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The Distributional Effects of Low Emission Zones: Who Benefits from Cleaner Air?

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Abstract

Low emission zones (LEZ) represent a key environmental policy instrument to address air pollution in cities. LEZs have reduced air pollution and associated health damages in regulated areas, but it remains unclear who has benefited from cleaner air. To examine the distributional effects of LEZs, we combine gridded data on resident characteristics, including income and a proxy for ethnicity, with high-resolution estimates of fine particle (PM_{2.5}) concentrations in Germany, the country with the highest number of LEZs. We estimate heterogeneous treatment effects with a difference-in-differences approach and show that PM_{2.5} pollution reductions are distributed unequally across society. While residents with German name origins experience larger improvements within LEZs, residents with foreign names disproportionately live in LEZs and thus benefit more when assessed at a nationwide scale. Monetizing air quality benefits following governmental guidance, we find that they are distributed pro-poor within LEZs, disproportionately benefiting lower-income residents. From a nationwide perspective, benefits are distributed almost proportionally although the sign is sensitive to how benefits from cleaner air scale with income. Overall, our results suggest that LEZs have nuanced distributional implications that differ sharply between a national perspective and local assessments that focus on effects within LEZs.

JEL-Codes: J150, Q520, Q530, Q580.

Keywords: air pollution, distributional effects, low emission zones, traffic regulation.

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1 Introduction

Air pollution represents a major public health and economic policy threat throughout the world. Many cities continue to see pollution levels that exceed thresholds set by the World Health Organization (WHO, 2004), resulting in over 4 million avoidable deaths every year worldwide, with over 200,000 in Europe (Fuller et al., 2022; EEA, 2023). Around the world, a range of public policy instruments have been enacted to regulate and reduce air pollution, ranging from specific fuel content regulations (e.g., Auffhammer and Kellogg, 2011), transport, fuel or emissions pricing (e.g., Oliva, 2015; Simeonova et al., 2021; Basaglia et al., 2023; Greenstone et al., 2025), to encompassing approaches such as the Clean Air Act in the United States (e.g., Aldy et al., 2022; Currie and Walker, 2019) and China’s recent “war on pollution” (Greenstone et al., 2021). While the distributional implications of policy-induced pollution reductions have been studied in different settings across the United States (e.g., Grainger, 2012; Fowlie et al., 2012; Bento, 2013; Bento et al., 2015; Grainger and Ruangmas, 2018; Currie et al., 2023; Hernandez-Cortes and Meng, 2023; Sager and Singer, 2025), similar efforts in Europe remain scarce (Drupp et al., 2025).

In this paper, we shed light on the distributional effects of policy-induced pollution reductions in Europe’s largest economy: Germany. The European Union (EU) enacted its Clean Air Directive in 2008, setting out more stringent guidelines for ambient air pollution concentrations (EU, 2008). As a prominent policy tool to meet these standards, many cities have introduced low emission zones (LEZs) that restrict access of high-emission vehicles, thus aiming to improve local air quality. Among the EU member states, Germany stands out as it moved early and implemented the largest number of LEZs in 58 of the most populated cities, directly affecting more than 10 million inhabitants. Prior empirical evaluations of the introduction of LEZs have documented air quality improvements (Wolff, 2014), substantial health and well-being benefits (e.g., Gehrsitz, 2017; Margaryan, 2021; Klauber et al., 2024; Pestel and Wozny, 2021; Rohlf et al., 2020; Sarmiento et al., 2023), improvements in educational outcomes (Brehm et al., 2022), improvements in congestion (Galdon-Sanchez et al., 2023), but also increases in rents and property values (Gruhl et al., 2022).

While prior work on LEZs has focused on the average treatment effect of the policy, i.e. the average change in pollution levels across targeted cities, a detailed analysis of the distributional effects of LEZs is missing. This is important because the distribution of costs and benefits can alter the overall welfare assessment of a policy, and because environmental justice (EJ) is often a core focus of public policy discourse. Our aim is to fill this gap by providing, for the first time, systematic evidence on how air quality improvements and associated benefits induced by LEZs are distributed across income and ethnic groups (proxied by name origin) in Germany.

To capture the distributional effects of LEZs in Germany, we first estimate changes in $PM_{2.5}$ concentrations using a difference-in-differences approach. Going beyond prior work, we allow

for effect heterogeneity along multiple dimensions. Pairing local treatment effect estimates with high-resolution spatial data on resident characteristics allows us to calculate the benefits for various population groups in Germany. In a final step, again rarely undertaken in the literature, we monetize those air quality benefits using official pollution cost estimates by the German Environment Agency ([Umweltbundesamt, 2020](#)).

We document several findings on pollution disparities and differences in the ex ante likelihood of living in LEZs (policy exposure) as well as on heterogeneous air quality improvements in LEZs and the unequal distribution of resulting benefits. We start by providing average treatment effects of LEZs on population-weighted $PM_{2.5}$ concentrations and find that LEZs improve air quality in targeted areas by 9 percent, on average, and by 1.2 percent nationwide. We then turn to the distributional analysis. First, we document smaller initial $PM_{2.5}$ exposure disparities between ethnic and income groups in Germany than similar studies find in other countries, notably the United States (e.g., [Jbaily et al., 2022](#); [Currie et al., 2023](#); [Sager and Singer, 2025](#)). Second, we document heterogeneous treatment effects. In particular, air quality improvements are larger in more polluted areas but smaller in areas that have higher incomes and higher shares of foreign residents. Third, differences in the baseline pollution level and policy exposure lead to unequal benefits across ethnic and income groups. As relatively more persons with a non-German origin live in cities, they are more likely to benefit from the introduction of an LEZ (see [Figure A1](#)). However, while these residents benefit more due to this higher policy exposure across the nation, residents with German names benefit more within targeted areas. In the income dimension, we find that benefits are distributed pro-poor on average. However, we find substantial variation across cities, showcasing how local population distributions shape the benefit incidence from improved air quality due to LEZs.

Our paper contributes to the broader literature on the distributional effects of air pollution regulations (e.g., [Bento, 2013](#); [Bento et al., 2015](#); [Colmer et al., 2024](#); [Currie et al., 2023](#); [Grainger, 2012](#); [Sager and Singer, 2025](#)) and to the literature evaluating the effects of LEZs (e.g., [Wolff, 2014](#); [Margaryan, 2021](#); [Klauber et al., 2024](#); [Pestel and Wozny, 2021](#); [Sarmiento et al., 2023](#)). While Environmental Justice concerns are subject to considerable academic and policy attention in the US (e.g., [Banzhaf et al., 2019b](#); [Drupp et al., 2025](#); [Cain et al., 2024](#)), they have received much less attention in Europe (e.g., [Drupp et al., 2025](#)). By documenting the distributional impacts of air quality benefits generated by LEZs in Germany, Europe's most populated country, this paper aims to begin closing this gap.

The remainder of this paper is structured as follows. In [Section 2](#) we provide background information on LEZs and stylized, descriptive facts on the distribution of $PM_{2.5}$ pollution concentrations as well as the probability to live in an LEZ across socio-economic characteristics such as

income and a proxy for ethnic background. In Section 3 we introduce our data and estimation strategy. Section 4 presents our results. We first provide evidence on average and heterogeneous LEZ treatment effects on pollution concentrations and subsequently analyze the distribution of air quality reductions and their monetized benefits due to LEZs. Section 5 closes with a discussion and conclusion.

2 Background and stylized facts

In 2008, the European Parliament and the Council of the European Union agreed on more stringent measures to improve ambient air quality (EU, 2008). This included a reduction in the threshold values required to avoid, prevent, and reduce harmful effects on human health. For PM_{10} , the annual mean threshold was set to $40\mu g/m^3$, and for $PM_{2.5}$ to $25\mu g/m^3$.¹ The directive particularly targeted agglomeration areas and cities with more than 100,000 inhabitants. Every agglomeration area or city with pollution levels in excess of the threshold(s) was instructed to develop an air quality action plan, setting out measures to achieve air quality improvements.

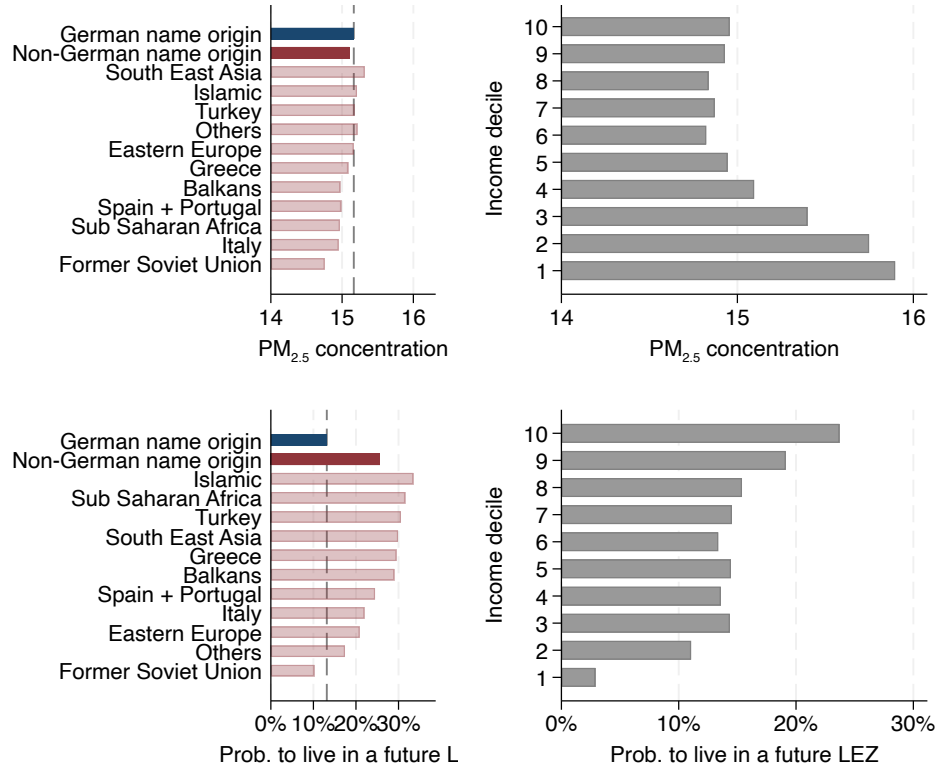
In response to the EU's Clean Air Directive, many German cities introduced Low Emission Zones (LEZ). By prohibiting high-emission cars from entering urban city centers, LEZs aim to reduce air pollution levels from road transport. To enforce the regulation, cities required cars to have a color-coded sticker (red, yellow, green) indicating emission classes displayed on their windshield. Initially, most cities only banned cars without a sticker or with a red sticker. Later, at least a yellow or green sticker was required to enter the targeted areas.

Design and implementation of LEZ was decentralized, resulting in a lot of heterogeneity. Each city independently defined the boundary and size of the local LEZ, and even some cities smaller than 100,000 people have introduced one. Consequently, some LEZ target only a small area around the city center where less than 5,000 people live (e.g., Ilsfeld and Overath), while other LEZ target larger regions with more than 1.2 million (Berlin) or 2.8 million inhabitants (Ruhr area). Moreover, due to the decentralized process, there has been a staggered introduction of LEZs across cities between 2008 and 2018.

Overall, more than 11.5 million inhabitants (i.e., 14 percent of the German population) live in LEZ areas and are thus directly exposed to the policy. Figure 1 provides some descriptive statistics on baseline $PM_{2.5}$ exposure levels in 2005 and eventual exposure to an LEZ. The top-left panel shows only modest variation in baseline $PM_{2.5}$ exposure across households with different name origins, which is our proxy for ethnic background (further discussed below). The gap between the German and non-German name groups is less than $0.1\mu g/m^3$, notably smaller than

¹In addition, the daily mean of PM_{10} should not exceed $50\mu g/m^3$ on more than 35 days a year.

Figure 1: Baseline pollution disparities and policy exposure by ethnicity and income.



Notes: The top panels show the average PM_{2.5} pollution for different ethnic and income groups before the introduction of LEZs in 2005. The bottom panels illustrate differences in the policy exposure for these different ethnic and income groups. Linguistic name origin is used as a proxy for ethnic group. The top-left panel shows small PM_{2.5} pollution disparities between ethnic groups. Larger pollution disparities between income groups, however, reveal the top-right panel. They highlight that wealthy and poor inhabitants face more pollution than middle-income inhabitants nationwide. The bottom-left panel shows large differences in the policy exposure between native residents and those with a non-German ethnic origin. In addition, the bottom-right panel shows that wealthy individuals are also more likely exposed to the policy.

the gap of around $1.5 \mu\text{g}/\text{m}^3$ between Black and White residents of the United States during the early 2000s, for example (cf. [Jbaily et al., 2022](#); [Currie et al., 2023](#); [Sager and Singer, 2025](#)).

The top-right panel of Figure 1 shows larger pollution disparities between income deciles. The highest- and lowest-income deciles face more pollution than the middle-income deciles. In part, this is due to a higher concentration of high-income households in larger, more polluted cities. Within (future) LEZ areas, however, there exists a clear negative relationship between income and pollution exposure (see Figure A2). These patterns align with those found for NO₂ exposure variation across US Metropolitan Statistical Areas ([Hsiang et al., 2019](#)) and may be explained by residential sorting.

Exposure to an eventual LEZ is more unequal than exposure to baseline pollution. The bottom-left panel of Figure 1 shows the probability of living in a future LEZ for different ethnic groups before the policy implementation in 2005. While around 13 percent of residents with

German names are exposed to the policy, 26 percent of residents with non-German names were affected, for a total of 1.5 million (see Figure A1). This twofold exposure for is primarily driven by the higher concentration of residents with non-German names in larger cities. For a similar reason, as already discussed above, policy exposure correlates positively with income, shown in the bottom-right panel. Richer people are more likely to be affected by LEZs.

3 Methods

We construct a high-resolution panel dataset that combines annual air pollution concentration counts with residential characteristics. This allows us to estimate changes in $PM_{2.5}$ levels due to the introduction of LEZs, allowing for treatment effect heterogeneity, and to explore the distribution of the resulting air quality benefits.

3.1 Data

We combine gridded estimates of annual $PM_{2.5}$ concentrations from [van Donkelaar et al. \(2021\)](#)² with high-resolution spatial data from RWI-GEO-GRID. Based on original data intended for geographically targeted marketing, RWI-GEO-GRID contains resident characteristics for 1×1 km grid cells covering most of Germany ([Breidenbach and Eilers, 2018](#); [RWI microm, 2020](#)). In Figure A4, we map the grid-cell average income and share of residents with non-German ethnic background across Germany. The figure shows that high-income households and those with foreign backgrounds are more concentrated in large cities.

We use the LEZs boundaries from OpenStreetMap and manually add missing ones using maps from the German Environment Agency. Figure A4 indicates these LEZ borders. To identify grid cells in cities with more than 100,000 inhabitants, we rely on city boundaries from the Urban Audit 2004 ([Eurostat GISCO, 2009](#)). We also add weather observations on the annual mean air temperature, total precipitation, and sunshine duration at each grid cell’s centroid from Germany’s National Meteorological Service ([DWD, 2024a,b,c](#)). Finally, we add the share of traffic-related $PM_{2.5}$ concentration for each grid cell estimated by [McDuffie et al. \(2021\)](#). The result is a balanced panel of grid cells, observed annually between 2005 and 2021. In addition, we evaluate pre-trends in $PM_{2.5}$ pollution levels back until 1998. We show descriptive statistics for grid cells located in cities with more than 100,000 inhabitants in Table A1.

The RWI-GEO-GRID data includes information about the share of households in a given cell who belong to one of twelve ethnic origin groups. This ethnic background is assigned based on a

² $PM_{2.5}$ estimates by [van Donkelaar et al. \(2021\)](#) are based on reanalysis procedures which combine satellite-based particle counts with chemical transport models that are calibrated to match ground-level monitor readings.

linguistic analysis of the household head’s first and last names. Hence, these classifications may not reflect the actual number of persons who are foreign-born, their duration of stay in Germany, or their social level of integration (Breidenbach and Eilers, 2018). Still, name-based classification of ethnic origin is clearly correlated with those factors, and has been linked to socio-economic and residential circumstances in Germany (Sager, 2012). In addition, discrimination is often directly based on names (e.g., Bertrand and Mullainathan, 2004; Oreopoulos, 2011; Christensen and Timmins, 2023), so we proceed with this classification as a proxy to study heterogeneous effects along (historical) ethnic background.

Besides ethnic origins, we explore distributional impacts along income. Here, we rely on estimates of the total purchasing power in each grid cell, which equals income after taxes and transfers received cumulatively by the inhabitants of a cell. We divide this by the number of inhabitants to arrive at a proxy for income per person.³ Finally, we split all grid cells into ten income deciles using the number of inhabitants as population weights.

3.2 Identification and estimation strategy

Our main approach to estimating the effect of LEZs on PM_{2.5} concentrations is a standard Differences-in-Differences (DiD) model which we implement in a panel two-way fixed effect [TWFE] regression. Our baseline TWFE DiD model reads as follows:

$$y_{it} = \beta LEZ_{it} + \delta \mathbf{X}_{it} + \gamma_i + \lambda_t + \epsilon_{it} \quad (1)$$

where y_{it} represents the PM_{2.5} concentration in grid-cell i and year t . LEZ_{it} is a binary treatment indicator for an active LEZ in grid-cell i and year t . The vector \mathbf{X}_{it} controls for time-varying grid-cell-related weather observations. In particular, we control for mean temperature, precipitation, and sunshine duration. γ_i represents grid-cell fixed effects and λ_t year fixed effects. Finally, ϵ_{it} captures any remaining residuals. We apply a population weighting and give more weight to populated areas. Our coefficient of interest is β , which represents the (population-weighted) average treatment effect for the treated grid cells (ATT).

A crucial identification assumption is the “parallel trends” assumption. This means we must assume that, in the absence of the policy, PM_{2.5} concentration would have evolved similarly in the treated and untreated regions. As LEZs have not been randomly located, we use two approaches to draw up comparable control groups: First, we use a sample of untreated grid cells in German cities with more than 100,000 inhabitants (like Gehrsitz, 2017; Margaryan, 2021; Pestel and Wozny, 2021). This city sample is motivated by the fact that the EU directive targeted cities larger than

³When conducting distributional analyses, we thus implicitly assume that income is distributed equally within each 1 × 1km grid cell.

100,000 inhabitants. Hence, the control group contains areas that were, in principle, subject to the same rule that motivated LEZ adoption. Second, we conduct a matching between grid cells in treated (LEZ) areas and untreated grid cells (like Wolff, 2014) from any other German region. The matched sample avoids a potential self-selection issue among eligible cities and compares grid cells with similar levels of: baseline (in 2005) $PM_{2.5}$ concentration, socio-economic characteristics (population, income, unemployment), as well as $PM_{2.5}$ pre-trends (1998–2005), so as to avoid a potential overestimation of the effect (cf. Sager and Singer, 2025). For both samples, we observe very similar pollution levels and trends, as shown in Figure A5 for the city sample and Table A3 for the matched sample (see also Figure A9). We prefer the matched sample and show results for the city sample in the Appendix.

Because LEZs were introduced by different cities at different times, TWFE estimates could in principle be biased by an implicit weighting of underlying treatment effect parameters (c.f., Goodman-Bacon, 2021; de Chaisemartin and D’Haultfœuille, 2020). That is why we also estimate average effects using newer estimators for staggered settings suggested by Callaway and Sant’Anna (2021) and Wooldridge (2021), which produce very similar ATT estimates.⁴

Going beyond average effects explored in prior work evaluating LEZs, we estimate heterogeneous treatment effects that differ by baseline pollution, income, and ethnicity characteristics of each grid-cell. To do so, we add relevant interaction terms for a more flexible TWFE DiD model:

$$\begin{aligned}
y_{it} = & \beta_1 LEZ_{it} + \beta_2 (LEZ_{it} \times PM_{25}^{2005}) + \beta_3 (LEZ_{it} \times PM_{25}^{2005} \times PM_{25}^{2005}) \\
& + \beta_4 (LEZ_{it} \times Income^{2005}) + \beta_5 (LEZ_{it} \times Foreign^{2005}) \\
& + \delta X_{it} + \gamma_i + \lambda_t + \epsilon_{it}
\end{aligned} \tag{2}$$

where β_1 captures a constant baseline treatment effect across grid cells. On top of that, the interaction terms allow for heterogeneous treatment effects between grid cells along baseline pollution, income, and ethnicity. While β_2 can capture a linear relationship between baseline pollution in 2005 and the treatment, β_3 can capture a quadratic relationship. The rationale for this quadratic relationship is that more polluted areas may experience stronger reductions in $PM_{2.5}$ concentrations, e.g. due to lower marginal abatement costs or because they simply have more traffic. For income and ethnicity, we explore linear interactions captured by β_4 and β_5 respectively. The motivation here is that income and ethnic composition could be correlated with the ability of locals to comply with the regulation, by upgrading vehicles or using alternate transport modes, or differences in the local fleet composition.

⁴These alternative estimators consider the temporal variation of implementation dates, allow for parallel trends after conditioning on observables, and avoid implicit weighting of treatment periods. However, they do not allow us to explore effect heterogeneity, which is why we treat them as a robustness check for ATT estimates only.

4 Results

4.1 Average and heterogeneous treatment effects of LEZs

We start by corroborating findings from the literature that LEZs have, on average, improved air quality in the targeted areas. The prior literature has predominantly focused on coarser particulate matter (PM₁₀). Here we focus on fine particulate matter (PM_{2.5}; see also [Brehm et al., 2024](#)), estimating the effect on population-weighted PM_{2.5} concentrations. Our matched-sample TWFE results in Table 1 show that LEZs reduce PM_{2.5} concentration by 0.16 $\mu\text{g}/\text{m}^3$ in targeted areas on average. This is equivalent to a 1.2 percent reduction in the population-weighted traffic-related PM_{2.5} concentration in targeted areas, or 9 percent nationwide.

In addition to the TWFE specification outlined above, we also implement two newer estimators intended for greater robustness in a staggered treatment environment such as ours. As shown in Figure 2, both the CSDID estimator proposed by [Callaway and Sant’Anna \(2021\)](#) and the ETWFE estimator⁵ proposed by [Wooldridge \(2021\)](#) produce very similar, although slightly larger estimates of the ATT. Figure 2 also shows that we find very similar estimates of the ATT when we use the alternative control sample drawn from cities with 100,000 plus inhabitants (City). The magnitude of ATT estimates aligns with previous estimates of average air quality improvements resulting from LEZs (e.g., [Brehm et al., 2022](#); [Gruhl et al., 2022](#); [Gehrsitz, 2017](#); [Klauber et al., 2024](#); [Pestel and Wozny, 2021](#); [Rohlf et al., 2020](#); [Sarmiento et al., 2023](#); [Wolff, 2014](#)).

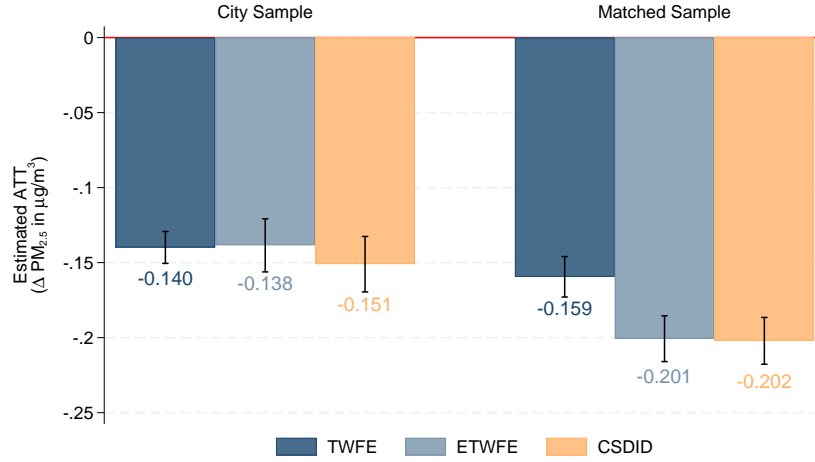
We now turn our attention to the question of effect heterogeneity. The significant interaction terms in Columns 2–5 of Table 1 suggest that treatment effects do indeed differ meaningfully along with baseline PM_{2.5} concentration, income, and ethnicity.⁶ In particular, they suggest an increasing treatment effect for areas with more baseline PM_{2.5} concentration. That means areas that were more polluted before the policy experience stronger improvements in air quality than areas that were already cleaner before. Since marginal abatement costs are usually lowest for the most polluted areas, this aligns with our expectations.

Besides baseline pollution levels, our results suggest the treatment effect is weaker for richer areas, contrary to the hypothesis that rich inhabitants have a better capacity to adapt and comply with the regulation. One explanation might be that income constraints lead low-income car owners to abandon dirty cars and stop emitting PM_{2.5} altogether by switching to bikes or public transport. Or perhaps the higher prevalence of polluting cars among poorer households leaves more room for reductions in PM_{2.5} emissions. Either way, differences in the local car fleet composition, together with potential income constraints, could explain our finding that air quality

⁵Both estimators are implemented with the ‘jwddid’ Stata routine.

⁶To rule out that the heterogeneous treatment effects are driven by changes in the local population composition, we explore potential changes in Figure A8. Overall, we find little changes in the composition of treated and untreated grid cells between 2005 and 2021.

Figure 2: Estimated reduction in $PM_{2.5}$ concentration due to LEZs.



Notes: Estimates of the average treatment effect (ATT) of LEZ adoption on population-weighted $PM_{2.5}$ concentrations. 'City Sample' compares grid cells in LEZ areas with grid cells in other cities with 100,000 or more inhabitants. 'Matched Sample' compares grid cells in LEZ areas with grid cells from anywhere that have similar levels of baseline levels (in 2005) of $PM_{2.5}$, socio-economic characteristics (population, income, unemployment), as well as $PM_{2.5}$ pre-trends (1998-2005). TWFE is the two-way fixed effect implementation of difference-in-differences shown in equation (1). CSDID and ETWFE are the alternative estimators for staggered treatment settings proposed by Callaway and Sant'Anna (2021) and Wooldridge (2021).

improvements are strongest in low-income areas. In addition, it should not be forgotten that local residents are only partially responsible for the air quality in their neighborhood. They may also benefit from a cleaner car fleet of others who pass through their neighborhood. Either way, our results suggest that low-income households, who also tend to be located in more polluted areas (see Figure 1), experience larger $PM_{2.5}$ reductions when a LEZ is introduced. Finally, our results suggest a weaker treatment effect for areas with a high share of households with a foreign ethnic origin – even after controlling for income and baseline pollution. Again, one could think of differences in the preference for cars and emission standards, for the mode of transportation, or in mobility behavior. We restrict ourselves to documenting this relationship and leave it for future research to further investigate these channels. All the patterns described above are confirmed when estimating effects in the alternative City sample, shown in Table A4.

We summarize the heterogeneous treatment effects in Figure 3. In the top panel, we divide grid cells into 20 vigintiles based on their baseline $PM_{2.5}$ concentration in 2005. For each $PM_{2.5}$ vigintile, we then predict the average ATT (blue), taking the mean income and mean share of foreign households into account. The overall relationship shows that the higher the baseline pollution levels are, the stronger the reductions in $PM_{2.5}$ concentration tend to be. This relationship

Table 1: LEZ effect on PM_{2.5}.

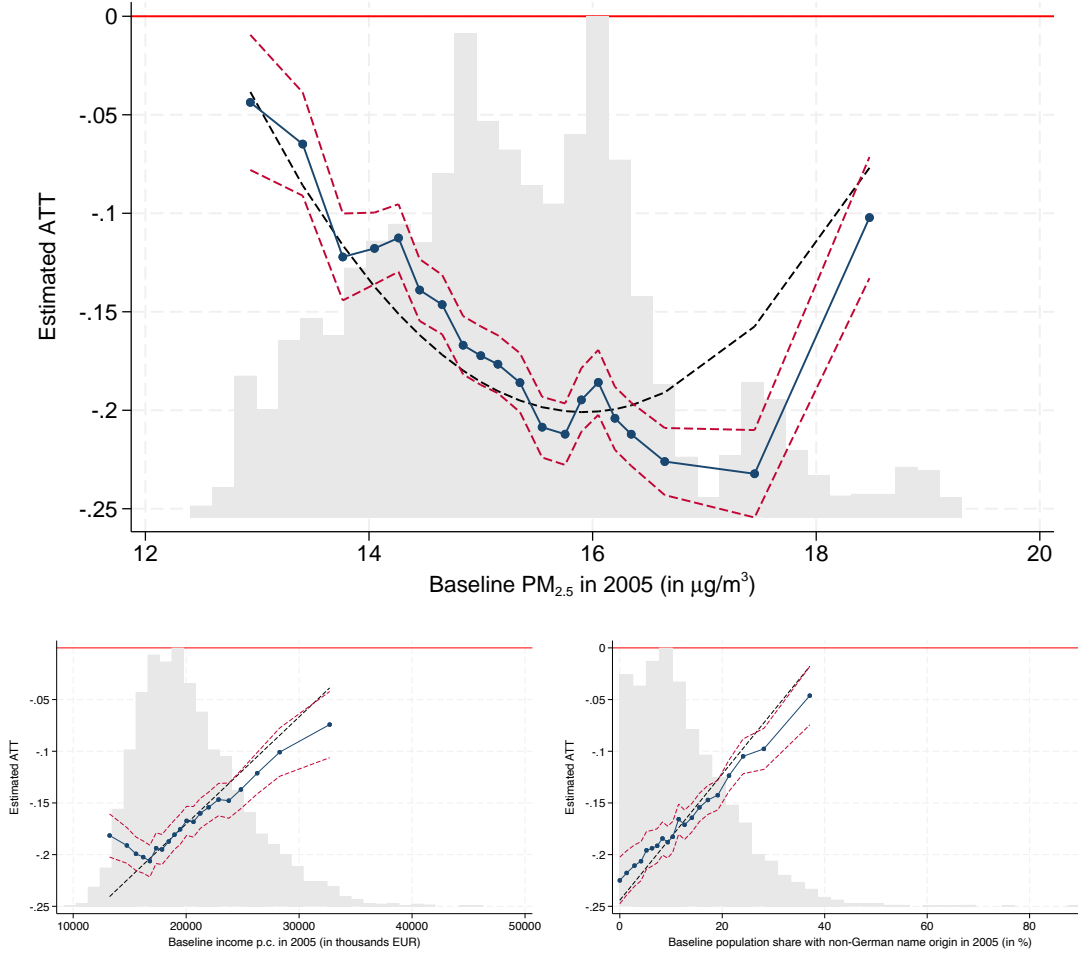
	(1)	(2)	(3)	(4)	(5)
LEZ	-0.159*** (0.007)	4.635*** (0.460)	-0.304*** (0.023)	-0.246*** (0.011)	4.132*** (0.463)
LEZ(x)PM25 ²⁰⁰⁵		-0.595*** (0.058)			-0.581*** (0.058)
LEZ(x)PM25 ²⁰⁰⁵ (x)PM25 ²⁰⁰⁵		0.018*** (0.002)			0.018*** (0.002)
LEZ(x)Income (in thousand EUR) ²⁰⁰⁵			0.007*** (0.001)		0.010*** (0.001)
LEZ(x)Non-German name origin ²⁰⁰⁵				0.006*** (0.001)	0.006*** (0.001)
N	102,476	102,476	102,476	102,468	102,476
Implied ATT	-0.159*** (0.007)	-0.152*** (0.007)	-0.155*** (0.007)	-0.152*** (0.007)	-0.138*** (0.007)
Sample	Matched	Matched	Matched	Matched	Matched
Pop. weighted	Yes	Yes	Yes	Yes	Yes

Notes: This table shows the effect of LEZs on air quality. Column 1 shows the average treatment effect of the treated from the introduction of LEZs on the annual PM_{2.5} concentrations in targeted areas. Columns 2–5 allow for heterogeneous treatment effects and include additional interaction terms with baseline PM_{2.5} in 2005, income, and ethnicity. Covariates include weather observations (air temperature, precipitation, and sunshine duration) as well as grid cell and year-fixed effects. The implied ATT is a linear combination of the coefficients and the respective mean values among the treated grid cells. It indicates the average treatment effect of the treated for the average treated grid cell. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

breaks down for the highest baseline PM_{2.5} vigintile, which however primarily includes grid cells in Berlin, and may thus capture a city-specific effect.

The bottom panels in Figure 3 show the heterogeneous treatment effects along baseline income and ethnicity. In line with the coefficients of Table 1, they illustrate a weaker predicted ATT for grid cells that are wealthier and for grid cells with a larger share of households with a non-German name origin. To differentiate between the impact of baseline pollution, income, and ethnicity (as proxied by name origin), the dashed black lines in Figure 3 show the predicted local ATTs for the respective interaction term only, holding the other two dimensions constant at the sample-wide mean. The fact that there are only small differences in the predicted ATTs (in black and blue respectively) suggests that the three dimensions capture fairly independent dimensions of effect heterogeneity.

Figure 3: Heterogeneous treatment effects of LEZ adoption on $PM_{2.5}$ levels.



Notes: This figure illustrates the heterogeneous treatment effects of LEZs along baseline $PM_{2.5}$ concentration, income, and the population share with a non-German name origin. The blue dots show the predicted average treatment effects for grid cells in each of the 20 baseline $PM_{2.5}$, income, and foreign ethnic share vigintiles. The predicted ATTs use the regression coefficients in Column 5 of Table 1 and the mean level for baseline $PM_{2.5}$, income, and the share of residents with a foreign ethnic background of each vigintile (i.e., the vigintile-mean levels). The dashed red lines show the corresponding 95% confidence intervals. To disentangle the impact of baseline pollution, income, and ethnicity, the dashed black line shows the predicted ATTs for the respective vigintiles, holding income and ethnicity constant at the sample-wide mean. The histogram in the background shows the distribution of the baseline $PM_{2.5}$ concentration of the treated grid cells.

4.2 Distributional analysis of air quality benefits from LEZ

After establishing that LEZs did result in air quality improvements, and that those improvements were quite heterogeneous, we now ask how the resulting benefits were distributed. To do that, we consider both the unequal exposure of various population groups to the policy (see Figure 1) and the heterogeneity of treatment effects along baseline pollution, income, and ethnicity (see Figure 3). We first quantify the distribution of traffic-related PM_{2.5} concentration reductions achieved by LEZs. Then we monetize these air quality improvements using official emission cost estimates from the German Environment Agency ([Umweltbundesamt, 2020](#)).

Air quality improvements from LEZs are unequally distributed

We convert the grid-cell-specific estimates of LEZ effects (Figure 3) to relative changes of population-weighted traffic-related PM_{2.5} exposure, following the source-attribution literature. Specifically, we use the gridded fractional source contribution shares of road transport among total particles from [McDuffie et al. \(2021\)](#). In Figure A3, we map the PM_{2.5} road contributions for Germany, which are 11 percent on average and range between 8 and 18 percent. The average traffic-related PM_{2.5} is $1.4 \mu\text{g}/\text{m}^3$ in the matched sample during our study period, while the observed average PM_{2.5} concentration is $13.7 \mu\text{g}/\text{m}^3$ (see Table A2). Adding to these the LEZ effect estimates gives us counterfactual traffic-related pollution levels in the absence of LEZs.⁷

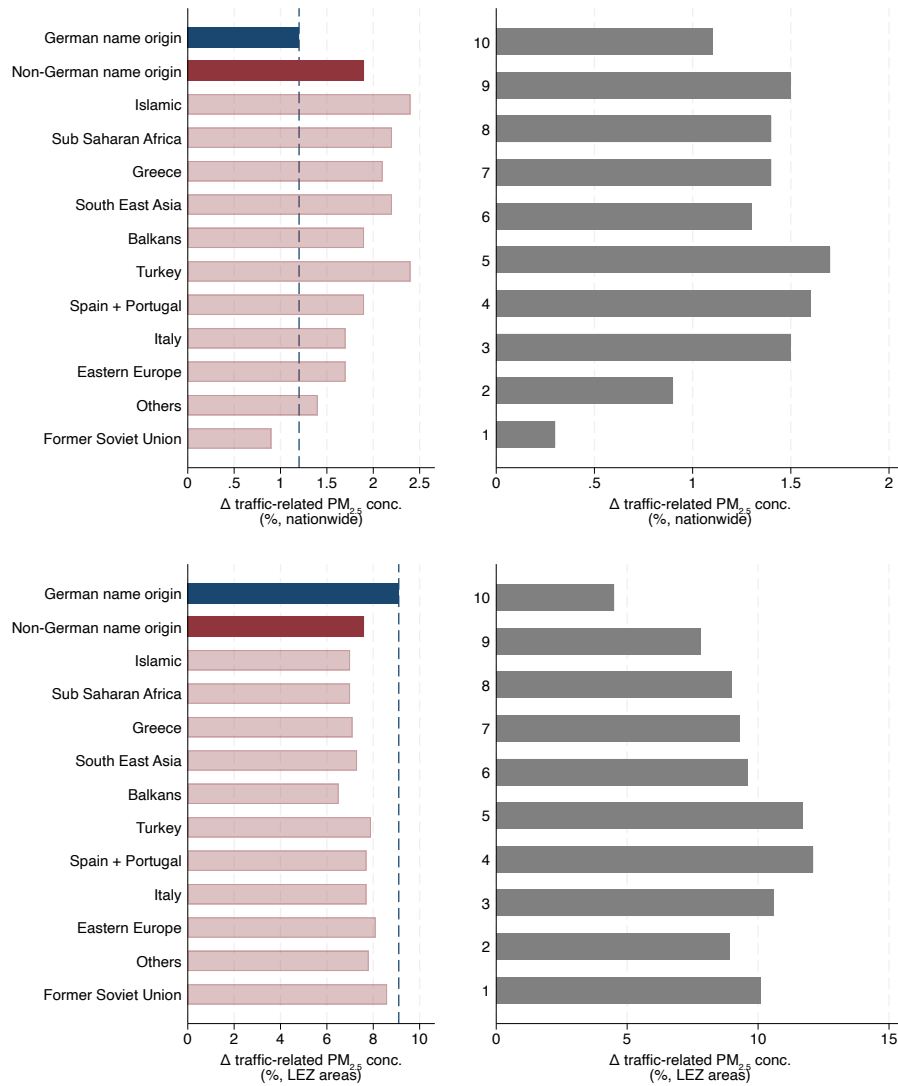
The motivation for singling out effects on traffic-related PM_{2.5} concentrations is twofold. Firstly, LEZ target road traffic emissions and it thus provides a more appropriate baseline to gauge effect size estimates. Secondly, damage cost estimates from ([Umweltbundesamt, 2020](#)) are provided separately by emission source, and we will use only the transport-related emission cost factors to calculate monetized benefits below.

Figure 4 shows the relative improvements in traffic-related PM_{2.5} exposure for different ethnic and income groups. The higher likelihood of being exposed to a LEZ among households with a non-German name origin translates into higher air quality improvements for this group nationwide (top left panel). For those with German names, LEZs improve the average traffic-related PM_{2.5} by 1.2 percent nationwide and for non-Germans by 1.9 percent. Almost all ethnic groups with a foreign origin benefit more than those with German names. A key explanation for this result is the higher concentration of non-German ethnic groups in large cities.

Within LEZs, however, German households receive the larger benefits (bottom left). Their traffic-related PM_{2.5} exposure decreases by 9.1 percent, while it decreases by 7.6 percent for

⁷Specifically, we calculate the local ATT for each grid cell, given the coefficients in Column 5 of Table 1 and each grid cell's baseline PM_{2.5} concentration, income, and ethnicity in 2005. We then add the local ATT to the observed traffic-related PM_{2.5} concentration to obtain the counterfactual pollution level. The relative change in traffic-related PM_{2.5} due to LEZ adoption is then simply given by the ratio between the observed and counterfactual PM_{2.5} concentration.

Figure 4: Improvements in traffic-related PM_{2.5} concentration by name origin and income.



Notes: The left panels show the population-weighted improvement in traffic-related PM_{2.5} exposure for different ethnic groups and the right panels for different income deciles. The top panels show the air quality improvements across Germany, and the bottom panels are for LEZ areas only. Differences in the policy exposure of LEZs, in baseline PM_{2.5} concentration, and stronger treatment effects in more polluted areas translate into unequal air quality improvements between population groups.

non-German households. Although the $PM_{2.5}$ exposure and average income are similar for Germans and non-Germans within LEZs (both $15.6\mu g/m^3$; and 20,100 and 19,300€, respectively), non-Germans often live in more ethnically diverse neighborhoods. While the average German household lives in a neighborhood where 12 percent are non-Germans, this share is 16 percent for the average non-German household, confirming older results on residential segregation by [Sager \(2012\)](#). Since we estimate smaller LEZ effects in more diverse neighborhoods (see Table 1), this translates into smaller improvements for non-Germans living in targeted areas.

Across income groups nationwide (top right panel), benefits are relatively flat among the top 80% of income earners. Although high-income groups are more exposed to the policy, middle-income groups face higher baseline pollution levels (see Figure 1), which translate into larger effects when a LEZ is introduced. The exception to the relatively flat distribution are the bottom two deciles who much less often live in cities large enough to benefit from a LEZ. Looking only within (bottom right), we observe that low-income households experience stronger reductions in traffic-related $PM_{2.5}$ concentration than high-income households. While the fourth income decile experiences reductions in traffic-related $PM_{2.5}$ concentration by up to 12.1 percent, the highest income decile experience the weakest reductions of 4.5 percent. This is again due to higher baseline pollution exposure of lower-income households which translates into larger treatment effects.

Overall, we find unequal air quality improvements across ethnic and income groups. Nationwide, residents with a non-German ethnic origin experience larger improvements, but this pattern is reversed within targeted areas. Across income deciles nationwide, improvements are smaller for low-income earners, who however experience larger improvements when they do live in targeted areas. Our explicit consideration of heterogeneous treatment effects along area characteristics (baseline pollution, income and ethnic shares) allowed us to uncover these patterns in ways that the prior literature, focused on average effects, could not. Our results highlight how population distributions can substantially shape the distributional effects of environmental policy.

Monetizing the air quality benefits of LEZs

Assessments of air pollution concentration changes are common in the LEZ literature, although our approach has added a focus on distribution and heterogeneity beyond the usual average effect estimates. In order to conduct meaningful distributional analysis in the tradition of welfare economics, however, it is important to translate air quality improvements into monetized benefits. To this end, we draw on official emission cost estimates from the German Environment Agency (UBA). Focusing specifically on road emissions, UBA estimates a cost of 255,300€ for each ton of $PM_{2.5}$ emitted in urban areas, 73,600€ in suburban areas, and 43,200€ in rural areas

(Umweltbundesamt, 2020). Before the policy, 48,000 tons of $PM_{2.5}$ had been emitted in 2005 from road transport (Umweltbundesamt, 2023). To approximate local $PM_{2.5}$ emissions from traffic in each grid cell, we assume that they are proportional to local annual traffic-related $PM_{2.5}$ exposure per person contained in our data. After multiplying the dedicated $PM_{2.5}$ cost estimates by the local $PM_{2.5}$ emissions in each grid cell, we estimate total damage of around 8.3 billion € or 101€ on average for each of the 82.2 million inhabitants per year between 2005 and 2021. In urban areas, the average damage costs of $PM_{2.5}$ emissions from traffic are 148€ per person and year; in suburban areas, 43€ per person and year; and in rural areas, 25€ per person and year.

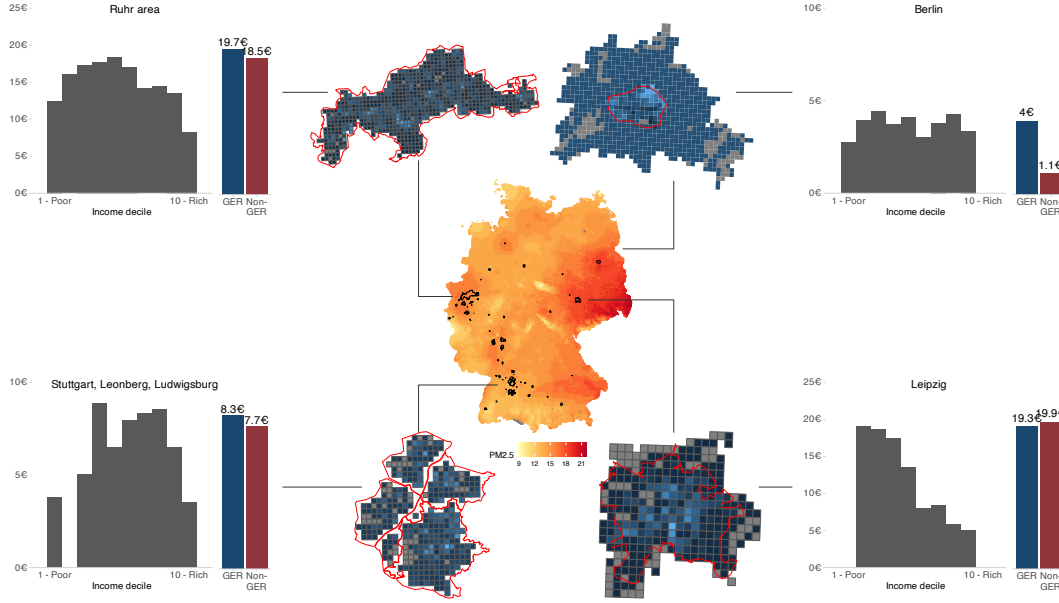
To monetize the local reduction in traffic-related $PM_{2.5}$ concentrations due to LEZ adoption, we also calculate the local $PM_{2.5}$ emission costs per person for the counterfactual traffic-related pollution levels in the absence of LEZs. By comparing the observed and counterfactual local emission costs, we can quantify the LEZ benefit in euros. Overall, we find a total benefit of 142 million €. That is 1.73 € on average per year across all residents in Germany, and 12.37 € per year for the average person living within a LEZ.

In Figure A6, we show the average LEZ benefits in euros for different ethnic and income groups. The patterns are very similar to Figure 4, but the units are in euros.⁸ We also explore how benefit estimates change once we adjust the local $PM_{2.5}$ emission costs to income. While the official pollution cost estimates by the UBA are provided at the aggregate level and thus do not vary by income (i.e., implicitly assuming an income-elasticity η of zero),⁹ we also consider a situation where $PM_{2.5}$ damages increase in proportion to income (i.e., assuming an income elasticity η of one). Doing so raises benefits for people with a higher income and lowers them for people with a lower income, all else equal. For the baseline scenario of $\eta = 0$, we find that nationwide, German residents receive, on average, a benefit of 1.7 € and non-Germans of 2.7€ per year. Within targeted areas, this pattern changes, and Germans experience an improvement worth 12.6 € and non-Germans 10.7 €. Across income groups, benefits range between 0.4 and 2.3 € nationwide, and between 6.0 and 16.8 € in targeted areas. For $\eta = 1$, results are more nuanced and polarize the distribution of benefits, especially across income deciles. Which choice of η is appropriate will depend on the use case and normative stance adopted, and may well alter the classification of the policy as pro- or regressive, as we show below.

⁸Slight differences between Figure A6 and 4 are primarily due to different UBA cost estimates between urban, suburban, and rural areas.

⁹It is a common choice in governmental guidelines to consider health damages as equally important within a country irrespective to how rich or poor an individual is that the damage accrues to. This “normative” practice of using an income elasticity of the value of a statistical life of $\eta = 0$ contrasts with “descriptive” evidence that the elasticity is oftentimes close to unity (e.g., Viscusi and Masterman, 2017).

Figure 5: Local distribution of LEZ benefits.



Notes: This figure shows the local distribution of LEZ benefits for selected cities and LEZs. The LEZ Ruhr area and Berlin are the most populated, while the LEZs in Stuttgart, Leonberg, Ludwigsburg and Leipzig are smaller. For each area, the histograms show the distribution of monetized benefits across income deciles, and between individuals with a German or non-German ethnic origin. The map highlights that local population distributions and residential sorting shape the distribution of benefits across population groups.

Disaggregating LEZ-induced pollution reduction benefits

So far, we have pooled the benefits of the LEZ introduction across cities and LEZs, focusing on the overall distribution across ethnic and income groups. However, our high resolution data and the estimated heterogeneous treatment effects enable us to go further and look into single cities.

In Figure 5, we show the local LEZ improvements across income deciles and ethnic groups for a selection of cities and LEZs (with the official base case assumption that benefits from pollution reductions do not scale with income, i.e. $\eta = 0$). Among these cities are the two most populated LEZs (Ruhr area and Berlin). We observe that most LEZs tend to have higher benefits for German residents, which aligns with the pattern in Figure A6. A notable exception is, however, Leipzig, where non-German residents receive larger benefits than those with German names. While benefits are relatively similar across income deciles in Berlin, most of the benefits are received by people in the lowest income deciles in Leipzig. While individual city-level case studies are beyond the scope of this paper, the substantial variation in Figure A6 showcases that local population distributions and characteristics are crucial in determining the distribution of benefits.

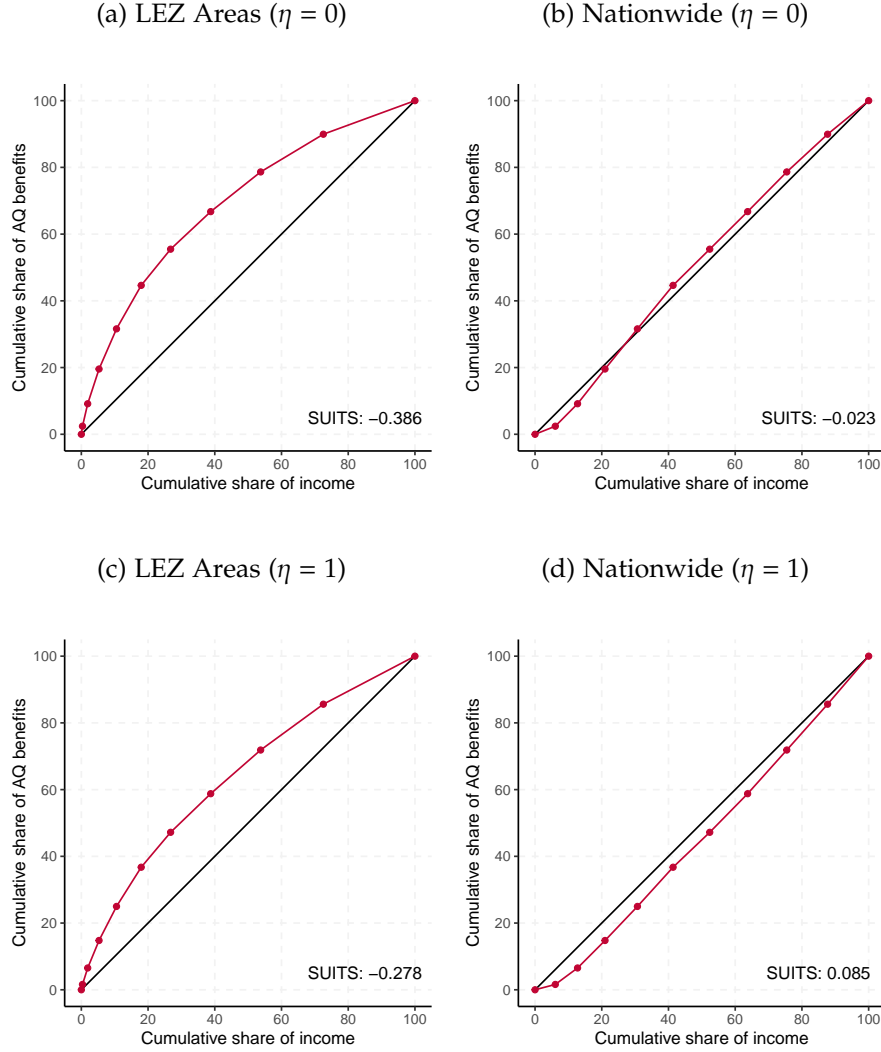
Air quality benefits within LEZ are distributed pro-poor

The observed distribution of benefits across income deciles in Figures A6 and 5 leads to the question of how progressive or regressive benefits are distributed. We explore the progressivity of monetized air quality benefits as final step of our analysis. In Figure 6, we plot the cumulative share of air quality benefits against the cumulative share of income for the ten income deciles. An advantage of this visualization is that it incorporates differences in income levels across deciles. For example, the first three income deciles only compromise 20 percent or less of total income. However, they receive more than 20 percent of the air quality benefits, both within LEZs (Panel a) and nationwide (Panel b). Results are considerably different between these two spatial scales for intermediate income levels. For instance, the lower five income deciles in LEZ areas, which make up around 20 percent of the total income in targeted areas, receive more than 50 percent of the benefits (Panel a). By contrast, while the lower five deciles nationwide exhibit a similar accumulated share of air benefits within LEZs, they make around 50 percent of the total income (Panel b). Taken together, visual inspection suggests that LEZ-induced air quality benefits may be more pro-poor within targeted areas than nationwide.

In order to quantify the pro-/regressivity of the air quality benefits, we calculate the Suits index (Suits, 1977). The Suits index ranges between -1 and 1. A negative index indicates that benefits are distributed pro-poor (here termed “progressive benefits”), and a positive index indicates that benefits accrue disproportionately to richer parts of the population (“regressive benefits”). Nationwide, we find a Suits index of -0.023 and within LEZ areas of -0.386 when computing benefits with the assumption that benefits do not increase along income ($\eta = 0$) as implicit in official guidelines. In Figure A7, we show the distribution of city-specific Suits indices, which range between -0.54 (Eschweiler) and 0.09 (Munich). Except for Munich and Mühlacker, where the benefits are regressively (pro-rich) distributed, they are progressive in all other 56 LEZs. This clearly speaks towards a progressive (pro-poor) distribution of the benefits within LEZ areas. That remains true even when we assume the larger income elasticity of pollution damages ($\eta = 1$) which results in a less pronounced (Suits Index of -0.278) but still very clear benefit progressivity (pro-poor distribution of benefits) within LEZs.

By contrast, we find that the distributional effect of LEZs from a nationwide perspective depends on how benefits scale with income. For a common descriptive assumption, in which WTP for air quality improvements increases proportionally with income ($\eta = 1$), we find a small positive Suits index (0.085), suggesting a relatively neutral albeit slightly regressive (pro-rich) distribution of benefits.

Figure 6: SUITS indices of LEZ-induced air quality benefits.



Notes: All figures indicate the distribution of the air quality benefits on the national level and within LEZ areas along income. The top panels consider an income elasticity of air pollution reduction benefits that do not differ across income levels ($\eta = 0$), as in the official German cost guidelines, and the bottom panels consider that benefits increase in proportion with income ($\eta = 1$), which is more closely aligned with empirical evidence. The figures show the accumulated share of air quality benefits along the accumulated share of income. This takes into account that the lower income deciles contribute disproportionately to the total income. The 45° line would represent a proportional policy that gives the same share of accumulated benefits to the same share of income. As the lower income groups receive a larger share of the benefits, air quality benefits due to the introduction of LEZs are distributed pro-poor within LEZ areas, but distributional effects depend on the income elasticity when assessed from a nation-wide perspective.

5 Discussion and Conclusion

This paper provides a first systematic account of the distribution of the pollution-reduction benefits generated by low emission zones (LEZ) across Germany—the key policy tool following the EU Clean Air Directive to reduce air pollution across European cities. Estimating grid-cell-specific treatment effects and monetizing air pollution changes using damage cost estimates between 2008 and 2021, we find a nuanced distribution of the air quality benefits shaped by population distributions as well as effect and appraisal heterogeneity. Looking at ethnic groups, we find that residents with non-German names benefited more from air quality improvements nationwide, mainly because they are over-represented in cities that adopt LEZs. Within targeted areas, however, it is residents with German names who benefit relatively more. The distribution across income levels is clear-cut within LEZ areas. We find that air quality improvements are relatively higher for low-income deciles, and that the monetized benefits are distributed highly pro-poor. However, we show that the distribution of benefits nationwide depends on how benefits are assumed to scale with income.

Our findings are subject to a number of limitations that we discuss below. Firstly, we use gridded data sources for both air pollution levels and population distributions, both of which are produced using interpolation methods. Those data sources are routinely used in the literature, and we are not aware of systematic biases that may affect our results, although the possibility remains. While we document and quantify important differences in the pollution and policy exposure of various ethnic and income groups, an investigation of the underlying mechanisms that explain unequal policy exposure and effect heterogeneity is beyond the scope of this paper.¹⁰

In addition, we only consider policy benefits that are reflected in the official cost estimates by the German Environment Agency. While they reflect predominantly health effects, we cannot make statements on the distributional impacts of LEZs in other domains, such as housing markets, worker productivity, or well-being, more broadly. This implies that the total monetized benefits from LEZs—which we estimate to be 12.37 € per year for the average person living within a LEZ—may well be higher than our estimate that is based on official cost estimates from the German Environment Agency ([Umweltbundesamt, 2020](#)). Moreover, despite the disaggregation of PM_{2.5} pollution damages between urban, suburban, and rural areas, these cost estimates remain fairly aggregated. Pollution damages are, however, likely heterogeneously distributed and non-linear across further aspects such as age and health vulnerabilities. To better investigate the distribution of LEZ-induced pollution reductions along these lines, more refined cost estimates would be needed.

¹⁰A separate strand of the literature focuses particularly on the mechanisms and is reviewed, for example, by [Banzhaf et al. \(2019a\)](#) and [Cain et al. \(2024\)](#).

Another important caveat is that we are focusing only on the benefits side of the equation, without quantifying the costs. LEZs will have generated at least some administrative costs. Moreover, any induced shift in consumer or firm behavior—altering transport modes, replacing older vehicles, and driving around LEZs—imply additional costs (see, e.g., [Wolff, 2014](#); [Aydin et al., 2024](#)). And driving restrictions may have also an effect on local economies, such as reduced local consumer spending ([Galdon-Sanchez et al., 2023](#)). We do not have reliable data for most of these. However, we do replicate our main estimation approach that we employ for pollution reductions also for two variables in the RWI-GEO-GRID dataset that measure local economic performance: purchasing power per grid cell resident and the unemployment rate. The results shown in Table A5 suggest that LEZ adoption may have been linked to a reduction in per capita income and an increase in local unemployment rates. However, we interpret these results with caution and leave a systematic analysis of the costs arising from LEZ adoption for future research.

Despite these limitations, we believe that our results highlight the important role of local population distributions and residential sorting in shaping the distribution of environmental policy benefits. Policy analysts and makers might wish to more actively consider those aspects when designing new regionally targeted air quality regulations such as LEZs. In the specific case of German LEZs, our analysis suggests that benefits are distributed pro-poor along the income dimension within LEZs, but results are less clear-cut when assessed from a nationwide perspective. When considering our proxy of ethnic origin, we find that while benefits accrue disproportionately to Germans when assessed within LEZs, they accrue disproportionately to persons with non-German names at a nationwide level. Thus, while our findings showcase that environmental policy can be both effective and equitable when solely income is considered, our analysis yield overall more nuanced Environmental Justice implications of LEZs.

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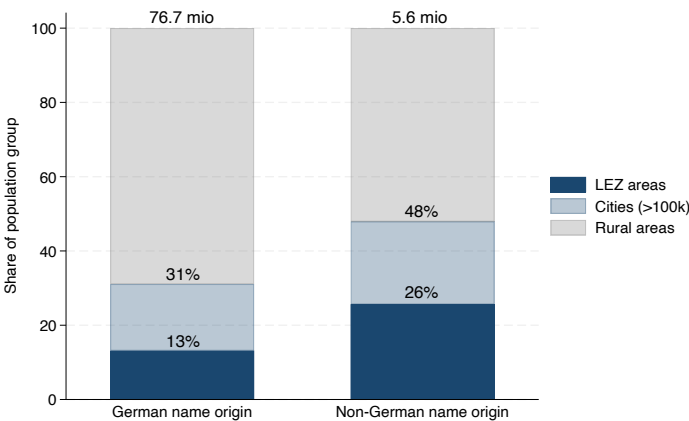
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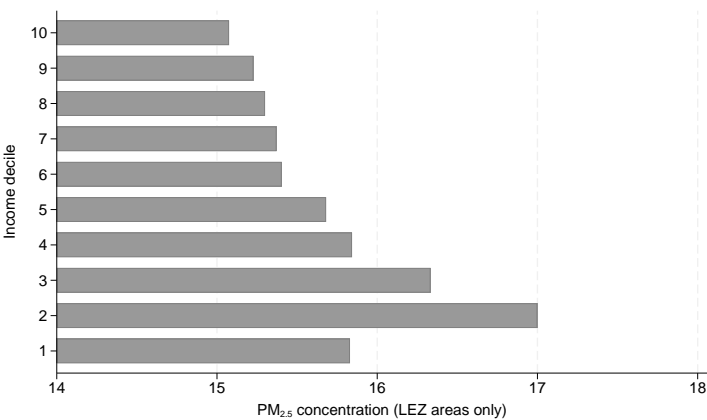
Appendix

Figure A1: Population share living in large cities and LEZ areas by ethnic origin.



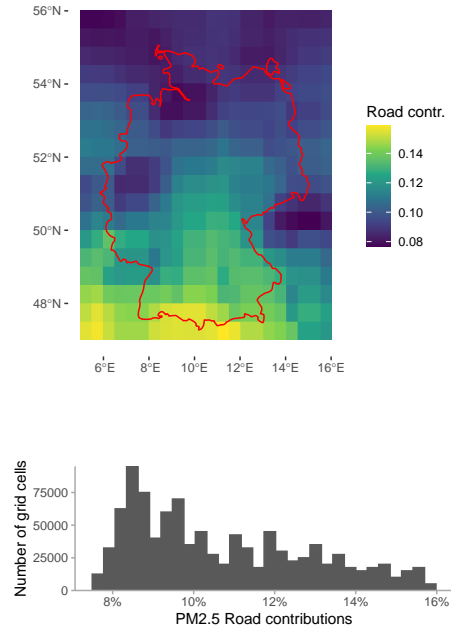
Notes: This figure shows the share of Germans and non-Germans that live in LEZ areas, cities with a population of more than 100,000 inhabitants, and those living in rural areas. On average, there are relatively more non-Germans living in urban areas than in rural areas.

Figure A2: Baseline PM_{2.5} pollution disparities by income within (future) LEZs.



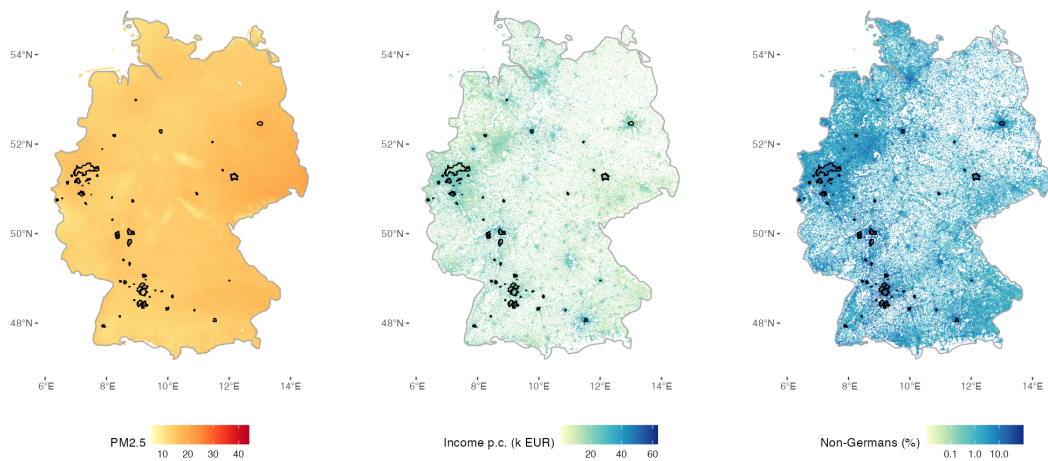
Notes: This figure shows the average baseline PM_{2.5} concentration in 2005 in future targeted areas. Within LEZs, high-income households usually live in cleaner neighborhoods.

Figure A3: PM_{2.5} concentration contributions from road traffic.



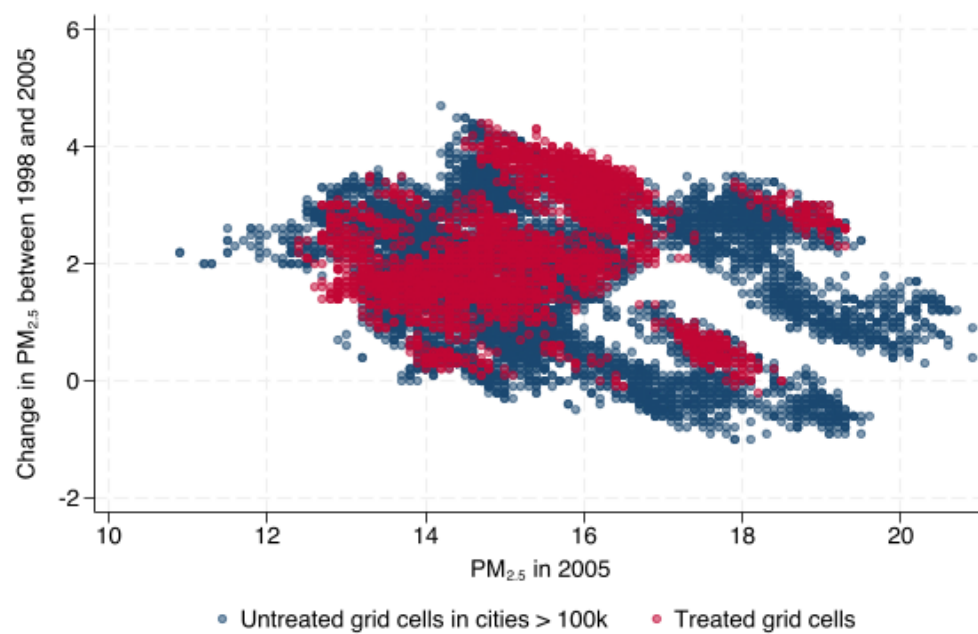
Notes: This figure shows the PM_{2.5} concentrations that are attributable to road traffic. Data is taken from [McDuffie et al. \(2021\)](#).

Figure A4: PM_{2.5} concentration, income, and ethnic distribution in Germany in 2005.



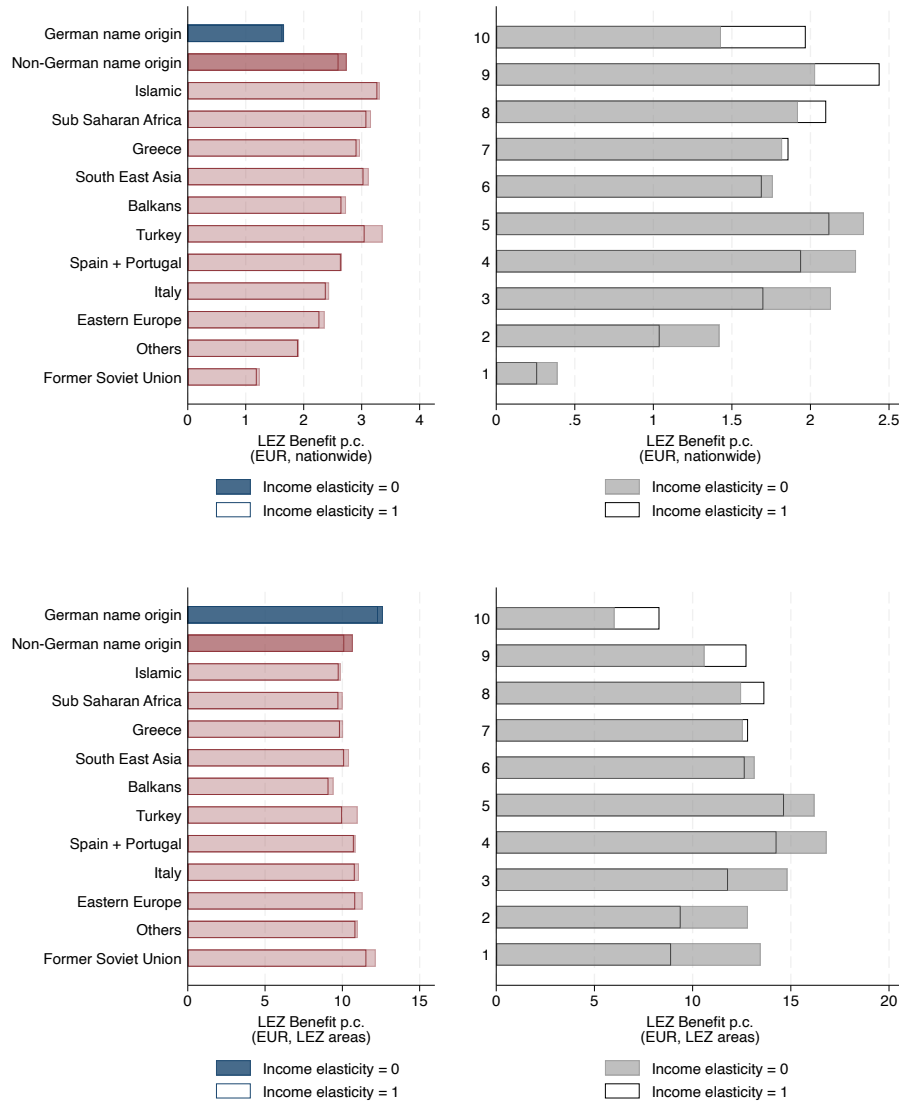
Notes: This figure maps the baseline PM_{2.5} concentration from ([van Donkelaar et al., 2021](#)), the LEZ boundaries, and the income and ethnic distribution from ([RWI microm, 2020](#)) before the LEZ introduction in 2005.

Figure A5: Balance check between treated and untreated grid cells in city sample.



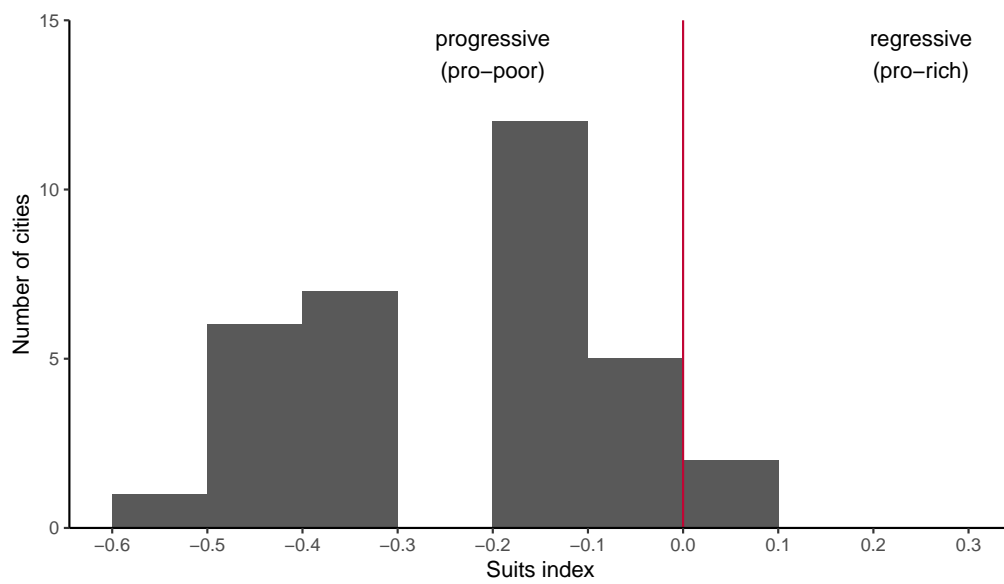
Notes: This figure shows the baseline PM_{2.5} concentration in 2005 and the change in PM_{2.5} concentration between 1998 and 2005 for treated and untreated grid cells in the city sample. We observe strong similarities which confirm balance between both groups

Figure A6: Improvements in traffic-related PM_{2.5} concentration by ethnicity and income in euro.



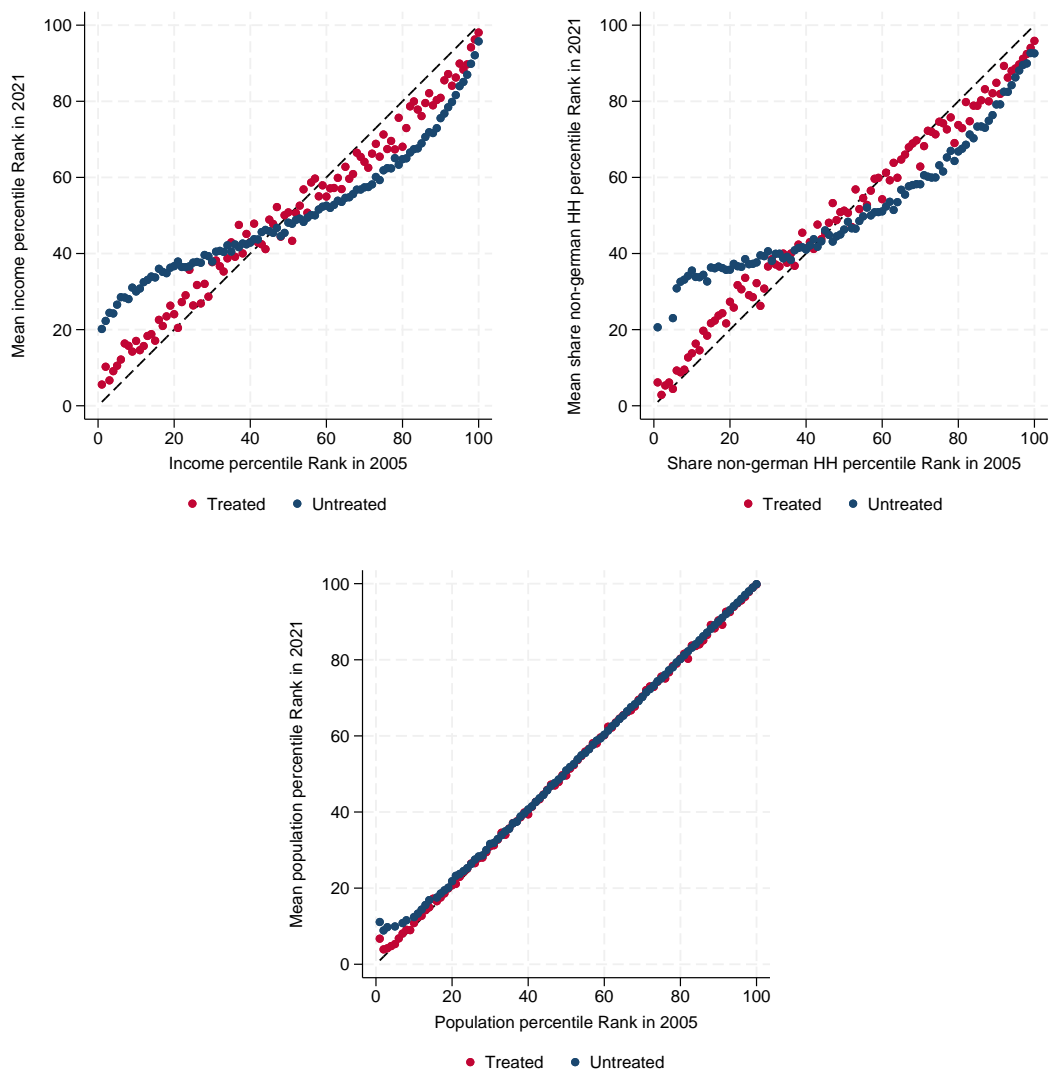
Notes: The left panels show the population-weighted improvement in traffic-related PM_{2.5} exposure in euro for different ethnic groups. The right panels show them for different income deciles. The top panels show the benefits across Germany, and the bottom panels are for LEZ areas only. We assume that local PM_{2.5} emissions are proportional to the local PM_{2.5} concentration and apply the official cost estimates for PM_{2.5} emissions from the German Environment Agency to monetize the air quality improvements. Differences in the policy exposure of LEZs, in baseline PM_{2.5} concentration, and the stronger treatment effects in more polluted areas translate into unequal benefits between population groups. Finally, we also explore how benefits change once we adjust the local PM_{2.5} emission costs to income and apply an income-elasticity (*eta*) of one instead of zero.

Figure A7: Distribution of Suits index.



Notes: This figure shows the distribution of the city-specific Suits indices. Except for Hannover (not shown due to an outlier) and Munich, the benefits from air quality improvements are progressively (pro-poor) distributed in all other 56 LEZs.

Figure A8: Compositional changes in the city sample.



Notes: This figure explores changes in the composition of grid cells with respect to income, ethnicity, and population. Between 2005 and 2021, low-income grid cells moved slightly up in the income distribution and high-income grid cells slightly down. This trend is similar between treated and untreated grid cells and reflects a slight reduction in income inequality over time. With respect to ethnicity, we do not observe strong changes in the composition of grid cells. The share of non-Germans in any given grid cell was similar in 2005 and 2021. Similarly, we do not observe big population movements between 2005 and 2021, as the population percentile rank in 2021 is almost the same as in 2005 for all grid cells.

Figure A9: Pollution trends.

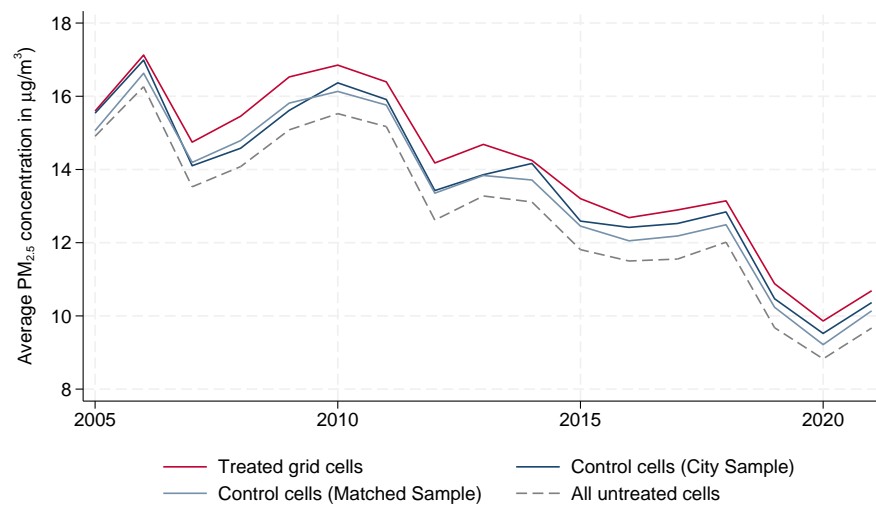


Table A1: Descriptive statistics of the city grid sample.

	N	Mean	SD	Min	Max
Year	199,223	2013.00	4.90	2005	2021
PM _{2.5} (µg/m ³)	199,223	13.69	2.52	6.7	21.4
Traffic-related PM _{2.5} (µg/m ³)	199,223	1.38	0.30	0.6	2.5
<i>LEZ information</i>					
LEZ (at any time)	199,223	0.28	0.45	0	1
LEZ (currently in place)	199,223	0.18	0.39	0	1
<i>Weather observations</i>					
Avg. Temperature (°C)	199,223	10.40	0.92	6	13
Total precipitation (mm)	199,223	724.34	164.87	267	1,765
Total sunshine duration (h)	199,223	1,693.30	170.23	1,326	2,294
<i>Population information</i>					
Inhabitants	163,932	2,313.79	2,918.87	0	27,098
Income per capita (in 2005)	199,223	21,446.59	5,035.81	7,855	46,278
Unemployment rate (in 2005)	199,223	7.82	5.59	0	29
City with more than 100k inhabitants	199,223	1.00	0.00	1	1
<i>Inhabitants with an ethnic origin from...</i>					
Germany (%)	164,027	84.77	14.08	7	100
Italy (%)	164,027	0.92	0.83	0	10
Turkey (%)	164,027	2.93	3.80	0	62
Greece (%)	164,027	0.59	0.58	0	10
Spain or Portugal (%)	164,027	0.34	0.32	0	6
Balkans (%)	164,027	1.92	2.52	0	52
Eastern Europe (%)	164,027	2.31	3.00	0	35
Sub-Saharan Africa (%)	164,027	0.31	0.33	0	4
Islamic country (%)	164,027	2.34	3.77	0	43
South East Asia (%)	164,027	0.34	0.78	0	22
Other countries (%)	164,027	1.61	1.14	0	17
Former Soviet Union (%)	164,027	1.61	2.64	0	27
Observations	199,223				

Notes: This table shows descriptive statistics for the city grid sample. The city grid sample includes grid cells in cities with more than 100,000 inhabitants and all grid cells treated with a LEZ. The study period ranges from 2005 to 2021.

Table A2: Descriptive statistics of the matched grid sample.

	N	Mean	SD	Min	Max
Year	102,476	2013.00	4.90	2005	2021
PM _{2.5} (µg/m ³)	102,476	13.74	2.56	6.8	22.3
Traffic-related PM _{2.5} (µg/m ³)	102,476	1.40	0.29	0.6	2.7
<i>LEZ information</i>					
LEZ (at any time)	102,476	0.55	0.50	0	1
LEZ (currently in place)	102,476	0.36	0.48	0	1
<i>Weather observations</i>					
Avg. Temperature (°C)	102,476	10.54	0.92	5	13
Total precipitation (mm)	102,476	724.89	153.94	281	1,995
Total sunshine duration (h)	102,476	1,696.58	170.85	1,286	2,294
<i>Population information</i>					
Inhabitants	84,304	3,015.02	3,384.15	0	24,961
Income per capita (in 2005)	102,476	20,829.89	5,528.95	7,111	61,875
Unemployment rate (in 2005)	102,476	8.52	5.85	0	38
City with more than 100k inhabitants	72,607	1.00	0.00	1	1
<i>Inhabitants with an ethnic origin from...</i>					
Germany (%)	84,375	83.87	14.51	15	100
Italy (%)	84,375	1.03	0.88	0	10
Turkey (%)	84,375	3.39	4.09	0	62
Greece (%)	84,375	0.67	0.65	0	10
Spain or Portugal (%)	84,375	0.36	0.32	0	4
Balkans (%)	84,375	2.17	2.74	0	34
Eastern Europe (%)	84,375	2.25	2.81	0	25
Sub-Saharan Africa (%)	84,375	0.32	0.33	0	4
Islamic country (%)	84,375	2.46	4.06	0	31
South East Asia (%)	84,375	0.38	0.81	0	19
Other countries (%)	84,375	1.58	1.04	0	12
Former Soviet Union (%)	84,375	1.50	2.43	0	23
Observations	102,476				

Notes: This table shows descriptive statistics for the matched grid sample. The matched grid sample includes control grid cells with similar pollution trends and levels prior to 2005, similar number of inhabitants and unemployment rates, as well as all grid cells treated with a LEZ. The study period ranges from 2005 to 2021.

Table A3: Balance test after matching.

	PM _{2.5} concentration		Inhabitants	Income	Unemployment
	Δ 1998-2005 (1)	in 2005 (2)	in 2005 (3)	in 2005 (4)	in 2005 (5)
Treated	-0.040 (0.025)	-0.065* (0.040)	374.727*** (102.487)	-832.233*** (150.707)	0.158 (0.155)
Observations	6,040	6,040	6,040	6,040	6,040
Treated	3293	3293	3293	3293	3293
Untreated	2747	2747	2747	2747	2747

Notes: This table shows OLS results. The matching aims to achieve balance on the PM_{2.5} concentration in 2005, the change in PM_{2.5} concentration between 1998 to 2005, the number of inhabitants in 2005, the average income per capita in 2005, and the unemployment rate in 2005. Standard errors are shown in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A4: LEZ effect on PM_{2.5} using the city sample.

	(1)	(2)	(3)	(4)	(5)
LEZ	-0.140*** (0.005)	5.936*** (0.402)	-0.322*** (0.020)	-0.250*** (0.010)	5.216*** (0.405)
LEZ(x)PM25 ²⁰⁰⁵		-0.765*** (0.051)			-0.740*** (0.051)
LEZ(x)PM25 ²⁰⁰⁵ (x)PM25 ²⁰⁰⁵		0.024*** (0.002)			0.024*** (0.002)
LEZ(x)Income (in thousand EUR) ²⁰⁰⁵			0.009*** (0.001)		0.014*** (0.001)
LEZ(x)Non-German name origin ²⁰⁰⁵				0.007*** (0.001)	0.008*** (0.001)
N	199,223	199,223	199,223	199,216	199,223
Implied ATT	-0.140*** (0.005)	-0.130*** (0.005)	-0.135*** (0.005)	-0.131*** (0.005)	-0.112*** (0.006)
Sample	City	City	City	City	City
Pop. weighted	Yes	Yes	Yes	Yes	Yes

Notes: This table shows the effect of LEZs on air quality. Column 1 shows the average treatment effect of the treated from the introduction of LEZs on the annual PM_{2.5} concentrations in targeted areas. Columns 2–5 allow for heterogeneous treatment effects and include additional interaction terms with baseline PM_{2.5} in 2005, income, and ethnicity. Covariates include weather observations (air temperature, precipitation, and sunshine duration) as well as grid cell and year-fixed effects. The implied ATT is a linear combination of the coefficients and the respective mean values among the treated grid cells. It indicates the average treatment effect of the treated for the average treated grid cell. Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

Table A5: LEZ effect on income and unemployment.

	Income per capita		Unemployment rate	
	(1)	(2)	(3)	(4)
LEZ	-380.993*** (18.869)	-216.600*** (26.708)	0.601*** (0.016)	2.577*** (0.028)
LEZ(x)Income (in thousand EUR) ²⁰⁰⁵		-0.001*** (0.000)		
LEZ(x)Unemployment ²⁰⁰⁵				-0.181*** (0.002)
Constant	23644.095*** (355.050)	23568.338*** (354.987)	16.774*** (0.295)	18.162*** (0.284)
N	84,102	84,102	84,379	84,379
Implied ATT	-380.993*** (18.869)	-430.862*** (19.713)	0.601*** (0.016)	0.680*** (0.015)

Notes: This table shows the effect of LEZs on income per capita and unemployment. Columns 1 and 3 show the average treatment effect of the treated from the introduction of LEZs on the income and unemployment rate. Columns 2 and 4 allow for heterogeneous treatment effects. Covariates include weather observations (air temperature, precipitation, and sunshine duration) as well as grid cell and year-fixed effects. The implied ATT is a linear combination of the coefficients and the respective mean values among the treated grid cells. It indicates the average treatment effect of the treated for the average treated grid cell. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.