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ABSTRACT

Greener Fleet, Cleaner Air: How Low Emission Zones Reduce Pollution*

Using a stacked differences-in-differences approach, we study the effects of Low Emission Zones (LEZs) in Germany. The implementation of stage 1 and 2 LEZs, which banned the most pollution-intensive vehicles from city centers, significantly reduced PM10 concentrations. The most restrictive third stage had no detectable, additional effect. Analyzing the mechanisms behind these improvements, we find weak evidence of a 2% traffic decline inside LEZs. Exploiting novel data, our main results document small but precisely estimated effects on the local fleet composition: LEZs induced the replacement of 50,000 older, emission-intensive diesel vehicles with newer, less polluting gasoline cars. Our estimates suggest that LEZs had lower social costs than previously estimated.

JEL Classification: Q52, Q53, Q58, R40

Keywords: low emission zones, vehicle fleet composition, emission standards, social costs, diesel cars

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1 Introduction

Air pollution is detrimental for health and productivity (Neidell, 2004; Currie and Walker, 2011; Zivin and Neidell, 2012; Chang et al., 2016, 2019). Responding to concerns about poor air quality, numerous cities worldwide have implemented policies to reduce traffic pollution. While some jurisdictions rely on price mechanisms in the form of congestion charges (Leape, 2006; Simeonova et al., 2021), more than 300 cities in Europe as well as numerous metropolitan areas in Asia and South America introduced Low Emission Zones (LEZs). Studies document that LEZs, which effectively ban cars with sub-par emission standards from entering city centers, improved air quality and health outcomes (e.g., Margaryan, 2021; Pestel and Wozny, 2021; Beshir and Fichera, 2022; Galdon-Sanchez et al., 2022; Klauber et al., 2024). The mechanisms shaping these benefits – declining traffic volumes and improvements in the vehicle fleet – have received little attention (Wolff, 2014), even though they are crucial for assessing the social costs of LEZs. This short paper aims to address this gap in the literature.

We study the effects of LEZs in Germany, where more than 70 cities have introduced zones with different stringency stages: stage 1 LEZs banned vehicles with the lowest ('Euro 1') emission standard; stage 2 and 3 LEZs also restricted vehicles meeting higher standards (Euro 2 and 3, respectively). Using a stacked difference-in-differences approach (similar to Cengiz et al., 2019), we separately estimate the impact of LEZs with different stringency levels on three sets of outcomes. First, we re-examine particulate matter (PM_{10}). Confirming results obtained from conventional two-way fixed effects (TWFE) estimates, we find that LEZs significantly reduced PM_{10} concentrations. As a novel contribution, our estimates indicate that this effect is primarily driven by stage 1 and 2 LEZs: the former caused a 0.8 $\mu g/m^3$ (3% relative to the control group mean), the latter an additional 1.0 $\mu g/m^3$ (4%) decline in PM_{10}. We do not detect any additional effect from increasing the stringency of LEZs to stage 3.

Second, turning to the potential mechanisms behind air quality improvements, we study traffic volumes. Our analyses provide some evidence suggesting that stage 1 and 2 LEZs induced a 2% drop in traffic. These estimates, however, are less precise. In contrast to particulate matter concentrations, which decline inside and outside of LEZs, adjustments in traffic volumes are concentrated inside the boundaries of the LEZs.

Third, we examine the composition of the local vehicle fleet. Leveraging novel administrative data, we evaluate whether LEZs accelerated the replacement of older, heavily polluting vehicles with newer, cleaner cars. Our results document small but precisely estimated changes in the local fleet composition: while we do not detect any impact on the total vehicle stock, LEZs reduced the market share of 'targeted' vehicles: the implementation of stage 1, 2 and 3 LEZs caused a decline in the share of Euro 1, 2 and 3 cars, respectively. Importantly, these effects are concentrated among diesel cars. We also find effects on 'non-targeted' cars (e.g., stage 1 LEZ lowered the share of Euro 2 diesel cars). Summing up all effects, each of the three LEZ stages contributed to a 0.3 to 0.5 percentage point (3–5%) decline in the share of Euro 1–3 diesel cars. Finally, our results indicate that old diesel cars were mainly replaced with modern gasoline cars (with the Euro 4 or higher standards). We document that this replacement pattern reduces average tailpipe PM_{10} emissions per kilometer by 94–98%. Hence, the seemingly small changes in the fleet composition caused by the LEZs are arguably the main channel behind the observed drop in PM_{10} concentrations. The small effect sizes also mean that the social costs associated with vehicle upgrades are smaller than previously assumed in the literature.

Our main contribution is providing comprehensive, causal evidence on the impact of local pollution policies on the composition of the local car fleet.[1] We thus complement studies that focus on health outcomes (e.g., Beatty and Shimshack, 2011). Using new, monthly data on precisely defined subgroups of cars, our analysis offers a more refined picture of the changes in the local fleet composition than prior work. Margaryan (2021), for instance, reports TWFE estimates that use annual data (pooling diesel and gasoline cars). She finds no effects on Euro 2 and 3 cars. Similarly, Klauber et al. (2024) only find effects on annual Euro 1 diesel car stocks. Our estimates, in contrast, reveal small but precisely estimated (LEZ-stage specific) effects on Euro 1, 2 and 3 diesel cars. Expanding our analysis, we are also the first to examine interactions between LEZs and Germany's large car scrapping program from 2009 (akin to the US' 'cash-for-clunkers' program). We only find weak evidence on interactions. The data suggests that the scrapping program and (stage 1) LEZs independently affected the vehicle market.

We also contribute to the literature by moving beyond traditional TWFE estimates that exploit the staggered roll-out of LEZs. Accounting for concerns raised in the modern diff-in-diff liter-

[1] Börjesson et al. (2012) and Ellison et al. (2013) offer descriptive evidence on changes in the car fleets.

ature (De Chaisemartin and d'Haultfoeuille, 2020; Goodman-Bacon, 2021), we deploy a stacked diff-in-diff approach (in the spirit of Cengiz et al., 2019; Fadlon and Nielsen, 2019; Butters et al., 2022) that allows us to estimate the effects from the changes in treatment stringency. The latter point distinguishes our work from Klauber et al. (2024), who use a stacked diff-in-diff approach, too, but do not separately analyze the different LEZ stages. Finally, we provide new evidence on the way LEZs affected traffic volumes. Our data are consistent with small declines in overall traffic but also in heavy-duty vehicle traffic. The latter finding – which complements Zhai and Wolff (2021) analysis of London's LEZ – is consistent with Sarmiento et al. (2023)' result, documenting a stronger PM_{10} decline during working days.

2 Background

When local pollution levels persistently exceed limits regulated by the EU, German states are legally obliged to develop 'Clean Air Plans' for these municipalities. A key policy measure frequently proposed in these plans is the introduction of a LEZ, which bans emission-intensive vehicles from designated areas within a municipality (typically city centers). Different layers of government then decide about the timing of a LEZ introduction, the spatial coverage, and its restrictiveness: stage 1 LEZs ban the most emission-intensive vehicles with the Euro 1 emission class. Stage 2 and 3 LEZs also target vehicles meeting the Euro 2 and 3 standard, respectively.[2] In practice, LEZs are enforced based on colored windscreen stickers, where red, yellow and green stickers indicate that a vehicle fulfills the Euro 2, 3 and 4 standards, respectively. Euro 1 cars do not get a sticker. Illegally entering a LEZ is punished with fines and demerit points which can result in driving license suspensions for repeat offenders.

Figure 1 illustrates the staggered implementation of different LEZs across German municipalities up to 2016. (A map depicting these LEZs is provided in Appendix Figure A.1.) Note that the exact timing of LEZ implementations was often shaped by idiosyncratic factors such as court cases or conflicts between local and state-level governments.[3] Early adopters, i.e., cities that introduced a stage 1 LEZ between 2008 and 2010, increased restrictiveness over time. Later

[2]A vehicle's emission classification is based, among others, on its particle emission level. By upgrading a vehicle with an additional filter, one could lift a car's emission classification to Euro 4 standard. Diesel cars can typically only be improved by one class (e.g., from Euro 1 to Euro 2). For older cars, upgrades were often not economical.

[3]The median time between the announcement and the implementation of a LEZ was around 4 months (126 days).

adopters sometimes skipped stage 1 or 2 and introduced a stage 3 LEZ right away. Finally, note that, within the time frame of our sample, German LEZs never targeted vehicles with Euro 4 or higher emission standards. Our analysis therefore examines the impact of LEZs on 'targeted' vehicle (e.g., the effect of stage 2 LEZs on the share of Euro 2 vehicles) but also on 'Euro 4+' vehicles that at least fulfill the Euro 4 emission norm.

3 Data

Our study leverages data from four sources. Based on a cooperation with the Federal Motor Transport Authority (*Kraftfahrt-Bundesamt*, henceforth KBA), we obtained monthly data on the detailed composition of the private vehicle fleet at the county level (400 counties in total). These data, which are based on the universe of all cars registered in Germany between January 2007 and December 2015, differ from publicly available KBA data in two ways. Firstly, the data allow us to examine more refined subgroups of cars (e.g., diesel cars of certain emission classes). Secondly, different from, e.g., Wolff (2014) and Margaryan (2021) who use yearly data, the monthly resolution of our data enables us to account for the exact timing when a LEZ was introduced (see Figure 1). We can thus offer a fine-grained evaluation of how LEZs affected the local vehicle fleet composition.

To replicate results from previous studies within our empirical framework, we also compiled data on air pollution. We work with daily readings for particulate matter (PM_{10}) recorded between 2006 and 2015, which are available for 535 distinct (non-industry) pollution stations administrated by the German Federal Environmental Agency (*Umweltbundesamt*, UBA).[4] Among these, 159 are located in a municipality that introduced a LEZ at some point before the end of 2015 (119 are located inside, 40 outside the specific LEZ boundaries within these municipalities). To eliminate extreme outliers associated with New Year's Eve fireworks, all our analyses exclude data from the last and first 3 days of each year.

[4]After excluding measurement stations in industrial areas, we are left with 247 traffic and 288 background stations. Traffic stations are generally located in highly urbanized areas along roads experiencing high traffic volumes. Background stations are located farther away from high-volume traffic areas; many of these are nevertheless located within highly urbanized municipalities.

We further gathered data on daily traffic volumes from the Federal Highway Research Institute (BASt).[5] Out of all traffic counting stations maintained by BASt, 165 are located in municipalities that adopted a LEZ during our sample period (29 inside and 136 outside of LEZ boundaries). Finally, we also collected weather data from the German Meteorological Service (DWD) to complement the traffic and pollution data by geo-coding all (pollution, traffic, and meteorological) measurement stations, calculating Euclidean distances and matching daily weather information from the closest meteorological stations to the daily pollution and traffic data.[6]

Figure 2 provides some descriptive information. It illustrates the evolution of the fleet composition, PM_{10} concentrations, and traffic volumes for early- and late-adopters – jurisdictions that introduced a LEZ before or after January 2010 – as well as for never-adopters. Observational units are counties for the vehicle data and measurement stations for air pollution and traffic. For all outcomes, we constrain the sample to jurisdictions with a population of at least 100,000.[7]

Panel (a) depicts the mean share of Euro 4+ vehicles (complying with the standards mandated by the EU for new vehicles built after 2005), relative to the total stock of vehicles within a county in a given month. The market share of these vehicles grew from 25% in 2007 to around 70% in 2015. Hence, the quality of the German vehicle fleet has improved substantially over time. However, these improvements occurred at similar rates in early-, late-, and never-adopting counties.[8] Before the first LEZs were introduced in 2008, the Euro 4+ share evolved in parallel between early- and late-adopters. In 2009, Germany introduced a large vehicle retirement and subsidy program (akin to the US 'cash for clunkers' program); many new cars entered the vehicle stock and replaced older ones. This translated into a strong increase in the share of Euro 4+ cars in 2009, a trend that appears slightly less pronounced among early adopters. This observation motivates us to examine possible interaction effects between LEZ introductions and the car retirement program below.

[5] BASt provides hourly traffic counts for 929 automated traffic counting stations on highways and 863 stations along federal roads across Germany. To match the pollution data, we aggregate the hourly traffic counts into daily numbers.

[6] Missing observations in the weather data are replaced by readings from the nearest meteorological stations.

[7] Without the latter constraint, we find patterns that are very similar to those reported in Figure 2.

[8] The Euro 4+ market share in never-adopting counties almost perfectly overlaps with late-adopters.

Panel (b) reveals that the share of diesel vehicles also increased in our sample period. Before 2008, early- and late-adopters once more followed a similar trend. Between 2008 and 2010, however, the gap in the diesel share between early and late adopters appears to narrow (with a lower growth among early LEZ adopters). This period again overlaps with the vehicle retirement program, which contributed to the observed increase in the share of diesel cars in 2009.

Panel (c) documents strong seasonal variation in the monthly mean PM_{10} concentrations (with fluctuations occurring symmetrically across all three groups). As EU regulations treat an annual PM_{10} average above 40 $\mu g/m^3$ as a critical threshold, the reported levels (especially those at the beginning of our sample period) must be considered problematic. Yet, PM_{10} concentrations declined over time. Finally, panel (d) illustrates the monthly mean of traffic counts. There are higher traffic volumes for early adopters but parallel fluctuations across the different groups. Overall, there is a small upward trend in traffic counts over time.

4 Empirical Strategy

We want to identify the effect of different LEZ stages on pollution, the composition of the vehicle fleet, and traffic volumes. To avoid potential issues with effect heterogeneity in TWFE regressions which exploit the staggered treatment roll-out (De Chaisemartin and d'Haultfoeuille, 2020; Goodman-Bacon, 2021), we apply a stacked difference-in-differences approach (as in, e.g., Cengiz et al., 2019; Fadlon and Nielsen, 2019; Butters et al., 2022). The approach effectively captures both the staggered implementation of LEZs and the discrete steps in tightening the stringency.[9]

We treat the introduction of a given stage $s = \{1, 2, 3\}$ LEZ in a given quarter τ as a separate sub-experiment.[10] A sub-experiment's treatment group is given by all jurisdictions that introduced the same LEZ stage s during quarter τ. Later adopters, i.e., jurisdictions that implemented this treatment at least T quarters later (but not before), serve as control group. The sample is then comprised of all treatment and control group observations for periods t with

[9]The varying treatment 'doses' associated with the LEZ stages are hard to model using other state-of-the-art methods (see Callaway et al., 2024).

[10]We 'pool' LEZ implementations from different months within one quarter (e.g., January, February, and March 2008) into one sub-experiment. Compared to a monthly event definition, this increases the number of treatment units within each sub-experiment and avoids using very similar control groups across different sub-experiments.

$\tau - T < t \leq \tau + T$. Iterating this approach (which is illustrated in Appendix Figure A.2) for all event quarters and stacking the data from the different sub-experiments together, we obtain three estimation samples (one for each LEZ stage). Our main analysis uses a symmetric pre- and post-treatment period of $T = 8$ quarters. This choice reflects the trade-off between focusing on short-run effects estimated in slightly larger samples and exploring longer outcome windows in smaller samples.[11] Below we will discuss the sensitivity of our results to changes in T. We will also explore alternative control groups that include never-adopters.

Using the stacked datasets for each stage s, we then estimate

$$Y_{jt} = \beta^s LEZ^s_{jt} + \kappa^s (D^s_\tau \times D_j) + \lambda^s (D^s_\tau \times D_{m(t)}) + \gamma^s \mathbf{X}_{it} + \varepsilon^s_{jt}, \tag{1}$$

where Y_{jt} is an outcome for unit j in period t. All models account for a full set of sub-experiment-specific two-way fixed effects (D_j indicates observational units, $D_{m(t)}$ year-months, and D^s_τ the different sub-experiment). For the high-frequency outcomes, we include covariates ($\mathbf{X}_{it}$) and additional fixed effects (see below). Our main parameters of interest, β^s, capture the effect of a stage s LEZ. Note that, for $s = \{2, 3\}$, the dummy LEZ^s_{jt} switches to one regardless of whether a jurisdiction increased the stringency or introduced a more stringent LEZ right away (see Figure 1). Below we report estimates for subsamples that only explore one-step reforms, where jurisdictions moved from stage 1 to 2 and stage 2 to 3 LEZs, respectively. We will present event-study estimates which capture dynamic effects.[12]

We consider two sets of outcome variables. First, the market share of certain vehicle groups (e.g., diesel vehicles with Euro 1 emission standard) relative to the total stock of vehicles. These shares, which we observe at a monthly level for all German counties, account for between-county differences in the fleet size. One might be concerned that LEZs could affect the total number of vehicles registered in a county. However, we fail to detect any statistically or quantitatively significant effects of LEZs on the number of vehicles (Table A.1, panel i) – an observation which one might interpret as a result in itself.

[11] Note that a shorter T implies fewer restrictions on the control group.

[12] Throughout the paper, we cluster standard errors at the level of observational units. For PM_{10} and traffic volumes, this implies clustering at the station level. This approach is more conservative since clustering at the jurisdiction level yields *smaller* standard errors, which might reflect the small number of cluster units (Cameron et al., 2008). Cluster-t bootstrapping and two-way clustering (at the level of observational units $\times$ sub-experiments) yields similar standard errors.

Second, we examine daily data on pollution and traffic levels. We present estimates in levels and logs to explore sensitivity regarding functional forms (Roth and Sant'Anna, 2023). All specifications include day of the week × measurement station fixed effects and controls for weather conditions.[13] The main estimation samples include only measurement stations that are located inside (current or future) LEZs. In complementary analyses, we estimate the effects on pollution and traffic inside and outside of LEZs.

5 Results

5.1 Main Results

Particulate matter. The different columns of Table 1 present our main stacked DID estimates. Panel (a) displays the PM_{10} results. In line with earlier results obtained from traditional TWFE estimates (Wolff, 2014; Gehrsitz, 2017; Margaryan, 2021; Pestel and Wozny, 2021), the stacked DID estimates indicate that LEZs caused a reduction in PM_{10}. Our estimates indicate that the first and the second LEZ stages are the main drivers behind this effect. For stage 1, we find a 0.78 $\mu g/m^3$ decline in PM_{10} levels (3.1% relative to the control group mean). The estimate in logs shows a statistically insignificant 1.3% decline. For stage 2, the estimates indicate an additional decline by 0.97 $\mu g/m^3$ (or 3.7%) and 3.1 log points, respectively. We do not detect any meaningful effect for stage 3.

Corresponding event-study estimates, which are reported in Appendix Figure A.3 (panel i), confirm the relatively noisy impact of stage 1 and 2 on PM_{10}. The event-study plots further document large variations in PM_{10} concentrations around the introduction of stage 3 LEZs. Overall, our evidence suggests that only stages 1 and 2, which targeted vehicles with the worst emission classes, achieved improvements in local air quality. Our approach, which uses station-level micro data for PM_{10} (rather than weighted means, aggregated over several stations), further indicates that the short-run effects of LEZs are relatively noisy.[14]

[13]Daily temperature (mean, max and min), precipitation, relative humidity, sunshine duration, vapor pressure, wind speed and maximum gust.

[14]Comparable results (aggregated at the yearly level) are reported in Margaryan (2021). Klauber et al. (2024), who construct weighted averages of quarterly PM_{10} concentrations at the country level, find more precise effects throughout the first five years after a LEZ implementation.

Vehicle Fleet. Next we turn to the impact of LEZs on the fleet composition. The first set of estimates reported in panel (b) of Table 1 shows that stage 2 caused a significant 0.29 pp drop in the share of targeted, i.e., Euro 2 vehicles. Relative to the control group mean, this corresponds to a 1.0% decline. The effect is mirrored by a 0.29 pp (0.8%) increase in the share of Euro 4+ vehicles. The estimates thus suggest that stage 2 LEZs caused a substitution from Euro 2 vehicles to more modern vehicles with improved emission classes. We do not observe similar effects for stage 1 and stage 3 LEZs, which had no meaningful effects on the share of Euro 1 or Euro 3 vehicles, respectively. Event study estimates, which are illustrated in Figure 3 (Panels a, c, and e), confirm these results: for stage 2, we observe a small but significant decrease in the share of Euro 2 vehicles and a pronounced increase in the Euro 4+ share.[15]

Table 1 further shows that all three LEZ stages had negative effects on the share of diesel vehicles. For each stage, diesel shares declined by between 0.24 and 0.34 pps. In relative terms, this corresponds to 1.6% (stage 1), 1.8% (stage 2), and 1.2% (stage 3) declines, respectively. These effects are predominantly driven by targeted diesel vehicles. For stage 1, we obtain a precisely estimated 0.10 pp decline in Euro 1 diesel cars. While this sounds like a negligible impact, it corresponds to a 14.7% drop in the prevalence of the oldest, most emission-intensive diesel cars. Similarly, stage 2 caused an 8.5% (0.33 pp) decline in Euro 2 diesel vehicles; stage 3 caused a smaller 3.3% (0.22 pp) reduction in the share of Euro 3 diesels.

All these effects are confirmed in the event-study plots presented on the right-hand side of Figure 3 (panel b, d and f). The event-study estimates further indicate that, in line with the overall negative effects on the total diesel share, there are no detectable increases in the share of Euro 4+ diesel vehicles.[16] This observation, which is confirmed by the estimates from Table 1, suggests that older diesel vehicles were mainly replaced with cleaner Euro 4+ gasoline vehicles. The pattern also indicates that retrofitting of old diesel vehicles was not the main driver of the changes in the fleet composition (see fn. 2).

In complementary analyses, we provide evidence documenting that the different LEZ stages also affected non-targeted vehicles from adjacent emission categories. Stage 1, for instance, caused a 7.1% decline in the share of Euro 2 diesel vehicles. Similarly, stage 2 LEZs had a

[15]Both effects seem to emerge already in the quarters before the stage 2 LEZ was implemented. This might reflect the fact that LEZ reforms were typically announced a few months in advance (see fn. 3).

[16]Panel (d) indicates positive but imprecise coefficients for Euro 4+ diesel.

negative effect on the share of Euro 3 vehicles (see Appendix Table A.1, panel ii). To account for these effects, we also estimate the impact of the different LEZ stages on the cumulative shares of, e.g., Euro 1 and 2 cars (see Table A.1, panel iii). The estimates show that each LEZ stage had a non-trivial negative effect on the most emission-intensive diesel vehicles: relative to the counterfactual, the share of Euro 1–2 diesel declined by 8%, 7%, and 3% respectively.[17]

Traffic. Panel (c) of Table 1 explores the effects of LEZs on the traffic counts at stations located inside the zones. The estimates indicate that the implementation of a stage 1 LEZ reduced the daily average of total vehicles counted inside LEZs by 2,035 (or 2.4%). For stage 2, we observe a similar drop by 1,761 vehicles per day (2.1%). Both effects are confirmed using log-transformed vehicle counts. In line with our previous findings, we do not detect any significant effects for stage 3. We also find imprecisely estimated declines in traffic related to heavy-duty vehicles (HDV), which might explain why Sarmiento et al. (2023) find stronger drops in PM_{10} levels on working days. For stage 2, the effect is statistically significant for HDV counts in levels (but not for log counts). The corresponding event-study estimates document that the pattern in traffic responses is not fully conclusive (see panel (ii) and (iii) of Appendix Figure A.3).[18] The estimates reported in panel (c) must therefore be interpreted cautiously.

5.2 Refinements

Our estimates document that Germany's LEZs, in particular their first and second stage, affected the composition of the car fleet: it reduced the market share of diesel vehicles with lower emission classes. Recall that several stage 1 LEZs were implemented during (or shortly before) the years 2009, a period that was heavily influenced by a large car scrapping and replacement program (see Fig. 1). We thus study whether the LEZ roll-out caused more pronounced effects during the period influenced by Germany's version of the US 'cash for clunkers' program.

Estimating models that augment our baseline equation (1) with an interaction term, we find no clear evidence for stronger effects on total vehicle shares (Table A.2, panel a). However, once we focus on diesel vehicles (panel b), we observe some weakly significant interaction effects:

[17] For Euro 1–3 diesel vehicles, the estimated decline is 3% (stage 1), 5% (stage 2), and 3% (stage 3).

[18] Similar as for PM_{10}, we observe large inter-temporal fluctuations in traffic (both total and HDV) before the implementation of stage 3 LEZs.

stage 1 LEZs introduced during the program period caused a stronger decline in the joint share of Euro 1 and 2 diesel vehicles. Yet, the estimated interactions are typically small.[19] Our analysis thus suggests that, beyond some conjoint effects on older diesel vehicles, Germany's scrapping program and (stage 1) LEZs affected the vehicle market independently from each other.

In a second extension, we assess the spillover of LEZs on the fleet composition in nearby counties. The analysis indicates that, with a few exceptions, LEZs had either no impact on the neighboring counties' fleet composition or may even reduced the share of Euro 1 and 2 diesel (see Appendix Table A.3 and the table notes for details on the estimation approach). The latter effects might reflect commuters' responses to nearby LEZs.

Our pollution and traffic analyses only considered measurement stations located inside the specific boundaries of LEZs (which typically coincide with city centers). In an extension, we also included stations outside of a LEZ (but within the relevant jurisdiction). This allows us to explore whether there are differential effects of LEZs on outcomes observed inside and outside city centers. The results differ between the two sets of outcomes (see Table A.4). Stage 2 caused a similar drop in PM_{10} inside and outside of LEZ boundaries.[20] (For stage 1 and 3, the estimates are again noisier.) In contrast, the decline in traffic observed after stage 1 and 2 LEZ implementations, is concentrated in city centers. Outside of the centers, the point estimates are positive (but imprecisely estimated), which suggests that LEZs could have caused some traffic displacement (as in, e.g., Bou Sleiman, 2023).

5.3 Robustness

To assess the robustness of our results, we first assess several steps in the way we compiled the stacked DID sample. The above analysis only includes observational units if they cover the full $T = 8$ quarters before and after the respective event quarter. Given that our fleet composition data only start in January 2007, this sample condition excludes early LEZ adopters from 2008. Similarly, towards the end of our sample period, we miss some late adopters.[21] To explore whether our results are sensitive to these cases, we constructed an augmented sample that relaxes

[19]Our estimates would imply, for instance, that stage 1 LEZs that started jointly with the cash for clunkers' program reduced the Euro 1 and 2 diesel share by 9.7% as compared to a 5.7% impact for stage 1 LEZs launched in different years (see the estimates and control group mean from Table A.2, panel b, column 7).

[20]Wolff (2014) reports a similar finding for the case of the LEZ in Berlin.

[21]The latter issue affects all three sets of outcomes (i.e., pollution, traffic, and fleet composition).

the sample constraint: we add observational units that are observed during at least 4 (rather than 8) pre- and post-event quarters. Essentially, this is equivalent to allowing for unbalanced panels in some of the sub-experiments. The estimation results obtained from this sample are hardly distinguishable from our main results (see Table A.5).

A key assumption used in the definition of our stacked sample is the pre- and post-event window of $T = 8$ quarters. As discussed in Section 4, this assumption not only defines the outcome period we consider but also constrains the control group (where a longer period T further restricts the set of untreated jurisdictions that can be included in the control group). To assess if and how the choice of T influences our main findings, we computed alternative (balanced) samples based on $T = 6$ and $T = 10$ quarters and re-ran our estimates. The results indicate that our findings for the impact of LEZs on the fleet composition and traffic counts are hardly sensitive to these permutations of T (see Table A.6, panel b). A notable exemption are the estimates for stage 3 LEZs, where a shorter outcome period (and the resulting larger control group) results in slightly larger point estimates. With $T = 6$ quarters, we find that stage 3 induced a statistically significant shift from Euro 3 to Euro 4+ vehicles (which is again largely driven by Euro 3 diesel vehicles).[22]

Our main estimates for the effect of stage 2 LEZs pool events where jurisdictions gradually increase the restrictiveness with events where they introduce a stage 2 LEZ straight away. Limiting our sample to jurisdictions that advanced by one step (i.e., from stage 1 to 2), yields estimates similar to our main results. Similarly, results for stage 3 are robust to restricting the sample to jurisdictions that changed from stage 2 to 3 LEZs (see Appendix Table A.7).

Finally, we replicated our estimates in samples that included never-adopters in the control group. Even though we maintain our focus on counties with a population of at least 100,000 inhabitants, this yields a strong increase in the sample size. The resulting estimates (which are presented in Table A.8) show, in general, a higher precision but remarkably similar point estimates as those presented in Table 1. For PM_{10}, including never-adopters confirms that it is mainly stage 1 and 2 (and not stage 3) LEZ implementations that caused a decline in PM_{10} levels.

[22] For $T = 6$, we further estimate that stage 3 LEZs would have caused a large increase in PM_{10} levels. A closer inspection of this counter-intuitive finding shows that the positive effect is driven by the shorter time window (and not by the conjoint changes in the control group): the large volatility in PM_{10} – which is also visible in Figure A.3, panel (i) – and the unusually low PM_{10} levels observed in the pre-treatment quarters, get implicitly a larger weight and thus contribute to the positive coefficient. The latter, however, quickly vanishes with $T = 8$ or $T = 10$ quarters.

The effects on the vehicle fleet again document, for all three stages, strong effects on the share of targeted diesel cars and some evidence pointing to a substitution to Euro 4+ gasoline cars. For traffic counts, we find a similarly strong decline in overall traffic for stage 1 LEZs (and, in fact, a stronger, statistically significant drop in HDV traffic) but, differently from our main estimates, no effects on traffic counts for stage 2 LEZs.

5.4 Discussion

We explored two mechanisms through which LEZ might improve local air quality. We found weak evidence that stage 1 and 2 LEZs reduced daily traffic by around 2%. Given that this decline in traffic is concentrated inside LEZs whereas PM_{10} levels drop at measurement stations inside and outside LEZs (see Table A.4), reduced traffic volumes seemed to have played a secondary role in reducing air pollution. In contrast, our analyses provide compelling evidence of small but important changes in the composition of the local vehicle fleet. We showed that the different LEZ stages reduced the market share of diesel vehicles with Euro 1–3 emission standards. The evidence further suggests that the older diesel cars were mainly replaced by Euro 4+ gasoline vehicles. These upgrades affected small segments of the vehicle fleet: Euro 1, 2 and 3 diesel cars accounted for, respectively, 0.7%, 3.9% and 6.7% of the control group counties' total fleet (see Table 1). We nevertheless argue that the replacement of roughly 10% of these old diesel cars is the key driver of the observed air quality improvements – and the associated health benefits documented in the literature.

Our argument is based on the vast differences in PM_{10} emissions across different types of cars, which are documented in Table A.9.[23] The Euro 1 emission norm, for instance, allowed diesel vehicles to emit up to 140 μg PM_{10} per kilometer traveled (with effective emissions potentially surpassing this level; see Alexander and Schwandt, 2022). An average Euro 4+ gasoline car, in contrast, would emit around 1–2 μg PM_{10} per kilometer (see Table A.9). Hence, replacing a Euro 1 diesel with a Euro 4 gasoline car might reduce PM_{10} emissions by more than 98%. For the replacement of a Euro 2 and 3 diesel, the corresponding values are 97% and 94%, respectively.

[23]Table A.9 reports average tailpipe PM_{10} levels for diesel and gasoline cars with different emission standards. The reported numbers present weighted averages across measures from different cars that are representative of the German fleet in 2010 in the various categories of cars.

These numbers underscore the huge improvement in particulate matter that can be achieved by substituting old diesel with modern gasoline cars.

The estimated effect sizes are also relevant for cost-benefit assessment of LEZs. Converting our point estimates into absolute numbers, suggests that, relative to the counterfactual, LEZs induced an upgrading of less than 50,000 additional diesel cars (see Appendix B for a more detailed discussion). This means that the direct replacement costs are only a quarter or half of the private costs considered in Wolff (2014) and Rohlf et al. (2020). The social costs and benefits of LEZs are obviously difficult to quantify. Following Wolff (2014), who considers replacement costs at $1,650 per car, our estimates would imply that LEZs caused private costs of $82.5 million. Klauber et al. (2024) put the health benefits to infants and cost savings on asthma medication alone at around $65 million. Once cost savings from other prescriptions (Rohlf et al., 2020), hospital visits (Pestel and Wozny, 2021), and ambulatory care claims (Margaryan, 2021) are taken into account, LEZs are highly likely to have passed a backward-looking cost-benefit analysis.

6 Conclusion

Using a stacked differences-in-differences approach, this paper documents how Low Emission Zones (LEZs) of different stringency affected particulate matter, traffic volumes, and the composition of the vehicle fleet. We provide three sets of results. First, confirming earlier findings based on simple TWFE estimates, we document that LEZs caused a significant decline in PM_{10} levels. As a novel contribution, our analysis reveals that short-run improvements in local air quality were only achieved by stage 1 and 2 LEZs. Second, we find weak evidence suggesting that stage 1 and 2 LEZs induced a 2% decline in traffic. However, different from the pollution outcome, where we observe a drop in PM_{10} concentrations inside and outside of LEZs, the drop in traffic is concentrated inside the regulated areas.

Third, our main findings reveal nuanced but important effects of LEZs on the composition of the local vehicle fleet. While the total vehicle stock remained unaffected, LEZs reduced the market share of targeted vehicles: stage 1 LEZs, which banned cars with the Euro 1 emission standard from entering city centers, caused a decline in the share of these vehicles (and similar for stage 2 and 3). We also observe effects on the share of cars from adjacent emission categories.

Importantly, all effects are concentrated among diesel vehicles. Moreover, our analyses suggest that Euro 1, 2, and 3 diesel cars were mainly replaced with modern gasoline cars.

The estimated effects on the modernization of the local fleet composition are small in absolute terms but non-trivial in relative terms. Most importantly, we document that small reductions in the number of old diesel cars led to out-sized PM_{10} reductions. This is because Euro 4+ gasoline cars emit, on average, between 97% and 98% less PM_{10} per kilometer than Euro 1 and 2 diesel cars. LEZ-induced improvements in air quality – and the associated social benefits in terms of improved health and well-being outcomes – thus appear to be driven by the replacement of roughly 50,000 old diesel cars. This result has important implications from a cost-benefit perspective, suggesting that the private costs of implementing LEZs were much smaller than previously estimated. At the same time, our stage-specific analysis also points to potentially diminishing returns in LEZ effectiveness, once the oldest and most polluting vehicles have come off the streets. It is up to future research to explore if (and at which level of stringency) LEZs are a cost-effective tool to further improve local air quality.

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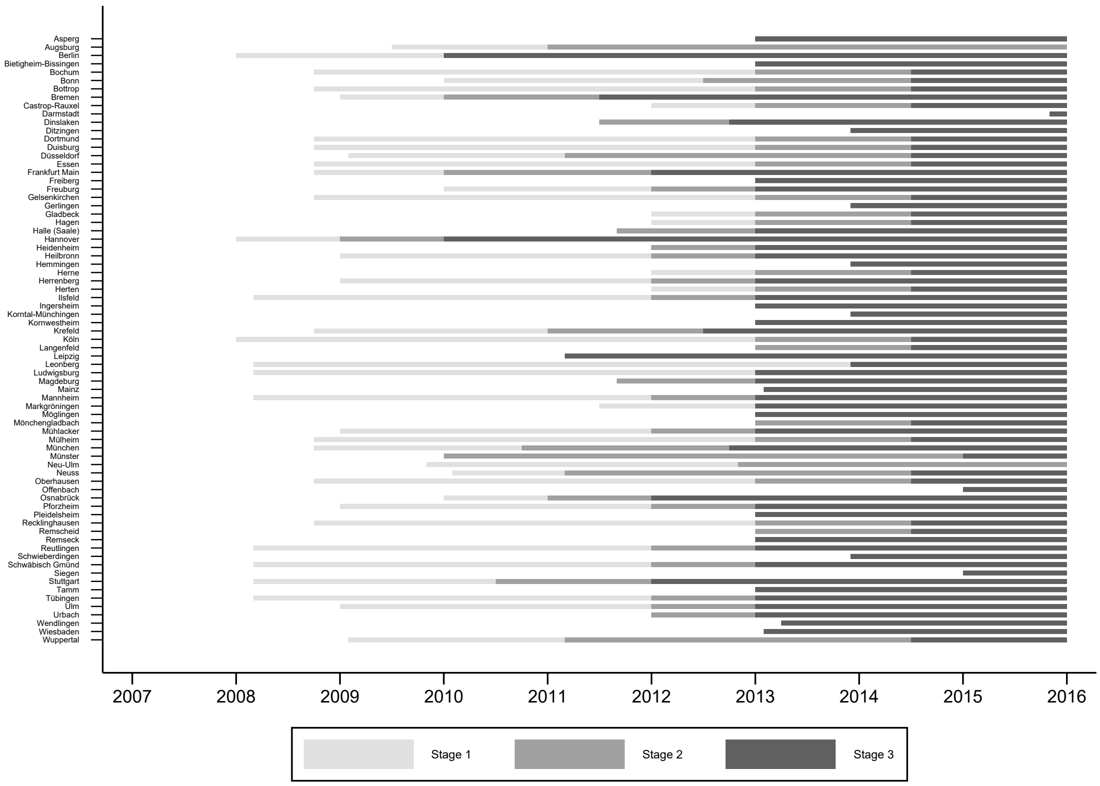
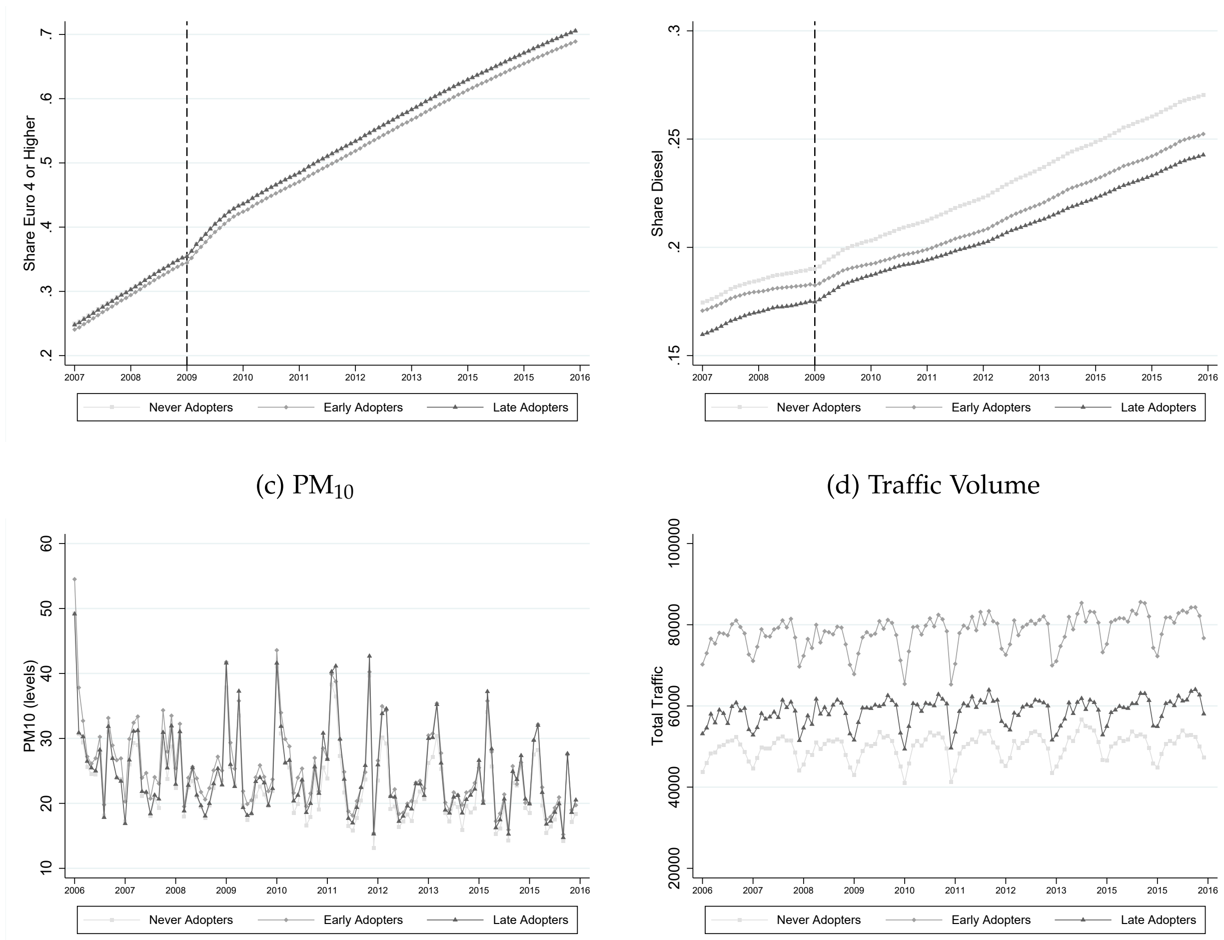
Main Figures & Tables

Figure 1: LEZ roll-out by stage across German Cities



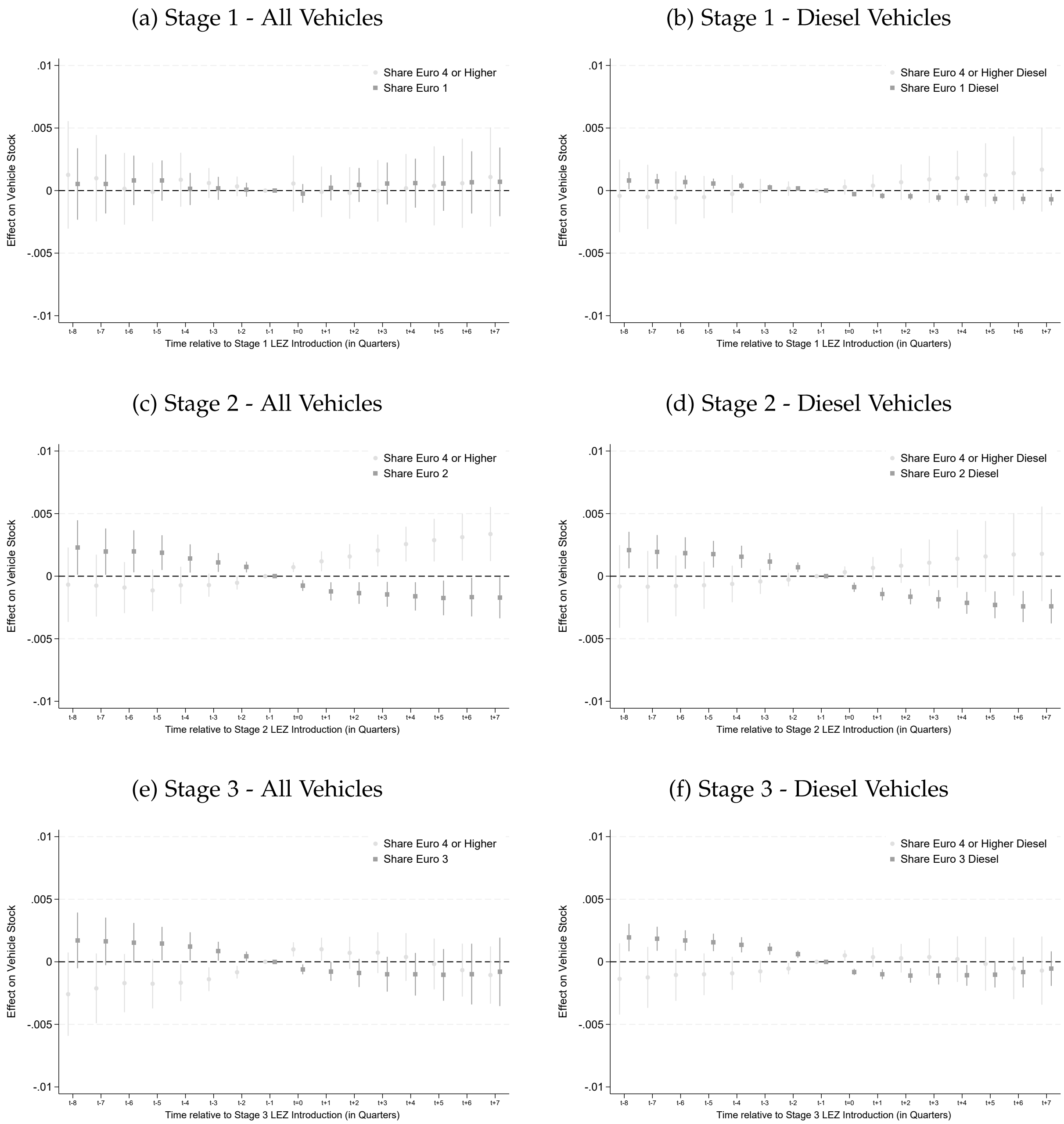
Notes: This figure illustrates staggered timing in the introduction of different Low Emission Zone (LEZ) stages. The y-axis lists all cities and towns in Germany that introduced a LEZ between 2008 and 2016. Horizontal lines indicate the existence of a LEZ in a given month. Light shade lines correspond to times during which a least restrictive – banning only vehicles of Euro 1 emission standard or lower – stage 1 LEZ was in place. Darker shaded lines indicate the presence of stage 2 (ban of Euro 2 or lower) and stage 3 (ban of Euro 3 or lower) LEZs, respectively.

Figure 2: Descriptive Analysis – Fleet Composition, Particle Pollution and Traffic



Notes: Panel (a) and (b) illustrate the mean share of vehicles fulfilling Euro 4 or higher emission standards and the share of diesel vehicles at the county level. The panels distinguish between *early-* (26 counties), *late-* (13), and *never-adopters* (34), i.e., jurisdictions that introduced a LEZ before January 2010, between January 2010 and December 2015, or did not implement one within our sample period. In panel (a), the Euro 4+ market share in never-adopting counties almost perfectly overlaps with late-adopters. Panel (c) displays monthly means of daily PM_{10} readings in $\mu g/m^3$ (48 stations from early-, 17 from late- and 49 from never-adopting municipalities). Panel (d) shows monthly means of daily total vehicle counts (72 stations from early-, 28 from late- and 82 from never-adopting municipalities). To avoid changes in the sample composition, panel (c) and (d) are based on stations that recorded data throughout the entire period. Moreover, all samples focus on jurisdictions with a population of at least 100,000.

Figure 3: Event Study Estimates - Fleet Composition



Notes: Figure 3 shows event study estimates of the introduction of different LEZ stages, separately for the overall fleet (left-hand side subfigures) and diesel vehicles (right-hand side subfigures). Outcomes are the share of the total fleet in a county that fulfill emission standard Euro 1, 2, 3, or 4+, respectively. Quarterly leads and lags are estimated using a stacked OLS regression that also includes sub-experiment by year-month and sub-experiment by county fixed effects. Event time $t-1$ captures the quarter prior to the introduction of stage s LEZ. 95% confidence intervals are constructed from standard errors that are clustered at the county level.

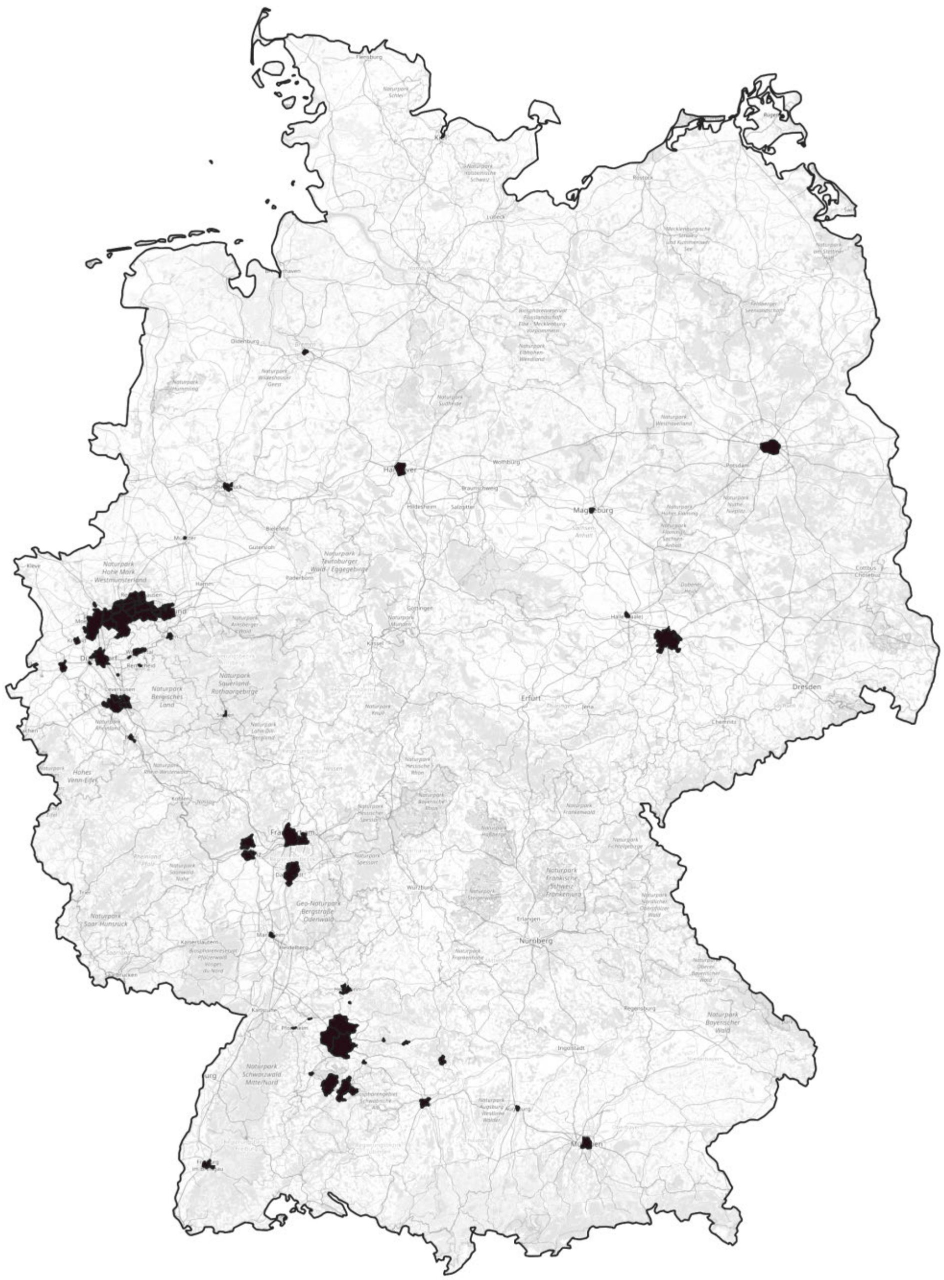
Table 1: Stacked DID Estimates

	Stage 1		Stage 2		Stage 3	
	Coef.	SE	Coef.	SE	Coef.	SE
(a) Pollution						
PM_{10} - Levels	–0.773*	(0.463)	–0.969*	(0.500)	0.168	(0.431)
PM_{10} - Logs	–0.013	(0.018)	–0.031*	(0.019)	–0.005	(0.017)
Mean ($\mu g/m^3$)	25.27		26.14		26.81	
Obs.	245,810		375,040		398,162	
(b) Fleet Composition						
Share Euro targeted	0.0001	(0.001)	–0.0029***	(0.001)	–0.0020	(0.001)
Mean	0.1316		0.2945		0.1853	
Share Euro 4+	–0.0002	(0.002)	0.0029**	(0.001)	0.0017	(0.001)
Mean	0.3285		0.3673		0.4372	
Share Diesel	–0.0029*	(0.002)	–0.0034**	(0.002)	–0.0024*	(0.001)
Mean	0.1764		0.1860		0.1987	
Share Diesel Euro targeted	–0.0010***	(0.000)	–0.0033***	(0.001)	–0.0022***	(0.001)
Mean	0.0068		0.0389		0.0671	
Share Diesel Euro 4+	0.0012	(0.002)	0.0017	(0.002)	0.0009	(0.001)
Mean	0.0585		0.0684		0.0881	
Obs.	2,976		7,296		7,056	
(c) Traffic Counts						
All Vehicles - Levels	–2.035**	(0.896)	–1.761***	(0.573)	0.891	(0.904)
All Vehicles - Logs	–0.025**	(0.010)	–0.020*	(0.010)	0.019	(0.014)
Mean (# 1,000 vehicles)	85.256		85.076		83.227	
Heavy-Duty Vehicles - Levels	–0.020	(0.088)	–0.278**	(0.128)	–0.107	(0.167)
Heavy-Duty Vehicles - Logs	–0.012	(0.015)	–0.061	(0.036)	–0.066	(0.074)
Mean (# 1,000 HDVs)	8.421		8.432		7.869	
Obs.	67,649		180,335		187,753	

Notes: Results from estimating equation (1). Panel (a) and (c) explore daily pollution and traffic counts (in 1,000 vehicles) from stations located within current and future LEZs. Panel (b) uses monthly vehicle fleet data at the county level. Euro targeted (and, analogously, Diesel Euro targeted) captures the effects of stage 1 LEZs on the share of Euro 1, stage 2 on Euro 2, and stage 3 on the share of Euro 3 vehicles, respectively. Estimates of all stages on all three emission classes are reported in Appendix Table A.1. The table reports control group means before the respective treatment. Standard errors are clustered at the level of observational units (counties or measurement stations). ***/**/* indicate significance at the 1%/5%/10%-level.

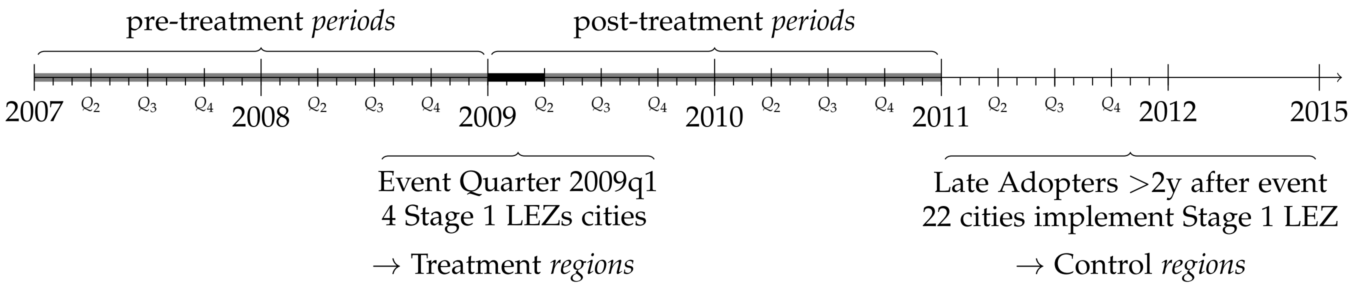
Appendix A: Figures and Tables

Figure A.1: LEZs in Germany in 2016



Notes: The map illustrates the location and shape of all LEZs implemented in Germany by January 2016.

Figure A.2: Exemplary Timeline and Data Sampling Strategy for Event Quarter 2009 Q1

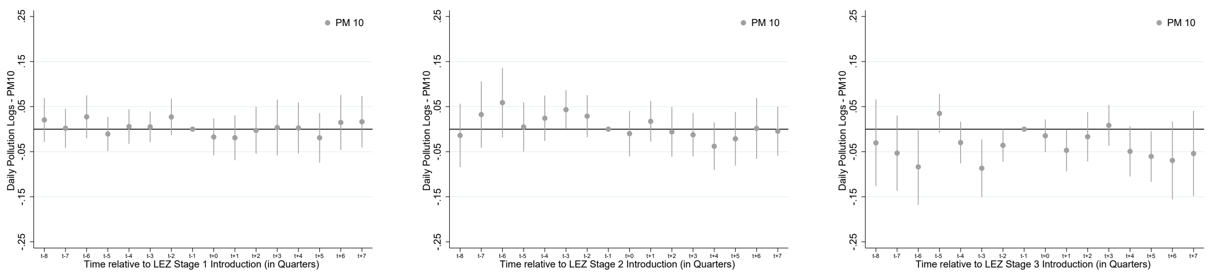


Notes: Exemplary timeline, sampled periods, and regions for stage 1 LEZ implementations in event quarter 2009 Q1. In this example, our treatment group is composed of jurisdictions that introduced a stage 1 LEZ in the first quarter of 2009. The control group is given by later adopters, i.e. jurisdictions that implemented a LEZ at least $T = 8$ quarters after the event quarter, that is between 2011 Q1 and 2015 Q4 (the end of our sample period). Jurisdictions that implemented a stage 1 LEZ before, are excluded from the control group. For this sub-experiment, the sample thus includes all observations for 8 quarters before and after the event quarter for the relevant control and treatment units. Our main analysis includes only observational units that cover the full pre- and post-treatment period. For the pollution and traffic data, we additionally constrain the sample to ensure that measurement stations include observations for at least 12×30 days before and after the treatment.

Figure A.3: Event Study Estimates: Pollution & Traffic Outcomes

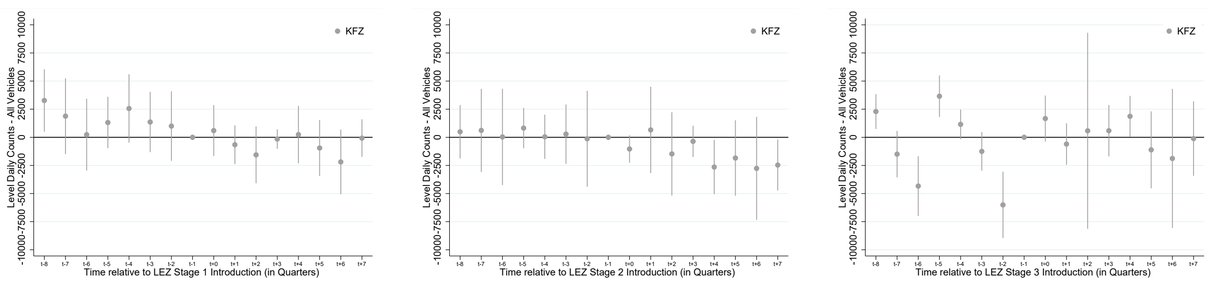
(i) **PM_{10} Outcome**

Stage 1 | Stage 2 | Stage 3



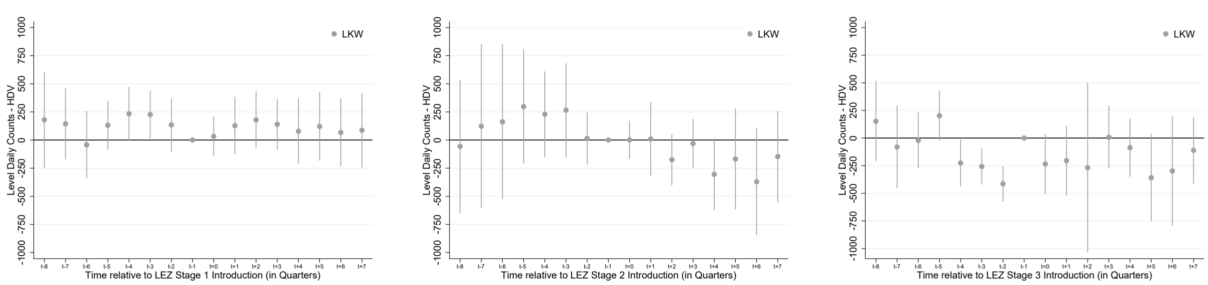
(ii) **Total Traffic**

Stage 1 | Stage 2 | Stage 3



(iii) **Heavy-Duty Vehicles**

Stage 1 | Stage 2 | Stage 3



Notes: The figure shows quarterly event-study estimates for the outcomes studied in panel (a) and (c) of Table 1: (i) PM_{10} logs, (ii) total traffic counts, and (iii) heavy duty vehicle (HDV) traffic counts. Quarterly leads and lags are estimated using a stacked OLS regression that also includes sub-experiment by year-month, sub-experiment by station and day-of-week by station fixed effects. Event time $t-1$ captures the quarter prior to the introduction of stage s LEZ. All estimates control for weather conditions. 95% confidence intervals are constructed from standard errors that are clustered at the level of measurement stations.

Table A.1: Refined Estimates for Fleet Composition

	Stage 1		Stage 2		Stage 3	
	Coef.	SE	Coef.	SE	Coef.	SE
(i) Fleet Size						
Log Num. of Vehicles	–0.0015	(0.003)	–0.0012	(0.003)	–0.0023	(0.003)
(ii) Effect by Euro Category						
Share Euro 1	**0.0001**	(0.001)	0.0023**	(0.001)	0.0009	(0.001)
Mean	0.1316		0.1174		0.0908	
Share Euro 1 Diesel	**–0.0010*****	(0.000)	–0.0002	(0.000)	0.0002	(0.000)
Mean	0.0068		0.0060		0.0046	
Share Euro 2	–0.0005	(0.002)	**–0.0029*****	(0.001)	–0.0011	(0.001)
Mean	0.3124		0.2945		0.2599	
Share Euro 2 Diesel	–0.0028***	(0.001)	**–0.0033*****	(0.001)	–0.0014***	(0.000)
Mean	0.0393		0.0389		0.0339	
Share Euro 3	0.0022	(0.002)	–0.0025*	(0.001)	**–0.0020**	(0.001)
Mean	0.1981		0.1914		0.1853	
Share Euro 3 Diesel	0.0001	(0.001)	–0.0018**	(0.001)	**–0.0022*****	(0.001)
Mean	0.0666		0.0674		0.0671	
(iii) Cumulative Effects						
Share $\leq$ Euro 2	–0.0004	(0.002)	–0.0006	(0.001)	–0.0001	(0.001)
Mean	0.4440		0.4119		0.3507	
Share $\leq$ Euro 2 Diesel	–0.0038***	(0.001)	–0.0034***	(0.001)	–0.0012**	(0.001)
Mean	0.0461		0.0449		0.0384	
Share $\leq$ Euro 3	0.0018	(0.002)	–0.0031**	(0.001)	–0.0021	(0.001)
Mean	0.6421		0.6033		0.5361	
Share $\leq$ Euro 3 Diesel	–0.0037***	(0.001)	–0.0052***	(0.001)	–0.0034***	(0.001)
Mean	0.1126		0.1123		0.1055	
Obs.	2,976		7,296		7,056	

Notes: Results from estimating equation (1) for additional fleet outcomes: (i) the log vehicle count; (ii) the effects of all LEZ stages on *all* three (including adjacent) emission classes; and (iii) cumulative shares of vehicles below a particular emission class (e.g., the combined share of Euro 1 and Euro 2 vehicles). In panel (ii), the coefficients marked in bold are the effects on targeted vehicle groups (e.g., from stage 2 on Euro 2 vehicles). The table also reports control group means before the respective treatment. Standard errors are clustered at the county level. ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.2: Interaction Effects of Stage 1 LEZs and 'Cash for Clunkers'

	(1) Euro 1	(2) Euro 2	(3) Euro 3	(4) Euro 4+	(5) ≤ Euro2	(6) ≤ Euro 3	(7) Diesel
(a) Effect on Overall Fleet							
LEZ^1	–0.0003	0.0013	0.0017	–0.0011	0.0010	0.0027	–0.0035**
	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)
LEZ^1 × C4C	0.0007	–0.0012	0.0005	0.0003	–0.0005	–0.0000	–0.0011
	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)	(0.002)	(0.001)
Mean	0.1392	0.3191	0.1994	0.3118	0.4584	0.6578	0.1724
(b) Effect on Diesel Fleet							
LEZ^1	–0.0009***	–0.0019***	–0.0001	–0.0003	–0.0027***	–0.0028***	
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	
LEZ^1 × C4C	–0.0003	–0.0016*	–0.0001	0.0011	–0.0019*	–0.0020	
	(0.000)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	
Mean	0.0072	0.0401	0.066	0.0536	0.0473	0.1134	
Obs.	5,144	5,144	5,144	5,144	5,144	5,144	5,144

Notes: This table presents stacked DID regression for stage 1 LEZs. Building upon equation (1), we interact the main effect with an indicator for whether a treatment county implemented a stage 1 LEZ such that the first post-treatment year overlapped with Germany's cash-for-clunkers program. More specifically, the C4C dummy indicates if a stage 1 LEZ was introduced in the last quarter of 2008 or during 2009. Panel (a) examines interaction effects for the overall vehicle fleet (on the share of, e.g., all Euro 1 vehicles); panel (b) focuses on the share of specific diesel vehicles (e.g., the share of Euro 1 diesel vehicles). As in Table A.5, the estimation sample includes counties with at least 4 (instead of 8) quarters before and after a LEZ implementation. This increases the power of the estimates, assuring that the sample includes sub-experiments with the earliest LEZ adopters that occurred in periods affected by the cash-for-clunkers program. Standard errors, clustered at the county level, are in parentheses. ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.3: Spillover Effects on the Fleet Composition of Neighboring Counties

	Stage 1		Stage 2		Stage 3	
	Coef.	SE	Coef.	SE	Coef.	SE
Share Euro 1	**–0.0003**	**(0.000)**	0.0009***	(0.000)	–0.0005*	(0.000)
Mean	0.1189		0.1047		0.0842	
Share Euro 1 Diesel	**–0.0007*** **	**(0.000)**	–0.0003***	(0.000)	0.0002***	(0.000)
Mean	0.0070		0.0065		0.0056	
Share Euro 2	–0.0003	(0.001)	**–0.0002**	**(0.000)**	–0.0001	(0.000)
Mean	0.3133		0.2924		0.2636	
Share Euro 2 Diesel	–0.0023***	(0.000)	**–0.0013*** **	**(0.000)**	0.0006*	(0.000)
Mean	0.0456		0.0444		0.0421	
Share Euro 3	0.0020***	(0.001)	0.0000	(0.000)	**0.0003**	**(0.000)**
Mean	0.2052		0.1998		0.1955	
Share Euro 3 Diesel	0.0008***	(0.000)	–0.0004*	(0.000)	**0.0001**	**(0.000)**
Mean	0.0795		0.0792		0.0808	
Share Euro 4+	–0.001	(0.001)	–0.0009	(0.001)	0.0002	(0.001)
Mean	0.3386		0.3796		0.4349	
Share Euro 4+ Diesel	0.0006	(0.001)	0.0001	(0.001)	–0.0017***	(0.001)
Mean	0.071		0.0835		0.1022	
Obs.	18,768		44,688		43,440	

Notes: This table presents an analysis of spillover effects of LEZs on neighboring jurisdictions. The sample for this analysis consists of all counties (independently of population size) that are located within a 100km centroid-to-centroid distance to a county that introduced a stage *s* LEZ. For each county, we identify the closest neighboring jurisdiction with an LEZ. We then estimate equation (1), again separately for each stage *s*, where the treatment is determined by the date at which a *neighboring* county introduces a stage *s* LEZ. The control group consists of counties whose closest neighbor is a later-adopting county that (a) has not yet introduced a stage *s* LEZ and (b) will not do so during the 2-year post-treatment period. Standard errors are clustered at the county level. ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.4: Effects on Pollution and Traffic Inside and Outside of LEZ boundaries

	Stage 1		Stage 2		Stage 3	
	Coef.	SE	Coef.	SE	Coef.	SE
PM_{10} - Levels						
Inside LEZ	–0.623	(0.447)	–1.027**	(0.470)	0.110	(0.367)
Outside LEZ	–0.014	(0.458)	–1.222***	(0.393)	0.620	(0.422)
Mean (μg/m^3)	24.64		25.08		25.59	
PM_{10} - Logs						
Inside LEZ	–0.006	(0.018)	–0.030*	(0.018)	–0.000	(0.015)
Outside LEZ	0.009	(0.022)	–0.055***	(0.019)	–0.008	(0.022)
Obs.	297,575		431,187		483,238	
Traffic Count - Levels						
Inside LEZ	–2.186**	(0.905)	–1.348**	(0.599)	0.191	(0.940)
Outside LEZ	0.674	(1.004)	0.405	(0.748)	1.634	(1.145)
Mean (# 1,000 vehicles)	81.396		83.615		81.993	
Traffic Count - Logs						
Inside LEZ	–0.026**	(0.010)	–0.014	(0.010)	0.005	(0.015)
Outside LEZ	0.000	(0.012)	0.009	(0.009)	0.029	(0.017)
Obs.	80,789		224,117		235,929	

Notes: The table presents results from augmented versions of equation (1) that estimate differential effects of a given LEZ^s on the outcomes observed at measurement stations that are placed inside and outside of LEZ boundaries within LEZ adopting jurisdictions, respectively. The table also reports control group means before the respective treatment. Standard errors are clustered at the level of measurement stations. ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.5: Stacked DID Estimates with relaxed Sample Criteria

	Stage 1		Stage 2		Stage 3	
	Coef.	SE	Coef.	SE	Coef.	SE
(a) Pollution						
PM_{10} - Levels	–0.773*	(0.463)	–0.969*	(0.500)	0.251	(0.420)
PM_{10} - Logs	–0.013	(0.018)	–0.031*	(0.019)	–0.003	(0.017)
Mean ($\mu g/m^3$)	25.27		26.14		26.74	
Obs.	245,810		375,040		426,217	
(b) Fleet Composition						
Share Euro targeted	0.0001	(0.001)	–0.0029***	(0.001)	–0.0017	(0.001)
Mean	0.1392		0.2945		0.1854	
Share Euro 4+	–0.0010	(0.001)	0.0029**	(0.001)	0.0014	(0.001)
Mean	0.3118		0.3673		0.4385	
Share Diesel	–0.0041***	(0.001)	–0.0034**	(0.002)	–0.0026**	(0.001)
Mean	0.1724		0.1860		0.1997	
Share Diesel Euro targeted	–0.0010***	(0.000)	–0.0033***	(0.001)	–0.0022***	(0.001)
Mean	0.0072		0.0389		0.0671	
Share Diesel Euro 4+	0.0003	(0.001)	0.0017	(0.002)	0.0007	(0.001)
Mean	0.0536		0.0684		0.0890	
Obs.	5,144		7,296		8,448	
(c) Traffic Counts						
All Vehicle Types - Levels	–2.035**	(0.896)	–1.761***	(0.573)	0.885	(0.902)
All Vehicle Types - Logs	–0.025**	(0.010)	–0.020*	(0.010)	0.019	(0.014)
Mean (# 1,000 vehicles)	85.256		85.076		83.227	
Heavy-Duty-Vehicles - Levels	–0.020	(0.088)	–0.278**	(0.128)	–0.109	(0.167)
Heavy-Duty-Vehicles - Logs	–0.012	(0.015)	–0.061	(0.036)	–0.066	(0.074)
Mean (# 1,000 HDVs)	8.421		8.432		7.869	
Obs.	67,649		180,335		208,342	

Notes: This table replicates our main estimates (Table 1) in a larger sample that includes observational units (counties and traffic stations) as long as these record data for at least 4 (instead of 8) quarters before and after an event. Given that stage 2 events are positioned in the 'middle' of our sample period, this only affects the stacked fleet composition samples for stage 1 and stage 3. Means correspond to control group means before the respective treatment. Standard errors are clustered at the level of observational units (counties or measurement stations). ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.6: Stacked DID Estimates with different Time-Windows T

	Stage 1		Stage 2		Stage 3	
	± 6Q.	± 10Q.	± 6Q.	± 10Q.	± 6Q.	± 10Q.
(a) Pollution						
PM_{10} - Levels	–0.710	–0.606	-1.030***	–1.017*	0.902***	0.083
	(0.473)	(0.456)	(0.356)	(0.554)	(0.322)	(0.481)
PM_{10} - Logs	–0.017	–0.011	-0.034**	–0.034	0.026**	-0.009
	(0.019)	(0.018)	(0.014)	(0.022)	(0.013)	(0.020)
Obs.	217,880	256,155	356,630	364,108	381,040	344,589
(b) Fleet Composition						
Share Euro targeted	–0.0001	–0.0002	–0.0024***	–0.0031**	–0.0025***	–0.0014
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Share Euro 4+	–0.0006	–0.0005	0.0027***	0.0030**	0.0030***	0.0012
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Share Diesel	–0.0035***	–0.0037***	–0.0023**	–0.0029***	–0.0001	–0.0018
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Share Diesel Euro targeted	–0.0010***	–0.0009***	–0.0026***	–0.0028***	–0.0020***	–0.0019***
	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)
Share Diesel Euro 4+	0.0004	–0.0002	0.0017	0.0011	0.0026**	0.0010
	(0.001)	(0.001)	(0.000)	(0.002)	(0.001)	(0.001)
Obs.	3,144	2,640	6,264	3,744	7,200	4,356
(c) Traffic						
All vehicles - Levels	–1.573*	–2.730**	–0.926*	–1.197*	–0.514	0.976
	(0.768)	(1.101)	(0.536)	(0.648)	(1.022)	(0.941)
All vehicles - Logs	–0.020**	–0.032**	–0.016**	–0.009	–0.017	0.021
	(0.008)	(0.012)	(0.008)	(0.012)	(0.018)	(0.014)
Obs.	51,679	73,434	164,576	185,144	183,575	155,632

Notes: This table replicates our main estimates (Table 1) using alternative values of T, the symmetric pre- and post-treatment window. For each stage, the table presents estimates from the sample obtained from $T = 6$ and $T = 10$ quarters, respectively. Panel (a) uses PM_{10} in levels ($\mu g/m^3$) and logs; panel (b) shows the results for vehicle shares; and panel (c) total traffic counts (in levels of 1,000 vehicles as well as logs) as dependent variables. Standard errors, clustered at the observational unit, are in parenthesis. $^{***}/^{**}/^{*}$ indicate significance at the 1%/5%/10%-level.

Table A.7: Estimates for Fleet Composition - Single LEZ-Stage Changes

	Stage 1 → 2		Stage 2 → 3	
	Coef.	SE	Coef.	SE
Share Euro 1	0.0039***	(0.001)	–0.0006	(0.001)
Mean	0.1184		0.0714	
Share Euro 1 Diesel	–0.0003*	(0.000)	0.0001	(0.000)
Mean	0.0053		0.0043	
Share Euro 2	**–0.0042****	(0.002)	–0.0002	(0.001)
Mean	0.2928		0.2307	
Share Euro 2 Diesel	**–0.0041*****	(0.001)	–0.0012*	(0.001)
Mean	0.0376		0.0313	
Share Euro 3	–0.0024**	(0.001)	**0.0010**	(0.001)
Mean	0.1889		0.1840	
Share Euro 3 Diesel	–0.0020***	(0.001)	**–0.0012***	(0.001)
Mean	0.0647		0.0703	
Share Euro 4+	0.0027*	(0.001)	–0.0004	(0.001)
Mean	0.3701		0.4886	
Share Euro 4+ Diesel	0.0073***	(0.002)	0.0001	(0.002)
Mean	0.064		0.1101	
Obs.	2,976		1,536	

Notes: Results from estimating equation (1) for a sample limited to jurisdictions that adjust the LEZ stringency by only one step: from stage 1 to 2 and from stage 2 to 3, respectively. The control group is composed of jurisdictions that make the same 1-step change at a later point in time. The table also reports the control group means before the respective treatment. Standard errors are clustered at the county level. ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.8: Stacked DID Estimates with Never-Adopting Units in Control Group

	Stage 1		Stage 2		Stage 3	
	Coef.	SE	Coef.	SE	Coef.	SE
(a) Pollution						
PM_{10} - Levels	–1.040***	(0.331)	–0.869***	(0.247)	-0.230	(0.211)
PM_{10} - Logs	–0.013	(0.014)	–0.018**	(0.008)	-0.000	(0.008))
Mean ($\mu g/m^3$)	21.52		21.65		21.68	
Obs.	2,469,074		3,076,856		2,836,775	
(b) Fleet Composition						
Share Euro targeted	–0.0010	(0.001)	–0.0002	(0.001)	–0.0017	(0.001)
Mean	0.1198		0.2745		0.1821	
Share Euro 4+	–0.0007	(0.001)	0.0009	(0.001)	0.0023*	(0.001)
Mean	0.3544		0.4172		0.4671	
Share Diesel	–0.0031***	(0.001)	–0.0054***	(0.001)	–0.0035***	(0.001)
Mean	0.1885		0.1986		0.2074	
Share Diesel Euro targeted	–0.0011***	(0.000)	–0.0034***	(0.001)	–0.0027***	(0.001)
Mean	0.0069		0.0367		0.0670	
Share Diesel Euro 4+	0.0011	(0.001)	–0.0001	(0.001)	0.0013	(0.001)
Mean	0.0662		0.0829		0.0977	
Obs.	12,768		23,616		20,112	
(c) Traffic Counts						
All Vehicles - Levels	–1.992**	(0.860)	0.665	(0.766)	1.286	(0.877)
All Vehicles - Logs	–0.015	(0.009)	0.004	(0.011)	–0.012	(0.011)
Mean (# 1,000 vehicles)	31.140		32.133		32.466	
Heavy-Duty Vehicles - Levels	–0.531***	(0.134)	–0.032	(0.078)	0.043	(0.087)
Heavy-Duty Vehicles - Logs	–0.043***	(0.017)	0.004	(0.018)	–0.022	(0.026)
Mean (# 1,000 vehicles)	4.017		4.048		4.069	
Obs.	10,206,012		15,141,400		13,954,847	

Notes: This table replicates our main estimates (Table 1) using an alternative sample definition that includes observations from never-adopting jurisdictions in the control groups. While we maintain our focus on counties with at least 100,000 inhabitants, this step significantly increases the sample size. Panel (a) and (c) explore daily pollution and traffic measures (from all stations located in the included jurisdictions). Panel (b) uses monthly data from counties. The line labeled Euro targeted (and, analogously, diesel Euro targeted) indicates the estimated effects of stage 1 LEZs on the share of Euro 1 / stage 2 on Euro 2 / and stage 3 on the share of Euro 3 vehicles. The table also reports control group means (before the respective treatment). Standard errors are clustered at the level of observational units (counties or measurement stations). ***/**/* indicate significance at the 1%/5%/10%-level.

Table A.9: PM_{10} Emission Levels of Diesel and Gasoline Cars

Emission Standard	*Diesel*	*Gasoline*
Euro 1	121.222	7.310
Euro 2	82.833	11.887
Euro 3	40.953	4.441
Euro 4	13.582	2.301
Euro 5	2.190	2.374
Euro 6	0.749	1.077

Notes: The table presents actual tailpipe PM_{10} emission levels (in μg per kilometer) for diesel and gasoline cars with different emission standards provided by the Handbook of Emission Factors for Road Transport (version 4.2). The presented values correspond to the reference year 2010 and capture so-called 'hot' emission factors (i.e., emissions of a hot engine, thus excluding excess emission factors resulting from a cold start of an engine). The values are based on various measurements via, e.g., portable emission measuring systems on the road, chassis dynamo-meters in laboratories, and roadside remote sensing data. For each engine (diesel or gasoline) and emission class, reported emission values are based on weighted averages of measurements with different cars that reflect the composition of the German car fleet (within each engine $\times$ emission class group) in 2010. The latter point also explains the non-monotonicity observed for gasoline cars: the values reflect that there were many emission-intensive Euro 2 cars but many Euro 1 cars with relatively low emissions (within that emission class).

Appendix B: Upgrading Costs induced by LEZs

To quantify how many cars were actually replaced due to low emission zones (LEZs), we return to our estimates from Table A.1, panel (ii). Note that these coefficients, which are again presented in Table B.1 below, capture the decline in market shares of diesel cars with different emission classes (relative to the counterfactual) relative to the total vehicle stock. To approximate the number of cars removed from the fleet (again relative to the counterfactual), we thus have to multiply these coefficients with the total number of cars in the treatment jurisdictions at baseline. These numbers (which vary between the different LEZ stages since different counties are included as treatment units in our three main estimation samples) are presented in the column 'Baseline' for the month (−1) or 24th month (−24) before the implementation of a given LEZ stage. Using the values from the pre-treatment month as baseline, we arrive at the number of (relative to the counterfactual) additional diesel cars replaced due to the three LEZs stages. Adding up the three values, 5,264 (stage 1), 25,563 (2) and 18,044 (3), we arrive at a total of 48,872 old diesel cars that were taken off the roads in response to the LEZs.

Table B.1: Number of Affected Diesel Cars

		Baseline:		Stage 1		Stage 2		Stage 3	
Stage	Month	Total Cars	Outcome	Coef.	Cars	Coef	Cars	Coef	Cars
1	–1	1,385,281	Diesel	–0.0010	1,385	—	0	—	0
	–24	1,370,333	Euro 1						
2	–1	5,012,357	Diesel	–0.0028	3,879	–0.0033	16,541	–0.0014	7,017
	–24	4,881,185	Euro 2						
3	–1	3,646,431	Diesel	—	0	–0.0018	9,022	–0.0022	11,027
	–24	3,545,057	Euro 3						
			Sum		5,264		25,563		18,044

Notes: The table presents an approximation for the total number of additional diesel cars replaced due to the implementation of different LEZ stages. The column 'Baseline' presents the total number of cars in the treatment counties (which are included in our main estimates) in the month (−1) or 24th month (−24) before implementing a stage 1, 2 or 3 LEZ, respectively. On the right-hand side, we reprint the estimated coefficients from Table A.1. We only focus on statistically significant coefficients obtained for diesel vehicles.

Note that we would obtain smaller values if we would consider the total number of cars from the 24th month (-24) before LEZ implementation as a baseline. Let us also stress that we would obtain a slightly smaller number if we would consider the sum of diesel and gasoline cars (as some of the coefficients for the pooled Euro 1, 2 and 3 shares from Table A.1, panel (ii) are larger in absolute terms (or even positive) than the coefficients obtained for the respective diesel-only shares). The number reported above thus constitutes an upper bound.

How does the number of cars compare to other estimates from the literature? Let us first consider the seminal paper from this field. Using a cross-section of 405 counties, Wolff (2014) approximates the impact of LEZs on the car fleet by regressing the change in the share of Euro 4 cars between 2008 and 2010 (Δ E4) against the spatial distance to the nearest LEZs. His cost-benefit analysis considers the Δ E4 observed for the county furthest away from a LEZ as the baseline (counterfactual) change in Euro 4 cars. Subtracting the estimated value for LEZ counties (0.021; see Figure 5 in Wolff, 2014) from this baseline (0.011; see Appendix F.2 in Wolff, 2014), one would obtain an (additional) increase in modern cars due to LEZs of 1% (0.01). If we extrapolate this number to the baseline stock of cars observed in our sample (i.e., multiplying the baseline for stage 1, 2 and 3 by 0.01 and summing up the numbers), this would imply a total of 100,441 extra Euro 4 cars – which is twice as large as the number of replaced diesel cars computed above. (Obviously, our back-of-the-envelope approximation is based on many strong, implicit assumptions. These are necessary, however, to compare our estimates with those from Wolff.)

Another interesting approximation of the private costs of LEZs is reported in Rohlf et al. (2020). The authors observe that 200,240 cars registered in LEZ counties (pre-treatment) do not comply with the respective LEZ restrictions. Our estimates deviate from this number in two ways. On the one hand, our estimates from Table A.1 show that LEZs also induce anticipatory responses and upgrades of not-yet-affected vehicles (e.g., a stage 1 LEZ that affects Euro 2 diesel cars). This would suggest that the number of affected cars might be higher than the number used by Rohlf et al. (2020). On the other hand, however, our estimates show that the LEZs only induce the replacement of 50,000 additional cars – as compared to the upgrading dynamics in the counterfactual counties. The latter point suggests that the number of 200,000 cars might be too large.

Overall, it is important to acknowledge that neither our nor any other number of affected cars allows for a clear-cut estimation of social costs. It is difficult to approximate the true social costs from upgrading once we account for the (private) benefits from driving a modern (and, typically, more fuel-efficient) car at an earlier point in time (than without any LEZs). One would also have to put a price tag on the reduced value of not-upgraded cars that can no longer be used to drive into city centers. In addition, LEZs might have impacted second-hand prices of used (but restricted) vehicles. Rather than making strong assumptions to quantify these (and further) cost components, we only note that our estimates suggest that the number of affected cars – and, thus, an important part of LEZs' overall social costs – might be smaller than has been estimated before.