, 10.1)
Bremen	−10%	(−30.01, 10.12)	−9.5	(−22.7, 3.9)
Magdeburg	−3%	(−14.34, 7.81)	−3.5	(−10.9, 4.3)
Erfurt**	−9.5%	(−10.92, − 8.36)	−8.5	(−9.4, − 8.0)
Halle	−2%	(−6.22, 2.77)	−5	(−14.6, 4.8)
Leipzig*	−5%	(−7.38, − 3.03)	−0.5	(−2.8, 1.9)
Munich**	−15%	(−21.12, − 9.92)	−17	(−29.4, − 5.1)
Augsburg**	−15%	(−26.84, − 3.05)	−11.5	(−21.3, − 2.0)
Münster	−1.2%	(−5.57, 3.05)	−2.5	(−6.9, 2.4)
Osnabrück	+2.5%	(−2.69, 7.25)	+0.5	(−1.7, 2.3)
(Aachen)	−2%	(−6.19, 1.97)	−2	(−8.7, 4.8)
(Cologne**)	−12%	(−21.05, − 4.03)	−4	(−8.3, − 0.12)

* significant decrease of PM_{10} concentration. ** significant decrease of PM_{10} concentration and number of exceedance days.

The section has shown that the inefficiency in Berlin cannot be explained solely by its location even though most infringements were made by non-resident vehicle owners. In fact, other isolated LEZs perform significantly better than the average. Besides, a familiarisation period can be ruled out as the zone was the first one established and also one of the first ones to be upgraded to Euro 4. A look in Table A7 reveals that the Euro 4** treatment suggests decreased PM_{10} concentration until 2014. After 2014 the signs switch, which can be due to the simultaneous increase of infringements. Furthermore, 65.000 violations annually cannot be affiliated with the presence of a saturation effect. This number represents fined violations only and does not account for verbal warnings or undetected violations, which means that the true value of cars not complying with the restriction is even larger. Whether these violations alone can explain the findings regarding the Euro 4** treatment cannot be unequivocally shown with the present data. Even though Berlin is indeed the city with by far the most reported infringements and additionally the only city with an increasing trend, this number might not be representative as only 11% of German municipalities actively check the windshield labels. However, considering the limited information, I still assume this to be the most valid explanation. Traffic observation in Munich or Augsburg, for instance, report a decrease in the number of vehicles not complying with the policy. On the one hand, the public order office reported less than 3000 cases in Munich and around 6500 cases in Augsburg in 2017 (Steiner, 2018). On the other hand, these cities show a significant decrease of 15% in PM_{10} concentration (Table 7).

Even though the numbers in Munich, Augsburg and Berlin do indicate a negative relationship between zone efficacy and the number of non-complying vehicles, this evaluation is strictly qualitative and observations of three cities are not enough to prove the assumption. The monitoring interval, the true number of violations or other unobserved factors might differ and substantially change the results. A possible future analysis targeted at correlations between infringements and LEZ efficacy might provide accurate insights.

6 Conclusion

LEZs are one of the most aggressive tools designed to decrease air pollution (Wolff, 2014). They are adopted in Europe, Asia and the USA but yet face controversial opinions regarding their efficacy as well as with respect to the proportionality of the intervention. The uncertainty about their effectiveness is owed to the numerous individual studies, of which a majority is commissioned by stakeholders. Aside from that, different time frames, varying, and sometimes questionable methodologies impede undistorted implications on their basis. Furthermore, this study shows that it is fairly easy to deliver beneficial results for supporters as well as for critics of the policy if particular regions are selected or omitted.

This paper quantifies the efficacy of LEZs on the basis of 63 cities which have adopted the policy. The selection of these cities is only premised on the availability of air pollution monitoring stations which deliver hourly mean values. I include all available observations between the first implementation of the policy in 2008 and the end of 2017 and additionally show that the obtained results are robust to the applied methodology. Whereas my focus was an overall evaluation, the created dataset additionally allows for an individual LEZ performance assessment in 63 out of 82 cities that adopted the policy. Furthermore, this study is the first to distinguish between the applied restriction levels Euro 2, Euro 3 and Euro 4 and with regard to the adaption method.

Overall, I find that the majority of LEZs are associated with moderately reduced PM_{10} concentrations as well as with a decrease in the number of annual exceedance days. Depending on the restriction level, PM_{10} levels are reduced up to 4.5%. After 2015, no monitoring station recorded more than 28 days on which the daily mean exceeded 50 μm/m³. Both findings imply that LEZs can be an appropriate measure to ensure the EU's legal requirements, regarding PM_{10}, are met. However, LEZs which start at restriction level Euro 4 without any preceding treatment are not related to decreased pollution. Even though these LEZs are currently in the minority, they serve as a proxy for all future zones since this implementation method is applied since 2013. Furthermore, I find indications for a transition period during which regions close to LEZs are adversely affected by the treatment. The adverse effect is prevailing in the first years after the initial adoption of the policy and is largest for the Euro 4* treatment. My results also suggest a saturation of the Euro 4 policy which presumably primary relates to non-commercial vehicles.

The study shows that the policy is not effective in every city and might have undesired side effects. The effectiveness of an individual LEZ as well as the corresponding adverse effects should be well evaluated before expanding the policy to Euro 5 or Euro 6. I discussed potential explanations for adverse effects but assessing them on a case-by-case basis is much easier. Thus, traffic-census, strengthened-controls or even automated checks can help to find the source of the inefficiency - if it exists. Furthermore, it can be individually assessed whether adverse effects are a socially efficient redistribution of pollution or if actions are required.

Finally, the introduction of a policy which affects millions of citizens should neither be based on assumptions nor on outdated studies by stakeholders. The UBA is collecting and providing detailed data for numerous pollutants besides PM_{10}. More long-term studies including further pollutants are in order to adequately inform policymakers and the public.

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Appendix

Figure A1: Relative Share of PM_{10} Sources

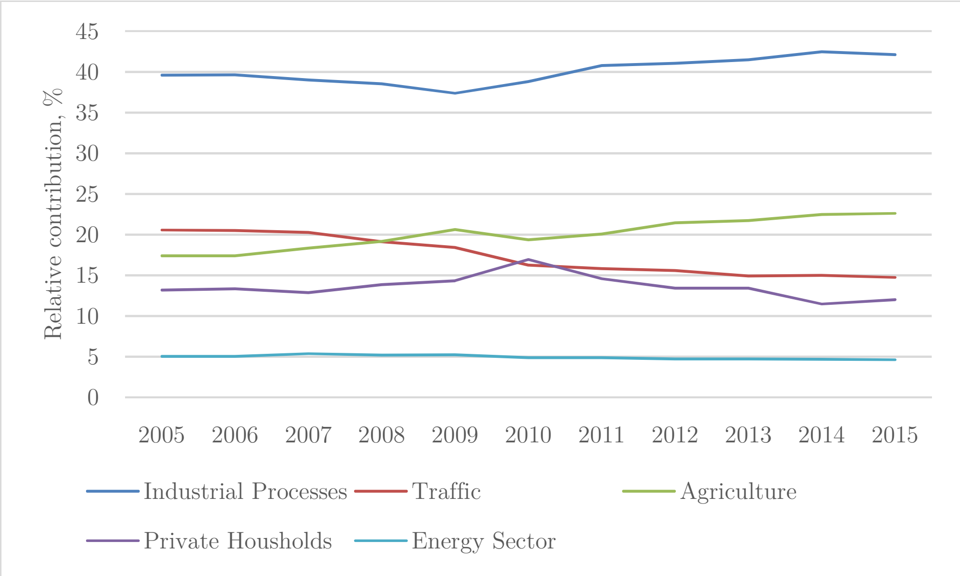
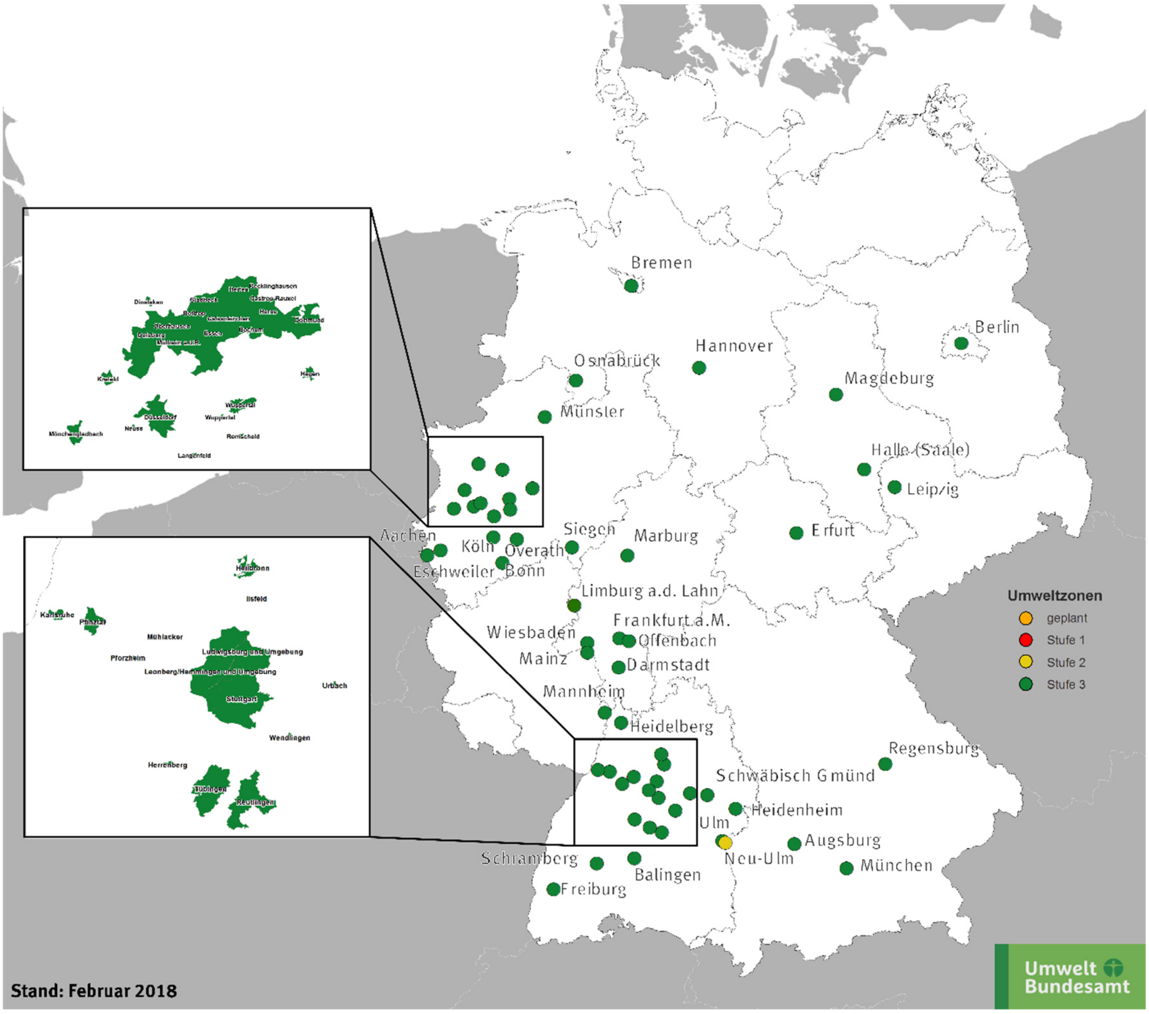


Figure A2: LEZs in Germany



Source: www.umweltbundsamt.de

Figure A3: LEZ Magdeburg (Example I)

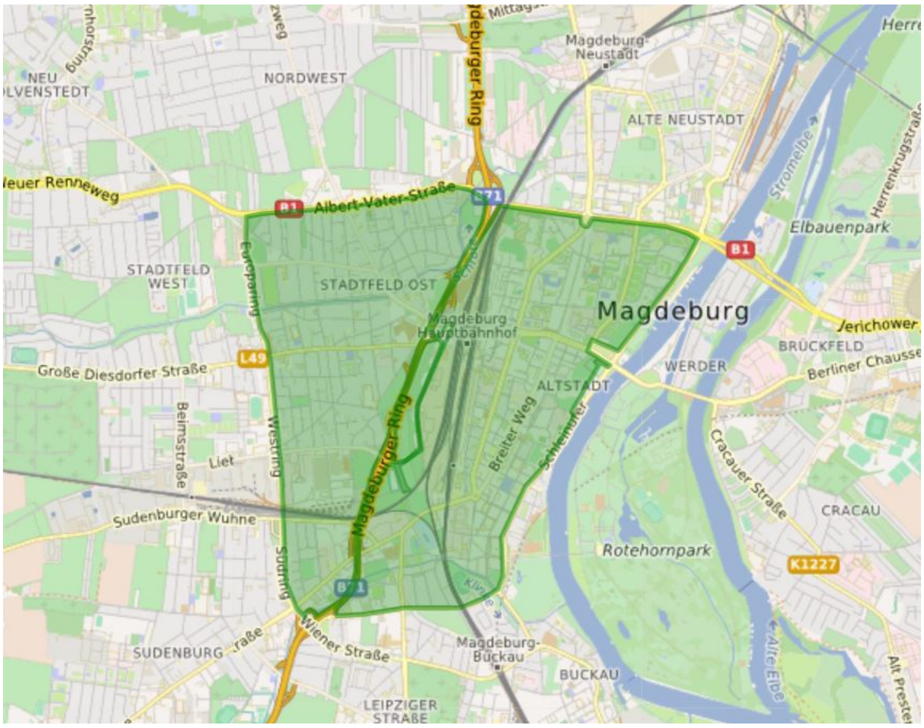


Figure A4: LEZ Ruhr Area (Example II)

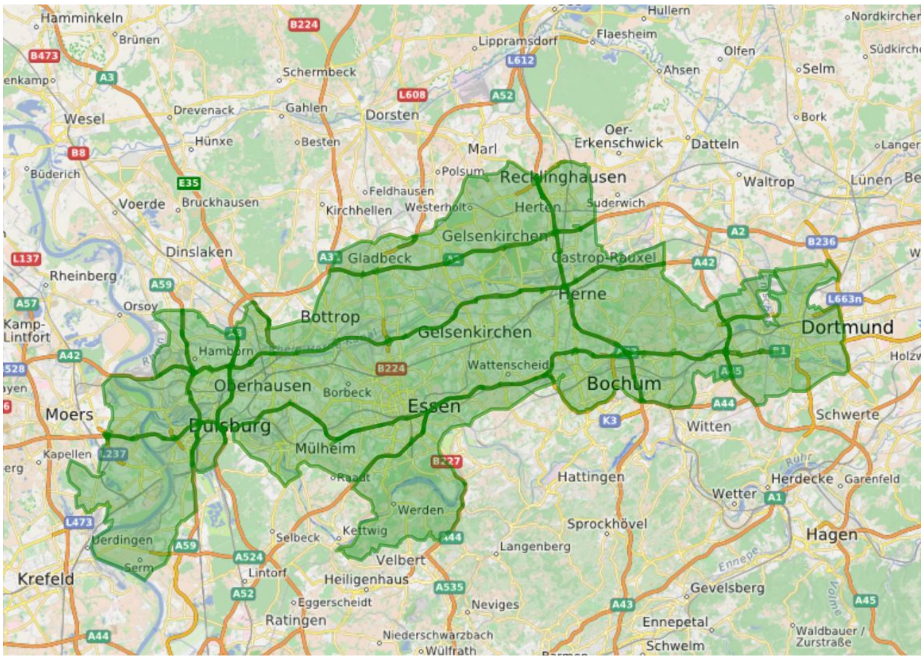


Figure A5: Relative Frequency of Treatment Starting Month

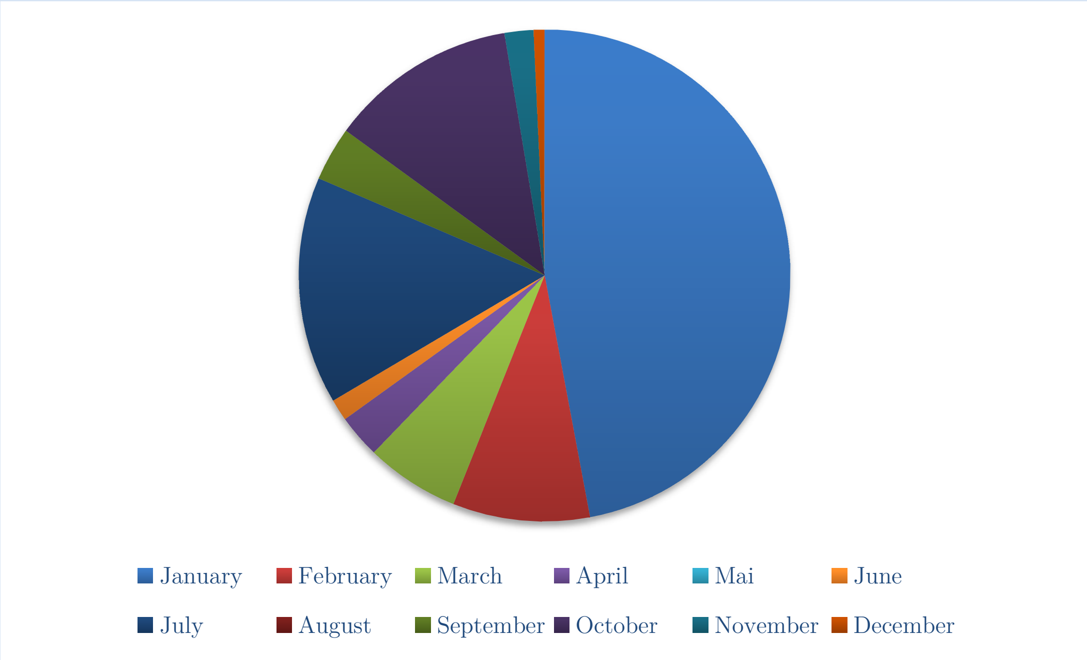


Figure A6: Monthly Mean PM_{10} Concentration in LEZ and No LEZ Regions.

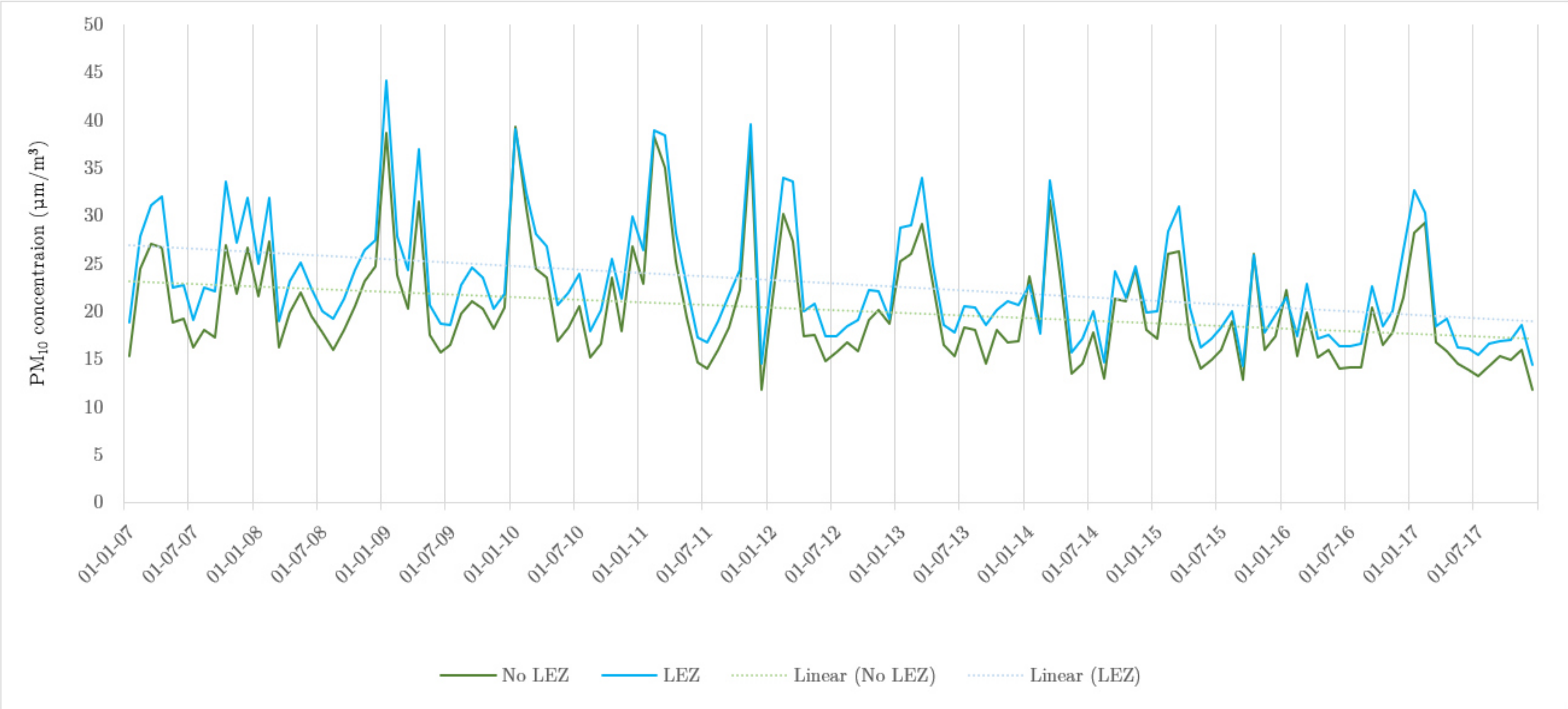


Figure A7: Monthly Mean PM_{10} Concentration: Dynamic Control and Treated

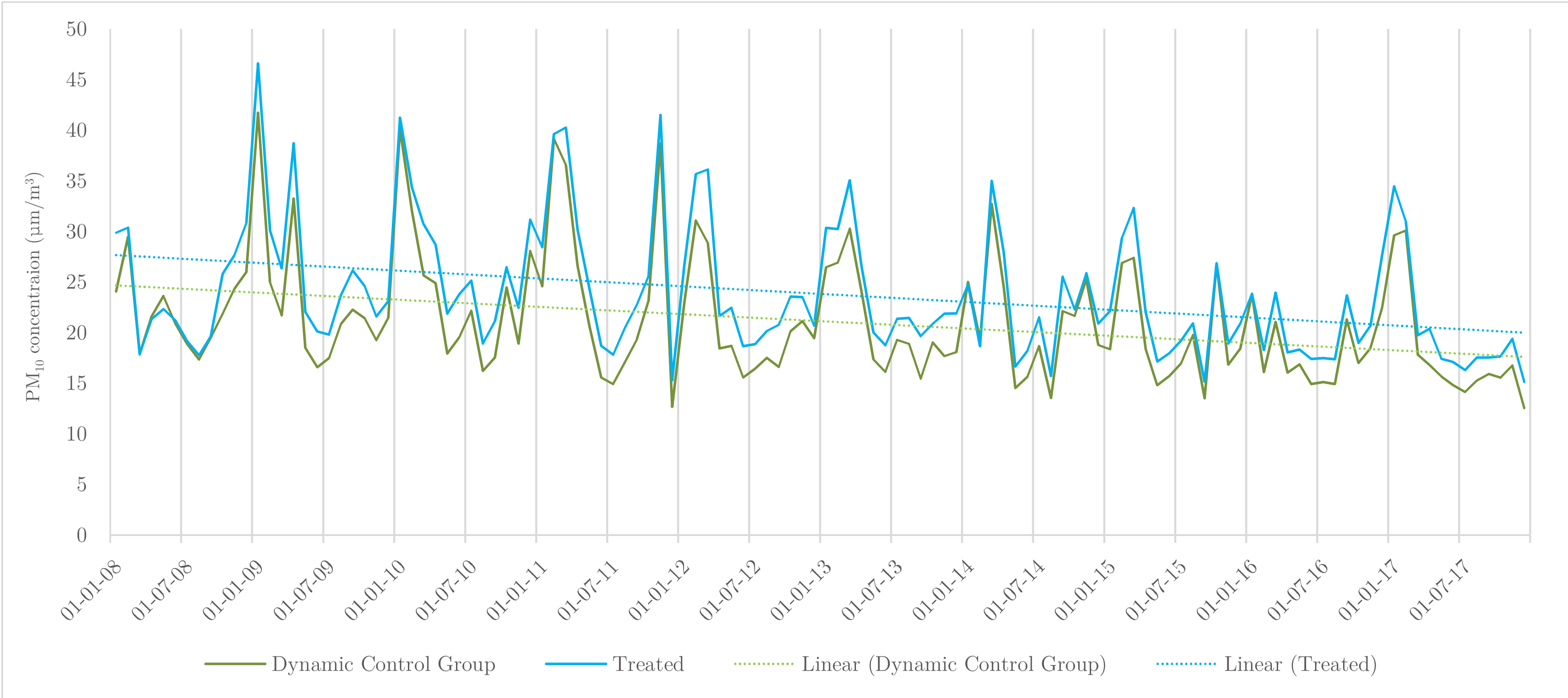


Figure A8: Monthly Mean PM_{10} Concentration: Treatment Group Only

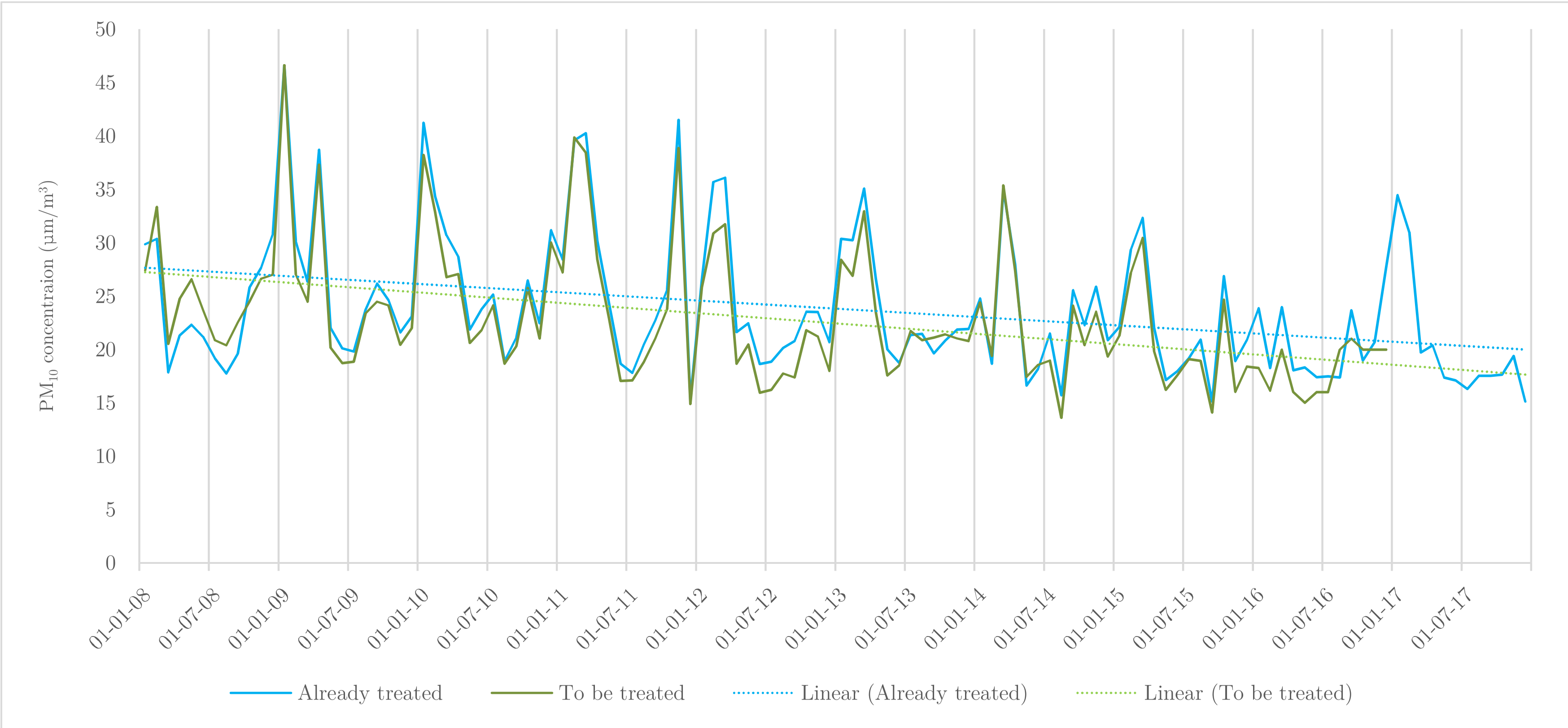


Figure A9: Kernel Density of Mean PM_{10} Concentration by Year

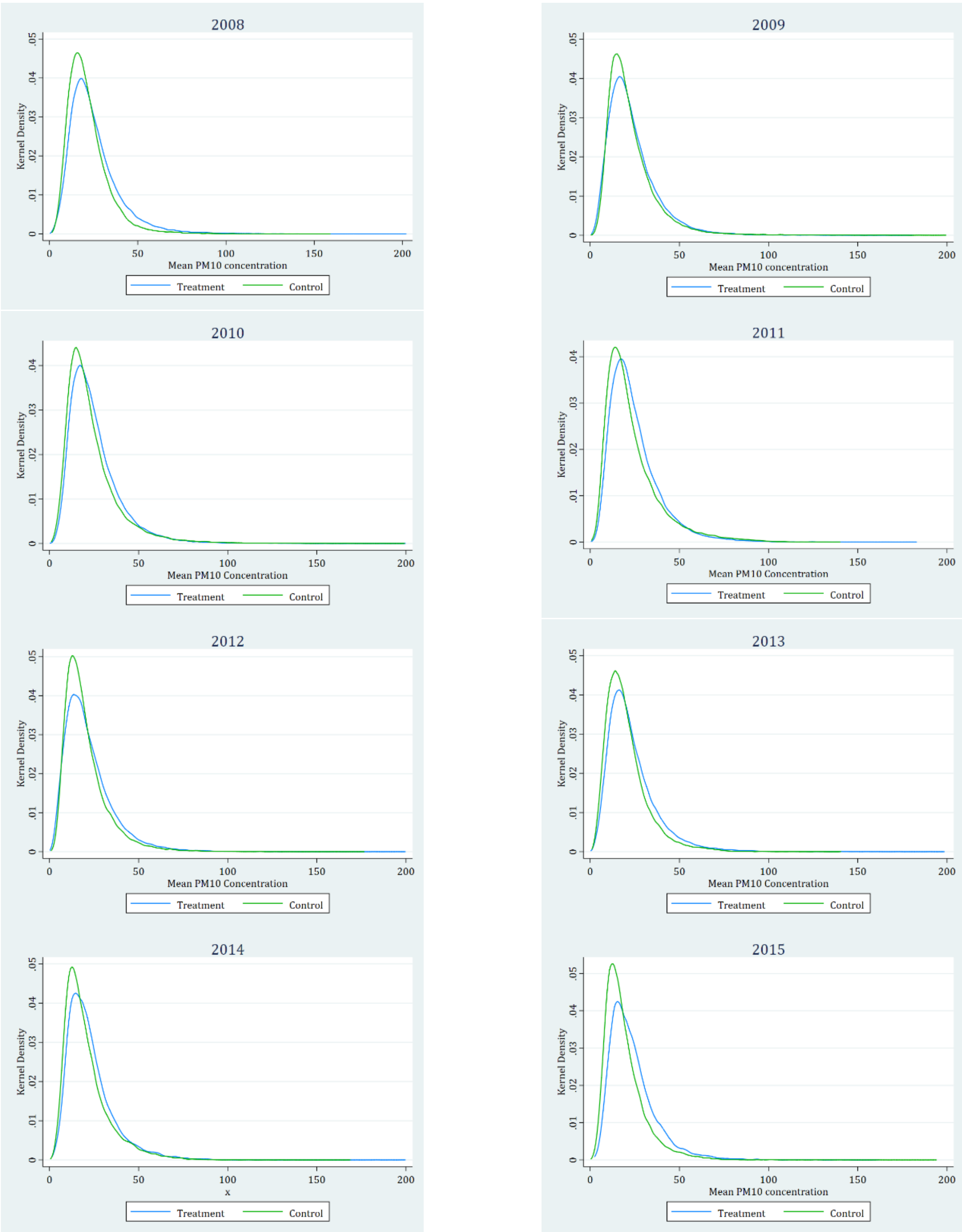


*Figure A10: Position Monitoring Stations, Near Euro 4**

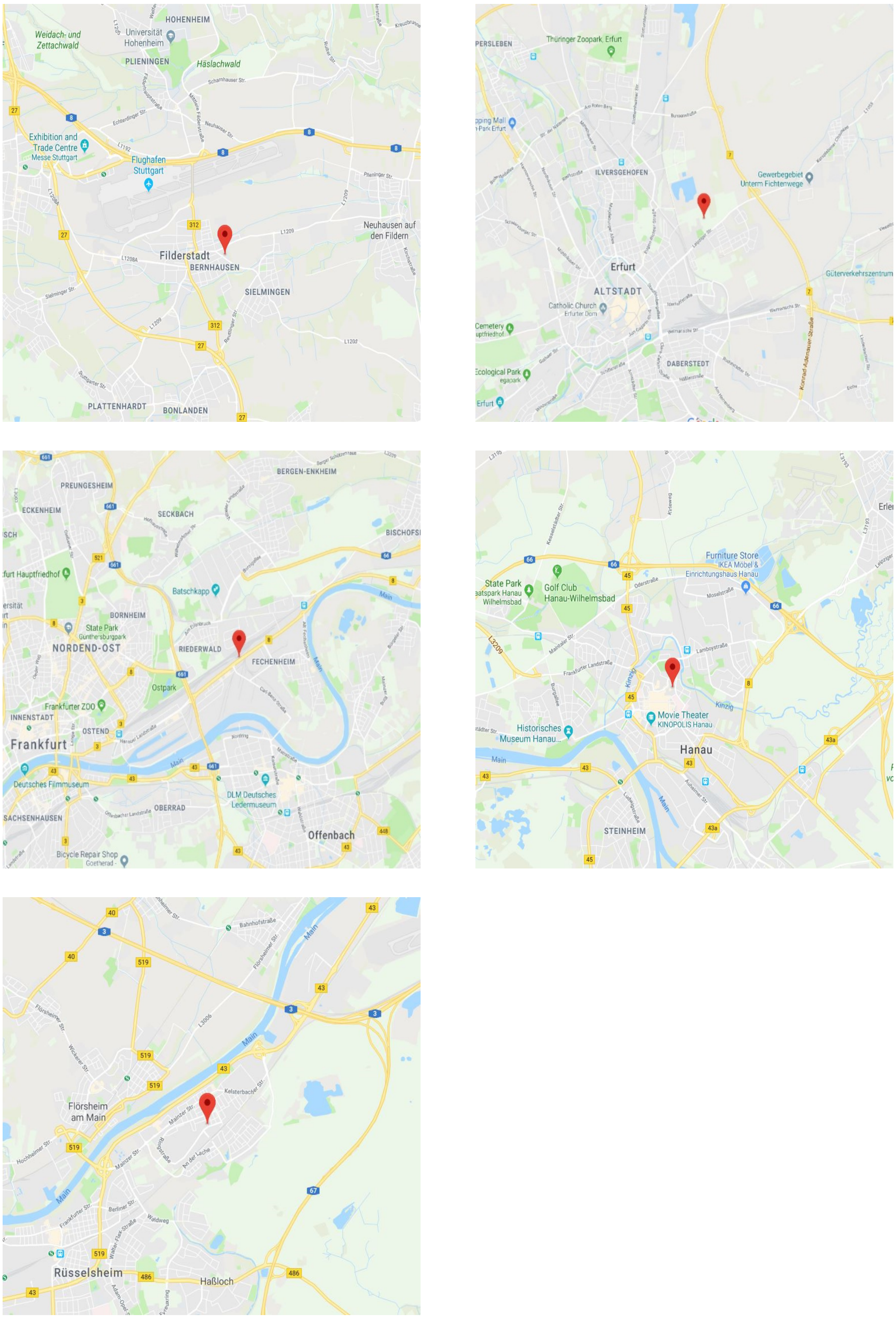


Table A1: Robustness; Excluding Proximity & Other Measures

VARIABLES	(1) Basic	(2) - Proximity	(3) - Other Measures
Euro 2	-0.0172	-0.0162	-0.0153
	(0.0112)	(0.0113)	(0.0112)
Euro 3	-0.0441***	-0.0421***	-0.0400***
	(0.0148)	(0.0149)	(0.0150)
Euro 4	-0.0420**	-0.0390**	-0.0409**
	(0.0167)	(0.0169)	(0.0170)
Euro 3*	-0.0384**	-0.0372**	-0.0334**
	(0.0150)	(0.0151)	(0.0151)
Euro 4*	0.00184	0.00480	0.00131
	(0.0225)	(0.0226)	(0.0223)
Euro 4** (Berlin)	-0.00815	-0.00560	-0.00410
	(0.0174)	(0.0175)	(0.0175)
Near Euro 2	0.0134		0.0141
	(0.0108)		(0.0115)
Near Euro 3	-0.00992		-0.00835
	(0.0143)		(0.0152)
Near Euro 4	-0.00190		-0.000781
	(0.0162)		(0.0166)
Near Euro 3*	0.0369**		0.0395**
	(0.0181)		(0.0181)
Near Euro 4*	0.100***		0.0984***
	(0.0235)		(0.0242)
Near Euro 4** (Berlin)	0.0286		0.0317
	(0.0226)		(0.0229)
Other Measures	-0.0341***	-0.0305**	
	(0.0127)	(0.0137)	
Observations	1,005,820	885,572	836,169
R-squared	0.711	0.713	0.714
Station FE	Yes	Yes	Yes
Day FE	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes

The dependent variable in each column is the natural logarithm of the measured PM_{10} concentration. Column (1) includes the basic reference model as in Table 5. In column (2) I exclude all monitoring stations within a radius of 20km around an LEZ in order to evaluate the impact of LEZs without the concern of spillovers. In column (3), I exclude all monitoring stations affected by other measures, besides LEZs. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A2: Adding Control Variables

VARIABLES	(1) Treatment	(2) + Proximity	(3) + Other Measures	(4) + Weather
Euro 2	-0.0157	-0.0148	-0.0166	-0.0172
	(0.0111)	(0.0112)	(0.0112)	(0.0112)
Euro 3	-0.0369**	-0.0359**	-0.0405***	-0.0441***
	(0.0146)	(0.0147)	(0.0147)	(0.0148)
Euro 4	-0.0411**	-0.0394**	-0.0461***	-0.0420**
	(0.0160)	(0.0161)	(0.0161)	(0.0167)
Euro 3*	-0.0304**	-0.0298**	-0.0338**	-0.0384**
	(0.0142)	(0.0142)	(0.0143)	(0.0150)
Euro 4*	0.0109	0.0120	0.00701	0.00184
	(0.0220)	(0.0219)	(0.0218)	(0.0225)
Euro 4** (B)	0.000467	0.00226	-0.00387	-0.00815
	(0.0170)	(0.0172)	(0.0171)	(0.0174)
Near Euro 2		0.0108	0.00885	0.0134
		(0.0109)	(0.0111)	(0.0108)
Near Euro 3		-0.00774	-0.0116	-0.00992
		(0.0148)	(0.0153)	(0.0143)
Near Euro 4		-0.00144	-0.00576	-0.00190
		(0.0165)	(0.0163)	(0.0162)
Near Euro 3*		0.0397**	0.0373**	0.0369**
		(0.0180)	(0.0181)	(0.0181)
Near Euro 4*		0.101***	0.0971***	0.100***
		(0.0222)	(0.0221)	(0.0235)
Near Euro 4** (B)		0.0334	0.0267	0.0286
		(0.0228)	(0.0229)	(0.0226)
Other Measures			-0.0328***	-0.0341***
			(0.0123)	(0.0127)
Observations	1,005,820	1,005,820	1,005,820	1,005,820
R-squared	0.687	0.687	0.688	0.711
Weather Controls	No	No	No	Yes
Station FE	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes

The dependent variable in each column is the natural logarithm of the measured PM_{10} concentration. Column (1) includes the treatment dummies only, column (2) adds the proximity variables, column (3) includes a dummy variable indicating whether other measures besides LEZs have been established. In column (4), a vector of twelve weather variables is added. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A3: Meteorological Control Variables Summary Statistics

Variables	Unit	Mean	St. Dev	Min	Max
Daily maximum wind speed	m/s	10.40	3.97	1.4	47.8
Daily mean wind force	m/s	3.70	1.84	0.2	21.2
Daily total precipitation	mm	1.94	4.11	0	140.1
Daily mean of relative humidity	%	78.56	11.94	9	100
Daily total sunshine duration hours	h	4.55	4.30	0	16.38
Daily degree of cloud coverage	*scale*	5.1	2.01	0	8
Daily mean vapor pressure	hPa	9.86	3.98	0.5	25.7
Daily mean air pressure	hPa	987.51	26.49	876.2	1045.35
Daily mean temperature	°C	9.61	7.32	-18.9	30.3
Daily min temperature	°C	5.48	6.52	-23	23.3
Daily max temperature	°C	13.67	8.62	-17.3	39.4
Daily min ground temperature	°C	3.50	6.67	-30	22.6

Table A4: Regression with Varying Radii

VARIABLES	(1) 10km	(2) 15km	(3) 20km
Euro 2	-0.0176	-0.0172	-0.0172
	(0.0112)	(0.0112)	(0.0112)
Euro 3	-0.0456***	-0.0441***	-0.0436***
	(0.0149)	(0.0148)	(0.0149)
Euro 4	-0.0450***	-0.0420**	-0.0411**
	(0.0168)	(0.0167)	(0.0168)
Euro 3*	-0.0395***	-0.0384**	-0.0379**
	(0.0150)	(0.0150)	(0.0150)
Euro 4*	-0.000548	0.00184	0.00261
	(0.0225)	(0.0225)	(0.0225)
Euro 4** (Berlin)	-0.0103	-0.00815	-0.00760
	(0.0173)	(0.0174)	(0.0175)
Near Euro 2	0.0129	0.0134	0.0104
	(0.0140)	(0.0108)	(0.00995)
Near Euro 3	-0.000679	-0.00992	-0.00829
	(0.0177)	(0.0143)	(0.0117)
Near Euro 4	-0.0141	-0.00190	0.00398
	(0.0181)	(0.0162)	(0.0148)
Near Euro 3*	0.0213	0.0369**	0.0330*
	(0.0234)	(0.0181)	(0.0168)
Near Euro 4*	0.112***	0.100***	0.0586**
	(0.0128)	(0.0235)	(0.0264)
Near Euro 4** (Berlin)	0.0166	0.0286	0.0271
	(0.0278)	(0.0226)	(0.0225)
Other Measures	-0.0361***	-0.0341***	-0.0342***
	(0.0128)	(0.0127)	(0.0128)
Observations	1,005,820	1,005,820	1,005,820
R-squared	0.711	0.711	0.711
Station FE	Yes	Yes	Yes
Day FE	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes

The dependent variable in each column is the natural logarithm of the measured PM_{10} concentration. In columns (1) - (3) the radius, affecting the 'Near Euro' variables is varied. The coefficients treatment coefficients Euro 2 - Euro 4** are robust to the changes in the radius, however, the absolute values of the spillover coefficients get smaller when increasing the distance. This is in line with the hypothesis that areas which are closer to an LEZ are affected more. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Dynamic, Semi Dynamic and Static Control Groups
Explanation for Table A5 & Table A6

In the subsection of chapter 4.1, I issue the concern of a dynamic control group and how it might affect the results. The following two tables show that this is in fact of minor importance. Each column in Table A3 and Table A6 contains regression results with a differently defined control group. Column (1) is similar to Table 5 or Table 6, with a dynamic control group. In column (2) and (3), each treatment Euro *i* as well as the according Near Euro *i* is regressed in an isolated specification. The control group in column (2) can be defined as semi dynamic as it consists of all monitoring stations, that are never within an LEZ and those that are not within an LEZ *so far*. This means that every treatment is separately checked against all monitoring stations, including those that are treated in future periods. Column (3) contains results of a static approach with a pre-defined control group which consists of monitoring stations in representative regions that are not within or near an LEZ throughout the study.

The results show that the key aspects of the study are robust to the applied control group. As expected the coefficients in column (2) and column (3) are smaller compared to those in column (1) since future LEZs, with a higher PM_{10} concentration are not part of the control group anymore.

Table A5: Robustness; Varying Control Group, PM_{10} Concentration

VARIABLES	(1) Dynamic	(2) Semi Dynamic	(3) Static
Euro 2	-0.0172	-0.0113	-0.0112
	(0.0112)	(0.00762)	(0.00765)
Euro 3	-0.0441***	-0.0213**	-0.0202**
	(0.0148)	(0.00876)	(0.00878)
Euro 4	-0.0420**	-0.0214*	-0.0205*
	(0.0167)	(0.0116)	(0.0116)
Euro 3*	-0.0384**	-0.0162	-0.0149
	(0.0150)	(0.0106)	(0.0106)
Euro 4*	0.00184	0.00438	0.00456
	(0.0225)	(0.0226)	(0.0227)
Euro 4** (B)	-0.00815	0.00201	0.00333
	(0.0174)	(0.0155)	(0.0157)
Near Euro 2	0.0134	0.00938	0.00921
	(0.0108)	(0.0108)	(0.0108)
Near Euro 3	-0.00992	-0.0110	-0.00998
	(0.0143)	(0.0132)	(0.0133)
Near Euro 4	-0.00190	-0.000974	3.21e-05
	(0.0162)	(0.0157)	(0.0158)
Near Euro 3*	0.0369**	0.0305*	0.0312*
	(0.0181)	(0.0167)	(0.0167)
Near Euro 4*	0.100***	0.102***	0.102***
	(0.0235)	(0.0229)	(0.0229)
Near Euro 4** (B)	0.0286	0.0169	0.0183
	(0.0226)	(0.0213)	(0.0215)
Weather Controls	Yes	Yes	Yes
Station FE	Yes	Yes	Yes
Day FE	Yes	Yes	Yes

The dependent variable in each column is the natural logarithm of the measured PM_{10} concentration. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A6: Robustness; Varying Control Group, # Exceedance Days

VARIABLES	(1) Dynamic	(2) Semi Dynamic	(3) Static
Euro 2	-4.018***	-0.0691	-0.239
	(1.055)	(0.854)	(0.867)
Euro 3	-7.541***	-4.097***	-2.816***
	(1.270)	(0.867)	(0.759)
Euro 4	-7.514***	-3.194***	-3.993***
	(1.372)	(0.951)	(0.956)
Euro 3*	-5.224***	-3.004***	-0.708
	(1.079)	(0.613)	(0.683)
Euro 4*	-0.762	-1.705	-0.902
	(1.138)	(1.141)	(1.136)
Euro 4**	4.718***	5.602***	7.143***
	(1.503)	(1.722)	(1.344)
Near Euro 2	-0.525	-0.920	-0.995
	(0.649)	(0.744)	(0.748)
Near Euro 3	-2.963***	-2.654***	-2.484***
	(1.005)	(0.850)	(0.875)
Near Euro 4	-0.424	1.025	1.054
	(0.842)	(0.654)	(0.655)
Near Euro 3*	1.148	-1.456	-1.459
	(1.279)	(1.188)	(1.174)
Near Euro 4*	3.588***	2.885***	3.665***
	(0.962)	(0.590)	(0.869)
Near Euro 4**	2.031	2.198	2.092
	(4.189)	(4.323)	(4.257)
Weather Controls	Yes	Yes	Yes
Station FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes

The dependent variable in each column is the annual number of exceedance days. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A7: Treatment x Year Interaction

	(1) Euro 2	(2) Euro 3	(3) Euro 4	(4) Euro 3*	(5) Euro 4*	(6) Euro 4**
2008	-0.0276*					
	(0.0154)					
2009	-0.0231	-0.0335**				
	(0.0159)	(0.0132)				
2010	0.0126	-0.0750**		0.00313		-0.0244
	(0.0125)	(0.0304)		(0.0133)		(0.0151)
2011	-0.0357**	-0.0368**	0.0413	0.0126	0.0156	-0.113***
	(0.0139)	(0.0150)	(0.0454)	(0.0244)	(0.0471)	(0.0194)
2012	-0.0271	-0.0302*	-0.0622**	-0.0560***	0.0469	-0.0559**
	(0.0179)	(0.0179)	(0.0279)	(0.0164)	(0.0374)	(0.0235)
2013		-0.00426	-0.0272	-0.00122	0.00734	-0.0529***
		(0.0181)	(0.0182)	(0.0230)	(0.0182)	(0.0163)
2014		-0.119***	-0.0787***	-0.102***	-0.0135	0.0439***
		(0.0184)	(0.0191)	(0.0192)	(0.0229)	(0.0143)
2015		-0.0404	-0.0462**		0.00947	0.00212
		(0.0403)	(0.0205)		(0.0288)	(0.0214)
2016		-0.104***	-0.0149		-0.000740	0.100***
		(0.0392)	(0.0196)		(0.0251)	(0.0362)
2017		-0.0622***	-0.0127		0.0119	0.117***
		(0.0154)	(0.0208)		(0.0336)	(0.0257)

The regression results correspond to those obtained from equation (1). However, all treatment and proximity dummies are interacted with the years 2007 to 2017 in order to evaluate their performance/pattern in a given year. Table A7 and Table A8 include results of the same regression. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Table A8: Proximity x Year Interaction

	(1) Near Euro 2	(2) Near Euro 3	(3) Near Euro 4	(4) Near Euro 3*	(5) Near Euro 4*	(6) Near Euro 4**
2008	0.0110					
	(0.0149)					
2009	0.00133	-0.0281				
	(0.0148)	(0.0180)				
2010	0.0529***	-0.0739**	0.0326	0.0526***		0.0416
	(0.0173)	(0.0332)	(0.0270)	(0.0119)		(0.0349)
2011	0.0107	-0.0126	-0.00735	0.0572		-0.0637**
	(0.0157)	(0.0224)	(0.0268)	(0.0384)		(0.0274)
2012	0.0309*	-7.54e-05	-0.0339	0.0148		-0.0262
	(0.0179)	(0.0144)	(0.0274)	(0.0341)		(0.0367)
2013		0.0515*	0.0297	0.0779**	0.0972**	0.00227
		(0.0290)	(0.0201)	(0.0374)	(0.0475)	(0.0343)
2014		-0.0889***	-0.0309	-0.0142	0.0636	0.0634*
		(0.0150)	(0.0196)	(0.0266)	(0.0408)	(0.0343)
2015		-0.0330***	-0.0157		0.111***	-0.0228
		(0.0116)	(0.0229)		(0.0266)	(0.0372)
2016		-0.161***	0.00858		0.122***	0.0681*
		(0.0124)	(0.0188)		(0.0307)	(0.0366)
2017			0.0449**		0.0801***	0.0998***
			(0.0189)		(0.0300)	(0.0301)

The regression results correspond to those obtained from equation (1). However, all treatment and proximity dummies are interacted with the years 2007 to 2017 in order to evaluate their performance/pattern in a given year. Table A5 and table A6 include results of the same regression. Robust standard errors in parentheses *** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table A9: Familiarisation Process

VARIABLES	(1) Before 2016	(2) Before 2015	(3) Before 2014
Euro 2	-0.0169	-0.0158	-0.0164
	(0.0112)	(0.0117)	(0.0118)
Euro 3	-0.0436***	-0.0415***	-0.0415***
	(0.0148)	(0.0156)	(0.0158)
Euro 4	-0.0415**	-0.0363**	-0.0368**
	(0.0167)	(0.0169)	(0.0172)
Euro 3*	-0.0381**	-0.0345**	-0.0306*
	(0.0150)	(0.0150)	(0.0163)
Euro 4*	0.00215	0.00212	0.00239
	(0.0225)	(0.0247)	(0.0247)
Euro 4** (Berlin)	-0.00760	-0.00642	-0.00655
	(0.0174)	(0.0175)	(0.0176)
Near Euro 2	0.0136	0.0143	0.0140
	(0.0108)	(0.0108)	(0.0110)
Near Euro 3	-0.00959	-0.00861	-0.00827
	(0.0143)	(0.0143)	(0.0147)
Near Euro 4	-0.00144	-0.00101	-0.00412
	(0.0162)	(0.0162)	(0.0165)
Near Euro 3*	0.0371**	0.0375**	0.0364**
	(0.0181)	(0.0181)	(0.0181)
Near Euro 4*	0.100***	0.100***	0.125***
	(0.0236)	(0.0236)	(0.0291)
Near Euro 4** (Berlin)	0.0291	0.0298	0.0300
	(0.0226)	(0.0227)	(0.0227)
Other Measures	-0.0337***	-0.0339***	-0.0335***
	(0.0127)	(0.0127)	(0.0128)
Observations	1,003,486	982,305	971,784
R-squared	0.711	0.711	0.711
Station FE	Yes	Yes	Yes
Day FE	Yes	Yes	Yes
Weather Controls	Yes	Yes	Yes

The dependent variable in each column is the natural logarithm of the measured PM_{10} concentration. Column (1) includes monitoring stations which are being treated before 2016, column (2) and (3) further exclude one extra year. Robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1