The effect of Low Emission Zones in the local economy: A synthetic control approach to German cities.

The skeleton of the real capstone

Abstract

Low Emission Zones (LEZ) have been widely adopted in Europe and proven successful in reducing air pollution, a growing public concern due to its effects on health and mortality. While LEZ policies are criticised for "hurting the economy", recent literature suggest LEZ could improve economic performance though various causal paths such as reduced pollution and congestion, making LEZs a policy that can both harm and boost economic growth. To solve this contradiction from a program evaluation perspective, I propose the use of a Synthetic Control Method (SCM) to study the effect of German LEZ in their aggregate economic and labour outcomes. + Explain how the methods worked, (if they did). + Explain the conclusions about methods and results.

***Keywords* —** Synthetic Control, Low Emission Zones, Air Pollution, Germany, GDP, Labour effects, Economic Geography

1 Introduction

1.1 Low Emission Zones

Prevalence of pollution, sources and relation with road traffic:

In European cities, Low Emission Zones (LEZ) have proven popular when trying to improve air quality and comply with the increasingly strict EU regulations (Holman et al., 2015). There is strong evidence that a very significant proportion of cities' air pollution comes from traffic, with 35-55% of PM_{10} particles coming from vehicles in EU cities (Viana et al., 2008). For Berlin, traffic produces a 38% and 23% of pollution gathered in close-to-traffic and background stations, respectively (Lenschow et al., 2001). Finally, there is strong causal evidence that the application of German LEZ has significantly reduced particle pollution inside them between 2 and 9% (Gehrsitz, 2017; Wolff, 2014).

Regulatory framework, INTENTIONS for LEZ: to reduce pollution to comply with regulations (cite German environmental quality plans):

Germany has been in the forefront of the application of LEZ with most German cities over 10.000 inhabitants having applied one from 2008 to 2013 (Gehrsitz, 2017). German LEZ have been supported and standardised by the federal government. All of them apply the same restrictions to high-polluting cars and are implemented in the same stages. Entering a LEZ without authorisation is fined with 80€ and implies a 1 demerit point in the central traffic registry (Gehrsitz, 2017).

But it has not been completely optional, which reduces the possibility politically-based confounding factors:

Most regional and national governments have been either threatened by fines or strongly incentivised to pursue decisive policy action by European regulation. 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", most of them including a LEZ (Gehrsitz, 2017). As a result of this legislation, the European Commission (EC) has opened infringement procedures against 16 Member States and the EU Court of Justice has already handed down judgements in Bulgaria and Poland[1].

For the availability of previous research, the standardisation of LEZ by the federal government, the exogenous incentive from European legislation and the availability of data (discussed in the "Data collection strategy" section), I am confident that German LEZ are the best subject of study to understand the causal effects between a strong environmental policy

[1]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

such as LEZ and economic performance. To the best of my knowledge, there is no published work on the causal effect of over 100 European LEZ on aggregate economic performance.

1.2 Economic critiques of LEZ

Explain how LEZ can hurt the economy and affect labour outcomes (Economic theory of sub-optimal allocation and externalities), Examples of critiques from business owners and **from which sectors this critiques usually come from** (retail, transport)

According to classic economic theory, we would expect these policies to damage a city's GDP as they involve taxes and prohibitions for certain vehicles, leading to claims of a "Jobs versus the Environment" trade-off as introduced by Morgenstern et al. (2002). The impact of LEZ on economic outputs such as economic growth, profits and employment has been a constant concern of citizens and local officials. And their concern is not unjustified. Most large cities that constitute the backbone of the German economy have applied restrictive LEZ (Berlin, Munich, Köln, Hannover, Dortmund and Stuttgart are some examples). It is crucial to know how Germany's economy has been affected by these predominant environmental measures to be able to develop a fair cost-benefit analysis of them.

1.3 Possible economic benefits of LEZ

Explain MULTIPLE ways it can improve the Economy and labour outcomes, (better clean air, tourism, positive demand shock, less congestion).

However, the effects of reducing congestion and pollution might offset other economic costs. This hypothesis is based on recent research on the effect of LEZ on increasing mobility (Kelly and Kelly, 2009) and decreasing health costs (Cesaroni et al., 2012) and air pollution by Wolff (2014) and Gehrsitz (2017) (who give results for German LEZ).

Furthermore, recent studies suggest that air pollution reduces aggregate economic output (Dechezleprêtre, 2018; Hao et al., 2018). This can happen through various labour-market effects such as increasing mortality (Xie et al., 2016), reducing productivity (Adhvaryu et al., 2014; Chang et al., 2016; Graff-Zivin and Neidell, 2012) and cognitive performance (Ebenstein et al., 2016; Roth, 2015; Zhang et al., 2018) or increasing absenteeism (Hanna and Oliva, 2015; Ransom and Pope, 1992). Include research that points to women as principal beneficiaries from a reduction in absenteeism as they are usually the ones taking care of vulnerable population.

1.4 My research questions

Main question:

- What was the effect of the application of Low Emission Zones (LEZ) on German cities economic outcomes and labour market indicators?

Complementary questions: *(subject to the adequacy of methods and time constraints)*

- Which sectors are more affected by the policy?
- Has it improved labour outcomes for women?
- What would be the effect of a "German" LEZ in other German or European cities that have not applied it? (probably won't have time but I think it could be of great value)

2 Data collection strategy

Mostly the same as MY400, to Re-read, complete and improve

I used data on treated regions (German cities that applied a LEZ) and a pool of control regions (German or other European cities that have not applied any similar measure) on: (1) Sufficient pre- and post-intervention aggregate outputs and predictors of outputs both to test the validity of the identification strategy and be able to see the short and mid term effects of the intervention. (2) Detailed description of the application of policies for all cities considered to correctly assign treatment and create a carefully selected control pool, clean of any similar intervention.

The data was gathered from different sources and aggregated by geographical location. First, Eurostat's collection of regional statistics available for NUTS regions[2] (from 2000 to 2018 and covering the whole of the EU) provides yearly statistics for the main dependent variables such as GDP, GVA per sector and labour market statistics with various time and spatial coverage. Additionally, Eurostat provides local data on predictors and controls such as various demographics.

Secondly, the implementation of LEZ in Germany is well documented by the the German Environment Agency (Umweltbundesamt - UBA) with dates for the application of each "stage" of a given LEZ. The announcement date of each LEZ in the study was searched on historical documents such as each city's "Environmental Plan" published in their official websites and local news. Figure 4 summaries the treatment status of all LEZ in the study (announcement date and marker of the ones actually used in each sample to include). Additionally, data on the

[2]NUTS, or Nomenclature of Territorial Units for Statistics, is a geographical code to reference the subdivisions of countries. Granularity varies by country but its especially good in Germany where it tends to follow natural city boundaries.

implementation of LEZ and similar policies in European regions has been gathered from specialised databases such as *UrbanAccessRegulations.eu* (financed by the European Commission) and the "Green Zones" mobile application that informs professional carriers and drivers on the state of urban access regulations and LEZ in Europe.[3] Information on treatment status are freely available in their web page and public App and was recollected automatically and re-structured.[4]

An extensive summary of the potential variables and an illustration of the NUTS regions can be found in Table 1 and Figure 3 in the appendices.

3 Data Analysis strategy

Index of things to include here

- Broad explanation of Synthetic Control and Characteristics of the Generalized Synthetic Control *(what it controls, what are its assumptions and the reasons to choose this model)*.
- Outcomes I will look into and reasons for each of them *(in order of priority, the last ones can be left out if there is no time / words left)*
  - The effect of LEZ on small cities aggregate output (Justify why I believe a causal effect can be derived from this estimates → No major shocks + over 7 years of pre-treatment period -):
    - GDP/capita
    - GDP/worker (general and in relevant sectors: Retail, transport, public)
    - Proportion of GDP from relevant sectors
  - The effect of large LEZ on Labor outcomes:
    - $\frac{\text{Woman in active population}}{\text{Men in active population}}$
    - Proportion of employment from relevant sectors.
- Selection criteria for treated and control cities explaining which assumptions I want to control for and why they are important.
  - For control: 30-60km from treated region + only countries that do not show different outcome paths to Germany.
  - For treated: That pass the "pre-intervention" placebo test (a fake intervention is simulated 4y before the real one, if there are any estimated effects it means the city does not have a good synthetic control or has other shocks) + only treated cities that do not share a NUTS2/3 region with other treated cities.

[3] UrbanAccessRegulations.eu has been already used by Holman et al. (2015) as a source of data to review of the efficacy of European low emission zones to improve urban air quality.

[4] Neither of them have restrictions to web scraping in their web pages.

3.1 Synthetic Control and Generalised Synthetic Control

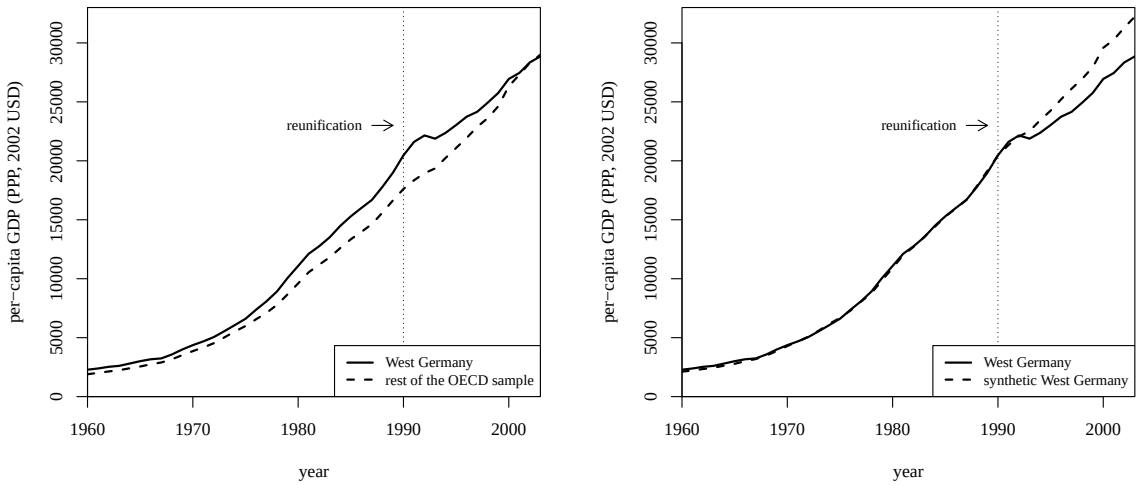
Explanation of Generalised synthetic control missing for now. I need to explain how it works, what it controls, what are its assumptions and the reasons to choose this model. Here follows a detail explanation of the classic Synthetic Control Method from MY400:

To answer the main question on the effect of LEZ in the city's various economic outputs I intend to use a Synthetic Control Method (SCM) such that the effects in each treated region can be quantified by constructing a synthetic control from all untreated regions both from Germany and other countries from the European Union. This method was introduced in Abadie and Gardeazabal (2003) to study the effect of terrorism in the Basque Country's macroeconomic performance and is extensively described and expanded in Abadie et al. (2010), Abadie et al. (2015) and Abadie (2019).[5] Even if the SCM has not yet been applied to cities' LEZ, previous related research has used very similar techniques. For example, Wolff (2014) and Gehrsitz (2017) applied differences-in-differences (DID) to estimate the causal effect of German LEZ in local air quality.

The SCM is similar from DID, both lay their main identification requirement on having similar trends before treatment and avoid the need of assuming an exogenous treatment assignment. In contrast, although DID allows for the presence of constant unobserved confounders (given they are constructed by taking time differences), the SCM also allows the effects of confounding unobserved characteristics to vary with time (Abadie et al., 2010).

The SCM tries to avoid ambiguity on how comparison units are chosen and account for the uncertainty that they will indeed reproduce "the outcome trajectory that the affected units would have experienced in the absence of the intervention or event of interest" (Abadie et al., 2010). It does it by creating a synthetic control from a weighted average of non-treated units such that it best follows the pre-treatment path of the treated unit and it is as similar as possible in some major predictors of the output. As an illustration of the methodology we can see the example of Abadie et al. (2015) where they created a synthetic control of West Germany to quantify the effects of Germany's reunification in its GDP. We can see the weights that construct the synthetic West Germany from the pool of other OECD members in Table 2, its resemblance in characteristics to the real West Germany in Table 3 and how closely the pre-treatment period is for both synthetic and real West Germany at Figure 1.

[5] Multiple methodologies build on the SCM and could be used in this research, some examples are Abadie and L'Hour (2019) where they include a penalisation term for pairwise differences on characteristics, the Generalized Synthetic Control Method that applies the methodology to multiple treated units (Xu, 2017) and Bayesian structural time-series models (Brodersen et al., 2015) developed in Google which uses other Machine Learning procedures to estimate the counterfactual and its credible interval. All 3 of them have author-developed packages in R or Python.



(a) West Germany and the mean of the control pool

(b) West Germany and its synthetic control

Figure 1: We can see how the Synthetic control closely follows the pre-intervention path of West Germany and deviates from if after the intervention.
Source: Abadie et al. (2015).

The SCM is especially appealing for comparative case studies for its transparency and theoretical foundations: (1) All estimations are done within the support of the data (no extrapolation) given it is constructed as a weighted average of control unitsthis is not necessarily true for the Generalised synthetic control but I will check that it happens. (2) We can clearly see the differences in pre-treatment paths and characteristics between treated and synthetic control making possible to assess its internal validity. This allows us to make all decisions regarding the set of controls and predictors by looking at the pre-treatment fit with a measure such as Mean Squared Prediction error (MSPE). Given we don't need access to post-treatment data, we are safeguarded against specification searches and p-hacking. (3) We know the weights of the control units that make the synthetic control, allowing us to evaluate its validity as a control.[6]

3.2 Assumptions and identifying requirements of the model

Explain which assumptions I want to control for and why they are important. No need to read this, it is mostly the MY400 text and we have discussed them in depth.

Following technical and practical guidance from Abadie et al. (2010) and Abadie (2019), careful thought has been given to the needed contextual requirements and assumptions of the SCM. They are discussed below.

[6]See tables 3 and 2 for illustrations from Abadie et al. (2015).

Identifying requirements:

1. **Sizeable effect:** To be able to identify a treatment effect, its size should be bigger than the individual transitory shocks of regional outcome variables. From preliminary inspection of the data I expect individual transitory shocks to be around 0.5-2% of regional GDP per capita[7]. Regarding estimates on the effect of LEZ on GDP the German pro-business Institute for Retail Research estimates a 7% decrease in customers in stores located within a city centre after the introduction of a LEZ (Lindstaedt, 2009), in contrast, a Transport For London study based of first differences found no significant effects (TFL, 2006). I expect the mediated effect pollution reduction associated with the introduction of a LEZ to be around 1% of GDP pollution given the estimates of Dechezleprêtre (2018) and Gehrsitz (2017).

2. **Non interference between units/cities:** I guide myself with the research done by Wolff (2014) and Gehrsitz (2017) on the effect of German LEZ on pollution, health and vehicle composition to understand the possible spillover effects present within and between German cities. A summary of their findings is as follows: (1) Wolff (2014) concludes that the application of a LEZ also reduces pollution in surrounding areas but this is only significant with big and strict LEZ . Gehrsitz (2017) finds a non-significant effect on pollution reduction in surrounding areas of a LEZ. (2) Wolff (2014) shows that the application of a LEZ correlates with a change towards cleaner vehicles and cities close to it also seem to experience these changes. The correlation is close to a 1-to-5% change in the vehicle composition of a nearby city. Nevertheless, Gehrsitz (2017) looks for a causal effect on pollution reduction and concludes that for a given city "the introduction of an LEZ in a nearby city does not appear to translate into reductions in fine particulate pollution." and adds that his results "indicate that any violations of the SUTVA due to spillovers are unlikely to induce substantial bias into the main results". In conclusion, some spillovers are possible in very specific cases for the outskirts of a large LEZ (that will be included in my NUTS3 regions), but unlikely and economically insignificant for nearby cities. This is crucial information given close cities might be especially good controls if these spillovers are not present.

3. **Valid comparison group:** To construct it I will create a set of European cities that have not applied similar measures or suffered large idiosyncratic shocks during the study period, avoiding biases from confounders and interpolation.[8] I will exclude cities that either suffer for large shocks on aggregate GDP and pollution or are listed in the UrbanAccessRegulations and "Green Zones" databases. Finally, I plan to perform

[7] If the noise in the outcome variables is relatively high, it's possible to use de-noising techniques such as the ones proposed by Amjad et al. (2019).

[8] To control for interpolation biases Abadie and L'Hour (2019) propose including a penalty term to the objective function that depends on the discrepancies between the characteristics of the treated unit and the units included in the synthetic control. The code is available on their GitHub.

robustness tests excluding German cities that have applied other Environmental Action Plans.

4. **No anticipation:** LEZ in general, and also in Germany, are usually publicised before being enacted specifically to incentivise the public to upgrade their vehicles. This will be accounted by creating an "announced" period, and setting it as the start-of-treatment date in the SCM as recommended in Abadie (2019).

Robustness and diagnosis checks:

Tn-time placebo treatments as in Abadie et al. (2015) will be done years before the announcement of the LEZ plans to test the adequacy of the synthetic control.

I use the application of the 58 LEZ applied in Germany in the last 12 years (available in Figure 4) as treatment to calculate both the heterogeneity of treatment effects and the average treatment effect on the treated. This gives a range of 8-18 years of pre-treatment data to create the synthetic controls and evaluate their fit.

The control pool is constructed from other German regions or regions from countries that share the similar economic trends as Germany such as Belgium, The Netherlands and Austria and have similar characteristics as the treated cities and have not applied similar measures.

3.3 Economic outcomes of small LEZ

To be able to extract a causal effect of LEZ the treated pool was carefully selected to avoid the presence of major confounding factors such as the financial crisis of 2008 and the already mentioned scrappage program from 2009. For those reasons, the treated pool consisted only on cities where the LEZ was announced after September 2009, when the program had already finished.

The sample of treated regions ends up being usually small cities (almost all major ones where either applied or announced before September 2009). Summary statistics of the treated and control sample can be found in table (TO DO).

The main result would be the effect of LEZ in GDP per capita, focusing later on GDP per worker and the share of GDP of sectors that are thought to be affected by the policy: Retail and Transport - where most of the critiques to LEZ come from - and the public sector. This will help understand which sectors are more affected by a LEZ. And if I have time... Results will be aggregated across cities to produce measures of Heterogeneous Treatment Effects (HTE) to investigate possible city characteristics that correlate with higher treatment effects such as the strength or stage of a LEZ.

3.4 Labour outcomes of large LEZ

The effect in labour outcomes is restricted by data availability. Data is only large NUTS2 regions and only some of them have one treated city inside them that is large enough so that the aggregate statistic of the zone has a direct relation with the outcome of the city. Only 5 cities comply with this restriction (list of cities) and all of them are announced before the end of the scrappage program. This implies that causal estimates can only be extracted from outcomes that are not affected by this program. Therefore, this analysis is centred on looking at the effect of the rate of women and men in the active population (to see if women indeed benefit from lower pollution in their labour outcomes) and the employment share of relevant sectors (to see if the economic effects are localised where the critiques to LEZ are.

3.5 Estimating potential treatment effects:

(Maybe I won't have time for this) As a methodological and policy contribution I plan to use the large set of treated regions to reverse the mechanism of the SCM and use it as a *"Synthetic Treated Method"* to estimate $Y^{1,1}$ and the potential treatment effect of a LEZ in cities that have not applied it. In other words, it will use the pool of treated regions to estimate a synthetic treated for a given control region.

After extensive research on the SCM and their similar methods I have not found this application of the SCM in the literature. If my understanding is correct, no further assumptions are needed and the properties of the classical SCM would apply. A natural case study to test this methodology will be the city of Hamburg (who is the largest German city that has not yet applied a LEZ) although other large European cities are also candidates to be studied.

4 Results

Presented in such a way we the general ATE is the main result. We then see the specific treated and synthetic control for some regions that are of special importance or act as good examples.

1. The pre-intervention placebo
2. Treatment effect
3. Map of control regions by weight

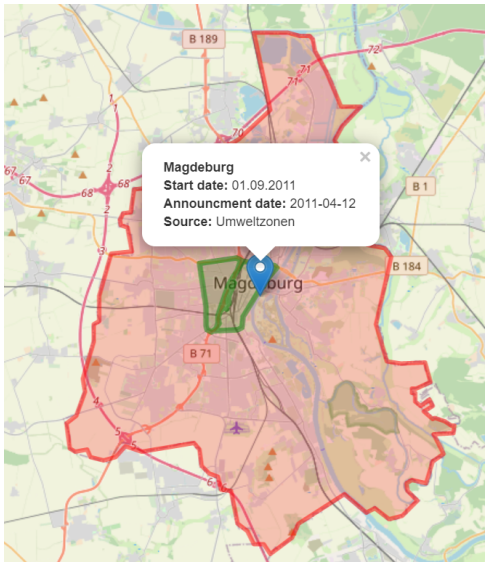
To see an example of the presentation of results see next page figure 2.

4.1 The effect of LEZ in small cities' aggregate output

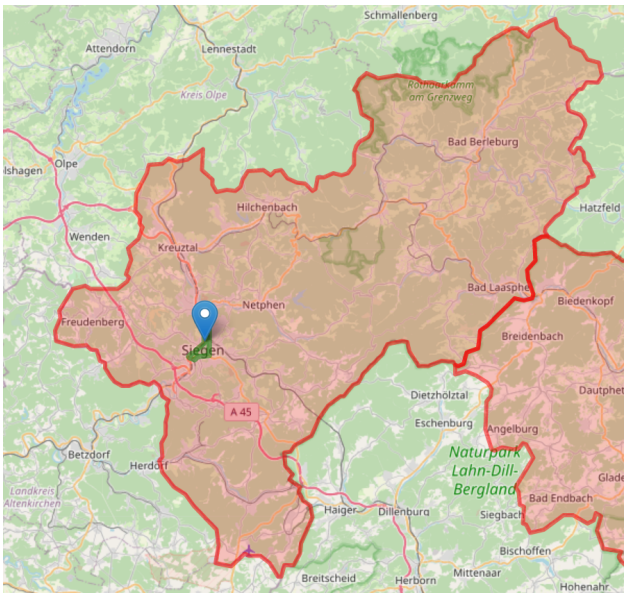
Explain that GDP $\neq$ aggregate utility and having less pollution is surely valuable

4.2 The effect of large LEZ on Labor outcomes

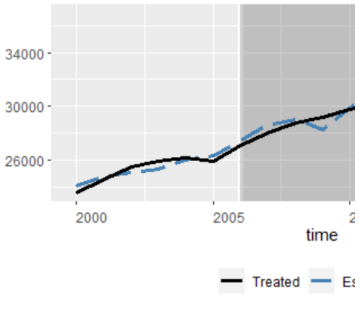
Be clear with limitations and assumption that the scrappage program does not affect the outcomes I present here.



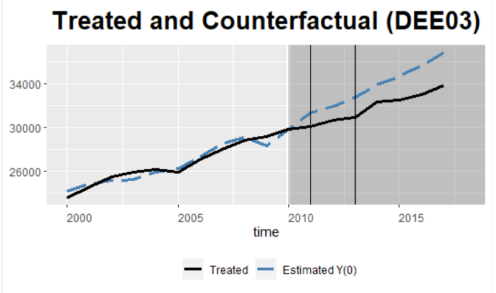
(a) Map of Magdeburg and NUTS 3 region



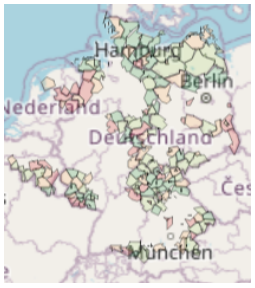
(b) Map of Siegen and NUTS 3 region



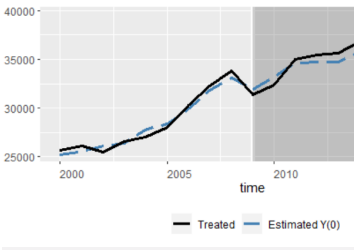
(c) Pre-intervention placebo



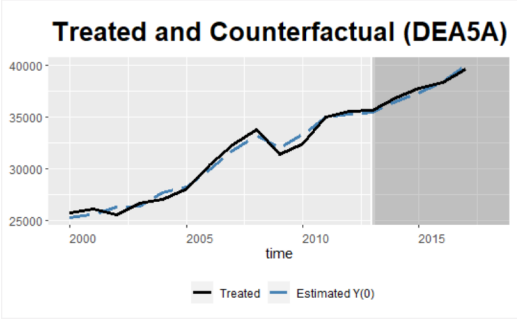
(d) Estimated effect with implementation



(e) Map of weights



(f) Pre-intervention placebo



(g) Estimated effect with implementation

(h) Map of weights

Figure 2: Example of results for the effect of GDP per capita for Magdeburg (first) and Siegen (second). Both correctly follow the same path before the announcement and while Siegen (small city relative to region) has no effect on GDP, we can see a 5% decrease in GDP after 5 years of the announcement of a LEZ in Magdeburg.
While Synthetic Magdeburg takes weights (green color) from eastern an northern Germany, synthetic Siegen is created with rural areas from western and southern Germany.

5 Conclusions

Mostly from MY400, work as a basis to write the final ones.

To explain: Motivations for research, research strategy, results and limitations. Finally explain degree of external validity and further research (mention MASC and possibility of doing mediation analysis if pollution data without much noise can be gathered).

These estimates and conclusions will try to help construct more effective and fair public policies on LEZ that take into account the results in similar cities. Additionally, the results will be of especial interest to policy makers and business leaders as they investigate local short-term effects that concerns them directly.

Regarding external validity, I believe it would be safe to interpret the results in an European context with restrictions similar to the ones in German LEZ and especially good if city-specific characteristics could be matched to one of the treated units. Nevertheless, it would be hard to extrapolate results to developing countries where, for example, individuals have less disposable income to change a vehicle to a less polluting one.

When concluded, the results should provide a significant and novel contribution that informs pressing public policy on LEZ and air pollution control and works as an example of the application of novel techniques. They could also promote further research on the potential economic effects of LEZ in low- and middle-income countries, especially in those that are highly growth-dependent such as China and India, where the costs of air pollution appear to be very high and policy advice is much needed.

References

Abadie, A. (2019). Using Synthetic Controls: Feasibility, Data Requirements, and Methodological Aspects. *Journal of Economic Literature*, Forthcoming.

Abadie, A., Diamond, A., and Hainmueller, J. (2010). Synthetic control methods for comparative case studies: Estimating the effect of California's tobacco control program. *Journal of the American Statistical Association*, 105(490):493–505.

Abadie, A., Diamond, A., and Hainmueller, J. (2015). Comparative Politics and the Synthetic Control Method. *American Journal of Political Science*, 59(2):495–510.

Abadie, A. and Gardeazabal, J. (2003). The economic costs of conflict: A case study of the Basque Country. *American Economic Review*, 93(1):113–132.

Abadie, A. and L'Hour, J. (2019). A Penalized Synthetic Control Estimator for Disaggregated Data. *Working Paper,*, (May):1–35.

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*.

Amjad, M., Misra, V., Shah, D., and Shen, D. (2019). Mrsc: Multi-dimensional robust synthetic control. *Proc. ACM Meas. Anal. Comput. Syst.*, 3(2).

Brodersen, K. H., Gallusser, F., Koehler, J., Remy, N., and Scott, S. L. (2015). Inferring causal impact using bayesian structural time-series models. *Annals of Applied Statistics*, 9:247–274.

Cesaroni, G., Boogaard, H., Jonkers, S., Porta, D., Badaloni, C., Cattani, G., Forastiere, F., and Hoek, G. (2012). Health benefits of traffic-related air pollution reduction in different socioeconomic groups: the effect of low-emission zoning in Rome. *Occupational and Environmental Medicine*, 69(2):133–139.

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.

Dechezleprêtre, A. (May 18, 2018). The economic cost of air pollution: Evidence from Europe. Conference on Environmental regulation and industrial performance, TSE.

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.

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

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.

Hao, Y., Peng, H., Temulun, T., Liu, L.-Q., Mao, J., Lu, Z.-N., and Chen, H. (2018). How harmful is air pollution to economic development? new evidence from pm2.5 concentrations of Chinese cities. *Journal of Cleaner Production*, 172:743 – 757.

Holman, C., Harrison, R., and Querol, X. (2015). Review of the efficacy of low emission zones to improve urban air quality in European cities. *Atmospheric Environment*, 111:161 – 169.

Kelly, F. J. and Kelly, J. (2009). London air quality: a real world experiment in progress. *Biomarkers*, 14(sup1):5–11.

Lenschow, P., Abraham, H.-J., Kutzner, K., Lutz, M., Preuß, J.-D., and Reichenbächer, W. (2001). Some ideas about the sources of pm10. *Atmospheric Environment*, 35:S23 – S33. Selected Papers Presented at the Venice Conference.

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

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.

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

Roth, S. (2015). The effect of indoor air pollution on cognitive performance: Evidence from the UK. Unpublished.

TFL (June, 2006). Central london congestion charging, impacts monitoring. fourth annual report.

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.

Xie, Y., Dai, H., Dong, H., Hanaoka, T., and Masui, T. (2016). Economic impacts from pm2.5 pollution-related health effects in China: A provincial-level analysis. *Environmental Science & Technology*, 50(9):4836–4843. PMID: 27063584.

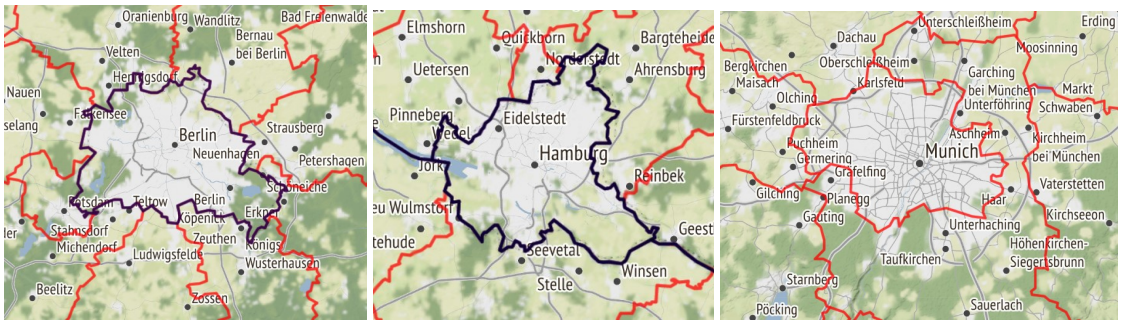
Xu, Y. (2017). Generalized synthetic control method: Causal inference with interactive fixed effects models. *Political Analysis*, 25(1):57–76.

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.

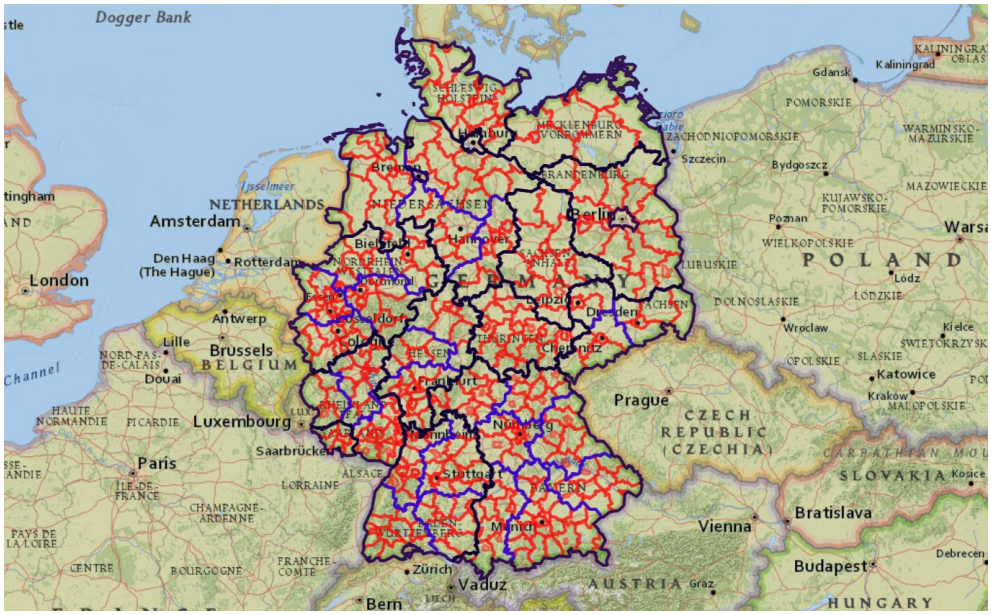
Appendices

Variable	Coverage	Geography	Start	End	Delta	Source
Outcomes (Y):						
GVA at basic prices by NACE activites	EU	NUTS 3	1995	2017	1 year	Eurostat
GDP	EU	NUTS 3	2000	2017	1 year	Eurostat
GDP at current prices	EU	NUTS 4 (LAU 1)	2000	2017	1 year	Eurostat
Spatial variation (X):						
Boundaries of LEZ zones	EU	georeferenced	Most recent			urbanaccessregulations.eu
Boundaries of LEZ zones	EU	georeferenced	Most recent			"Green-Zones" App
Boundaries of LEZ zones	Germany	georeferenced	Most recent			"Umweltzone" App
Boundaries of LEZ zones and details on their implementation	EU	Complete	All	All	1 day	Official and legal documents
Boundaries of LEZ zones and details on their implementation	EU	georeferenced	Partial	Partial	Varies	openstreetmap.org
Details on LEZ's implementation	Germany	Complete	2008	2020	1 day	Umweltbundesamt
Details on LEZ's implementation	Germany	"Described"	All	2017	1 month	Gehrsitz (2017) and Wolff (2014)
Predictors and secondary outcomes:						
Employed persons by NACE	EU	NUTS 3	1995	2017	1 year	Eurostat
1000 Hours Worked	EU	NUTS 2	2000	2017	1 year	Eurostat
Total and active population by sex, age, employment status, residence one year prior to the census	EU	NUTS 3	2001	2001	1 year	Eurostat Census
Population by age and sex	EU	NUTS 3	1990	2018	1 year	Eurostat
Investment	EU	NUTS 2	1995	2017	1 year	Eurostat
Employer business demography by NACE Rev. 2	EU	NUTS 3	2008	2016	1 year	Eurostat
Employer business demography by size class	EU	NUTS 3	2008	2016	1 year	Eurostat
Business demography and high growth enterprise by NACE Rev. 2	EU	NUTS 3	2008	2016	1 year	Eurostat
Business demography by size class	EU	NUTS 3	2008	2016	1 year	Eurostat
Community design (CD) applications	EU	NUTS 3	2003	2016	1 year	Eurostat
Patent applications to the EPO by priority, IPC, sections and classes	EU	NUTS 3	1977	2012	1 year	Eurostat
High-tech patent applications to the EPO by priority year	EU	NUTS 3	1977	2012	1 year	Eurostat
Patent applications to the EPO by priority year	EU	NUTS 3	1977	2012	1 year	Eurostat
N° of vehicles by emission category	Germany	districts/cities	2008	2018	1 year	Kraftfahrtsbundesamt
Other variables (mostly control):						
Number of deaths	EU	NUTS 3	1990	2017	1 year	Eurostat
Population change	EU	NUTS 3	2000	2018	1 year	Eurostat
Land use (degree of urbanization)	EU	NUTS 3	2015	2020	5 years	JRC
Live births	EU	NUTS 3	1990	2017	1 year	Eurostat
Area (m^3)	EU	NUTS 3	1990	2015	1 year	Eurostat
Live births by age of the mother	EU	NUTS 3	1990	2017	1 year	Eurostat
Fertility rate	EU	NUTS 3	1990	2017	1 year	Eurostat
Age dependency ratio by age class	EU	NUTS 3	2014	2018	1 year	Eurostat
Shape files:						
NUTS and LAU regions	EU	NUTS and LAU	All	All	All	Eurostat
Functional Urban Areas	EU	NUTS and LAU	All	All	All	Eurostat
Metropolitan Areas	EU	NUTS and LAU	All	All	All	Eurostat

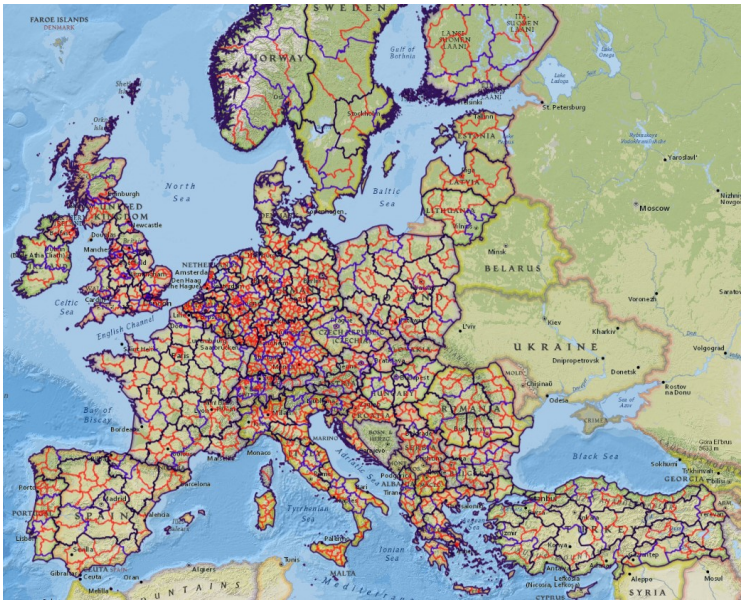
Table 1: Variables for the analysis with their source, geographic and time coverage.



(a) Berlin (b) Hamburg (c) Munich



(d) German NUTS regions



(e) Main coverage of NUTS 3 zones

Figure 3: Main coverage of NUTS zones across Europe and Germany, with examples of cities. Borders of NUTS 1, 2 and 3 regions are coloured in black, blue and red, respectively. *Source: Eurostat and own work.*

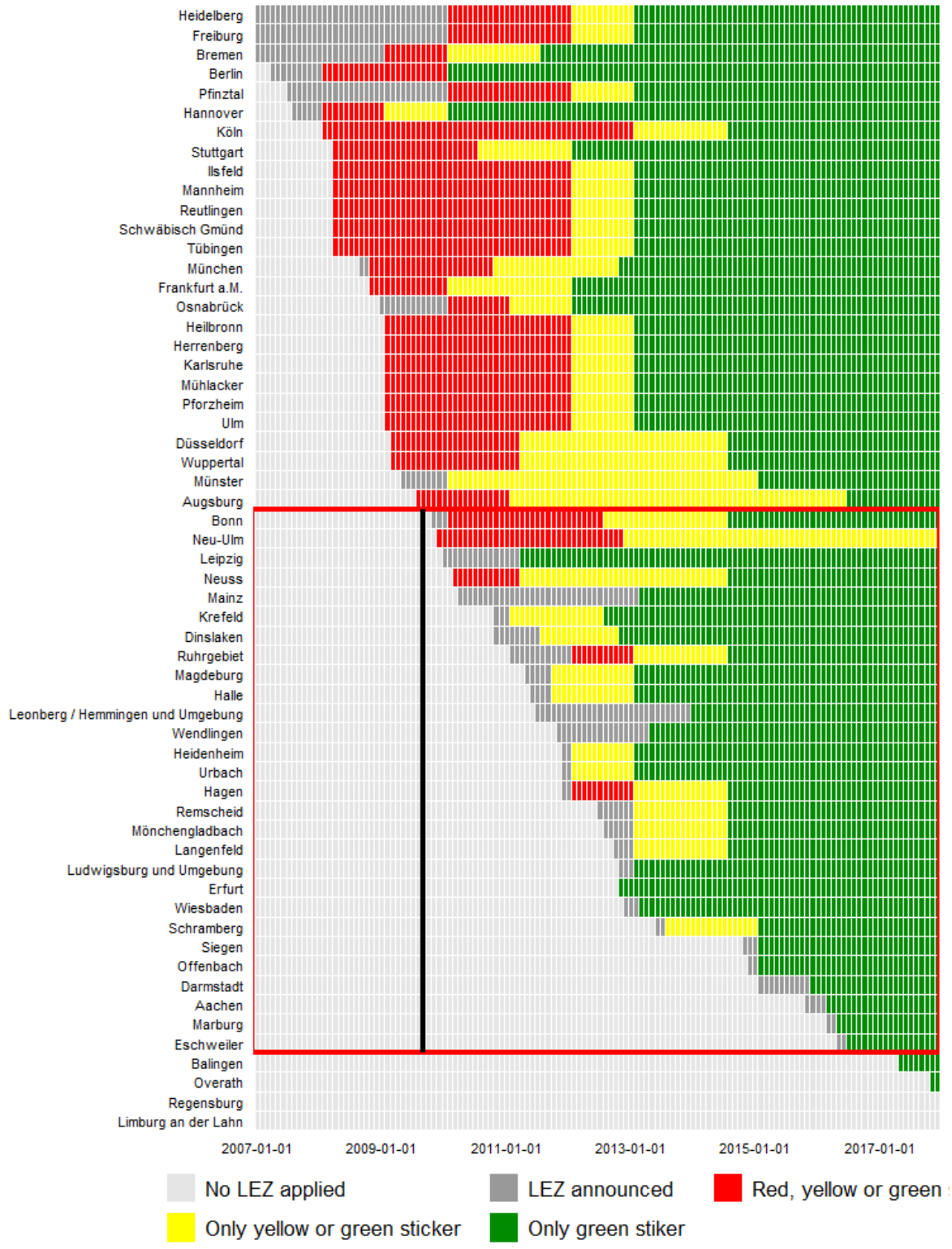


Figure 4: Application of LEZ in Germany during the period studied by category of environmental stickers allowed and month of the year. LEZ where where the effect of GDP is studied are marked with a red square and the end of the scrappage program is marked with a black vertical line
Source: Umweltbundesamt and my own work.

Countries	Weights
Australia	-
Austria	0.42
Belgium	-
Denmark	-
France	-
Greece	-
Italy	-
Japan	0.16
Netherlands	0.09
New Zealand	-
Norway	-
Portugal	-
Spain	-
Switzerland	0.11
UK	-
USA	0.22

Table 2: Weights of different countries in the control pool that construct the synthetic Germany in Abadie et al. (2015). This helps us judge the plausibility of the control group and avoid spurious correlations.
Source: Abadie et al. (2015).

	West Germany	Synthetic West Germany	Rest of OECD Sample
GDP per-capita	15808.9	15802.2	8021.1
Trade openness	56.8	56.9	31.9
Inflation rate	2.6	3.5	7.4
Industry share	34.5	34.4	34.2
Schooling	55.5	55.2	44.1
Investment rate	27.0	27.0	25.9

Table 3: Here we can see the resemblance in characteristics of West Germany and its synthetic control compared to the mean of the rest of OECD sample..
Source: Abadie et al. (2015).