The effect of Low Emission Zones in local production: The case of German cities

Preliminary.
Please do not cite or share without author's permission.

February 11, 2022

Abstract

More than 400 Low Emission Zones (LEZ) have been adopted in Europe. While LEZ impose restrictions on vehicle use and are sometimes criticised for "hurting the economy", recent literature suggests LEZ could improve economic performance through their proven reduction of air pollution. As LEZ are discussed as a policy that can either harm or boost economic growth, this paper provides the first estimates of the impact of Low Emission Zones on the growth and structure of the local economy by using their staggered introduction in German cities since 2008. We find that the application of Low Emission Zones permanently reduced local GDP by 4.5% on average (≈790€ billion per year for the subset of cities studied). The driving factor of this reduction was a reduction in productivity and employment with total population being unaffected. While the aggregate output of the Trade and Personal Services sector was not negatively affected, LEZ slightly changed the structure of the local economy away from industry (decreased from 25% to 23.5% of GVA) and towards public services (increased from 24% to 14.8% of GVA) and local commerce and personal services (increased from 20% to 20.7% of GVA) . Finally, we find insignificant results for the effect of LEZ announcement. These results suggest that the restrictions from LEZ, and the substantial capital losses they generate to sectors that rely on high-polluting vehicles, might produce large and previously unaccounted costs (and changes) to the local economy.

Keywords — Low Emission Zones, Local growth, Germany, GDP

1 Introduction

The effects of air pollution on human health and wellbeing are a major global concern. Over 3 million deaths a year worldwide and 446.000 in Europe are attributed to air pollution alone (European Environmental Agency, 2019; Shaddick et al., 2018). Air pollution is the second biggest environmental concern for Europeans, after climate change (European Commission, 2017), and is considered "the most important environmental risk to human health" by the European Environmental Agency (2020). Substantial and diverse policy initiatives to reduce urban air pollution have been implemented around the world, most of them being restrictions to the use of vehicles[1]. As one of these alternatives, Low Emission Zones (LEZ) - geographical areas with restricted access for highly-polluting cars - have been widely adopted across Europe with at least 404 LEZ either implemented or planned for the near future, and most of Europe's largest cities having applied one (Sadle Consultants Europe, 2022).

Their implementation has delivered on the promise of reducing air pollution (Gehrsitz, 2017) and thus positive impacts on health, worker productivity and human capital formation (Zivin and Neidell, 2018). Nevertheless, they create restrictions and cause substantial capital losses to owners and sectors that rely on highly-polluting vehicles that are either prohibited or need to be retrofitted to attain the new emissions standards (Wolff, 2014). In Germany, the opposition to this measure has been strong and widespread, with local retail businesses being particularly afraid of negative economic effects.

In this paper, we study the causal effect of the announcement and application of Low Emission Zones in the local production, productivity and economic structure of a large group of German cities. To estimate this, we use the staggered announcement and adoption of LEZ across German cities from 2008 to 2017 together with unique data on city-level GDP, population, employment and Gross Value Added (GVA) for 6 sectors of the local economy. Germany is an optimal case study for this policy as the application of Low Emission Zones is triggered by local violations of the European Union air quality standards and thus it is forced upon cities by state governments responsible for compliance to EU legislation. Moreover, German LEZ were standardised by the federal law in 2006, so they apply the same fines and restrict the same classes of vehicles on each of their stages.

[1]Some examples include pedestrian areas, parking schemes, Low Emission Zones, congestion pricing schemes, limitations for certain vehicles at certain times of the day, lanes exclusive for massive transport vehicles, retrofitting of taxis and public buses or subsidies for electric or hybrid cars.

We use a panel data of local macroeconomic variables of German districts (*Kreise*) from 1991 to 2018 together with a new dataset of the announcement dates of German Low Emission Zones. After carefully selecting the treatment and control cities, we apply the staggered differences-in-differences method from Callaway and Sant'Anna (2021) to estimate the effect of the announcement and application of German LEZ their cities' GDP, GDP per capita, employment rate, population , and the relative shares of GVA of the major economic sectors in cities: Trade and Personal Services (TPS), Professional Services, Public Services (including education, health and arts), Construction, and Industry.

To avoid confounding the effects of the application of Low Emission Zones and two major and possibly confounding events (the 2008 financial crisis and the 2009 German scrappage program), we carefully divide our treated cities into those that announced the LEZ before the start of the crisis (2008) and those that announced it after its end (2010). The group of early adopters, comprised of large metropolitan areas, uses a control set of comparable not-yet-treated regions while the late adopters are compared with a restricted sample of cities that have the same demographic and economic structure but have not applied a LEZ. We further allow for a 60km buffer between control and treated cities to avoid spatial spillovers. Covariates are balanced in both pairs of treated and control cities and outcomes exhibit parallel trends of more than 15 years before LEZ announcement.

Our main results suggest that the application of Low Emission zones permanently reduced local GDP by 4.5% on average, roughly equivalent to 1400€ per person per year and a total of $\approx$ 790€ billion per year for a subset of cities studied, a large and previously unaccounted economic cost. From decomposing local GDP into productivity, employment and population we find that the driving factor of this negative effect is an almost equivalent reduction in GDP per capita and not changes in population. Finally, the Trade and Personal Services sector, which was the most vocal opposition in Germany against Low Emission Zones, was not negatively affected, having a positive (although insignificant) effect from the announcement and application of LEZ.

Concerning the changes in the composition of the local economy, the application of Low Emission Zones promoted a significant increase in the weight of the Trade and Personal Services sector on the local GVA (a 0.68% increase over a previous 20% share) and the Public Services sector (a 0.85% increase over a previous 24% share). On the other hand it prompted a large decrease of the weight of Industry (without construction) of 1.5% (over an initial share of 25%). These changes in economic structure and are mostly driven by the cities that applied a LEZ in 2011[2]. This goes in line with what we would expect from such a measure. Focusing on effects on working productivity and human capital, the local industry is not expected to benefit as much as retail or personal services from a reduction in air pollution in the city centre given it is usually located in the outskirts of cities. Furthermore, from the supply side, the costs of upgrading old commercial vehicles might be higher for the local industry. These changes in the economic structure can have long-run effects on economic development, employment and income as they could increase the production of non-tradable over tradable goods and services.

Overall, this paper contributes to the literature on the effects of Low Emission Zones with the estimation of their impacts in two previously unstudied outcomes: local production and economic structure. First, it contributes to the growing literature on the effects of Low Emission Zones on economic outcomes such as the costs of substitution of old vehicles (Wolff, 2014) and its effect on local commerce and trade, a contentious topic central to the historic opposition to LEZ. While previous literature already found neutral effects on consumer revenue in retail for Madrid LEZ (Galdon-sanchez et al., 2021), We complement these findings by studying the effects on a sector level for a large number of cities. Finally, this paper contributes to the literature on the macroeconomic effects of negative capital shocks in an open economy (Alvarez-Cuadrado, 2008) by providing a case study of local economies and decomposing the effect on GDP into relevant macroeconomic indicators such as productivity, employment and population.

The results of this paper indicate that although Low Emission Zones have proved to have reduced air pollution and thus improved outcomes in health and human capital, they can change the structure of the economy away from industry and towards public services, local commerce and personal services, and create large costs in the form of reductions in GDP and GDP per capita. With the announcement and application of increasing restrictions to vehicle traffic in Europe, these results might prove useful to policymakers deciding over a wide range of urban traffic policies to protect public health and to reduce emissions of air pollutants.

The remainder of this paper is structured as follows: Section 2 describes the institutional background and situates our work in the broader literature. Section 3 explains the data collection and analysis strategy. Section 4 describes and interprets the results. Section 5 concludes.

[2]Hagen, Halle (Salle), Heidenheim, Magdeburg, and the Ruhr metropolitan area.

2 Institutional Background and Research Questions

2.1 German Low Emission Zones

The application of Low Emission Zones has the objective to improve air quality standards and based on two main facts: First, a significant proportion of cities' ambient air pollution comes from traffic, a especially harmful source to humans given they are emitted close to the ground (35-55% of PM_{10} particles in average for Europe according to Viana et al. (2008)). Second, old vehicles can have emissions orders of magnitude larger than their newest counterparts[3]. By restricting the use of the most polluting vehicles LEZ can reduce air pollution emissions of an especially dangerous source while minimizing their disruption.

The large scale application of LEZ around Europe has been heavily shaped by European legislation on air pollution levels. Most regional and national governments have been either threatened by fines or strongly incentivised to pursue decisive policy action by European regulation. As a result of this European legislation, infringement procedures have been opened against 16 Member States[4] and the EU Court of Justice has already handed down judgements in Bulgaria and Poland.[5].

From 2005 to 2007, two-thirds of German cities with more than 100.000 persons were violating European limits and were forced to develop Clean Action Plans (in German: *Luftreinhaltepläne*), defining a set of measures to attain compliance with EU standards. Most of them had a LEZ as the principal measure (Gehrsitz, 2017) and 46 LEZ were implemented over the course of 5 years between 2008 and 2015, including most German cities with more than 10.000 inhabitants. This was possible because German LEZ have been supported and standardised by the federal government: all of them require an "emissions windshield sticker" to access, with the colour of the sicker signalling their emission standard. Stickers, in increasing pollution emissions, go from green to yellow to red. The strictest LEZ only allow cars with green stickers and the most polluting cars have no sticker at all and are forbidden from all LEZ. With time, German LEZ have become increasingly restrictive and more cars have been banned from entering them (from March 2018, all German LEZ but one only allow vehicles with green stickers)[6]. As an example of the level of disruption the application of a LEZ

[3]An old petrol car with a Euro 1 emission standard generates 10 times more emissions than a newer vehicle with a standard of Euro 4

[4]Belgium, Bulgaria, the Czech Republic, Germany, Greece, Spain, France, Hungary, Italy, Latvia, Portugal, Poland, Romania, Sweden, Slovakia and Slovenia

[5]Communication from the EC, "A Europe that protects: Clean air for all", accessible here: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018DC0330&from=GA

[6]For a graphical representation of these stages for all German LEZ see figure 1 in the Appendix.

can represent, in 2008 when 7 LEZ were already introduced in major cities such as Berlin, Stuttgart and Köln (and had been announced for years) 20% of commercial (and 3% of private) vehicles in circulation were completely banned from entering these major cities (Wolff, 2014). Entering a LEZ with a banned vehicle is fined with 80€ and implies a 1 demerit point in the central traffic registry (Gehrsitz, 2017). But, what macroeconomic consequences can we expect from such a policy?

2.2 Plausible effects and research questions

Low Emission Zones are a restriction to the use of highly polluting vehicles in a delimited area of the city, usually the city centre, Old cars are prohibited, some cars have to be retrofitted to attain the new emissions standards and all cars have to be labelled by their level of emissions, creating sizeable costs to the owners of such cars.

The effect of LEZ can be especially damaging to individuals and businesses that work or depend on the transport of commercial goods given most costs are being imposed in their supply chains. Furthermore, local commerce and personal services (such as restauration or accommodation) that rely on tourists could also be severely affected if a proportion of their clients is excluded from entering a city's commercial areas (such as the historic centre). These short-term costs can end up reducing savings and investment in specific sectors, having an impact on their medium- or long-run economic growth and changing the structure of the economy.

In an online survey from 2009, over 91% of Germans rejected LEZ as being "too bureaucratic and likely having little effect" while store owners complained that LEZs lead to declining sales (Wolff and Perry, 2010). Furthermore, the German pro-business "Institute for Retail Research" estimated a 7% decrease in customers for stores located within a city's centre after the introduction of a LEZ (Lindstaedt, 2009). An example is the city of Freiburg, often visited by neighbouring French and Swiss tourists, being estimated to lose close to 100M€ per year in revenue by their local retail association (Badische Zeitung, 2009).

The effects on the freight transport sector are, in principle, ambiguous. While a LEZ can impose strong direct costs to transport companies they can also benefit from an improvement of their fleet, a higher degree of industry consolidation or a reduction of congestion. Direct costs can come from multiple forms such as the retrofitting of old vehicles, the costs of new ones, or the reduction in the residual value of vehicles that become non-compliant with the new LEZ. On this subject, the study from Browne et al. (2005) of London's LEZ explains that the effect is strongly dependent on the LEZ restrictions and the rate of vehicle replacement of companies. They continue by saying that companies with specialised vehicles, small companies and self-employed owner-drivers end up bearing most of the costs. Dablanc and Montenon (2015) complement these findings by saying that the application of LEZ reduces the number of firms that perform deliveries. They mark this effect as socially desirable as it is expected to promote efficiency by expelling small and less-profitable firms that "find it difficult to maintain a sufficient level of business activity without breaking the freight sector's labour laws and safety standards".

From these costs, a narrative of "Jobs versus the Environment" (Morgenstern et al., 2002) can emerge in which regulators have to balance both objectives and make compromises. This might not be the case for LEZ, as they also have the potential to have positive consequences through the reduction in air pollution. This hypothesis is based on recent research by Wolff (2014), Gehrsitz (2017) and Pestel and Wozny (2021), showing the significant effect of German LEZ on the reduction of pollution and health costs. Specifically, the application of German LEZ reduced average pollution (from -0.67 to -1.3μg/m^3) (Gehrsitz, 2017) and cardiovascular and respiratory diseases in nearby hospitals (Pestel and Wozny, 2021). After pollution particles are inhaled, they can enter the lungs and pass to the bloodstream, finally affecting multiple organs such as the heart and the brain (Calderón-Garcidueñas et al., 2014; Du et al., 2016; Ranft et al., 2009).

Additionally, recent studies suggest that air pollution reduces aggregate economic output. Dechezleprêtre et al. (2019) show how air pollution causes economy-wide reductions in productivity and economic activity. He concludes that a 1 μg/m^3 ($\approx 10\%$) increase in PM$_{2.5}$'s yearly average concentration causes a 0.8% decrease in GDP and, strikingly, that air pollution abatement costs would be two orders of magnitude smaller than the associated economy-wide reductions in productivity. Fu et al. (2017) also find a significantly negative impact of air pollution on GDP per capita, with an increase of 5 $\approx 10\%$) in PM$_{2.5}$'s yearly average concentration in China causing a reduction of 0.4% of GDP per capita. Air pollution has also been found to increase absenteeism (Aragón et al., 2017; Hanna and Oliva, 2015; Holub et al., 2006; Ransom and Pope, 1992), reduce the productivity of physical and intellectual work (Adhvaryu et al., 2014; Chang et al., 2016; Graff-Zivin and Neidell, 2012) and reduce cognitive performance (Ebenstein et al., 2016; Zhang et al., 2018). Using the estimates of literature cited above of the effect of German LEZ in air pollution and the effect of air pollution on aggregate GDP, back of the envelope calculations suggest that German LEZ could foster an increase of local GDP between 0.2 and 1.6%.

In summary, Low Emission Zones can have both negative and positive effects on local aggregate production though various channels and have the potential to change the structure of the local economy away from sectors relatively penalised and towards sectors relatively benefited by it. To shed light on the magnitude of these two plausible effects, this paper looks at the effect of LEZ in local aggregate production (GDP), decomposed into productivity, average employment, and population and the structure of the local economy, measured as changes in the relative shares of different sectors over total GVA. We finally look at German cities economic production from the Trade and personal services (TPS) sector.

3 Data collection and analysis strategy

To explore the causal effect of Low Emission Zones on the various outcomes mentioned above I use a staggered differences-in-differences (DiD) procedure. As the whole family of DiD methods, this will consist in comparing the outcome paths of a set of treated and control cities before and after treatment. In the next paragraphs, we explain the sources, characteristics, and context of our data, and how we select the treated and control cities to satisfy the necessary assumptions to claim causality.

The initial sample includes all German districts (*Kreise*, equivalent German to NUTS3 regions) from 1991 to 2017 . Data on outcomes and controls was gathered from the European ARDECO database which aggregates data from Eurostat and National sources and provides yearly statistics on GDP, GVA per sector[7] and population. Although the spatial boundaries of German districts are usually a very good representation of a city extent (from large cities such as Berlin or Hamburg to very small cities of less than 50.000 inhabitants such as Amberg), they do not represent Functional Urban Areas or Travel-to-work areas. Furhtermore, a small number of LEZ have been implemented in small rural towns where “rural districts” (*Landkreise*) do not follow their town boundaries. An example of both representative and unrepresentative boundaries is presented in Figure 2 in the Appendix. All LEZ applied in small towns without a representative county are excluded from our analysis. An illustration of the boundaries of German districts can be found in Figure 5 in the Appendix.

[7] GVA per sector is divided into 6 aggregate sectors of economic activity according to the NACE Rev.2 codes, in parenthesis: **(A)**: Agriculture, forestry and fishing, **(B-E)**: Industry - except construction -, **(F)**: Construction, **(G-J)**: Trade and Personal Services or “Wholesale and retail trade; transport; accommodation and food service activities; information and communication”, **(K-N)**: Financial; real estate; professional, scientific; technical; administrative and support service activities, and **(O-U)**: Public administration and defence; compulsory social security; education; human health and social work activities; arts, entertainment, repair of household goods and other services.

Additionally, a detailed calendar of the announcement and application of LEZ in Germany was constructed from two sources: On one hand, the implementation of LEZ in Germany is well documented by the German Environment Agency (UBA, *Umweltbundesamt* in German) with dates for the application of each "stage" of a given LEZ. On the other hand, the announcement dates of each LEZ are not documented on a structured database and were searched individually on historical documents such as local news and each city's "Environmental Plan" published on their respective official websites. This is crucial to assign the announcement period as the start of the treatment. Figure 1 in the Appendix summarises the treatment status of all LEZ in Germany included in our analysis from 2006 to 2017.

3.1 Identifying requirements and sample selection

In other to claim that our estimates from the differences-in-differences procedure can be interpreted as causal estimates various requirements have to be met:

First, the application of the policy has to be exogenous to the outcome paths of treated units, conditional on covariates. This would imply that treatment and control units would exhibit parallel outcome trajectories for all periods in the absence of treatment. Although this is an untestable assumption for any situation outside a randomized experiment, two key points make this assumption plausible in the case of German Low Emission Zones. First, as explained above, the policy was exogenously forced upon cities by state governments or court rulings based on of EU air quality legislation Pestel and Wozny (2021). Having parallel trends of the outcomes before the policy is implemented for a sufficient number of years would increase the confidence in this assumption. The data allows for visual inspection of parallel treatments for more than 15 years before the policy, a period larger than most empirical applications. To further increase the confidence in this crucial assumption, we restrict the control pool to assure the balance on key economic and demographic variables between treatment and control cities.

Second, the policy should not have any unaccounted anticipation effects as they would bias the estimated effects. This can be an issue given LEZ are usually publicised before being enacted to incentivise the public to upgrade their vehicles before its application. As an example, Wolff (2014) shows how the German city of Regensburg had a very strong relative increase in green-labelled cars after the LEZ announcement but before its application. This is accounted for by creating an "announced" period, and setting it as the start-of-treatment date. Although this looks like a potential source of bias, previous research on LEZ tends not to control for it. Wolff (2014), Gehrsitz (2017), Pestel and Wozny (2021), Morfeld et al. (2014), and Browne et al. (2005) are some examples.

Third, there must be no interference between units. In other words, control cities should not be influenced by the treatment of nearby treated cities. Wolff (2014) shows that the application of a LEZ correlates with a change towards cleaner vehicles and cities close enough also seem to experience these changes. For that reason, and based on Wolff (2014) data, only zones that are *at least* 60km away from any LEZ implemented in the studied period are included as controls[8].

Forth, there should be no significant events that affect treated (or control) units in the post-intervention period as their effect would be wrongly added (or subtracted) from the real causal effect of the treatment. Two main events of this sort could pose a threat to our data analysis: the great financial crisis, that lasted between 2008 and 2010 for Germany, and the 2009 German scrappage program. Our sample was carefully partitioned to avoid any influence of these two confounding events.

In the first place, it is hard to prove that the local growth and the economic structure of treated and control cities were similarly affected by the financial crisis. Most importantly, the 2009 German scrappage program (a policy specifically thought to stimulate the economy after the financial crisis) poses a potential source of bias for cities that had a LEZ either implemented or announced before the end of this program. As the largest policy of its type in the world, it offered a lump-sum subsidy of 2.500€ for buying a new car when the buyer scrapped their old one. From the 14^{th} of January to the 2^{nd} of September, 2009, two million car sales were subsidised, implying the substitution of two million cars older than nine years old for new cars with better emissions standards (at least “Euro 4” compliant and thus worthy of a ”green” sticker) (Kaul et al., 2012). The population of cities that had a LEZ implemented or announced during this period had stronger incentives to change their old cars for new ones given they were (or would) not be able to use them inside the LEZ. This implies that these cities would potentially receive larger sums of fiscal stimulus from the central government, having a direct effect on their economy.

To satisfy this last and crucial condition, we carefully divide our treated units into 3

[8]This is taken as the distance from the centre of a treated city to the closest point of a “control” NUTS 3 zone (and thus a conservative measure).

groups such that the financial crisis and the scrappage program do not influence the final results: First, those districts that announced their LEZ between the start and the end of the financial crisis (2008-2010) are discarded from our sample. This is because most of them had a LEZ while the scrappage program was on and, while we can check for parallel trends before their announcement, it is impossible to know if the financial crisis affected them differently than control districts. Second, we create a group of *early treated* units that announced their LEZ before 2008 and discard all outcomes after the start of the crisis as those outcomes would be affected both by the financial crisis and the scrappage program. Finally, we create a group of *late-treated* units that announced their LEZ after the end of the financial crisis (2010) given that for this group it is possible to test the pretreatment parallel trends before, during and after the financial crisis and the scrappage program, giving confidence on the validity of its control group.

This gives two final groups of treated units: *Early-treated* districts studied until 2008 and where we can see only the effects of LEZ announcement and *late-treated* districts where we can observe the effects of both the announcement and the application of LEZ (See Figure 1 in the appendix for reference). As these two samples show different stages of LEZ adoption we don't expect them to have the same results. To improve the balance on relevant economic determinants and the validity of comparison groups the early-treated regions are compared with cities that applied a LEZ after the start of the financial crisis and late-treated cities are compared with cities that have never introduced a LEZ. Tables 1 and 2 show the summary statistics for the early-treated and late-treated experimental settings, respectively where the balance economic characteristics can be inspected.

From Tables 1 and 2, we can conclude that, in both experimental settings, treatment and control are balanced in all relevant variables such as GDP per capita, population density, and the share of the major sectors in the economy. Sample means are comparable and the extreme values of the treated units are closely mirrored by the controls. To fully clarify the time, space, and treatment dimensions of early- and late-treated experimental settings, Figures 1, 3, and 4 in the Appendix show, respectively, the staggered adoption of LEZ for our complete sample, a step-by-step flow chart of the data selection procedure, and the geographic location of treated and control units.

Variable	**Group**	**n**	$\bar{x}$	s	**Min**	**Max**
GDP per capita (€)	Treated	12	44797.3	14257.8	25686.8	76618.0
	Not-yet-treated	22	33281.7	11999.9	18863.1	68031.3
log(population)	Treated	12	12.9	1.0	11.7	15.0
	Not-yet-treated	22	12.6	0.6	11.7	14.0
GDP per employee	Treated	12	71001.0	10624.3	57524.3	95883.4
	Not-yet-treated	22	64061.2	11731.3	48458.3	92562.6
Average employment	Treated	12	0.6	0.1	0.4	0.8
	Not-yet-treated	22	0.5	0.1	0.4	0.7
Population per km^2	Treated	12	1634.0	1046.4	257.7	3802.8
	Not-yet-treated	22	1778.7	1045.1	200.8	4041.3
Share of GVA (%) from:						
Industry	Treated	12	22.4	6.9	13.3	34.0
	Not-yet-treated	22	20.3	8.6	8.6	38.4
Construction	Treated	12	4.1	0.9	2.8	5.8
	Not-yet-treated	22	5.5	1.8	2.8	8.3
Trade and personal services	Treated	12	21.7	5.3	13.2	31.0
	Not-yet-treated	22	20.5	3.6	11.9	26.7
Agriculture, forestry and fishing	Treated	12	0.2	0.1	0.0	0.4
	Not-yet-treated	22	0.1	0.2	0.0	0.6
Public sector, education, health, and arts	Treated	12	24.3	6.7	15.3	34.3
	Not-yet-treated	22	26.0	6.1	16.2	40.0
Financial, real state, professional, scientific and technical activities	Treated	12	27.6	3.8	21.4	33.8
	Not-yet-treated	22	27.2	5.3	19.7	37.5

Table 1: Summary statistics for early-treated experimental setting

Variable	**Group**	**n**	$\bar{x}$	s	**Min**	**Max**
GDP per capita (€)	Treated	26	30958.2	8875.7	18863.1	66794.3
	Not treated	47	36852.6	10770.4	18153.7	64241.0
log(population)	Treated	26	12.5	0.6	11.7	13.4
	Not treated	47	11.7	0.8	10.5	14.4
GDP per employee	Treated	26	63452.0	8559.0	48458.3	78829.4
	Not treated	47	61751.6	8054.1	45176.4	92686.0
Average employment	Treated	26	0.5	0.1	0.4	0.9
	Not treated	47	0.6	0.2	0.3	0.9
Population per km^2	Treated	26	1462.8	944.9	200.8	3334.2
	Not treated	47	845.0	594.2	190.9	2667.8
Share of GVA (%) from:						
Industry	Treated	26	24.9	9.7	8.6	41.9
	Not treated	47	24.3	10.1	5.2	55.7
Construction	Treated	26	5.2	1.7	2.9	8.3
	Not treated	47	4.5	1.9	1.7	10.6
Trade and personal services	Treated	26	19.8	4.0	11.9	27.6
	Not treated	47	20.1	6.1	8.9	34.8
Agriculture, forestry and fishing	Treated	26	0.2	0.2	0.0	0.9
	Not treated	47	0.3	0.3	0.0	1.2
Public sector, education, health, and arts	Treated	26	24.1	6.7	13.3	40.0
	Not treated	47	26.6	8.3	12.7	50.2
Financial, real state, professional, scientific and technical activities	Treated	26	25.5	4.4	19.5	35.1
	Not treated	47	24.0	4.6	12.7	36.1

Table 2: Summary statistics for the late-treated experimental setting

3.2 Regression Model

Our objective is to explore the dynamic effects of the announcement and application of Low Emission Zones in the economic output and the structure of the economy of the cities that applied them. The staggered adoption of the treatment and the panel structure of our data motivates the use of difference-in-difference methods, and more specifically the use of a classic dynamic two-way fixed effect (TWFE) or 'event-study' model as follows:

$$y_{it} = \alpha + \sum_{k=-15, k\neq 1}^{+K} \beta_k LEZ_{ik} + \delta_i + \delta_t + \varepsilon_{it} \tag{1}$$

where y_{it} indicates the outcome of interest for city i at time t. LEZ_{ik} indicates dummy variables of yearly leads and lags up to 15 years before the announcement of a Low Emission Zone. Each β_k for $k < -1$ gives a test of parallel pre-treatment trends and each β_k for $k > 0$ represents the causal effect of the announcement or application of a LEZ relative to the year immediately before the announcement ($k = -1$). Finally, city fixed effects δ_i capture any time-invariant characteristics while time fixed effects δ_t control for any trends that are common for all cities. The error term ε is clustered at the city level.

Although the classic TWFE regression has been previously used to estimate the causal effects of German LEZ (Pestel and Wozny, 2021; Wolff, 2014), recent literature has shown that this recovers the unbiased causal parameters and correct pretreatment differences only if the treatment effect for each period since treatment (k) is equal for all treated units. This is not expected to be the case for the announcement and application of LEZ in Germany as cities have different treatment calendars, i.e. take different time spans to go from announcement to application or any other stage. Furthermore, we could expect the stages to become less restrictive as time passes given the number of high-polluting cars in circulation gets reduced in time. The bias of the dynamic TWFE comes from estimates for β_k being influenced by treatment effects at lags $k' \neq k$ and thus from having units that are treated at different time periods. This is further developed by Sun and Abraham (2021) and Goodman-Bacon (2021) and is clearly summarised by Roth et al. (2022).

This motivates me to use the more recent procedure by Callaway and Sant'Anna (2021) which estimates equation (1) separately for each group of treated units that apply the treatment on the same year, creating estimates that change by period and year ($\beta_{k,g}$). This avoids comparing units that are treated at different times and gives unbiased treatment effects even with heterogeneity of effects between cities.

Furthermore, this allows to control for determinants of treatment timing, that is a vector of time-invariant covariates measured before treatment $\mathbf{X}_i'$ which may have a time-varying impact on the outcome. In the case the parallel trends condition holds only conditional on these determinants, this method can control for them parametrically by including them in equation (1) or non-parametrically by constructing a group-specific propensity score to balance on covariates using Inverse Probability Weighting (IPW). Finally, we can construct aggregate estimates from weighted averages of $\beta_{k,g}$ such as the average treatment effect 2 periods after the announcement $\beta_{k=2}$ or the average effect of group of cities treated in 2011 $\beta_{g=2011}$. Further details are given by Callaway and Sant'Anna (2021) and Roth et al. (2022).

With this method, we estimate the average dynamic treatment effects β_k and the average treatment effect for each group β_g (with sufficient units) for both early-treated and late-treated experimental settings. In some specifications, parallel trends are attained conditional on pre-treatment covariates.

4 Results

The results are divided into 3 sections: the effect of LEZ on aggregate production, decomposing it on GDP per capita, GDP per employee, average employment and population (4.1), the effect on the structure of the economy, looking at the shares of individual sectors over total GVA (4.2), and the effect on the GVA from the Trade and Personal Services sector (4.3). In each of these 3 sections the results are given for both early-treated, in which we can only observe the effects of announcement, and late-treated, where we can see the effects of the whole implementation of LEZ. A summary of all the results is shown in Table 3. Various robustness tests have been conducted, such as including only information from West Germany or using the specification from Sun and Abraham (2021) with no significant changes in the results.

4.1 The effect of LEZ in aggregate production

We first document how the implementation of Low Emission Zones affected the aggregate production (GDP) of its city by regulating the entry of vehicles based on their emission levels. Secondly, we decompose GDP into relevant economic factors by the following identity

$$GDP \equiv \underbrace{\overbrace{\frac{GDP}{Employees}}^{\text{Productivity}} * \overbrace{\frac{Employees}{Population}}^{\text{Avg. employment}}}_{GDP\ per\ capita} * Population$$

and study the effect of each component separately. This allows us to understand the drivers of changes in aggregate GDP. We do not find any significant effect of LEZ announcement for the early-treated although coefficients for aggregate GDP and its components are usually positive. Without considering the statistic significance of the results, there is a higher change that the announcement of LEZ increased GDP of these cities trough an increase in productivity. For the late-treated, we find a negative and significant effect of LEZ application of a permanent 4.5% decrease in GDP with respect to 2005 values (95% CI = [-7.7, -2.1]), which is roughly equivalent to a reduction of 1400€ per capita and year, on average. This result is after controlling for pretreatment values of population size (2005), and GDP (1991, 2005) as the unconditional DiD exhibited a small pre-trend. This result is driven by a large negative effect on the group that announced the LEZ in 2011 (ATT = 6.9%) including the cities of Halle, Hagen, Heidenheim, Magdeburg, and the municipalities from Ruhr metropolitan area. This strong negative effect is mainly driven by reductions in GDP per capita (-4.93%) and not a reduction in population size. Figures 6 and 7 in the Appendix show a summary of the effects on GDP and GDP per capita for both early treated (announcement) and late-treated units (implementation).

4.2 The effect of LEZ on the structure of the local economy

Concerning the changes in the composition of the local economy, while the announcement had no effect on the early-treated cities, the application of Low

	Announcement (Early-treated cities)		Full application (Late-treated cities)	
	ATT	Heterogeneity of β_g	ATT	Heterogeneity of β_g
Aggregate production:				
GDP	(+) Non-significant	**[Non-sig, 2.6%]**	**-4.49%**	**[-6.9%, Non-sig]**
GDP/pop	(+) Non-significant	No	**-4.93%**	**[-6.5%, Non-sig]**
$GDP/employees$	(+) Non-significant	No	($-$) Non-significant	**[-3.0%, Non-sig]**
$Employees/pop$	($-$) Non-significant	No	**-1.9%**	**[-2.5%, Non-sig]**
$Population$	Non-significant	No	Non-significant	No
Relative production:				
GVA_{TPS}/GVA	Non-significant	No	**0.68%**	**[Non-sig, 0.88%]**
$GVA_{Industry}/GVA$	Non-significant	No	**-1.53%**	**[-2.45%, Non-sig]**
$GVA_{Construction}/GVA$	Non-significant	No	Non-significant	**[Non-sig, 0.5%]**
$GVA_{Prof.\ Serv.}/GVA$	Non parallel	No	Non-significant	No
GVA_{Public}/GVA	Non-significant	No	**0.85%**	**[Non-sig, 1.3%]**

Table 3: Summary of all treatment effects by experimental setting and outcome. All effects are expressed as changes relative to the value in 2005.

Emission Zones promoted a significant and permanent change in the late-treated cities. After the application of LEZ, there was a relative increase in the weight of the Trade and Personal Services and the Public service sector on the local GVA. On the other hand, there was a significant decrease of the weight of Industry (without construction). All these changes were more mostly felt by groups of cities that applied the measure in 2011.

The increase in the TPS has an ATT of 0.68% over a previous 19% share. It becomes significant the 3rd year after the announcement with an increase of 1% and is maintained until the 7th year after announcement notwithstanding with a higher standard error (fig. 9b). The decrease of the industrial sector (ATT of -1.53% over an initial share of 25%), follows a different path, being significant only after the 4th year after announcement and stabilising at the end with a total decrease of over 3% (fig. 9c). The group-specific ATT (β_g) varies widely between groups. The coefficients from years 2013 to 2017 are more unstable as only 1 or 2 LEZ were announced in those periods and thus are aggregated as only one group. The event-study results for these 3 sectors is available on Figure 9 in the Appendix.

4.3 The effect of LEZ in the Trade and Personal Services sector

As an additional outcome we study the outcome per capita from the Trade and Professional Services sector, as it was one of the most vocal sectors against this policy. We find that the outcome from the TPS sector was not negatively affected by the announcement or implementation of Low Emission Zones. Figure 8 in the Appendix shows a summary of the results. We find a non-significant positive average treatment effect of the announcement on early-treated cities: an increase in 1.96% in GVA per capita from the TPS sector with respect to 2005 values (95% CI = [-0.56%, 4.50%]). This result is after controlling for the population size (2005), population density (2005) and GVA per capita from the TPS sector (2000) as the plain DiD exhibited a significant pre-trend. This positive effect is significant for the group that announced the LEZ in 2006 with an ATT of 3.05% (see Figure 8b). We find no significant effects of the announcement and application in late-treated units.

5 Discussion and conclusions

This paper is the first to study the effect of Low Emission Zones on local production and the structure of the local economy. Using a sample of 31 German cities over the period from 1991 to 2017, we exploit the staggered introduction of Low Emission Zones in a differences-in-differences specification. Our results suggest that the application of Low Emission zones permanently reduced local GDP per capita by 4.5% on average, roughly equivalent to 1400€ per year with some regions having a reduction of up to 6.9% of their local GDP per capita. Using data on sector-specific GVA from each city we show that the Trade and Personal Services sector, which was the most vocal opposition in Germany against Low Emission Zones, was not negatively affected. The application of a LEZ had a positive, although insignificant, effect on the GVA per capita from TPS. We further investigate the effect of LEZ on changes in the structure of the local economy and find that the application of Low Emission Zones promoted a significant increase in the weight of the Public Services sector and a significant decrease in the weight of Industry (without construction). This goes in line with expectations as the industry might not benefit as much as personal services and retail from a reduction in air pollution in the city centre. These changes in the economic structure can have long-run effects on economic growth as they could increase the production of non-tradable over tradable goods and services.

Future research should overcome various data and context limitations of this work using the increasingly large number of regions in Europe and abroad that are applying similar policies. In particular, avoiding the confounding factor of major related events such as the financial crisis and the German scrappage program would allow researchers to focus on all cities that apply the measure and not only on a carefully defined set. Furthermore, the use of individual-level data on labour and productivity outcomes from businesses together with their specific location would allow to reduce measurement error, explore the heterogeneous effects of LEZ in the local economy and the potential causal mechanism of pollution reduction and improvement of health outcomes. All of this could help to explore the reasons behind the heterogeneity of treatment effects observed.

Overall, the results of this paper have important implications for policymakers as they indicate that although Low Emission Zones reduce air pollution and reduce hospital admissions, they might reduce overall GDP and GDP per capita while changing the structure of the economy away from industry and towards public services, local commerce and personal services.

References

Adhvaryu, A., Kala, N., and Nyshadham, A. (2014). Management and shocks to worker productivity: evidence from air pollution exposure in an Indian garment factory. *Unpublished Working Paper, University of Michigan*.

Alvarez-Cuadrado, F. (2008). Growth outside the stable path: Lessons from the european reconstruction. *European Economic Review*, 52(3):568–588.

Aragón, F. M., Miranda, J. J., and Oliva, P. (2017). Particulate matter and labor supply: The role of caregiving and non-linearities. *Journal of Environmental Economics and Management*, 86:295 – 309. Special issue on environmental economics in developing countries.

Badische Zeitung (2009). Wird die Feinstaubplakette zum Umsatzkiller? *Badische Zeitung*. https://web.archive.org/web/20100315222338/https://www.badische-zeitung.de/wird-die-feinstaubplakette-zum-umsatzkiller--22330565.html, accessed on 22-07-2020.

Browne, M., Allen, J., and Anderson, S. (2005). Low emission zones: the likely effects on the freight transport sector. *International Journal of Logistics Research and Applications*, 8(4):269–281.

Calderón-Garcidueñas, L., Torres-Jardón, R., Kulesza, R. J., Park, S.-B., and D'Angiulli, A. (2014). Air pollution and detrimental effects on children's brain. The need for a multidisciplinary approach to the issue complexity and challenges. 8.

Callaway, B. and Sant'Anna, P. H. (2021). Difference-in-Differences with multiple time periods. *Journal of Econometrics*, 225(2):200–230.

Chang, T., Zivin, J. G., Gross, T., and Neidell, M. (2016). The effect of pollution on worker productivity: Evidence from call-center workers in China. Working Paper 22328, National Bureau of Economic Research.

Dablanc, L. and Montenon, A. (2015). Impacts of environmental access restrictions on freight delivery activities: Example of low emissions zones in europe. *Transportation Research Record*, 2478(1):12–18.

Dechezleprêtre, A., Rivers, N., and Stadler, B. (2019). The economic cost of air pollution: Evidence from Europe. *"OECD Economics Department Working Papers"*.

Du, Y., Xu, X., Chu, M., Guo, Y., and Wang, J. (2016). Air particulate matter and cardiovascular disease: the epidemiological, biomedical and clinical evidence. *Journal of thoracic disease*, 8(1):E8—E19.

Ebenstein, A., Lavy, V., and Roth, S. (2016). The long-run economic consequences of high-stakes examinations: Evidence from transitory variation in pollution. *American Economic Journal: Applied Economics*, 8(4):36–65.

European Commission (2017). *Special Eurobarometer 468: Attitudes of European* *citizens towards the environment (v1.00)*. European Commission.

European Environmental Agency (2019). Air quality in europe - 2019 report. EEA Report No 10/2019.

European Environmental Agency (2020). *Air quality in Europe - 2020 report*. Number No 09/2020.

Fu, S., Viard, V. B., and Zhang, P. (2017). Air Pollution and Manufacturing Firm Productivity: Nationwide Estimates for China.

Galdon-sanchez, J. E., Gil, R., Holub, F., and Uriz-uharte, G. (2021). Benefits and Costs of Driving Restriction Policies : The Impact of Madrid Central on Congestion , Pollution and Consumer Spending . pages 1–51.

Gehrsitz, M. (2017). The effect of low emission zones on air pollution and infant health. *Journal of Environmental Economics and Management*, 83:121 – 144.

Goodman-Bacon, A. (2021). Difference-in-differences with variation in treatment timing. *Journal of Econometrics*, 225(2):254–277. Themed Issue: Treatment Effect 1.

Graff-Zivin, J. and Neidell, M. (2012). The impact of pollution on worker productivity. *American Economic Review*, 102(7):3652–73.

Hanna, R. and Oliva, P. (2015). The effect of pollution on labor supply: Evidence from a natural experiment in Mexico city. *Journal of Public Economics*, 122:68 – 79.

Holub, F., Hospido, L., and Wagner, U. J. (2006). Air pollution and labor supply: Evidence from social security data. *Unpublished Working Paper*.

Kaul, A., Pfeifer, G., and Witte, S. (2012). The incidence of cash for clunkers: an analysis of the 2009 car scrappage scheme in germany. *International Tax and Public Finance*, 23.

Lindstaedt, B. (2009). Einzelhandel, kundenverkehr und umweltzonen. Institut fuer Handelsforschung (IfH) Seminar Presentation.

Liu, L. and Xu, Y. (2018). panelview: an r package of visualizing panel data. Available at http://yiqingxu.org/software/panelView/panelView.html.

Morfeld, P., Groneberg, D. A., and Spallek, M. F. (2014). Effectiveness of Low Emission Zones: Large Scale Analysis of Changes in Environmental NO2, NO and NOx Concentrations in 17 German Cities. *PLoS ONE*, 9(8):e102999.

Morgenstern, R. D., Pizer, W. A., and Shih, J.-S. (2002). Jobs versus the environment: An industry-level perspective. *Journal of Environmental Economics and Management*, 43(3):412 – 436.

Pestel, N. and Wozny, F. (2021). Health effects of Low Emission Zones: Evidence from German hospitals. *Journal of Environmental Economics and Management*, 109:102512.

Ranft, U., Schikowski, T., Sugiri, D., Krutmann, J., and Krämer, U. (2009). Long-term exposure to traffic-related particulate matter impairs cognitive function in the elderly. *Environmental Research*, 109(8):1004 – 1011.

Ransom, M. R. and Pope, C. A. (1992). Elementary school absences and pm10 pollution in Utah Valley. *Environmental Research*, 58(1):204 – 219.

Roth, J., Sant'Anna, P. H. C., Bilinski, A., and Poe, J. (2022). What's Trending in Difference-in-Differences? A Synthesis of the Recent Econometrics Literature.

Rufibach, K. (2009). reporttools: R functions to generate LaTeX tables of descriptive statistics. *Journal of Statistical Software, Code Snippets*, 31(1).

Sadle Consultants Europe (2022). Urban Access Regulations in Europe. https://urbanaccessregulations.eu/userhome/map. Accessed: 2022-01-28.

Shaddick, G., Thomas, M. L., Green, A., Brauer, M., van Donkelaar, A., Burnett, R., Chang, H. H., Cohen, A., Dingenen, R. V., Dora, C., Gumy, S., Liu, Y., Martin, R., Waller, L. A., West, J., Zidek, J. V., and Prüss-Ustün, A. (2018). Data integration model for air quality: a hierarchical approach to the global estimation of exposures to ambient air pollution. *Journal of the Royal Statistical Society: Series C (Applied Statistics)*, 67(1):231–253.

Sun, L. and Abraham, S. (2021). Estimating dynamic treatment effects in event studies with heterogeneous treatment effects. *Journal of Econometrics*, 225(2):175–199. Themed Issue: Treatment Effect 1.

Tennekes, M. (2018). tmap: Thematic maps in R. *Journal of Statistical Software*, 84(6):1–39.

Viana, M., Kuhlbusch, T., Querol, X., Alastuey, A., Harrison, R., Hopke, P., Winiwarter, W., Vallius, M., Szidat, S., Prévôt, A., Hueglin, C., Bloemen, H., Wåhlin, P., Vecchi, R., Miranda, A., Kasper-Giebl, A., Maenhaut, W., and Hitzenberger, R. (2008). Source apportionment of particulate matter in europe: A review of methods and results. *Journal of Aerosol Science*, 39(10):827 – 849.

Wolff, H. (2014). Keep Your Clunker in the Suburb: Low-Emission Zones and Adoption of Green Vehicles. *The Economic Journal*, 124(578):F481–F512.

Wolff, H. and Perry, L. (2010). Policy Monitor: Trends in Clean Air Legislation in Europe: Particulate Matter and Low Emission Zones1. *Review of Environmental Economics and Policy*, 4(2):293–308.

Zhang, X., Chen, X., and Zhang, X. (2018). The impact of exposure to air pollution on cognitive performance. *Proceedings of the National Academy of Sciences*, 115(37):9193–9197.

Zivin, J. G. and Neidell, M. (2018). Air pollution's hidden impacts. *Science*, 359(6371):39–40.

Appendices

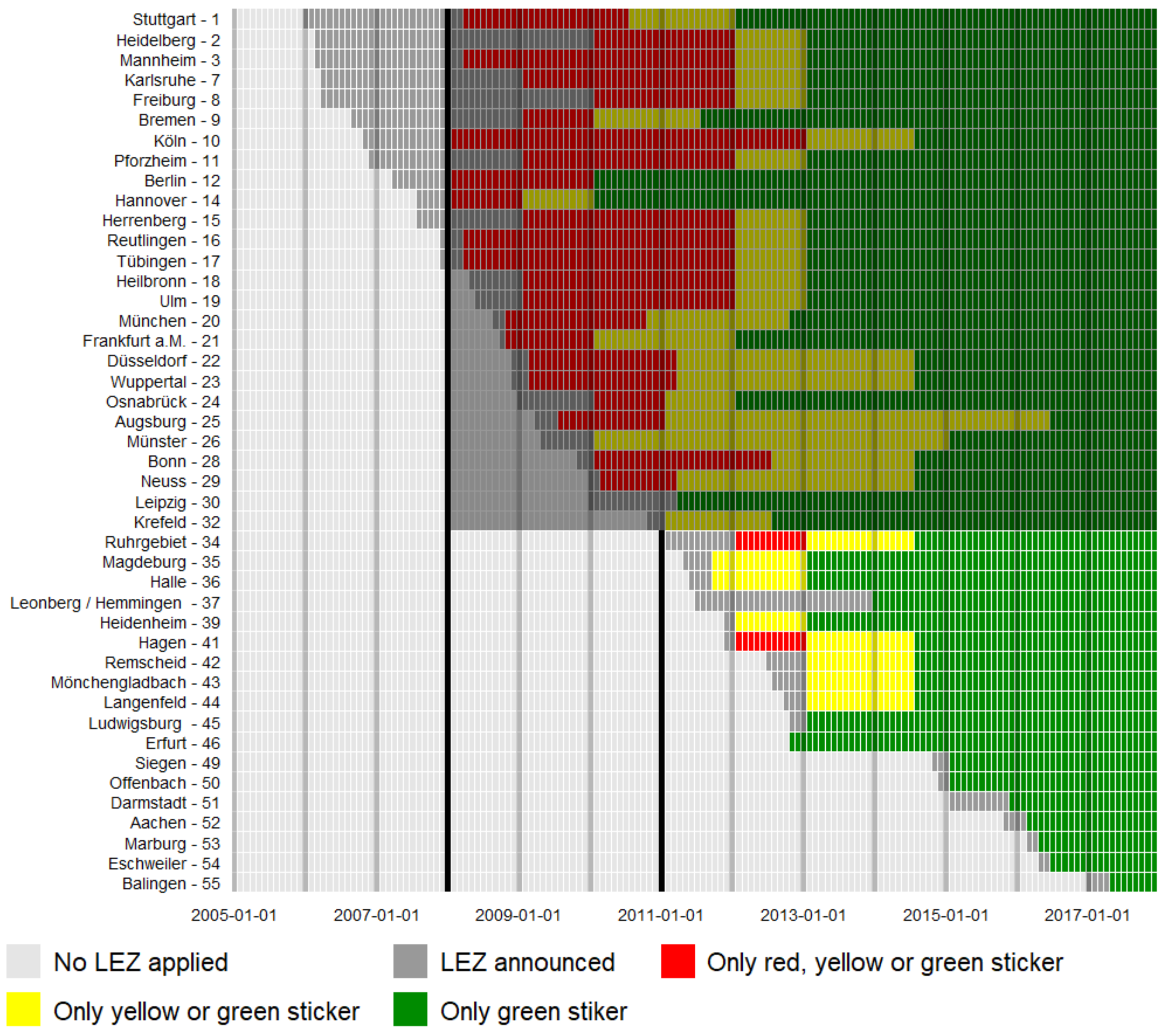
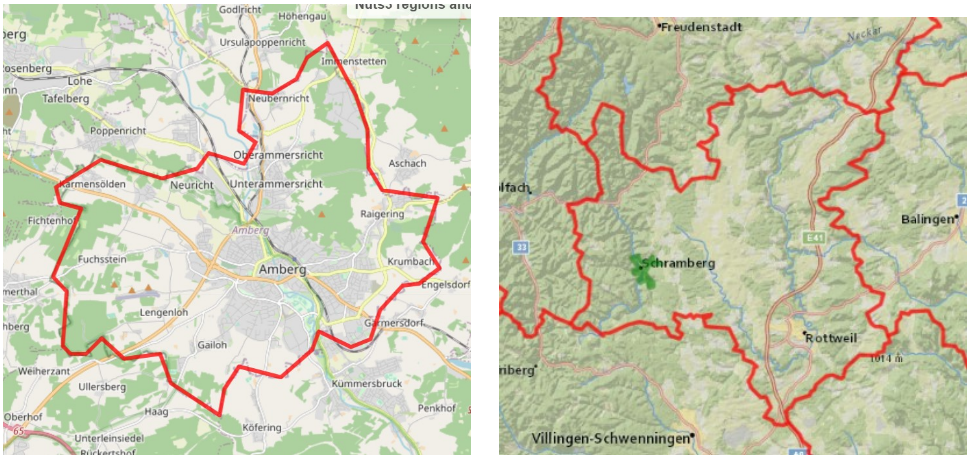


Figure 1: Announcement and application of German LEZ included in the study. Colours mark the announcement date and category of environmental stickers allowed. The start and the end of the financial crisis are marked with two vertical lines. All outcomes in the area shaded in grey are ignored as the effect of the financial crisis might confound the estimates.
Sources: Umweltbundesamt and local "Environmental plans".



(a) Well represented city extent (b) Bad measurement

Figure 2: Districts (NUTS3) can be imperfect spatial proxies of small cities or towns.

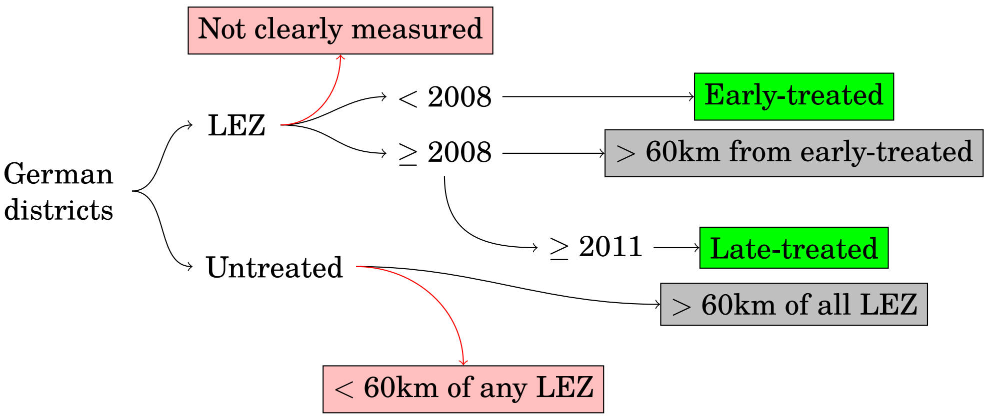
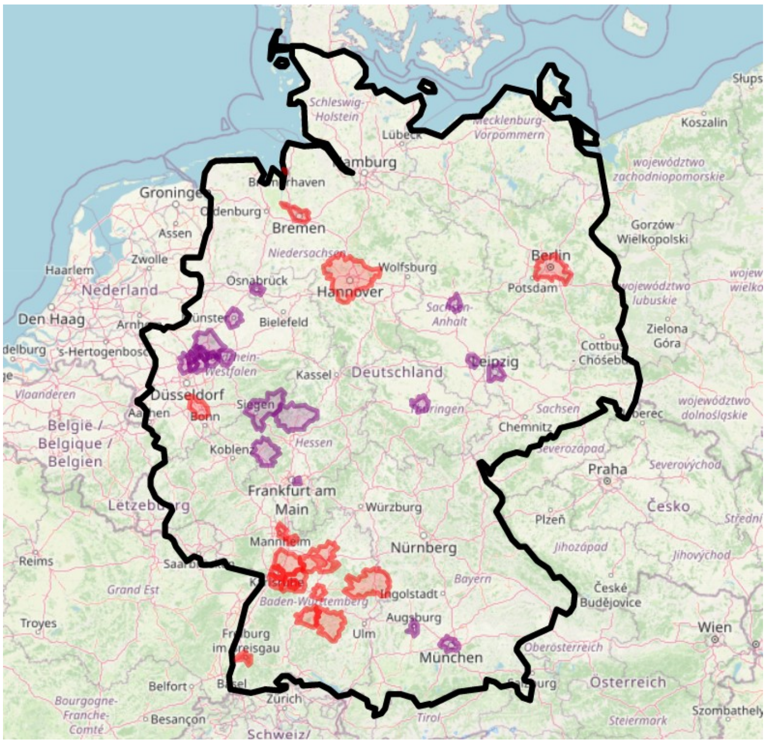
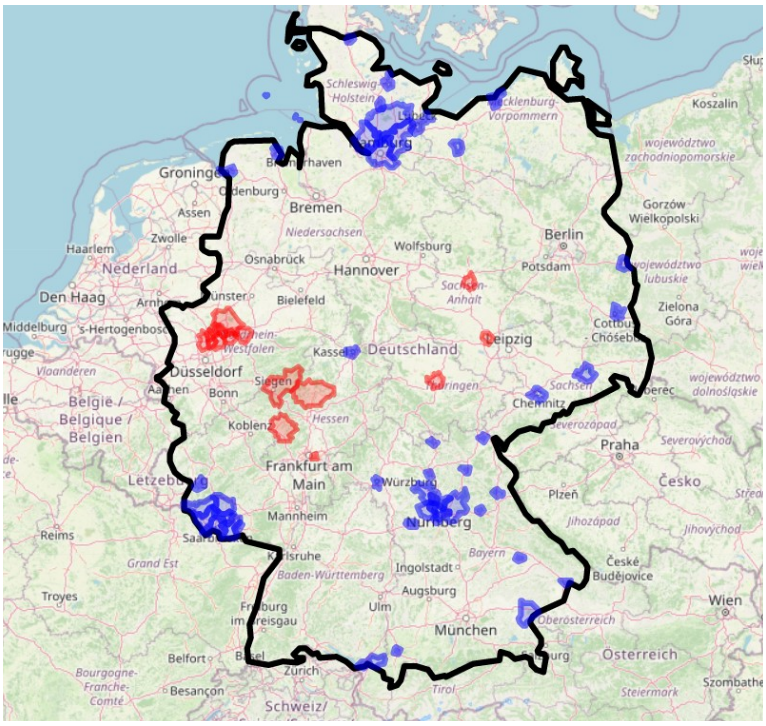


Figure 3: Diagram of the construction of the two experimental settings



(a) Treated (red) and not-yet-treated in January 2008 (purple)



(b) Treated after 2010 (red) and never treated (blue)

Figure 4: Treated and control units for both experimental settings
.

© EuroGeographics for the admin. boundaries.

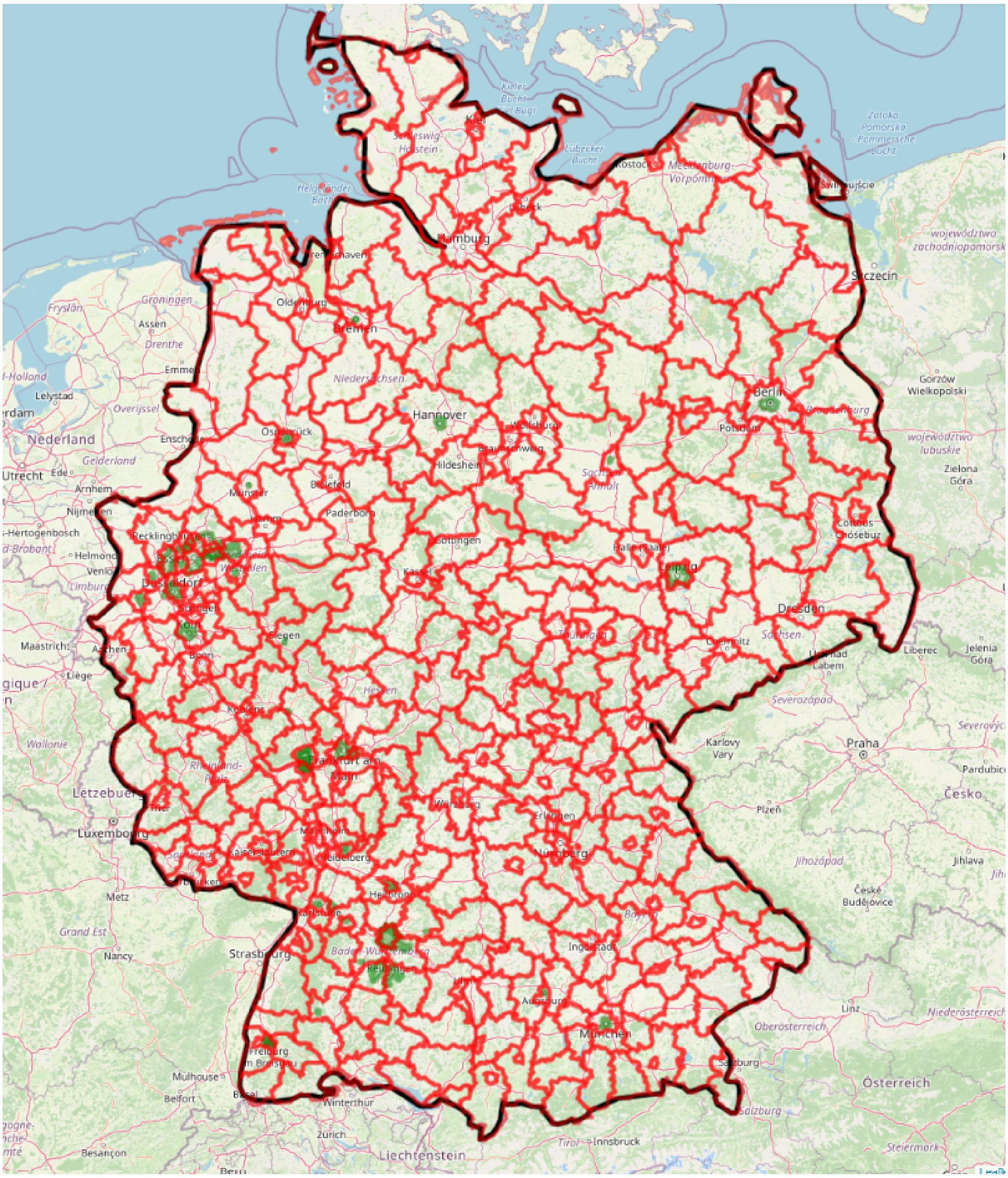
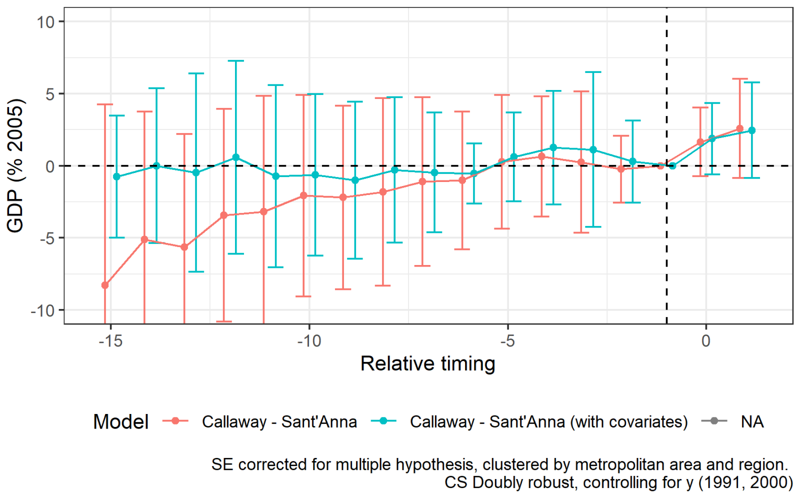
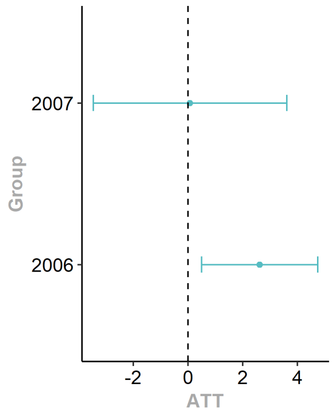


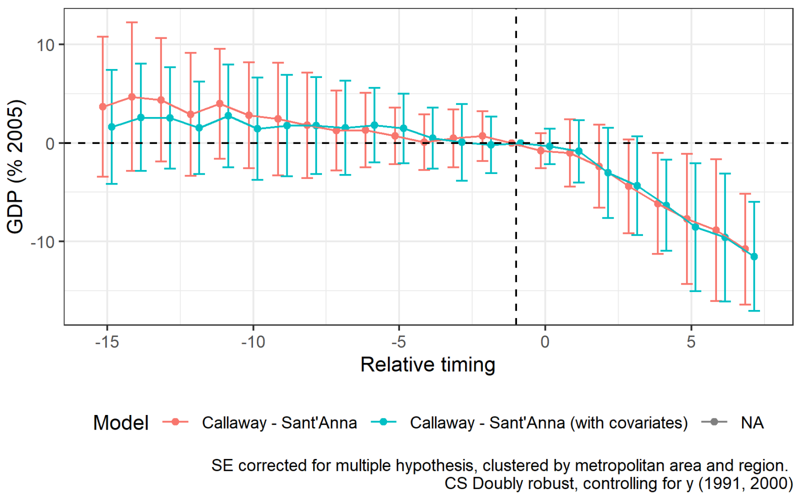
Figure 5: Main coverage of NUTS3 regions (districts) across Germany



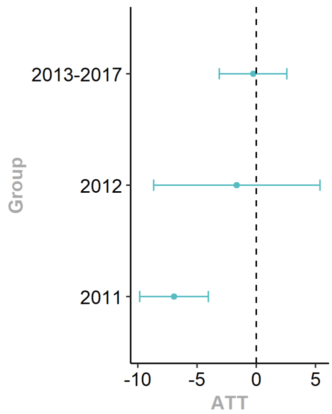
(a) Dynamic effects of LEZ announcement for the early-treated (β_k)



(b) Average effect of announcement for each group for the early-treated (β_g)

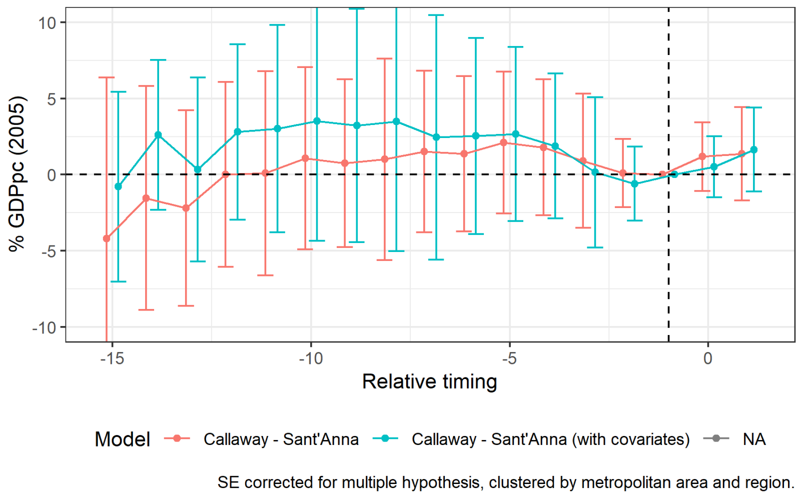


(c) Dynamic treatment effects for the late-treated (β_k)

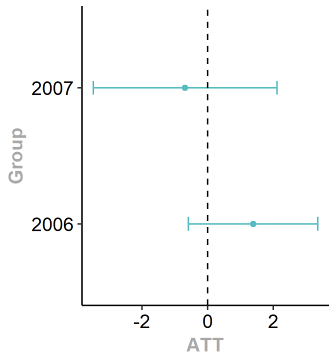


(d) Average treatment effect for each group of the late-treated (β_g)

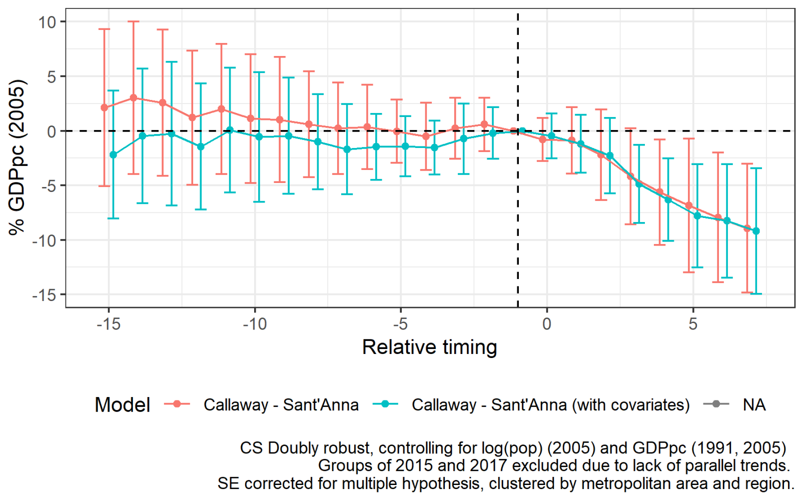
Figure 6: Effect of LEZ in the total GDP. All SE are clustered by city and take into account multiple hypothesis testing.



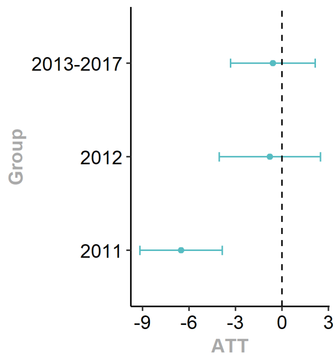
(a) Dynamic effects of LEZ announcement for the early-treated (β_k)



(b) Average effect of announcement for each group for the early-treated (β_g)

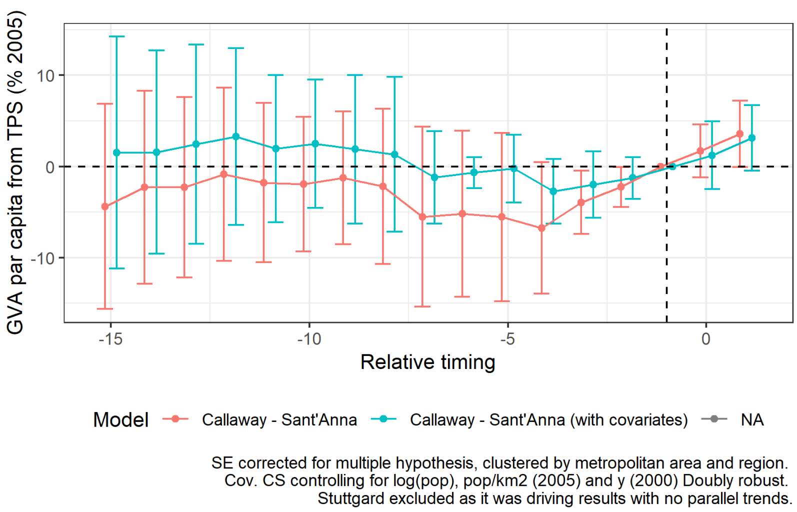


(c) Dynamic treatment effects for the late-treated (β_k)

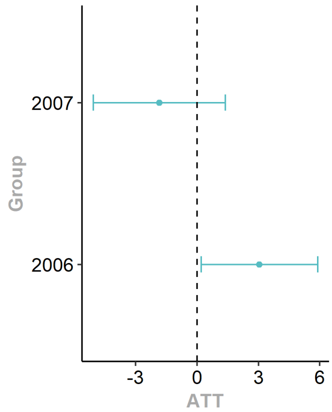


(d) Average treatment effect for each group of the late-treated (β_g)

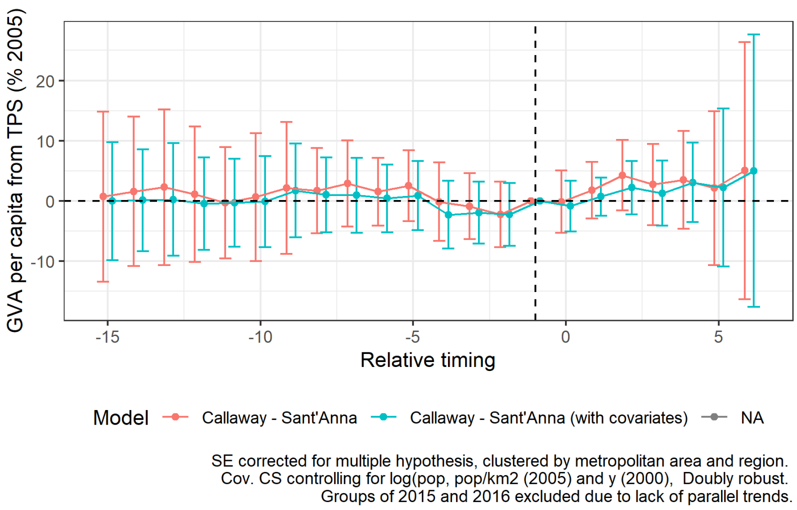
Figure 7: Effect of LEZ in the total GDP per capita. All SE are clustered by city and take into account multiple hypothesis testing.



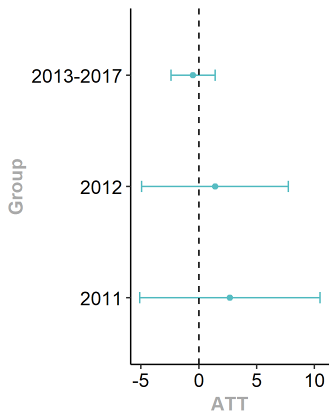
(a) Dynamic effects of LEZ announcement for the early-treated (β_k)



(b) Average effect of announcement for each group for the early-treated (β_g)

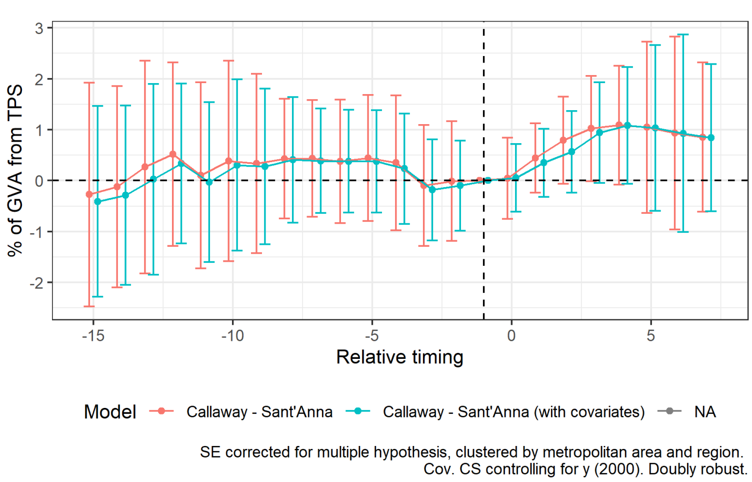


(c) Dynamic treatment effects for the late-treated (β_k)

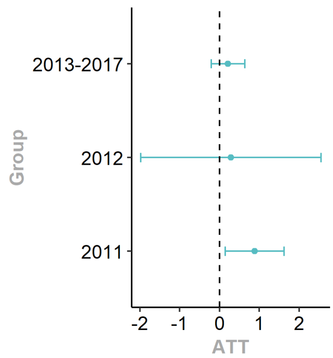


(d) Average treatment effect for each group of the late-treated (β_g)

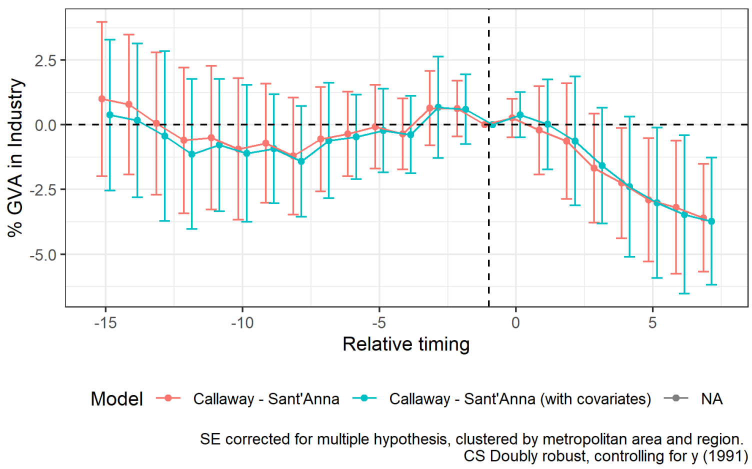
Figure 8: Effect of LEZ in the total GVA per capita from the Trade and Profesional Services sector. All SE are clustered by city and take into account multiple hypothesis testing.



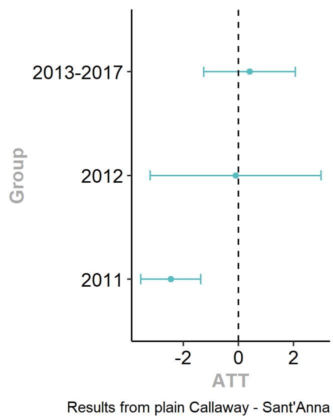
(a) Dynamic effects of LEZ announcement for the share of TPS in GVA (β_k)



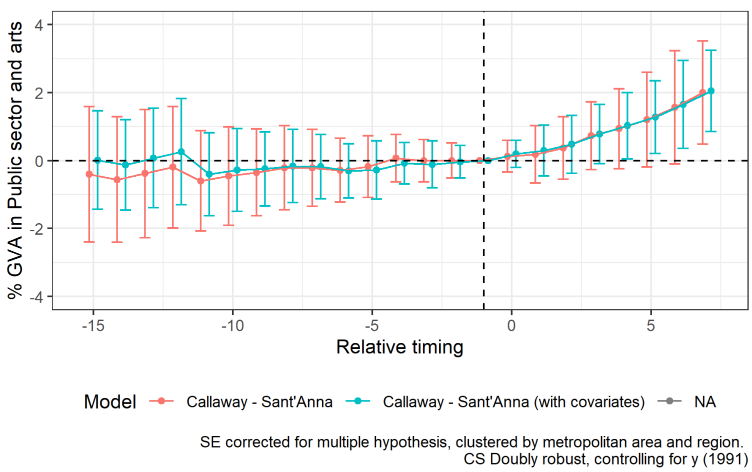
(b) Average effect of announcement for each group of the early-treated (β_g)



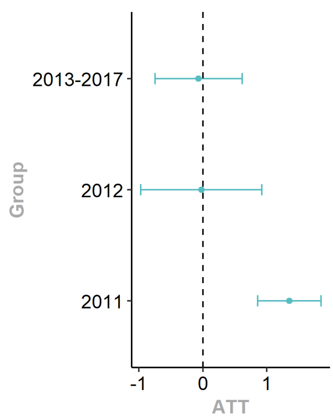
(c) Dynamic effects of LEZ announcement for the share of Industry (without construction) in GVA (β_k)



(d) Average treatment effect for each group of the late-treated (β_g)



(e) Dynamic effects of LEZ announcement for the share of Public Services and arts in GVA (β_k)



(f) Average treatment effect for each group of the late-treated (β_g)

Figure 9: Effect of LEZ in the the share of GVA for TPS, Industry (without construction), and Public sector and arts. All SE are clustered by city and take into account multiple hypothesis testing.