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Diesel bans and urban air quality: A causal study of NO_2 emissions in Germany using synthetic control

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ABSTRACT

Urban air pollution is a growing public health and environmental issue. This study investigates the effectiveness of diesel traffic bans in reducing nitrogen dioxide emissions in four German cities: Berlin, Darmstadt, Hamburg, and Stuttgart, from 2012 to 2022. Each city has implemented similar policies to comply with the European Union's emission standards. Using the synthetic control method, we evaluate the effects of policies restricting diesel traffic on selected streets, street segments, and urban areas. Our results indicate that the implementation of diesel traffic bans led to significant reductions in nitrogen dioxide emissions per capita in Darmstadt and Stuttgart. However, the policy appeared to have a limited effect in Berlin and Hamburg. The study suggests that policy effectiveness is influenced by factors such as city size, pre-existing traffic patterns and the extent of diesel restrictions. In addition, our findings highlight the importance of tailoring policies to local conditions and underscore the value of using rigorous research methods when assessing the effectiveness of environmental policies.

1. Introduction

Since the Industrial Revolution, humanity has released billions of tons of additional greenhouse gases (GHG) into the atmosphere, making the planet warmer [1]. GHG emissions cause the temperature on the surface of the Earth to rise [2,3]. The increase in gases in the atmosphere means that it will lead to environmental and health problems. The goal of climate change mitigation policies is to reduce emissions and limit global warming to a level that avoids the most dangerous and catastrophic impacts [4]. Emissions from a variety of sources, including transport, industry, and energy production, contribute to the deterioration of air quality and the associated adverse health effects [5]. Hence, air pollution is a significant threat to public health and environment.[1]

Transport is one of the largest contributors to GHG emissions, accounting for 19.5% (149 million tons of CO_2) by 2021 [7].[2] The transport sector is also a major contributor to NO_2 emissions, especially in urban areas with high traffic volumes. NO_2 is a non-greenhouse gas (non-GHG[3]) and is one of the most harmful pollutants in the world because it can cause health problems for humans. In particular, NO_2 can cause a variety of cardiovascular problems, such as higher blood pressure, changes in heart rate variability, decreased micro-vascular function, and autonomic nervous system dysfunction [10–13]. In addition, the symptoms of those who already suffer from lung or heart disease may be exacerbated by exposure to NO_2. In many developed countries, the transportation sector is the biggest contributor to NO_2 emissions [13]. Diesel engines are a significant source of NO_2, especially in urban areas where they are widely used for transport [11], and diesel cars emit more NO_2 than petrol cars [14]. Trains, ships, and aircrafts are other sources of NO_2 emissions in the transport sector. Minimizing emissions in the transport sector can be achieved by reducing the energy demand of vehicles or by using alternative energy sources such as gas and electricity [15]. However, significant changes in emissions in the transport sector will require considerably stricter policies than the existing ones [16]. Reducing air pollution from diesel engines is not only important for public health but also for climate change mitigation. Diesel engines are a significant contributor to GHG emissions as well, which are

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[1] Air pollution is determined as the presence of pollutants in the air in large quantities for long periods [6].

[2] The global passenger demand was estimated to more than double between 2015 and 2050, from 50 000 to 120 000 billion passenger kilometers, which means that the number of cars worldwide would increase [8].

[3] Non-GHG emissions include pollutants like sulfur dioxide (SO_2), nitrogen oxides (NOx), volatile organic compounds (VOCs), and particulate matter (PM) [9].

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responsible for global warming and its associated impacts, such as rising sea levels, more frequent extreme weather events, and loss of biodiversity [13,17]. NO_2 can harm the environment by altering soil chemistry and negatively impacting biodiversity in sensitive environments [18]. Therefore, policies that reduce diesel engine emissions may also have the potential to contribute to the fight against climate change. Due to these two impacts of diesel (health and environment), much effort has been put into developing different types of policies to reduce and prevent harmful effects of air pollution. There are a number of ways to tackle vehicle emissions, such as investing in public transport, increasing taxes on diesel or petrol, encouraging the uptake of electric vehicles through tax breaks and subsidies, and restricting access to low-emission vehicles in urban areas [15,19–21].

Following the Paris Agreement, Germany committed to drastically reduce its emissions (§3 Nationale Klimaschutzziele - Bundes-Klimaschutzgesetz) and is now one of the most promising countries to achieve complete carbon neutrality by 2050. It has a target of reducing CO_2 emissions to 98 million tons by 2030, therefore the policy measures are key to the achievement of this target [22]. A crucial strategy involves substantial emission reductions in the domestic transport sector. Diesel cars in Germany comprise 30.5% of vehicles [23] accounting for 45.4% of domestic passenger car mileage in 2020 [24]. Despite the existing literature, comprehensive and comparative analyses of the effectiveness of diesel vehicle bans and environmental zones in different cities around the world, including Germany, are still lacking. In this paper, we address this gap by providing a comparative case study of the effectiveness of diesel vehicle bans in four German cities: Berlin, Darmstadt, Hamburg, and Stuttgart. We chose these four cities for two main reasons. First, they are the cities with the strictest diesel ban policies compared to other German cities as of July 2022.[4] Second, they are also among the cities with the highest NO_2 emissions in Germany.

We want to understand how these policies affect NO_2 emissions in these urban areas. To assess the impact of the diesel vehicle bans, we use the Synthetic Control Method (SCM). SCM is the most important innovation in the policy evaluation literature in the last 15 years [25]. Using SCM, researchers want to estimate the evolution of aggregate outcomes for a unit affected by a particular event happening and compare it to the same aggregates estimated for some control group that is not affected [26–29]. To estimate the impact of the diesel traffic ban on NO_2 emissions in Stuttgart, Berlin, Hamburg and Darmstadt, we selected counterfactual German cities. These counterfactual (donor) cities are selected based on four criteria: they must be German cities, they must not have been subject to a similar intervention, data must be available, and they must have an average monthly emission of around 20 μg/m^3 NO_2 or more. This approach allows us to assess whether these bans have made a significant contribution to reducing NO_2 emissions, thereby providing a clearer understanding of the effectiveness of the policy in reducing air pollution.

We find that in Stuttgart, regulations banning diesel vehicles in entire neighborhoods or significant parts of the city helped to reduce NO_2 emissions. In Darmstadt restricting access to sections of road that limited access to the city center led to a reduction in NO_2 emissions. In contrast, in Berlin and Hamburg, where restrictions were limited to specific streets, no significant emission reductions were observed. This is because diesel vehicles still had access to most parts of the city. These results suggest that the effectiveness of diesel vehicle bans in reducing air pollution depends on whether a whole area is restricted or only specific streets. That is, the success of this type of policy largely depends on the extent of the restricted area; city-wide restrictions are more effective than those imposed on individual streets. Our results are confirmed by placebo and robustness tests.

The remainder of this paper is organized as follows: Section 2 discusses the effects of pollution on human health and climate, and also discusses the existing literature, referring to various studies on the effectiveness of Low Emission Zones (LEZs). Section 3 provides some background information on the nature and purpose of the LEZs. Section 4 describes our methodology and data. Section 5 presents the results. Section 6 examines the significance of the results. Section 7 reports the robustness tests. Section 8 discusses the results and policy implications, while Section 9 draws some conclusions.

2. Related literature

Diesel vehicles, a primary source of NO_2 emissions, contribute significantly to high NO_2 concentrations in urban areas [30]. In order to reduce pollution and GHG emissions from the transportation sector, the German government has implemented different policies specifically targeting urban transport. For example, one effective policy that has been implemented and has had a positive impact is the German eco-tax motor fuel [31]. The policy was introduced in 1999 and it led to a notable decrease in emissions by 11.5% by 2005, without reducing total road transport. Despite initial delays, the eco-tax led to a significant reduction in transport-related carbon emissions, amounting to a reduction of 0.2-0.35 tons of CO_2 per person per year, highlighting the policy's role in encouraging technological advances for environmental benefits.

There is a growing literature on environmental zones that examines the effectiveness of these policies in reducing NO_2 emissions as well as other GHG and non-GHG emissions. Several studies are optimistic and show that banning diesel vehicles can significantly reduce emissions in certain areas. For example, a study carried out an analysis on the effectiveness of the LEZ in Lisbon implemented in phases between 2011 and 2015 and showed an improvement in air quality in Lisbon due to LEZ [32]. Particularly PM_{10} concentrations decreased by 22% in Zone 1 and 25% in Zone 2, while NO_2 concentrations decreased by 13% in Zone 1 and 22% in Zone 2. The measures of [33] predict significant savings in Dublin in terms of reduction of PM_{10} and NO_x emissions, which were found to be 47% and 52% respectively in the year 2030 compared to the year 2015 levels. In their turn, [34] found that vehicle bans significantly promote battery electric vehicles for mini-sized vehicles and hydrogen fuel cell vehicles for light and heavy-duty vehicles. In addition, [35] analyzed the effect of the LEZs on air quality in Amsterdam and they found that since the implementation of the LEZs, the traffic contribution concentrations compared to the roadside site concentrations have decreased by 4.9% for NO_2, 5.9% for NO_x, 5.8% for PM_{10} [36]. Finds that LEZs in German cities led to modest reductions in PM_{10} pollution—around 4% on average and up to 8% in highly polluted areas but did not produce measurable improvements in infant health outcomes. The study highlights that LEZs are more effective in cities with higher baseline pollution, suggesting that the impact of such policies depends on implementation scale and local conditions [37]. Claim that that LEZs are an effective policy instrument to reduce levels of air pollution in Germany. In particular, LEZs reduced PM_{10} and NO_2 levels by about 5% and led to modest but significant declines in hospitalizations for circulatory and respiratory diseases, particularly in hospitals located within LEZ boundaries. The paper accentuates that even moderate air quality improvements can yield meaningful health benefits. In summary, there are studies that show, using the example of different cities, that the concentrations of different types of emissions (*PM*, NO_2) have decreased due to the implementation of LEZs [38,39]. However, the magnitude of the reduction varies from city to city [40]. As a result of emission controls, air quality in cities in Europe has generally improved.

At the same time, some studies have suggested that the impact of these bans in terms of emission reductions has not shown any significant

[4] Over time, some cities have lifted their diesel bans. In Berlin, for example, the diesel ban introduced in 2019 was lifted on all roads by the Berlin Senate in September 2022. After five years, Hamburg also lifted its diesel ban policy (around September/October 2023). Meanwhile, Munich implemented its diesel ban policy on February 1, 2023. This ban applies to diesel vehicles that meet the Euro 4/IV emission standard or worse. An extension of this ban to include Euro 5/V vehicles, originally planned for October 2023, has been postponed.

changes in emissions [41,42]. This may be due to several factors, including low compliance rates, limited enforcement, displacement effects, and management practices that are often static, meaning that the restrictions remain the same regardless of the level of air pollution in the area. For example, [42] examined the effectiveness of LEZs in reducing air pollution on eight major streets in five Dutch cities and found that LEZ policies did not have a significant impact on traffic-related air pollutants. According to [38], car bans could contribute to both climate change and air quality goals. However, most car bans announced so far lack enforcement mechanisms and are therefore not bans at all.

From a methodological perspective, some studies primarily rely on Difference-in-Differences (DiD) frameworks (e.g., [36]), Regression Discontinuity Design (RDD) (e.g., [43]), or simple before-and-after comparisons (e.g., [42]). Some studies, such as [44], also incorporate Monte Carlo simulations to assess uncertainty in emissions trends. Despite this progress, two important gaps remain. First, few studies use SCM to compare multiple cities within the same national context to understand variation in policy effectiveness. Second, there is limited research that quantifies how implementation scope (i.e., full-city vs. single-street bans) influences outcomes using robust causal inference tools. This paper addresses these gaps by applying SCM to four major German cities (Berlin, Hamburg, Darmstadt, and Stuttgart) that implemented diesel traffic bans between 2018 and 2020. By comparing synthetic and actual NO_2 outcomes, this study contributes to the growing literature on urban air quality interventions and policy heterogeneity.

3. Low emission zones and diesel traffic bans

Climate change mitigation policies play a crucial role in addressing the global climate crisis, with the aim of limiting warming and protecting the environment for future generations. Alongside its national initiatives, Germany aligns with European regulatory policies on vehicle emissions. In 1970, a standardized European regulation for car emissions came into force with limit values for carbon monoxide and hydrocarbons (Richtlinie 70/220/EWG 1970). Exhaust legislation for passenger cars and light commercial vehicles began in 1992 with the introduction of the Euro 1 emission standard when the European guideline came into force (Richtlinie (91/441/EWG) 1991). After Euro 1, several standards were introduced. For example, the Euro 6 standards significantly reduced emission limits for a number of pollutants emitted from vehicle exhaust, including *PM*, NO_x, and other pollutants [45].

Besides, Germany have introduced LEZs in many cities. LEZs are geographical areas where certain types of vehicles are prohibited from entering. The aim of these zones is to reduce air pollution (NO_2 and PM_{10} emissions), especially from diesel vehicles, and improve air quality. Restrictions can take several forms, including the banning of certain types of vehicles, the imposing of charges on high-polluting vehicles, or the setting of emission standards that vehicles must meet in order to enter the zone [46]. LEZs control vehicle access based on emission levels with the aim of improving air quality, reducing GHG emissions, and promoting alternative modes of transportation in urban areas [36,47]. As of July 11, 2022, Germany had 56 LEZs and four diesel traffic restriction zones [48]. Only vehicles that meet certain emission standards are allowed to enter these zones. To facilitate this, vehicles are categorized into different groups, identified by color-coded stickers [49]. These classes range from the least environmentally-friendly (Euro 1 to Euro 4 for passenger cars and Euro I to Euro IV for heavy-duty diesel engines) to the most compliant (Euro 5 and Euro 6 standards). Vehicles can enter an environmental zone by displaying the appropriate sticker, with the level of stringency of the LEZ set by the local authority. Vehicles without a sticker, or with a sticker from a less compliant group, are restricted from entering designated environmental zones.

In response to high NO_2 pollution, some cities have implemented a stricter restriction: diesel traffic bans, also called the "NO_2-free Emission Zones," where vehicles with Euro 5 or lower emission standards are prohibited. Cities like Darmstadt, Hamburg, Berlin, and Stuttgart have implemented this policy (details in Appendix A). We use the SCM to evaluate the effectiveness of these policies in Germany's major NO_2-polluting cities.

4. Method

As mentioned above, we use the SCM, which is designed to estimate the causal effect of an intervention, in this case, the diesel ban policy by comparing the observed outcomes with the synthetic control. The differences between the outcomes of the treated unit (Berlin, Darmstadt, Hamburg, Stuttgart) and the synthetic control group is the causal impact of the diesel ban. SCM is a way of evaluating the impact of an intervention or treatment by comparing the treated unit with a weighted combination of untreated units that are similar to it before the intervention. The idea is to create a "synthetic" version of the treated unit using the weighted average of similar, unaffected units, which serve as a counterfactual or baseline for what would have happened in the absence of the intervention. By comparing the actual outcomes of the treated unit to the synthetic control, we can estimate the effect of the intervention. This method is particularly useful for evaluating policies and understanding the impact of large-scale events. The SCM, based on German cities without the intervention, creates a "synthetic" control group (or donor pool) that reflects the characteristics of the treated unit (e.g., Stuttgart, Berlin, Hamburg, Darmstadt) before the intervention (e.g., the ban on Euro 5 diesel vehicles). The SCM relies on several key assumptions. First, there must be no anticipation or pre- treatment effects, meaning that the intervention has no impact on the outcome variable prior to its implementation. Second, the treated unit's pre-intervention trajectory must be well approximated by a weighted combination of control units from the donor pool. Third, the treated unit must lie within the convex hull of the donor pool in terms of its pre-intervention characteristics, which requires that the donor unit weights are non-negative and sum to one. Fourth, there should be no spillover effects, meaning that the intervention should not influence the outcomes of donor units, thereby avoiding contamination of the control group. Finally, the Stable Unit Treatment Value Assumption (SUTVA) must hold what [29] refers to as the "no interference" condition implying that the potential outcomes for each unit depend solely on its own treatment status and not on the treatment assignment of other units.

We have $J+1$ units (e.g., German cities in our case) indexed by j, where $j = 1$ is the case of interest or the "treated unit" (Hamburg, Darmstadt, Stuttgart and Berlin) and units $j=2$ to $j=J+1$ are potential comparisons or the "donor pool". Our sample is a balanced panel, where all units are observed at the same time periods. We have a positive number of pre-intervention periods, T_0, as well as a positive number of post-intervention periods, T_1, with $T = T_0 + T_1$. In short, we observe the NO_2 per capita emissions of $J+1$ cities for T, and only the first cities, Berlin, Darmstadt, Hamburg, and Stuttgart, implemented the diesel traffic ban, while, the remaining J cities serve as the control group.

Suppose that T_0 is the year that the diesel traffic ban was implemented, Y_{it}^N is the outcome for unit i at time t if unit i is not exposed to the intervention. That is, in our case Y_{it}^N is the NO_2 per capita emissions that could be observed for the city i at the time t in the absence of the diesel traffic ban. Y_{it}^I is the outcome for unit i at time t if unit i is exposed to the intervention. That is, Y_{it}^I is the NO_2 per capita emissions that could be observed for city i at time t if city i is exposed to the implementation of the traffic ban in periods T_{0+1} to T. Hence, we suppose that $\alpha_{it} = Y_{it}^I - Y_{it}^N$ is the effect of the intervention for unit i at time t. For example, $\alpha_{1t} = Y_{1t}^I - Y_{1t}^N$ represents the impact of the diesel traffic ban policy on NO_2 per capita emissions in Berlin, Hamburg, Stuttgart and Darmstadt. We also assume that the intervention has no effect on the outcome before the implementation period. In particular, because the NO_2 per capita emissions in all cities are not influenced by the diesel traffic ban before T_0 (when $t \leq T_0$), then we have that $Y_{it}^I = Y_{it}^N$, when $T_0 < t \leq T$.

We let $\alpha_{it} = Y_{it}^I - Y_{it}^N$ be the effect of the intervention for unit i at time

t, and we let D_{it} be an indicator that takes value one if unit i is exposed to the intervention at time t and value zero otherwise. The observed outcome for unit i at time t is $Y^I_{it} = Y^N_{it} + \alpha_{it}D_{it}$. We have D_{it} as a dummy variable: $D_{it} = 1$ if $i = 1$ and $t > T_0$, otherwise $D_{it} = 0$. When $t \leq T_0$, $D_{it} = 0$, the observed outcome for unit i at time t is $Y^I_{it} = Y^N_{it}$.

We aim to estimate $(\alpha_{1t}T_{0+1},\ldots,\alpha_{1t}T_1)$. For $t > T_0$,

$$\alpha_{1t} = Y^I_{1t} - Y^N_{1t} = Y_{1t} - Y^N_{1t}. \tag{1}$$

Because Y^I_{1t} is the observed real NO_2 per capita emissions of Berlin, Darmstadt, Hamburg, and Stuttgart after the adoption of the traffic ban policy, to estimate α_{1t}, we just need to estimate Y^N_{1t}. Assume that Y^N_{it} is given by a factor model:

$$Y^N_{it} = \delta_t + \theta_t Z_i + \lambda_t \mu_i + \epsilon_{it} \tag{2}$$

where δ_t is an unknown common factor, Z_i are observed covariates which are not affected by the diesel traffic ban, λ_t are unobserved common factors, θ_t are unknown parameters, ϵ_{it} are error terms, and μ_i are unknown factor loadings.

Suppose that a weight vector W is used to estimate Y^N_{it}, where $W = (w_2, w_3,\ldots,w_{J+1})$, $w_j \geq 0$, and $w_2, w_3,\ldots,w_{J+1} = 1$. Given a set of weights, the synthetic control estimators of Y^N_{1t} and α_{1t} are, respectively:

$$\widehat{Y}^N_{1t} = \sum_{j=2}^{J+1} w_j Y_{jt} \tag{3}$$

and

$$\widehat{\alpha}_{1t} = Y_{1t} - \widehat{Y}^N_{1t}. \tag{4}$$

We followed these requirements, and the most basic requirement for inclusion in the donor pool is not to be affected by the same or similar policy intervention. Another requirement is to be a German city. That is, due to the factor that German cities share the same culture and the same institutional system, the donor pool consists only of German cities. Another criterion to be in our donor pool is to emit at least about 20 μg/m^3 NO_2. Many German cities have implemented LEZs policies (as of July 2022, there were about 56 LEZs in Germany). This means that we should not include the German cities that have already implemented LEZs in our donor pool. In the end, we have 13 German cities in the donor pool (based on the selection criteria mentioned above): Braunschweig, Dresden, Gießen, Göttingen, Kassel, Kiel, Koblenz, Leverkusen, Ludwigshafen, Nürnberg, Potsdam, Rostock, Saarbrücken.[5] The weights assigned to each control unit in the construction of the synthetic control unit are determined by the degree of similarity between the variables of the control units and those of the treated unit. We then compare the evolution of monthly NO_2 per capita emissions in Stuttgart, Berlin, Hamburg, and Darmstadt with that in the counterfactual control group (the synthetic control group which did not receive the treatment) after the diesel traffic ban was introduced. If actual emissions in the treated German cities fall below relative to the synthetic counterfactual, we conclude that the diesel traffic ban was effective. The counterfactual monthly NO_2 per capita is constructed as a weighted average of the monthly NO_2 per capita emissions of the other German cities, the so-called donor cities.

5. Data

As the outcome variable, we use the monthly NO_2 emissions at the city level.[6] First, we obtained the daily NO_2 emissions at the city level which we collected from the German Federal Environmental Agency (Umweltbundesamt, UBA). Then we converted it into the monthly NO_2 emissions. Finally, the monthly NO_2 value was then divided by the population of the city, resulting in the monthly NO_2 emissions per capita. The values of NO_2 emissions and covariates fall between January 1, 2012 and July 23, 2022 making a total of 3857 entries per city.[7] It is also important to note that the population numbers for Berlin and Hamburg were not based on the total population of these cities, but only on the number of people living near the stations recording emissions. In the case of Berlin, the population used was the population of the districts of Mitte, Charlottenburg, Tempelhof and Friedrichshain-Kreuzberg; these are the districts where the stations are located [51]. In the case of Hamburg the population number included the residents of the districts of Mitte, Altona and Eimsbüttel, where the monitoring stations were located [52]. For Darmstadt the number of daily commuters was added to the city's existing population; Darmstadt has approximately 100,000 commuters [53]. For Stuttgart, we considered the whole population of the city because the entire area was affected by the policy.

Covariates are the variables that the SCM uses to create a weighted combination of control units that can look like the results of the treated unit before the intervention. These variables are used to figure out what factors might affect the outcome of interest in both the treated and the control units. Although the use of a set of covariates is optional, providing a set of covariates that predict the post-intervention outcome in the absence of the intervention can improve causal inference [29, 54].[8] Our choice of covariates is based on the literature on air pollution and transport. The inclusion of the share of diesel cars is motivated by studies showing diesel vehicles as dominant sources of NO_2 emissions in urban settings [36,42]. The percentage of commuters captures inter-city mobility, which contributes significantly to urban emissions [42]. The employment rate reflects transit demand and daily mobility patterns associated with work-related travel [36,44]. Finally, GDP per capita proxies for economic activity, which correlates with car ownership and traffic intensity, both of which are strongly associated with urban pollution levels [36,42]. The goal is to select covariates that are highly related to the outcome of interest and capture the differences between the treatment and control units, which are then used to construct a synthetic control unit with pre-intervention outcomes that are roughly comparable to those of the treated unit.

Fig. 1 illustrates the bar chart of the average monthly mean NO_2 emissions for the chosen German cities between 2012 and 2022, showing a wide range of variation in monthly NO_2 emissions (the same figure but in per capita terms can be found in Appendix C). The city with the highest mean NO_2 emissions is Stuttgart, which stands out significantly from the other cities. Other cities such as Berlin, Darmstadt, and Hamburg, highlighted in red, also exhibit relatively high NO_2 emissions. In contrast, cities like Koblenz, Gießen, and Ludwigshafen show moderate levels of NO_2 emissions. At the lower end of the spectrum, Kassel and Dresden have the lowest mean NO_2 emissions.

Table 1

We now focus on the NO_2 emissions of Germany's major cities in 2021-2022. Fig. 2 shows the trends of NO_2 emissions in 17 German cities (4 treated and 13 untreated) between 2012 and 2022[9]. As can be seen,

[5] In total, there were only 13 cities that met the requirements to be a donor city during the study period. A similarly low number of donor units can also be found in other studies, e.g. [50].

[6] For the use of the outcome variables, the selected station must be the same as the street that received the treatment.

[7] See the sources of the data in Appendix B.

[8] We ran the SCM analysis both with and without the key predictors and found no major changes in the results.

[9] The summary statistics for each city separately can be found in Appendix D in Table D1, the values of the variables for the treated cities and donor cities in the pre- and post- intervention periods can be found in Appendix D in Table D2 and the map of the NO_2 emissions of the selected cities in 2012 and 2022 are presented in Appendix E.

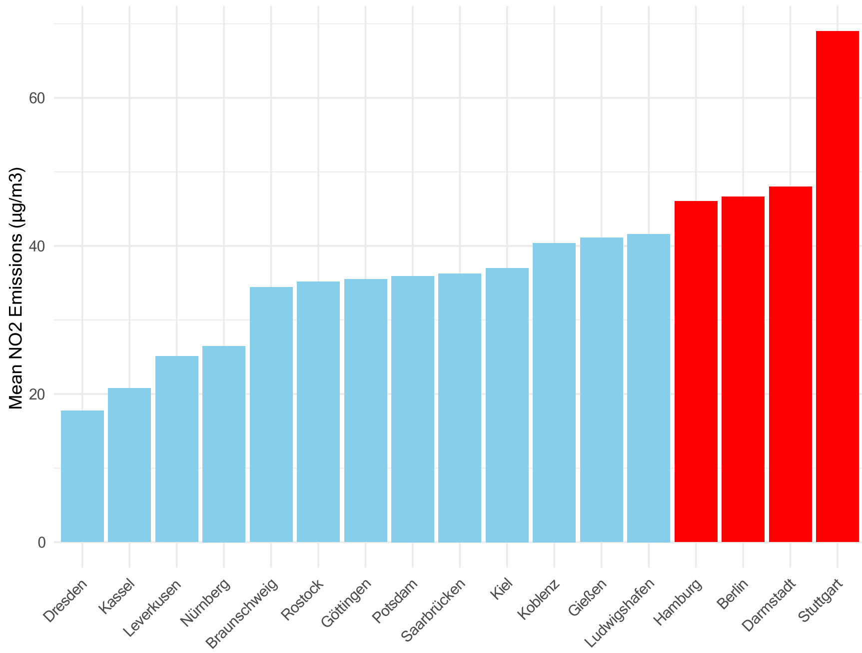


Fig. 1. The monthly mean values of the NO_2 emissions of selected German cities in the period 2012–2022.

Table 1
Overview of variables used in the analysis in the period 2012–2022.

Variable	Mean	Median	SD	Min	Max
NO_2 (µg/m^3)	37.49	34.60	19.37	1.86	174.25
Employment Rate (Percentage)	67.65	67.18	12.46	10.72	95.57
GDP per capita (in 1000 Euro)	52.98	47.15	16.86	29.09	91.71
Diesel Cars (Percentage)	25.05	29.30	11.63	1.00	39.73
Commuters (Percentage)	48.78	49.71	13.90	21.03	69.59

Notes: The employment rate, which measures the number of people employed in a month, is related to the number of people who need to use transit to get to their jobs. GDP per capita is a way to measure the wealth of a city, assuming that cities with high GDP see more cars and, as of 2022, produce more local NO_2 as a result. Diesel cars is the share of diesel vehicles out of all passenger cars. The percentage of diesel vehicles in a city is important because diesel vehicles are major emitters of NO_2. Finally, the percentage of commuters, which captures differences in the distance between cities for direct commuting to work, indicates higher amounts spent on transportation into a city and therefore higher emissions.

NO_2 emissions have decreased or remained constant in all cities since 2012. The magnitude of the decrease varies from city to city, some cities experiencing more significant decreases than others. Most of the cities in the donor pool (untreated units) had almost the same NO_2 emissions. The largest emitter remains Stuttgart, followed by Berlin, Darmstadt, and Hamburg following behind. Darmstadt and Stuttgart show a significant decrease around the year 2020. In 2012, majority of the cities in this study were above the European Commission's maximum level of 40 µg/m^3 NO_2 levels which is the red line in the figure [55].[10] Already in 2022 almost all cities are below the red line.

There are some very strong polluting cities for the full period (Fig. 1); however, overall we see a continuous decline for all cities across time (Fig. 2). The strongest polluters introduced a ban. But has that been pivotal for the decline? To study this, we apply SCM. The variation in NO_2 emissions across the cities has significant implications for public health and environmental policies. High NO_2 levels in cities like Stuttgart, Berlin, and Hamburg pose substantial health risks to residents, including respiratory issues and reduced lung function. Therefore, stringent environmental regulations and policies are essential in these cities, such as promoting public transportation, implementing LEZs, and encouraging the use of electric vehicles. Overall, the two figures highlight the disparities in NO_2 emissions among different German cities, emphasizing the importance of targeted interventions and policies to mitigate NO_2 pollution, particularly in urban centers with higher emissions. The data underscores the need for comprehensive urban planning and environmental strategies to improve air quality and protect public health.

6. City-specific implementations of the diesel ban and their effectiveness

Berlin: Implemented on July 1, 2019, Berlin's diesel ban policy targeted eight street sections in the city center. However, it did not completely restrict access to the city center, allowing alternative routes. The results show (Fig. 3a) that NO_2 emission levels in synthetic Berlin did not change after the diesel ban policy (vertical dashed line), and the trend remained consistent with that of the actual Berlin, sometimes even reaching higher emission levels. The average difference in NO_2 emissions between synthetic and actual Berlin after the intervention (that is, our average effect of the intervention) is -2.36 µg/m^3. The difference before and after the intervention is not large. Both real and synthetic Berlin show similar NO_2 emission trends after policy implementation, with no significant reduction. Synthetic Berlin (based on Dresden, Göttingen and Saarbrücken) mirrors this trend, indicating the policy's limited impact on emissions (see Table 2 for the donor city weights used to construct each synthetic control, highlighting the composition of counterfactual trends). We can say that the diesel traffic ban had no significant effect on Berlin's NO_2 emissions, despite its implementation.

Hamburg: Implemented on May 31, 2018, the policy targeted two streets with alternative routes provided by the government. This may indicate that the policy was not intended to restrict access to the city center. The SCM analysis shows no significant emission reductions after the policy, with real and synthetic Hamburg (based on Dresden and

[10] To be consistent with the European Commission's maximum level, absolute values are used in Section 4. In Sections 6, 6.1 and 6.2, we use per capita emissions due to methodological peculiarities. That is, using per capita measures, we ensure that the baseline characteristics of the treated and control units are more comparable, leading to more reliable and valid causal inferences.

Fig. 2. Temporal trends of monthly NO_2 emissions in 17 cities in Germany (2012-2022).
The horizontal red line is the maximum level of 40 μg/m^3 of NO_2 set by the European Commission.

Potsdam) showing similar trends (Fig. 3c). The average difference in NO_2 emissions between synthetic and actual Hamburg after the intervention is -2.11 μg/m^3. In this case too, the difference before and after the intervention is not large. The results suggest that the policy did not have a significant impact on NO_2 emissions in Hamburg. Interestingly, Dresden receives a high weight in the synthetic control constructions for both Berlin and Hamburg due to the close similarity in their average NO_2 emissions per capita during the pre-intervention period (which is critical for weight determination in SCM).[11] This alignment in pre-treatment trends is essential for accurately approximating the counterfactual trajectory in SCM.

Darmstadt: The diesel ban, implemented in June 1, 2019, impacted two streets in the city center. As a result, access to the city center became extremely difficult, with few alternative routes available to drivers. Darmstadt's smaller size and limited alternative routes made this policy more impactful than in Berlin. The SCM analysis shows a notable gap between the real and synthetic NO_2 emissions of Darmstadt, after the policy implementation (Fig. 3b). Besides, the average difference in NO_2 emissions between synthetic and actual Darmstadt after the intervention is -46.81 μg/m^3[12]. Hence, the difference before and after the intervention is large.

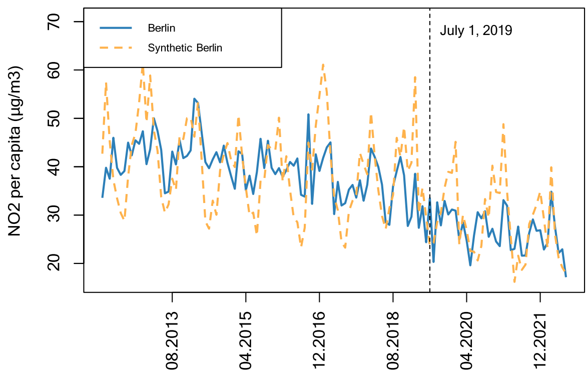
Stuttgart: The policy of banning diesel traffic was introduced in Stuttgart on January 1, 2019. The policy was one of the strictest among the cities studied. Unlike the policies implemented in Berlin, Darmstadt, and Hamburg, Stuttgart's ban covered the entire city center and subsequently also additional areas. As a result, the percentage of diesel vehicles that were prevented from entering the city center increased from 23.08% in 2019 to 37.10% in 2020 [56]. Our analysis reveals a significant divergence between real and synthetic Stuttgart (based on Braunschweig, Ludwigshafen and Nürnberg) in terms of NO_2 emissions, indicating the policy's effectiveness (Fig. 3d). The average difference in NO_2 emissions between synthetic and actual Stuttgart after the intervention is about -30.06 μg/m^3. The difference before and after the intervention is large. The observed reduction in NO_2 emissions in Stuttgart indicates that the policy implementation was effective in positively impacting the city's air quality.[13]

In summary, the main findings indicate that policies banning diesel

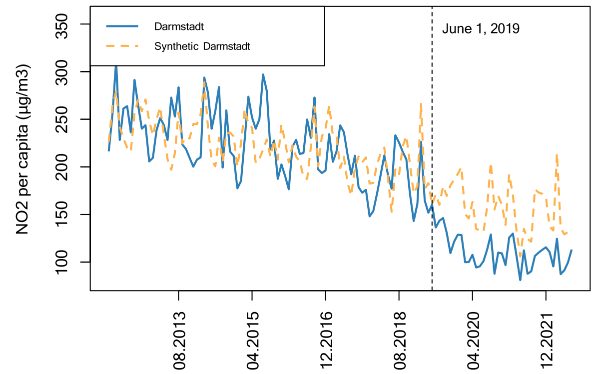
[11] This is particularly evident when looking at Fig. C1 in Appendix C.

[12] Synthetic Darmstadt is based on Koblenz, Ludwigshafen, and Nürnberg.

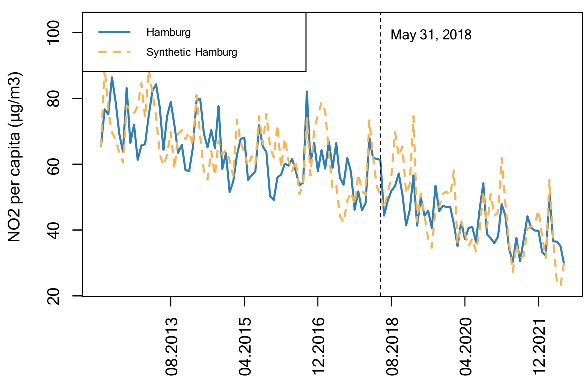
[13] In Figs. 3a to 3d to improve pre-treatment fit, we can relax the requirement that weights must sum to one, keeping only the non-negativity condition. However, this might lead to overfitting or underfitting. To avoid these issues, we follow the default rule that weights must add up to one. But we relax the requirements as a robustness test.



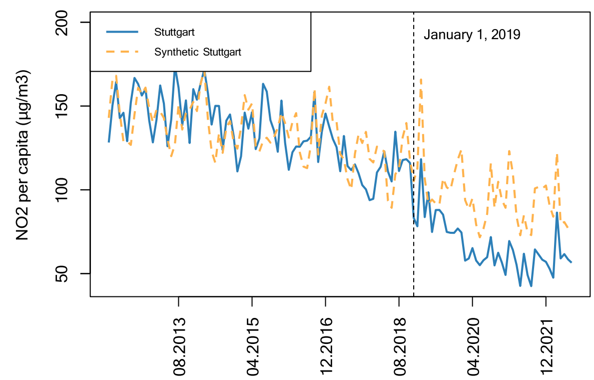
(a) Berlin (July 1, 2019)



(b) Darmstadt (June 1, 2019)



(c) Hamburg (May 31, 2018)



(d) Stuttgart (January 1, 2019)

Fig. 3. Synthetic Control estimation of diesel traffic ban by the example of four cities. The vertical dashed line in each subfigure indicates the diesel ban policy implementation date. The yellow dashed line represents the synthetic city, and the blue line is the actual city.

Table 2
Weights of the donor cities for constructing synthetic cities.

Synthetic Berlin		Synthetic Hamburg		Synthetic Darmstadt		Synthetic Stuttgart	
Weight	City	Weight	City	Weight	City	Weight	City
0.000	Braunschweig	0.000	Braunschweig	0.000	Braunschweig	**0.267**	**Braunschweig**
0.949	**Dresden**	**0.863**	**Dresden**	0.000	Dresden	0.000	Dresden
0.000	Gießen	0.000	Gießen	0.000	Gießen	0.000	Gießen
0.035	**Göttingen**	0.000	Göttingen	0.000	Göttingen	0.000	Göttingen
0.000	Kassel	0.000	Kassel	0.000	Kassel	0.000	Kassel
0.000	Kiel	0.000	Kiel	0.000	Kiel	0.000	Kiel
0.000	Koblenz	0.000	Koblenz	**0.240**	**Koblenz**	0.000	Koblenz
0.000	Leverkusen	0.000	Leverkusen	0.000	Leverkusen	0.000	Leverkusen
0.000	Ludwigshafen	0.000	Ludwigshafen	**0.388**	**Ludwigshafen**	**0.235**	**Ludwigshafen**
0.000	Nürnberg	0.000	Nürnberg	**0.372**	**Nürnberg**	**0.498**	**Nürnberg**
0.000	Potsdam	**0.137**	**Potsdam**	0.000	Potsdam	0.000	Potsdam
0.000	Rostock	0.000	Rostock	0.000	Rostock	0.000	Rostock
0.016	**Saarbrücken**	0.000	Saarbrücken	0.000	Saarbrücken	0.000	Saarbrücken

vehicles in entire districts or large areas of the city contributed to a reduction in NO_2 emissions, as observed in Stuttgart. Conversely, banning access to parts of streets did not lead to significant improvements in NO_2 emissions if diesel vehicles were still able to pass through the city, as was the case in Berlin and Hamburg. However, restricting access to parts of streets that limited access to the city center resulted in a decrease in NO_2 emissions, as seen in the case of Darmstadt. The smaller size of the city and the limited availability of alternative routes made it almost impossible for diesel vehicles to pass through the city center, making the policy intervention more similar to Stuttgart than to Berlin or Hamburg. The key point is that the effectiveness of the policy is due to its nature as an area restriction policy. It is important to note that the results in Darmstadt and Stuttgart show a clear relationship that restricts access to the city center. The implementation areas in both cities were relatively large compared to their overall size and population, which may have made it easier to enforce the policy and for residents to adapt to the changes. This suggests that the success of the policy may be due to a combination of its specific features and the characteristics of the cities in which it was implemented.

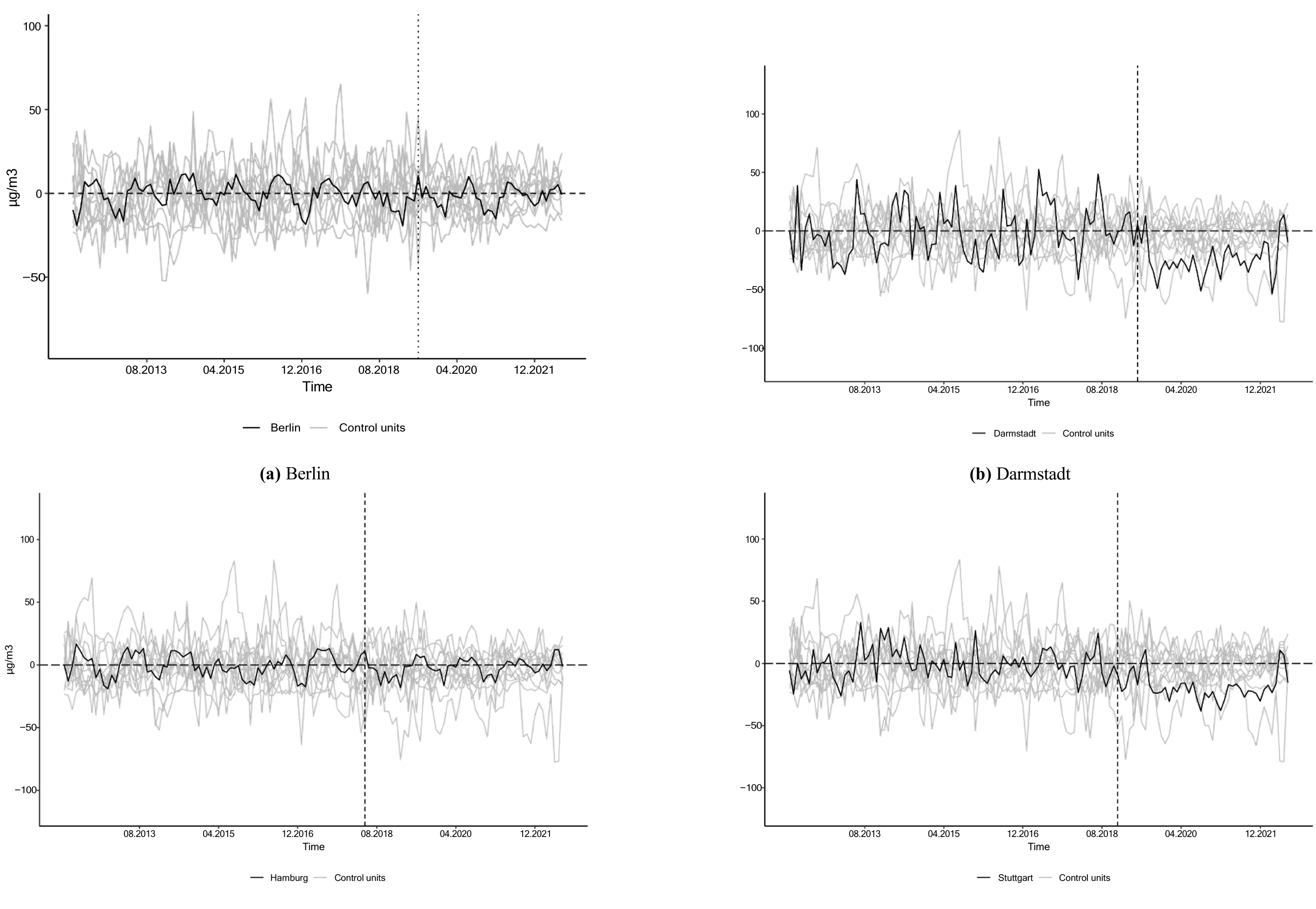
6.1. Placebo tests

Placebo studies in the SCM involve testing the validity of the SCM results by comparing the outcomes of the treated unit with the outcomes of the synthetic control unit constructed using a placebo donor pool. In other words, the placebo study involves applying the SCM to a data set where the intervention did not occur, but where the synthetic control unit should still match the treated unit on pre-intervention outcomes [27]. We conducted placebo studies to see if the difference in NO_2 emissions was really caused by the diesel traffic ban policy and not by chance, i.e., if the empirical estimates were statistically significant.

In these placebo studies, the city that received a policy intervention was added to the control group with the remaining 13 German cities. One city in the control group was then assumed to have implemented the same policy (diesel ban) instead of one of the treated units (Berlin, Darmstadt, Hamburg, or Stuttgart). The SCM was then used to construct a synthetic version of the selected control unit and estimate the impact of the intervention. Then all cities remaining in the control group were iteratively tested for the difference between synthetic and real NO_2 emissions. The results of all control units in the placebo studies were then compared with the results of the treated unit from the empirical analysis. If the differences in NO_2 emissions of treated control units are much larger than those of placebo control units, then the difference in NO_2 emissions between real and synthetic treated units is due to the implementation of the diesel traffic ban, i.e. the results of the empirical analysis are credible [27]. Note that placebo tests are a critical step in SCM analysis, because they help to rule out potential biases and confounders that could affect the estimated treatment effect. They explain that placebo tests are particularly useful when the SCM analysis is applied to a single treated unit, as it allows researchers to test the robustness of the results and to assess the likelihood of spurious results due to chance or other factors.

Fig. 4a-d show the monthly estimates of the impact of the diesel ban policy. Fig. 4a and Fig. 4c focus on Berlin and Hamburg, respectively. They compare the per capita NO_2 emissions between Berlin/Hamburg and a synthetic counterpart, revealing no significant change in these cities' emissions in post-intervention period of time. Fig. 4b and Fig. 4d focus on Darmstadt and Stuttgart, respectively. They highlight the significant decrease in per capita NO_2 emissions relative to their synthetic versions post-intervention. These figures suggest a substantial and increasing effect of the diesel ban policy over time, showing its impact on reducing emissions in both cities.

Another way to measure how well the synthetic control unit can predict the outcomes of the treated unit after the intervention the rooted mean squared prediction error (RMSPE) can be calculated. The RMSPE measures the magnitude of the gap in the outcome variable of interest between each city and its synthetic counterpart [28]. A large post-intervention RMSPE is not indicative of a large effect of the intervention if the synthetic control does not closely reproduce the pre-intervention outcome of interest [28]. That is, a large post-intervention RMSPE does not indicate a large effect of the intervention if the pre-intervention RMSPE is also large. For each city, we



(a) Berlin　(b) Darmstadt　(c) Hamburg　(d) Stuttgart

Fig. 4. Per capita NO_2 emissions gaps in four cities and placebo gaps in all control states. The figures show the gaps in NO_2 emissions for each city compared to the placebo gaps in the control states. The gray lines in all figures show the difference in per capita NO_2 emissions between each state in the donor pool and its respective synthetic version. The superimposed black line indicates the gap estimated for Berlin, Darmstadt, Hamburg, and Stuttgart. The vertical dashed line is the intervention date for each city.

divide the post-ban RMSPE by the pre-ban RMSPE.

Berlin and Hamburg: Fig. 5a and Fig. 5c report the ratios between the post-diesel traffic ban RMSPE and the pre-diesel traffic ban RMSPE for Berlin/Hamburg and all the cities in the donor pool. The ratio for Berlin is about in the middle of the cities, showing almost no significance. If one were to pick a city at random from the sample, the chances of obtaining a ratio as high as this one would be $6/14 = 0.42$ or 42% (not significant). These results support the earlier findings, i.e. the implementation of the diesel traffic ban in Berlin was ineffective. The ratio for Hamburg also shows no significance. If one were to pick a city at random from the sample, the chances of obtaining a ratio as high as this one would be $11/14 \approx 0.78$ or 78% chance. This supports the conclusion that the diesel ban had no significant effect on Hamburg's NO_2 levels too.

Darmstadt and Stuttgart: Fig. 5b and Fig. 5d show the distribution of post/pre-diesel ban RMSPE ratios in Darmstadt/Stuttgart and the other 13 control cities. The ratio for both cities stands out clearly from the rest. If one were to randomly select a city from the sample, the probability of obtaining a ratio as high as that for Darmstadt and Stuttgart would be $1/14 \approx 0.0714$ or 7%, suggesting a low probability of observing such a large post-/pre-RMSPE ratio by chance. While this does not meet the conventional 5% threshold for statistical significance, it still provides indicative evidence of a meaningful treatment effect. This result suggests a deviation in per capita NO_2 emission trends in these cities and supports the conclusion that the observed reductions are attributed to the diesel ban policy. To sum up, the estimated difference in NO_2 emissions between Darmstadt and Stuttgart, and the control cities from 2012 until 2022 was notably large whereas in Berlin and Hamburg this was not the case. Since the placebo studies included 14 cities, the probability of the estimation result was calculated as $1/14 \approx 0.0714$.

6.2. Robustness tests

6.2.1. Augmented Synthetic Control Method, Generalized Synthetic Control Method and Synthetic Difference-in-Differences

As a robustness test, we implement the Augmented Synthetic Control Method (ASCM) introduced by [57], which augments the standard SCM by incorporating an outcome model to improve pre-treatment fit and accommodate extrapolation beyond the convex hull of the donor pool. ASCM helps reduce bias in cases where SCM may fail to closely match pre-intervention trends. The post-intervention average treatment effects (ATE) estimated by ASCM closely mirror our baseline SCM conclusions.

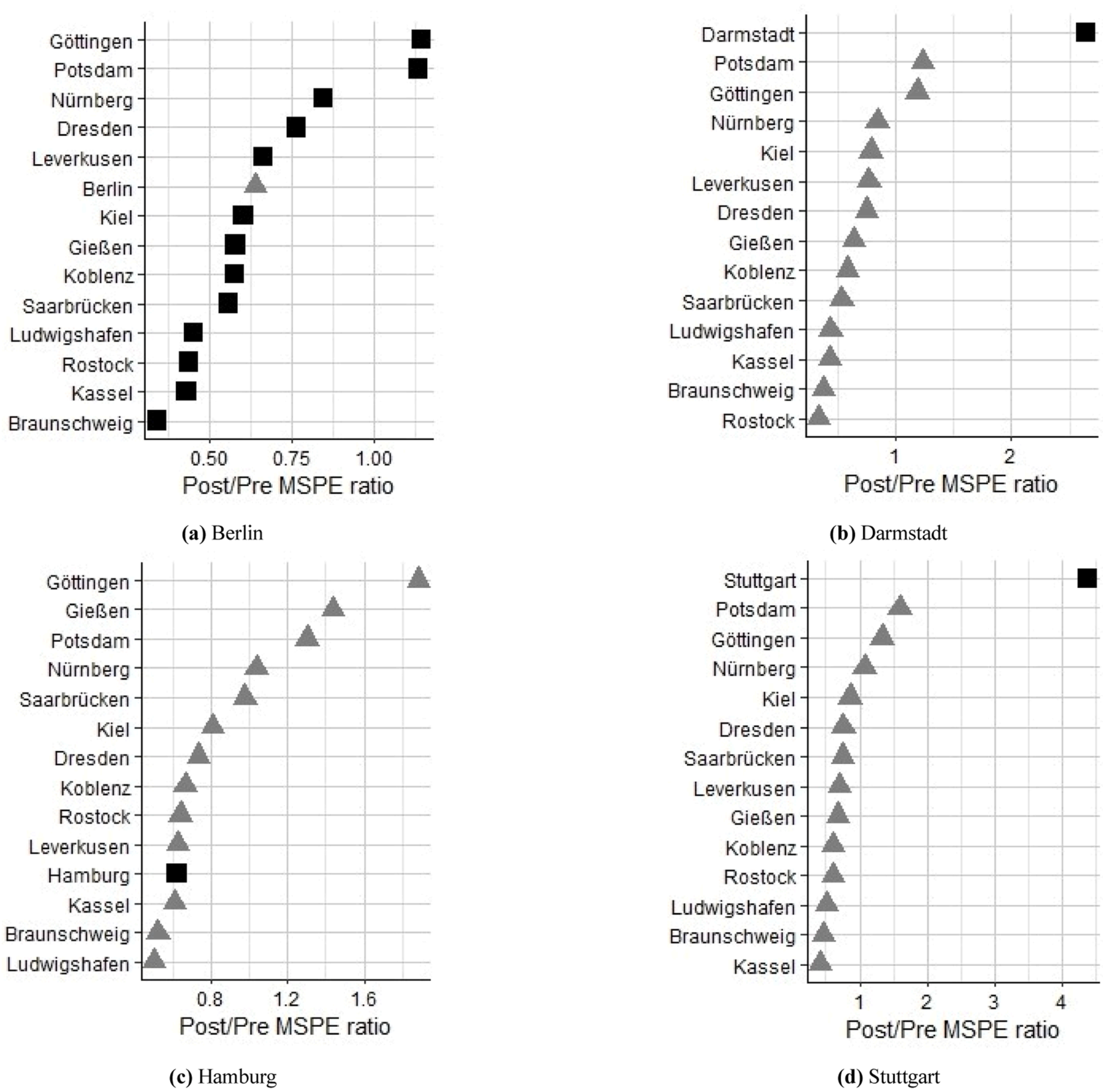


Fig. 5. Ratio of post/pre-diesel traffic ban Root Mean Squared Prediction Error (RMSPE) for Berlin, Darmstadt, Hamburg, and Stuttgart, alongside their respective control cities. A higher ratio suggests greater deviation between the observed and synthetic trends after the diesel traffic ban, implying a stronger policy effect.

For Berlin, ASCM produces a positive ATE of 4.26 μg/m^3, and for Hamburg, an estimate of –0.03 μg/m^3, both reinforcing the original conclusion that the diesel bans were largely ineffective in these cities. In contrast, the ASCM results for Darmstadt (–31.66 μg/m^3) and Stuttgart (–22.82 μg/m^3) continue to show substantial reductions, confirming the effectiveness of diesel ban policy. These patterns are clearly visible in the ASCM plots (Fig. F1 and F2), where the gap between actual and synthetic emissions widens after the intervention in Darmstadt and Stuttgart, while Berlin and Hamburg display either convergence or negligible divergence post-treatment. Overall, the ASCM figures visually support the numerical ATE estimates and further validate the robustness of our main findings.

As an additional robustness check, we apply the **Generalized Synthetic Control Method** (GSCM) developed by [58], which extends traditional SCM by modeling both observed covariates and unobserved common factors through an interactive fixed effects framework. GSCM offers several advantages, including the ability to accommodate multiple treated units with staggered interventions and to explicitly model unit and time heterogeneity. Our GSCM results further support the conclusions drawn from the baseline SCM and ASCM analyses. Specifically, the post-treatment ATE estimates from GSCM indicate a strong negative treatment effect for Stuttgart (–19.24 μg/m^3) and Darmstadt (–8.79 μg/m^3), aligning with the observed visual gap in the post-treatment period and confirming the effectiveness of diesel ban restriction in these cities. In contrast, Berlin (0.42 μg/m^3) and Hamburg (–1.02 μg/m^3) again show minimal to no sustained effects, consistent with their more limited diesel ban policy. These patterns are reinforced by the GSCM counterfactual plots (Fig. F3), where clear divergence between treated and estimated values appears only in Darmstadt and Stuttgart following the policy intervention, while Berlin and Hamburg show parallel trends. The time-series evolution of the treatment effects visualized in the plots, combined with the numeric ATEs, reinforces the robustness of our core findings.

As a further robustness check, we employ the **Synthetic Difference-in-Differences** (SDiD) method developed by [59], which combines the strengths of traditional Difference-in-Differences (DiD) and SCM-s. SDiD addresses some of the limitations of standard SCM such as sensitivity to extrapolation outside the convex hull while also mitigating biases from potential violations of parallel trends assumptions inherent in DiD. The post-treatment ATE estimates from SDiD are largely consistent with our baseline findings. For Darmstadt (–29.80 μg/m^3) and Stuttgart (–11.79 μg/m^3), SDiD indicates reductions in NO_2 levels, reaffirming the effectiveness of diesel bans. In contrast, Berlin (12.54 μg/m^3) and Hamburg (3.99 μg/m^3) display positive or weak treatment effects, suggesting little or even counterproductive impact. These patterns are visually reinforced in the SDiD outcome plots (Fig. F4), where a clear post-treatment divergence is observed for Darmstadt and Stuttgart, while treated and synthetic lines in Berlin and Hamburg remain closely aligned or reverse direction. Together, the numeric and visual evidence from SDiD support the core conclusion that policy scope and geographic coverage play a crucial role in determining the effectiveness of diesel-related traffic restrictions in improving urban air quality. Inspired by the bootstrap approach in [60], we further assess the statistical robustness of our SDiD estimates through placebo-based inference. The resulting bootstrap distributions (Fig. F5) show that the treatment effects for Darmstadt and Stuttgart lie at or beyond the tails of the 95% confidence intervals, indicating statistically significant effects. In contrast, the estimates for Berlin and Hamburg fall well within the placebo distribution bounds, underscoring the lack of robust policy impact in those cities.

To sum up, the robustness checks using ASCM, GSCM, and SDiD reaffirms the baseline SCM findings. Across methods, Berlin and Hamburg exhibit negligible or even slightly positive post-treatment ATEs, indicating that their limited street-level bans were ineffective. In contrast, Darmstadt and Stuttgart show substantial and statistically significant NO_2 reductions under all three approaches, confirming that larger-scale or central area restrictions yield stronger impacts. These results, supported both numerically and visually, underscore that policy effectiveness depends heavily on the scope and geographic coverage of the diesel bans, with area-wide interventions producing far greater improvements in air quality than narrowly targeted street segments.

6.2.2. Leave-one-out estimation

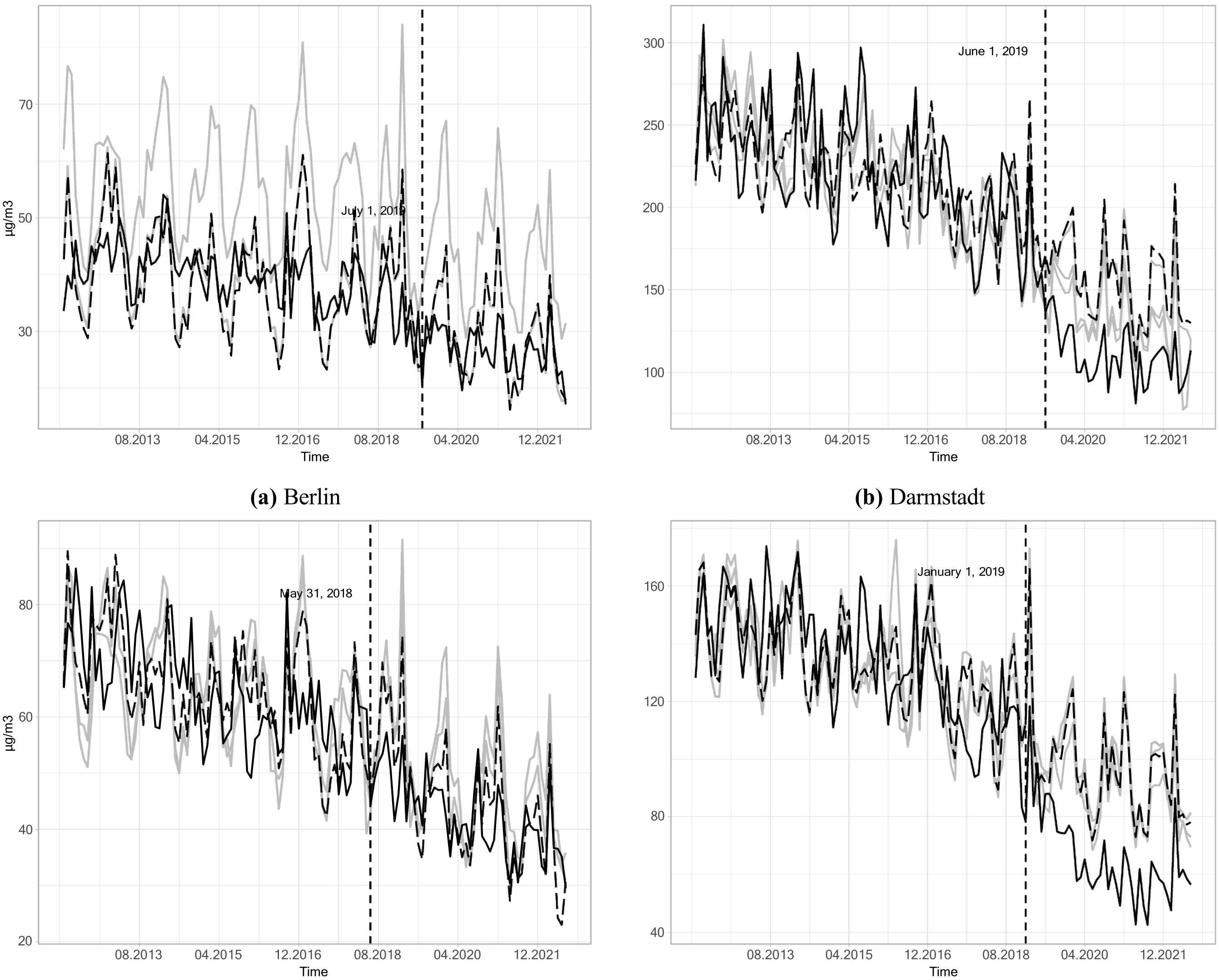
We also conduct a robustness check to test the sensitivity of our main results to changes in the city weights. Here we iteratively re-estimate the baseline model to construct a synthetic Berlin, Hamburg, Darmstadt and Stuttgart omitting in each iteration one of the cities that received a positive weight. By excluding cities that received a positive weight, we sometimes sacrifice goodness of fit, but this sensitivity check allows us to assess the extent to which our results are driven by a particular control city. As an example of a robustness test, Fig. 6a-d show the results of a leave-one-out reanalysis of the diesel traffic ban, where each of the cities contributing to the synthetic control is removed from the sample one at a time. Fig. 6a-d show the results, reproducing Fig. 3a-d (solid and dashed black lines) while also incorporating the leave-one-out estimates (gray lines). This figure shows that the results of the previous analyses are quite robust to the exclusion of a particular city from our sample of comparison cities. Thus, we also conducted robustness checks to assess the sensitivity of our results to the changes in the study design. The main conclusion of our estimates of the diesel traffic ban on NO_2 per capita is robust to the exclusion of any particular city.

7. Discussion and policy implications

Our main findings suggest that the policy of banning diesel vehicles in whole districts or large areas of the city has contributed to the reduction of NO_2 emissions, as observed in Stuttgart. Thus, the stricter the policy, the more effective are the expected results. Conversely, banning access to parts of streets did not lead to significant improvements in NO_2 emissions if diesel vehicles were still able to pass through the city, as was the case in Berlin and Hamburg. However, restricting road sections that limit access to the city center has led to a reduction in NO_2 emissions, as was the case in Darmstadt. The smaller size of the city and the limited availability of alternative routes made it almost impossible for diesel cars to pass through the city center, making the policy intervention more similar to Stuttgart than to Berlin or Hamburg. Our results are consistent with those of [32,35,39], who found that area restricting policies are effective. At the same time, the results for Berlin and Hamburg show that our results are consistent with [42]'s results, who found that the reduction in air pollution did not differ significantly across the streets of Dutch cities (there, the LEZ policy was only effective on one street due to the drastic reduction in traffic flows).

It is important to emphasize that the effectiveness of the policy lies in its nature as an area-restricting policy. The results in Darmstadt and Stuttgart show that the policies in these two cities have a clear similarity, i.e., both restrict access to the city center. By the example of Darmstadt, we have seen that it is also possible to restrict only a few streets to achieve the effect of an area-restricting policy, which means that urban planning conditions are important. Of course, this may be due to the size of the cities and the restricted areas for diesel vehicles. The implementation areas in both cities were relatively large compared to their overall size and population, which may have made it easier to enforce the policy and for residents to adapt to the changes. This suggests that the success of the policy may be due to a combination of its specific features and the characteristics of the cities in which it was implemented. These findings highlight the importance of considering the specific circumstances of each city when implementing policies to reduce NO_2 emissions and improve air quality.

Table 3 shows the area of the banned streets in Berlin, Darmstadt, Hamburg and Stuttgart. City Area with Implementation is the length of the street in each city multiplied with the width of the city where the policy was implemented. Entire City Area is the total area of the each city. This gives an idea of what percentage of streets are actually affected



(a) Berlin **(b)** Darmstadt **(c)** Hamburg **(d)** Stuttgart

Fig. 6. Leave-one-out estimates of the effect of the diesel traffic ban policy for four cities. The solid and dashed black lines are actual and synthetic cities, the gray lines are the leave-one-out estimates.

Table 3
Comparison of diesel ban policy implementation areas across selected cities (source of the values: [61,62]).

City	City Area with Implemen-tation	Entire City Area	Ratio (%)
Berlin	3,648 ha	89,180 ha	0.004%
Darmstadt	1,164 ha	12,220 ha	9.521%
Hamburg	2,616 ha	75,520 ha	0.003%
Stuttgart	7,779 ha	20,740 ha	37.507%

by the policy. Comparing Berlin and Hamburg, we see that they have almost the same percentage, and Darmstadt has a higher percentage of the affected area. The case of Stuttgart is more interesting. The ratio shows that the area of the city affected by the diesel ban policy is about 38% of the entire city.

However, in larger cities such as Berlin and Hamburg, where the areas where the policy was implemented were smaller and more dispersed, it may have been more difficult to enforce the policy and for residents to adapt, and made it easier for residents to escape the policy. In addition, there may have been more vehicles on the road in these cities, making it harder to see a significant reduction in NO_2 emissions if some drivers are free to use the parallel road without repercussion. After the ban went into effect in Hamburg, the government set up alternative routes so that drivers could get around the city center and other parts of the city without using the banned roads. Our analysis therefore highlights the importance of the scope of the policy and the specific areas in which it is enforced. Policies need to be carefully designed to cover areas large enough to make it difficult to circumvent the restrictions, thereby increasing their effectiveness. In addition, the characteristics of the city, such as its size and the availability of alternative routes, can have a significant impact on the effectiveness of diesel vehicle bans. In cities where alternative routes are limited or non-existent, such as Darmstadt, restrictions can lead to more significant reductions in NO_2 emissions. This implies that urban planning and policy should take into account the unique geographical and infrastructural aspects of each city. That is, policymakers should tailor diesel ban policies to the specific characteristics of each city to maximize their impact.

The effectiveness of diesel bans depends on the scope and design of the intervention. Cities like Stuttgart and Darmstadt, which implemented area-wide or central district-wide restrictions, experienced substantial declines in NO_2 emissions. In contrast, Berlin and Hamburg, which restricted only select street segments with available bypass routes, saw negligible impact. This internal consistency across multiple cities reinforces the conclusion that spatial comprehensiveness is a key determinant of policy efficacy. The takeaway is clear: the design logic of the policy is as critical as its adoption. Our findings indicate that cities implementing diesel traffic bans should not only focus on regulatory enforcement but also on the strategic design of the restriction zones. First, the coverage area plays a pivotal role—bans targeting central or high-traffic urban areas are significantly more effective than isolated street-level interventions. To minimize evasion and maximize environmental impact, such zones should avoid offering nearby bypass routes or should be accompanied by complementary secondary restrictions. While area restriction policies can be effective, other measures should also be implemented, such as promoting public transportation, improving pedestrian and bicycle infrastructure, and encouraging the use of electric vehicles. This would help ensure that diesel restrictions do not simply shift pollution to other areas or increase congestion elsewhere. Finally, cities should consider long-term strategies that address air pollution, mobility, and sustainability in an integrated manner to ensure that policies are both effective in the short term and sustainable in the long term.

8. Conclusions

In summary, we use the SCM to analyze the effects of policies banning the use of diesel vehicles in certain areas of four German cities: Berlin, Darmstadt, Hamburg, and Stuttgart. The policy was implemented in response to the high levels of NO_2 emissions in these cities, which posed a significant health risk to residents, degraded the environment, and did not comply with the levels imposed by the European Union. The difference between the observed NO_2 emissions in the areas affected by the policy and the predicted NO_2 emissions is based on a synthetic control constructed from a weighted combination of control areas that did not implement the policy.

The main findings show that, as in Stuttgart, regulations banning diesel vehicles in entire neighborhoods or significant parts of the city helped to reduce NO_2 emissions. As was the situation in Berlin and Hamburg, restricting access to some streets did not result in significant reductions in NO_2 emissions when diesel vehicles were still allowed to travel throughout the city. However, as in Darmstadt, restricting access to sections of road that limited access to the city center led to a reduction in NO_2 emissions. The policy intervention was more appropriate for Darmstadt than for Berlin or Hamburg because the smaller size of the city and the lack of alternative routes made it nearly impossible for diesel cars to pass through the city center. Robustness checks using ASCM, GSCM, and SDiD further validate the findings. For example, all three methods confirmed significant post-treatment declines for Stuttgart and Darmstadt, while Berlin and Hamburg remained largely unaffected. Leave-one-out tests and RMSPE ratios align with these outcomes, adding credibility through triangulation.

It is important to remember that the effectiveness of the policy stems from the fact that it is an area restriction policy. The results in Darmstadt and Stuttgart show a clear link that hinders access to the city center, which is important to note. Of course, the size of the cities and the restricted locations for diesel vehicles may be responsible for this. Both cities had relatively large implementation zones in terms of size and population, which may have made it easier to implement the policy and help residents adjust to the changes. This suggests that the success of the policy may be due to a combination of its specific features and the characteristics of the cities in which it was implemented. This proposes that the success of the policy could be attributed to a combination of its specific features and the characteristics of the cities in which it was implemented.

While our analysis provides valuable insights into the four German cities, it will be difficult to generalize these findings to other cities (especially outside of Germany) because different cities may have different levels of public transportation infrastructure, cultural attitudes toward car use, and urban layouts, all of which could affect the effectiveness of diesel bans. The environmental benefits of the policy are clear, but such a policy may impose an economic burden on low-income individuals who rely on older diesel vehicles. There may also be challenges related to compliance and enforcement of diesel vehicle bans. Finally, SCM is a robust approach for causal inference in policy evaluations, but one of the major drawbacks of the method is the choice of appropriate control units.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used “ChatGPT” and“DeepLWrite” for checking the grammar of English language. After using these tools, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication. “ChatGPT” was also used in the coding to improve the code.

CRediT authorship contribution statement

Narek Mirzoyan: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ingrid Ott:** Writing – review & editing, Validation, Supervision, Investigation, Conceptualization. **José Ricardo Castro:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

A. Details on diesel traffic bans in Darmstadt, Hamburg, Berlin, and Stuttgart

Some cities have implemented a stronger restriction: diesel traffic bans, also called the “NO_2-free Emission Zone.” All vehicles with Euro 5 or lower emission standards are not allowed to pass through these restricted zones from any city.

Berlin: The city of Berlin was one of the first cities to introduce an environmental zone on January 1, 2018. The Berlin Senate has introduced further restrictions for August 1, 2019: only diesel cars and motor vehicles with a standard emission norm of Euro 6/VI are allowed to drive through eight important streets in the city center. The diesel bans introduced in 2019 were lifted on all roads in September 2022 by the Berlin Senate.

Fig. A1

Fig. A1. Implementation of diesel traffic ban in Berlin: affected streets [63].

The exact areas were:

- In Leipziger Straße between Leipziger Platz and Charlottenstraße for a total length of approx. 850 m.
- In Brückenstraße between Köpenicker Straße and Holzmarktstraße for a total length of approx. 500m.
- In Reinhardtstraße between Charitéstraße and Kapelle-Ufer for a total length of approx. 230 m.
- In Alt-Moabit between Gotzkowskystraße and Beusselstraße for a total length of approx. 160 m.
- In Friedrichstraße between Unter den Linden and Dorotheenstraße for a total length of approx. 160 m.
- In Stromstraße between Bugenhagenstraße and Turmstraße for a total length of approx. 200 m.
- In Hermannstraße between Silbersteinstraße and Emser Straße for a total length of approx. 240 m.
- In Silbersteinstraße between Hermannstraße and Karl-Marx-Straße for a total length of approx. 700 m.

Darmstadt: In June 2019, the Hessian Ministry of the Environment decided to restrict access for vehicles with European standard emissions of Euro 5/V and lower to two sections of two different streets in the city (See Fig. A2). Diesel vehicles of Euro standards 1 to 5 and gasoline vehicles of Euro standards 0 to 2 are affected. In addition, buses and trucks of Euro standards I to V are not allowed to operate on the affected section of Heinrichstraße.

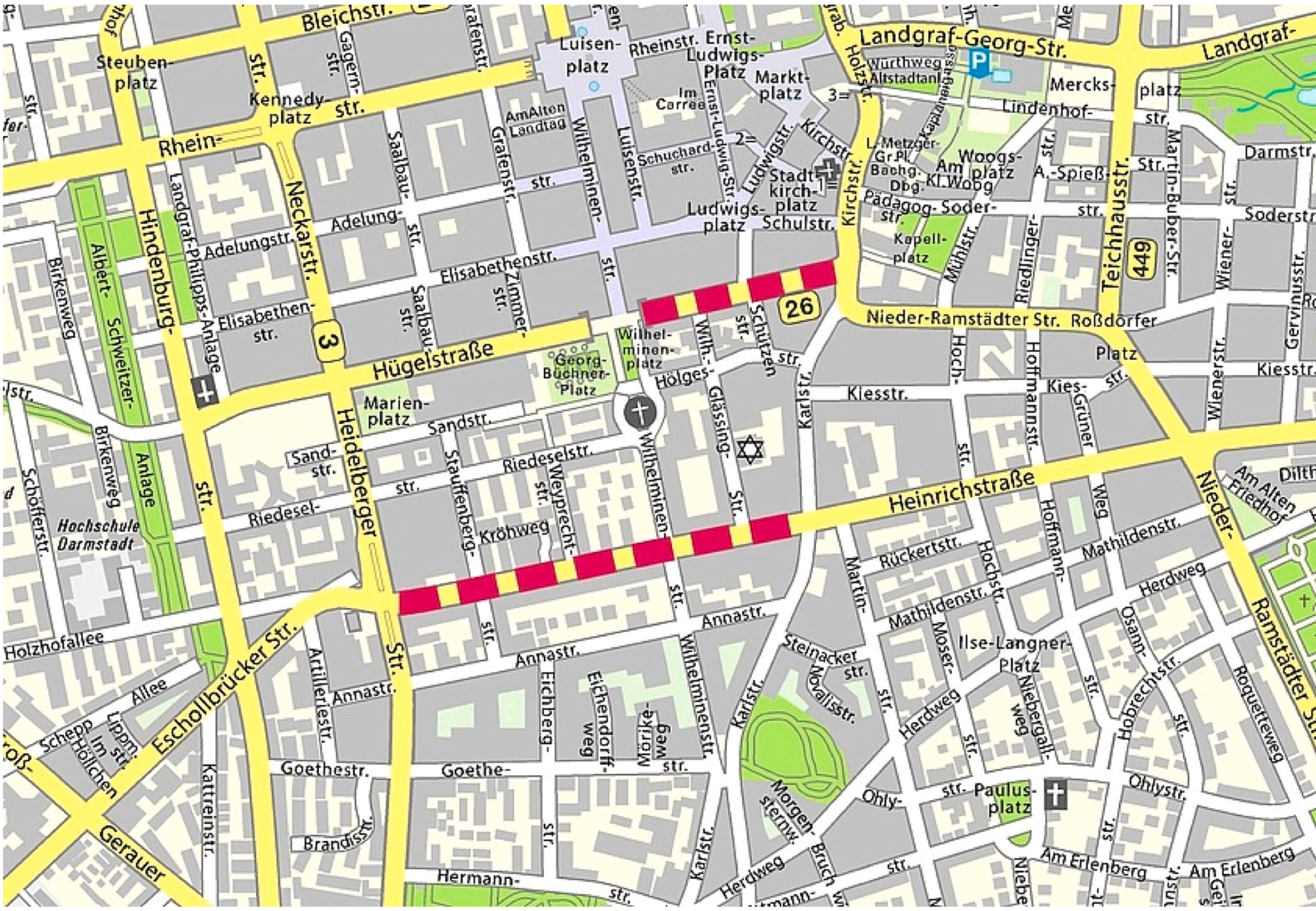


Fig. A2. Implementation of diesel traffic ban in Darmstadt: affected streets [64].

The exact areas are:

- In Heinrichstraße between Heidelberger Straße and Karlstraße for a total length of approx. 640 m.
- In Hügelstraße between the eastern tunnel exit and Karlstraße for a total length of approx. 330 m.

Hamburg: On June 30, 2017, the Senate of the Free and Hanseatic City of Hamburg approved the second revision of the Clean Air Plan. The amendment was made because Hamburg continued to exceed its annual average limit value for NO_2, which is intended to protect public health. In order to comply with the European Union's average NO_2 limit, the Senate had to ban older diesel vehicles from two particularly polluting stretches of road. As a result of the calculations and considerations, the Senate made it illegal for Euro VI diesel cars and trucks to drive on two sections of road as of May 31, 2018. The diesel restrictions for Max-Brauer-Allee apply to cars and diesel-powered vehicles with diesel engines up to and including Euro 5/V. Also for Stresemannstraße, diesel-powered vehicles with a total permissible weight exceeding 3.5 tons. The city provides alternative routes for vehicles with higher pollution standards, which can be seen in the figure (different colors than red).

Figs. A3 and A4

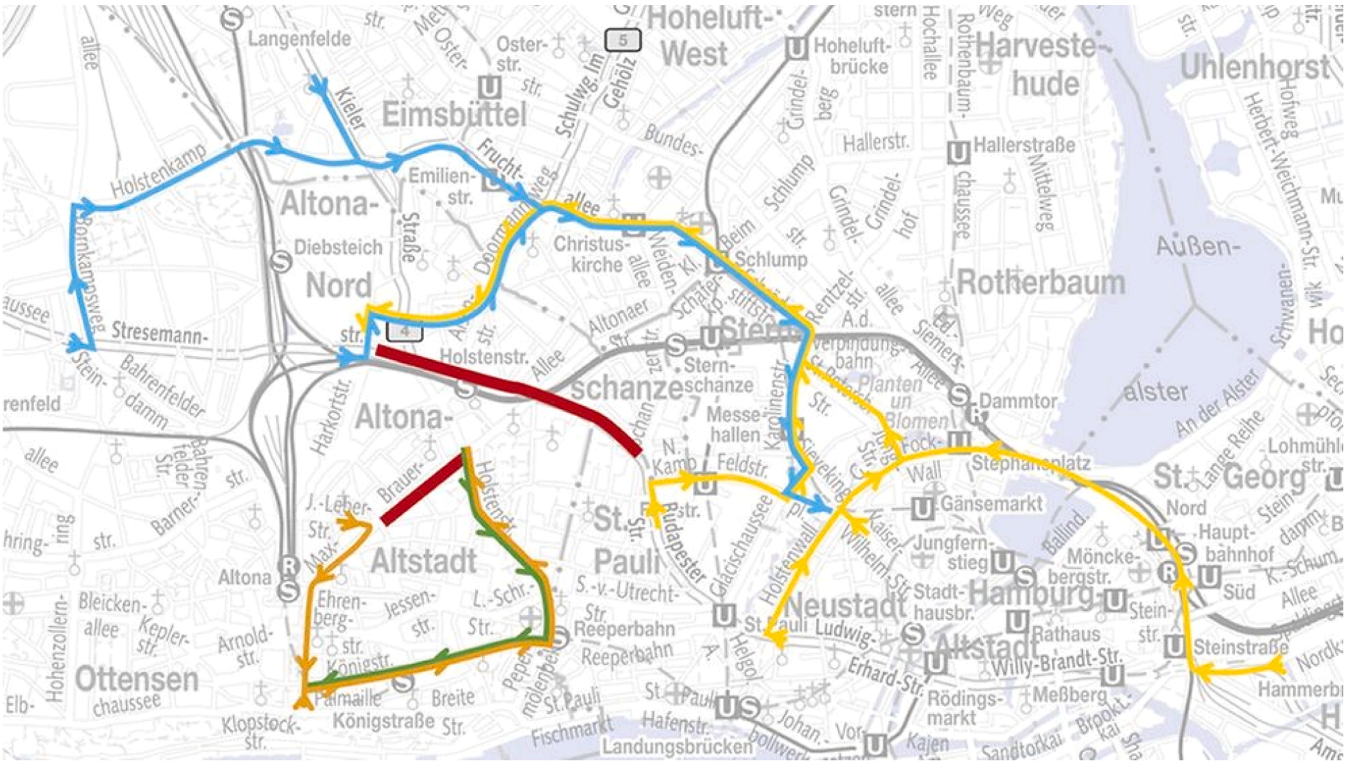


Fig. A3. Implementation of diesel traffic ban in Hamburg: Affected streets [65].

The exact areas are:

- In Max-Brauer-Allee between Julius-Leber-Strasse and Holstenstrasse for a total length of approx. 580 m.
- In Stresemannstrasse between Kaltenkircher Platz and Neuer Pferdemarkt for a total length of approx. 1,600 m.

Stuttgart: Due to court rulings, the state of Baden-Württemberg had to ban certain diesel vehicles from the streets of Stuttgart in order to meet the city's NO_2 limits. Since January 1, 2019, a LEZ for vehicles with diesel engines of emission class Euro 4/IV and lower (the blue and orange areas on the map) has been in place in the entire city of Stuttgart.

As of July 1, 2020, the Stuttgart Valley and the districts of Bad Cannstatt, Feuerbach and Zuffenhausen is subjected to a zonal traffic ban (a more restricted LEZ) for diesel vehicles of emission class Euro 5/V and lower (the orange area on the map) - the so-called "small environmental zone". However, there are some exceptions. In general, business deliveries, people with certain disabilities, medical emergencies, and two- and three-wheeled vehicles are exempt.

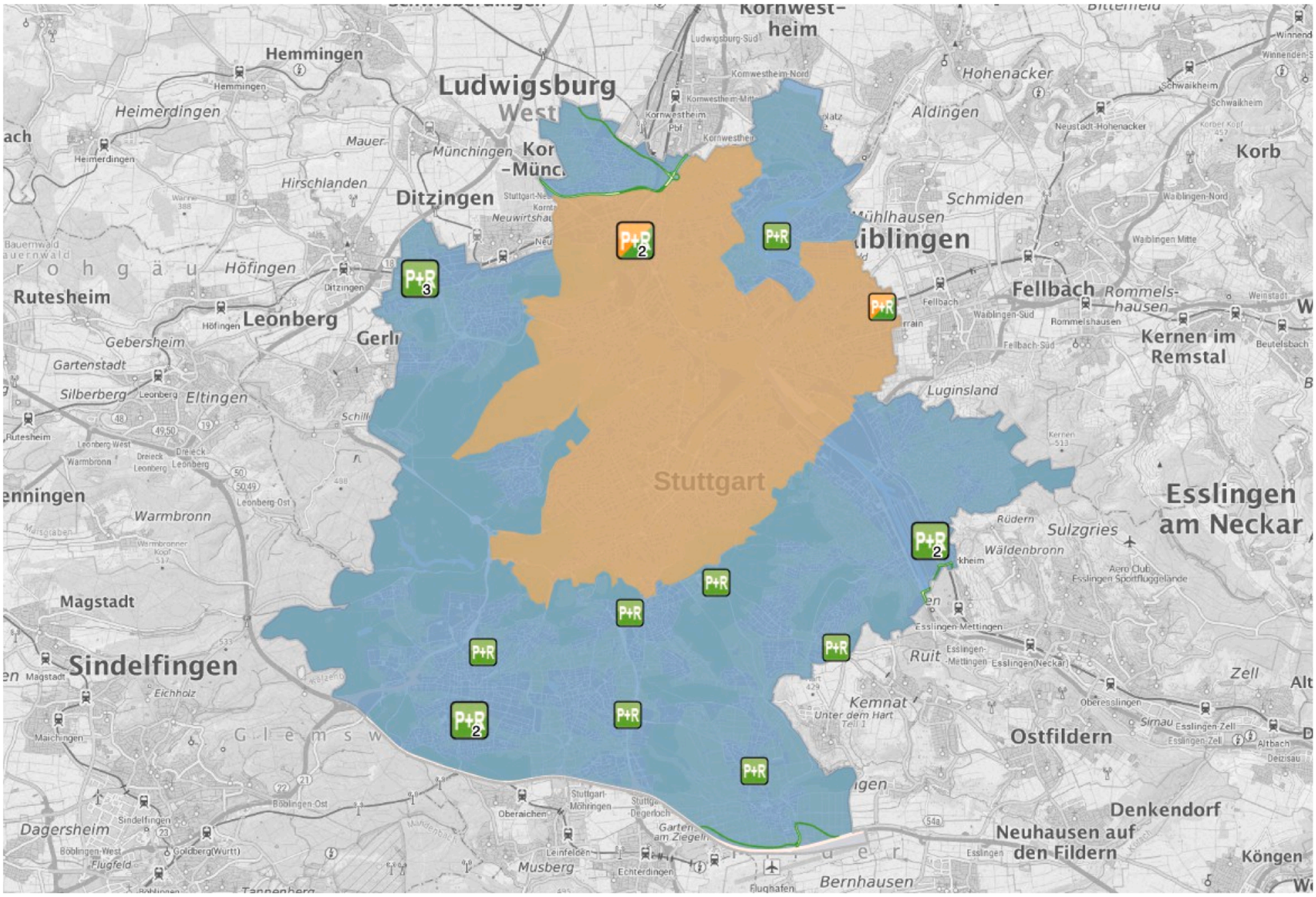


Fig. A4. The image shows area of Stuttgart where the policy is in place [66].

B. Data sources of variables

Table B1

Table B1
Variables and data sources.

Variable	Source	Website
NO_2 Emissions (μg/m^3)	German Environment Federal Office (UBA)	https://www.umweltbundesamt.de/en
Employment Rate (Percentage)	German Federal Employment Agency (BA/AA)	https://statistik.arbeitsagentur.de
GDP per capita (1000 Euro)	National Accounts of the Ger- man Federal States (VGRdL), via Destatis	https://www.statistikportal.de/de/vgrdl
Diesel Cars (Percentage)	German Federal Motor Transport Authority (KBA)	https://www.kba.de
Commuters (Percentage)	German Federal Employment Agency (BA/AA)	https://statistik.arbeitsagentur.de

All links verified as of June 30, 2025.

C. Monthly mean NO_2 per capita values for the selected German cities

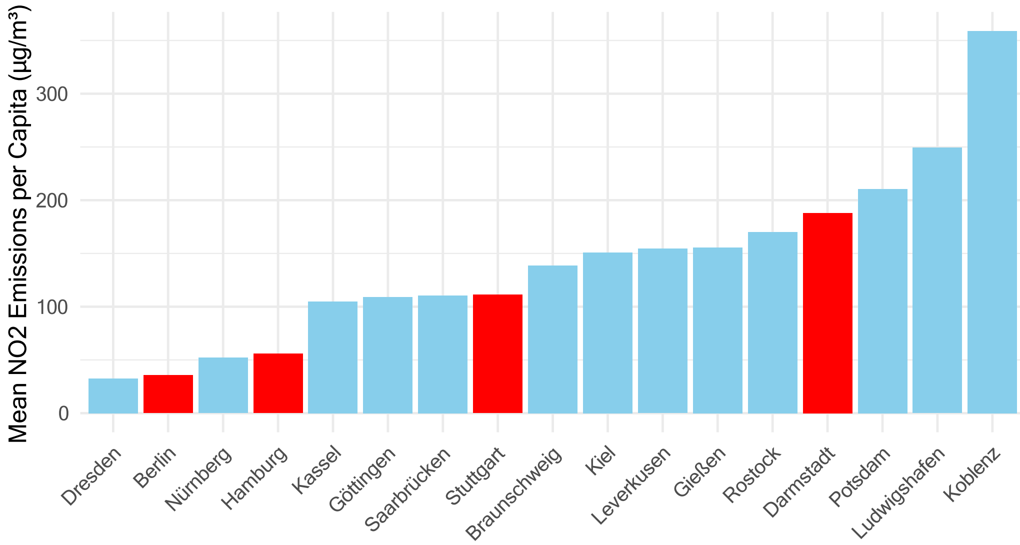


Fig. C1. The monthly mean values of the NO_2 per capita emissions of selected German cities in the period 2012–2022.

Fig. C1

D. Summary statistics for each city.

Table D1
Summary statistics for all cities in the period 2012–2022.

City	Variable	Mean	Median	SD	Min	Max
Berlin	NO_2 ($\mu g/m^3$)	46.65	44.69	18.67	5.80	128.05
	Employment Rate (Percentage)	54.22	54.38	1.91	51.70	56.52
	GDP per capita (Euro)	38.21	39.11	3.85	32.52	42.91
	Diesel Cars (Percentage)	23.57	23.63	1.69	20.33	25.86
	Commuters (Percentage)	21.69	21.76	0.36	21.03	22.06
Braunschweig	NO_2 ($\mu g/m^3$)	34.42	32.94	12.86	6.94	93.62
	Employment Rate (Percentage)	65.94	66.93	1.83	10.72	67.76
	GDP per capita (Euro)	72.21	73.88	6.42	63.04	82.60
	Diesel Cars (Percentage)	1.00	1.00	0.00	1.00	1.00
	Commuters (Percentage)	49.45	49.71	0.54	48.50	50.07
Darmstadt	NO_2 ($\mu g/m^3$)	48.02	45.13	22.35	5.50	158.00
	Employment Rate (Percentage)	85.80	86.15	0.94	83.84	86.70
	GDP per capita (Euro)	74.96	78.52	6.61	66.14	82.00
	Diesel Cars (Percentage)	33.05	33.08	1.92	28.43	35.34
	Commuters (Percentage)	69.08	68.95	0.24	68.83	69.59
Dresden	NO_2 ($\mu g/m^3$)	17.73	15.85	8.60	2.79	71.61
	Employment Rate (Percentage)	60.16	59.88	0.92	58.84	61.31
	GDP per capita (Euro)	38.34	39.07	3.53	32.17	42.47
	Diesel Cars (Percentage)	26.83	27.63	1.90	22.76	28.50
	Commuters (Percentage)	36.11	36.15	0.35	35.62	36.71
Gießen	NO_2 ($\mu g/m^3$)	41.11	40.89	11.49	8.92	84.01
	Employment Rate (Percentage)	52.09	52.40	0.53	51.05	52.64
	GDP per capita (Euro)	34.65	35.36	2.02	31.45	37.20
	Diesel Cars (Percentage)	31.99	32.41	1.67	28.32	33.92
	Commuters (Percentage)	34.04	34.25	0.76	32.85	34.97
Göttingen	NO_2 ($\mu g/m^3$)	35.50	35.15	11.64	6.35	81.70
	Employment Rate (Percentage)	53.54	53.51	0.74	52.50	54.59
	GDP per capita (Euro)	33.86	34.43	2.20	30.18	36.56
	Diesel Cars (Percentage)	29.90	31.07	1.79	26.12	31.28
	Commuters (Percentage)	29.40	28.68	1.04	28.34	31.14
Hamburg	NO_2 ($\mu g/m^3$)	46.07	43.60	17.55	6.49	118.86
	Employment Rate (Percentage)	68.83	68.61	0.79	67.81	70.05
	GDP per capita (Euro)	62.95	63.69	4.58	55.90	70.59
	Diesel Cars (Percentage)	32.26	32.05	1.77	29.18	34.53
	Commuters (Percentage)	36.63	36.38	0.56	36.00	37.58
Kassel	NO_2 ($\mu g/m^3$)	20.78	19.17	9.57	3.19	62.97
	Employment Rate (Percentage)	75.93	75.76	0.69	74.71	77.02

(continued on next page)

Table D1 (*continued*)

City	Variable	Mean	Median	SD	Min	Max
	GDP per capita (Euro)	48.94	50.73	2.91	43.84	53.03
	Diesel Cars (Percentage)	30.85	31.04	1.66	27.38	32.69
	Commuters (Percentage)	58.14	57.87	0.72	57.30	59.37
Kiel	NO_2 (μg/m^3)	37.04	36.02	13.76	2.11	96.29
	Employment Rate (Percentage)	69.26	68.97	1.30	67.12	71.31
	GDP per capita (Euro)	45.33	45.92	3.00	40.25	49.18
	Diesel Cars (Percentage)	31.39	31.92	1.73	27.61	33.16
	Commuters (Percentage)	49.21	49.00	0.34	48.84	49.82
Koblenz	NO_2 (μg/m^3)	40.40	39.84	14.78	3.76	97.08
	Employment Rate (Percentage)	94.04	94.72	1.23	92.00	95.57
	GDP per capita (Euro)	66.56	67.75	3.31	60.85	71.24
	Diesel Cars (Percentage)	33.56	34.06	1.79	29.63	35.49
	Commuters (Percentage)	66.74	66.74	0.16	66.55	67.05
Leverkusen	NO_2 (μg/m^3)	25.11	24.15	9.99	1.87	75.83
	Employment Rate (Percentage)	50.09	50.16	0.68	49.05	50.99
	GDP per capita (Euro)	45.96	45.93	3.52	40.69	51.85
	Diesel Cars (Percentage)	27.58	27.67	1.46	24.94	29.56
	Commuters (Percentage)	56.08	56.34	0.86	54.90	57.05
Ludwigshafen	NO_2(μg/m^3)	41.60	40.42	14.75	6.61	103.90
	Employment Rate (Percentage)	74.39	74.19	1.09	73.02	75.89
	GDP per capita (Euro)	78.38	77.43	3.66	74.09	84.05
	Diesel Cars (Percentage)	28.31	28.68	1.61	24.93	30.16
	Commuters (Percentage)	68.83	68.88	0.19	68.53	69.14
Nürnberg	NO_2 (μg/m^3)	26.48	25.29	10.50	4.01	79.63
	Employment Rate (Percentage)	76.20	76.81	1.00	74.53	77.74
	GDP per capita (Euro)	57.30	59.77	4.14	50.55	63.25
	Diesel Cars (Percentage)	34.00	33.82	2.40	30.16	39.74
	Commuters (Percentage)	52.26	52.25	0.37	51.76	52.85
Potsdam	NO_2 (μg/m^3)	35.95	34.18	14.91	4.12	103.81
	Employment Rate (Percentage)	65.49	64.80	1.57	64.31	69.61
	GDP per capita (Euro)	41.02	41.34	2.89	36.75	44.57
	Diesel Cars (Percentage)	1.00	1.00	0.00	1.00	1.00
	Commuters (Percentage)	57.99	57.89	0.60	57.15	59.06
Rostock	NO_2 (μg/m^3)	35.19	34.08	14.15	4.66	97.53
	Employment Rate (Percentage)	56.20	56.14	1.47	53.72	57.88
	GDP per capita (Euro)	35.02	36.08	3.02	29.10	39.74
	Diesel Cars (Percentage)	25.99	27.38	2.23	21.24	27.94
	Commuters (Percentage)	37.41	37.34	0.21	37.15	37.78
Saarbrücken	NO_2 (μg/m^3)	36.26	35.28	14.26	4.81	91.22
	Employment Rate (Percentage)	64.09	64.00	0.40	63.53	64.90
	GDP per capita (Euro)	43.02	43.31	1.35	40.29	45.04
	Diesel Cars (Percentage)	1.00	1.00	0.00	1.00	1.00
	Commuters (Percentage)	45.93	46.10	0.52	45.26	46.60
Stuttgart	NO_2 (μg/m^3)	69.03	67.41	29.99	7.24	174.25
	Employment Rate (Percentage)	83.90	83.60	1.20	81.95	86.49
	GDP per capita (Euro)	83.96	84.12	4.40	77.80	91.71
	Diesel Cars (Percentage)	33.70	33.85	3.43	24.01	37.28
	Commuters (Percentage)	60.42	60.41	0.16	60.18	60.63

Tables D1 and D2

Table D2
Pre- and post-intervention summary statistics for NO_2 levels (in μg/m^3).

City	Period	Mean	Median	SD	Min	Max
Berlin	Pre-intervention	46.67	47.02	19.59	15.01	100.88
Berlin	Post-intervention	46.65	44.66	18.65	5.80	128.05
Hamburg	Pre-intervention	56.38	53.48	18.14	25.00	100.71
Hamburg	Post-intervention	45.86	43.39	17.48	6.49	118.86
Darmstadt	Pre-intervention	64.36	64.00	20.32	20.81	113.64
Darmstadt	Post-intervention	47.64	44.59	22.25	5.50	158.00
Stuttgart	Pre-intervention	88.23	85.89	32.71	21.57	162.01
Stuttgart	Post-intervention	68.61	66.88	29.80	7.24	174.25
Donor Pool	All Months	32.89	31.47	14.65	1.87	103.90
Donor Pool (Berlin cutoff)	Pre-intervention	40.73	40.00	15.66	3.93	96.88
Donor Pool (Berlin cutoff)	Post-intervention	32.71	31.27	14.57	1.87	103.90
Donor Pool (Hamburg cutoff)	Pre-intervention	39.71	39.14	15.46	3.93	96.88
Donor Pool (Hamburg cutoff)	Post-intervention	32.75	31.32	14.60	1.87	103.90
Donor Pool (Darmstadt cutoff)	Pre-intervention	40.79	40.07	15.66	3.93	96.88
Donor Pool (Darmstadt cutoff)	Post-intervention	32.71	31.27	14.57	1.87	103.90
Donor Pool (Stuttgart cutoff)	Pre-intervention	40.41	39.64	15.68	3.93	96.88
Donor Pool (Stuttgart cutoff)	Post-intervention	32.72	31.29	14.58	1.87	103.90

E. Nitrogen dioxide emission developments in 2012 and 2022

Fig. E1 shows the NO_2 emissions of each city considered in this study, with the treated units identified in the maps. It shows the changes in NO_2 emissions in 17 (four treated and 13 untreated cities combined) German cities between 2012 and 2022. The left map in Fig. 24 (2012) shows that Stuttgart is the worst polluter; the remaining cities showed similar trends, with Dresden emitting the least NO_2. Comparing the two maps, the majority of the cities experienced a decrease in NO_2 emissions. The right map in Fig. 24 shows that some of the cities, including Berlin and Hamburg, have experienced a decrease in NO_2 emissions in recent years. The most notable example is Darmstadt, which was one of the top five polluters in 2012 and it fades into the background alongside its neighbors by 2022.

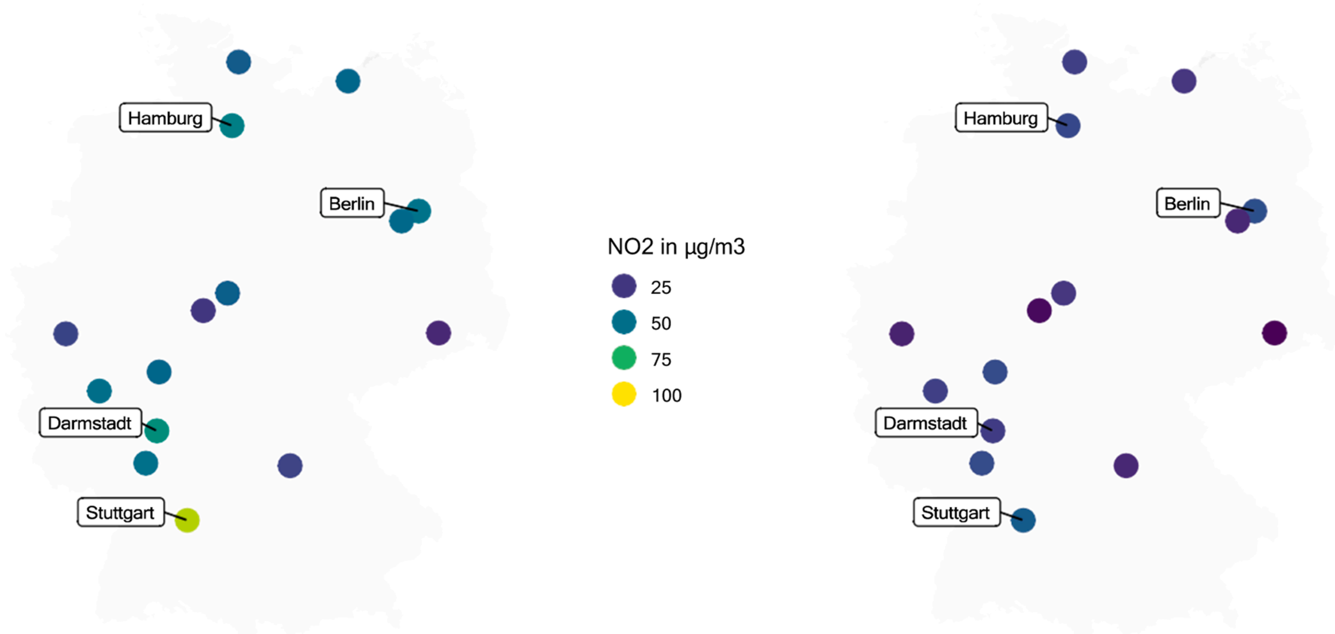
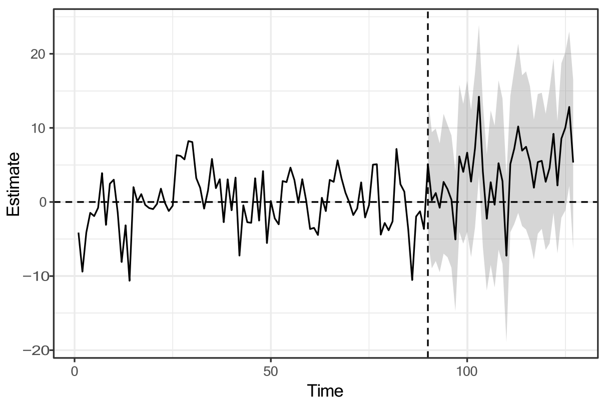
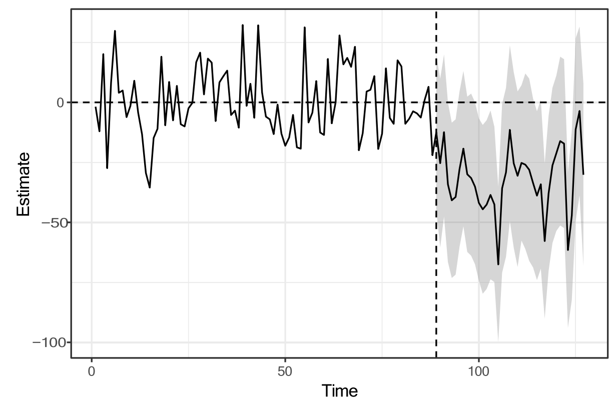


Fig. E1. Monthly NO_2 emissions in absolute values in 17 German cities in 2012 (left map) and 2022 (right map).

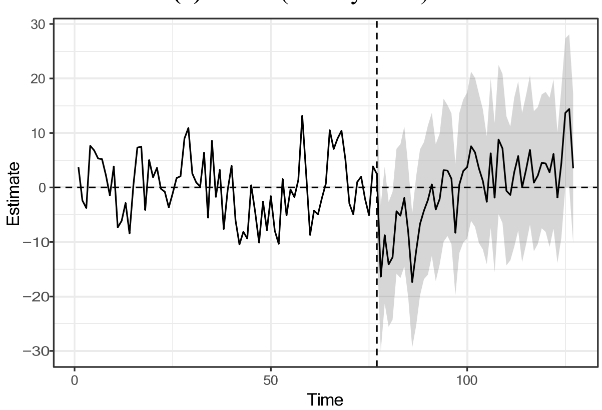
F. Augmented synthetic control methods results



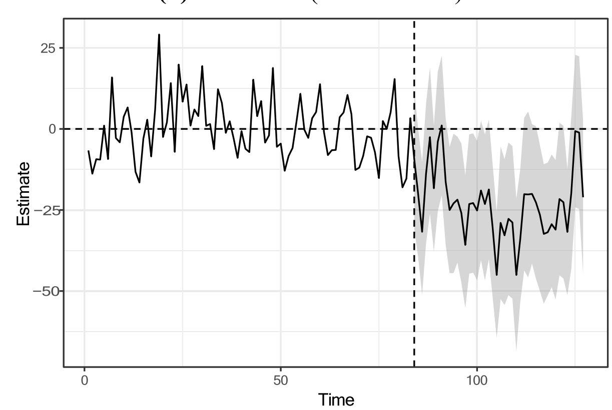
(a) Berlin (01 July 2019)



(b) Darmstadt (01 June 2019)

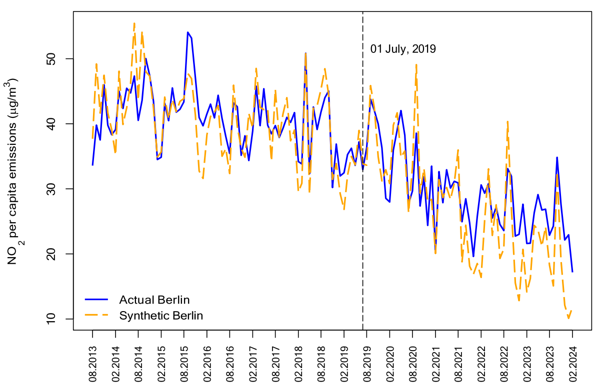


(c) Hamburg (01 August 2018)

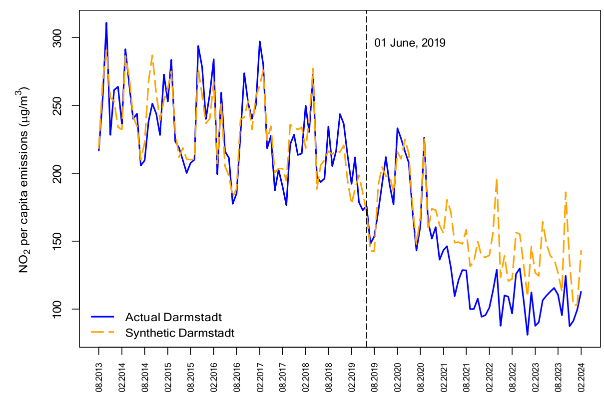


(d) Stuttgart (01 January 2019)

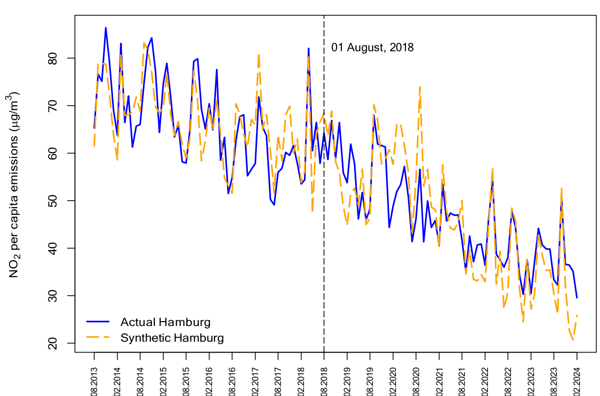
Fig. F1. Estimated treatment effects and confidence intervals from the Augmented Synthetic Control Method for four German cities. Solid lines represent the estimated ATT (Average Treatment Effect on the Treated), and grey lines indicate confidence intervals across time.



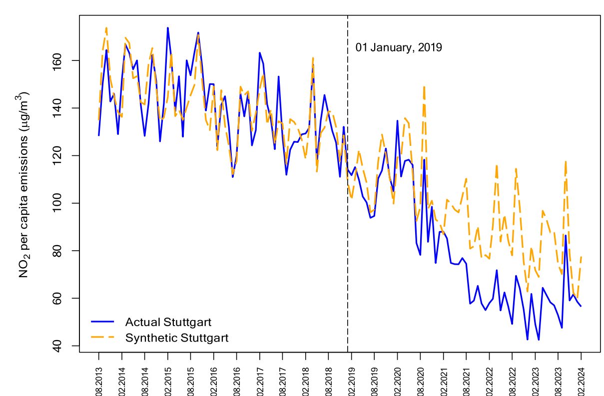
(a) Berlin (01 July 2019)



(b) Darmstadt (01 June 2019)

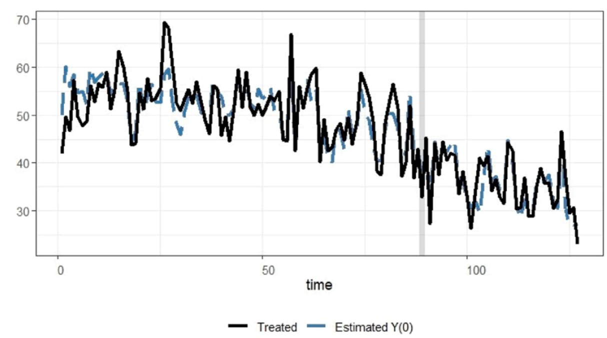


(c) Hamburg (01 August 2018)

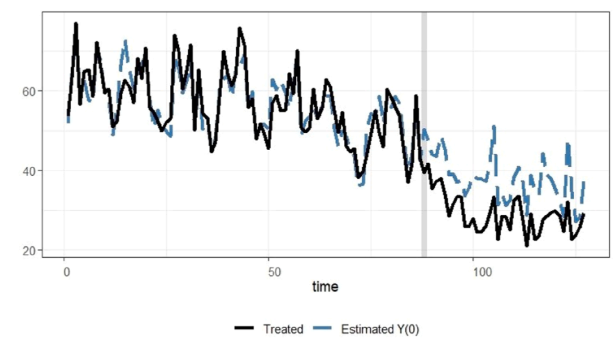


(d) Stuttgart (01 January 2019)

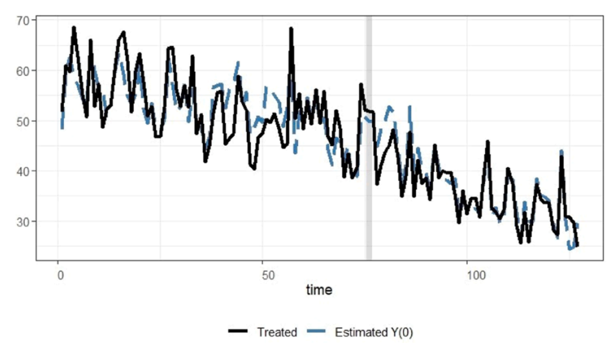
Fig. F2. Augmented Synthetic Control Method results for four German cities. The vertical dashed line indicates the diesel ban policy implementation date. The solid blue line shows actual NO_2 levels, while the dashed yellow line represents the estimated counterfactual from the synthetic control.



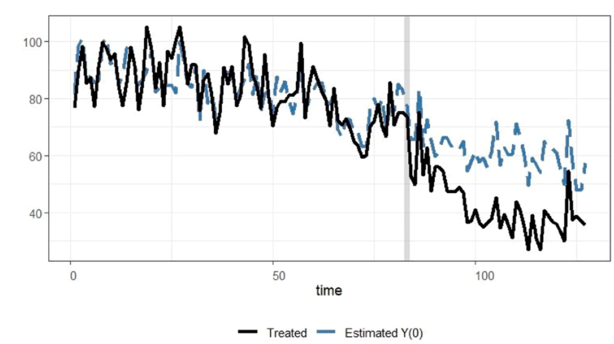
(a) Berlin (01 July 2019)



(b) Darmstadt (01 June 2019)

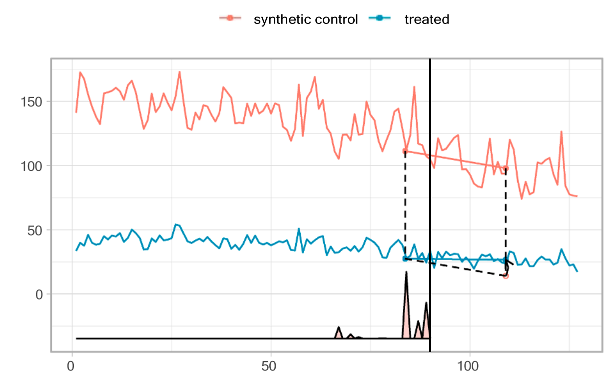


(c) Hamburg (01 August 2018)

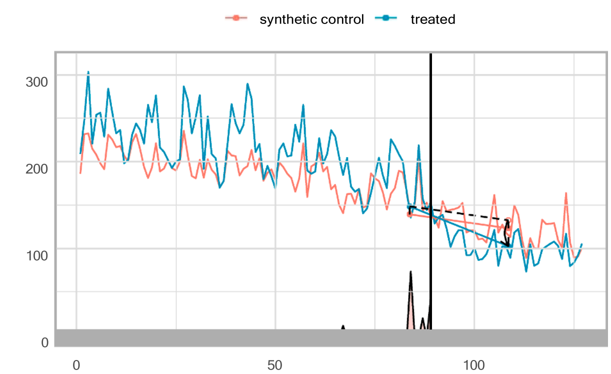


(d) Stuttgart (01 January 2019)

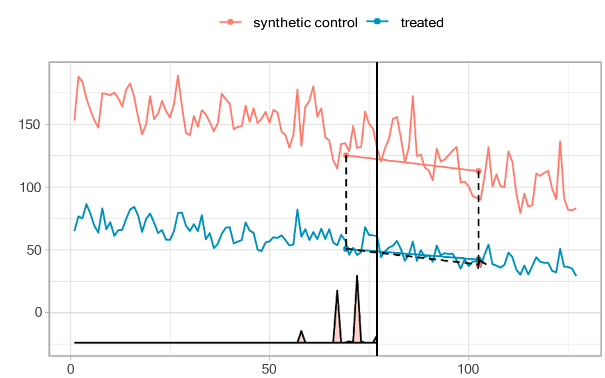
Fig. F3. Generalized Synthetic Control Method results for four German cities. The vertical gray line marks the implementation date of the diesel ban policy. The solid black line shows observed NO_2 concentrations, while the dashed blue line displays the estimated counterfactual levels in the absence of the intervention.



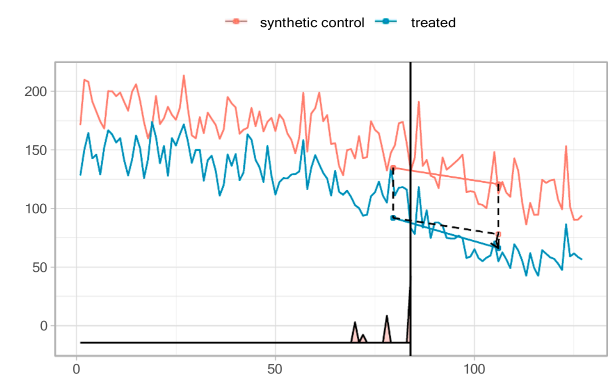
(a) Berlin (01 July 2019)



(b) Darmstadt (01 June 2019)



(c) Hamburg (01 August 2018)



(d) Stuttgart (01 January 2019)

Fig. F4. SDiD results for four German cities. The solid blue lines represent the observed NO_2 concentrations in the treated cities, while the solid red lines show the counterfactual outcomes estimated from the SDiD model. The post-treatment period, typically shown within a dashed vertical rectangle, marks the time after the implementation of the diesel ban. The average treatment effect is illustrated by a curved arrow or bracket indicating the vertical difference between the treated and synthetic lines over this period. Darmstadt and Stuttgart display negative treatment effects, while Berlin and Hamburg exhibit negligible or even positive gaps, indicating limited policy impact.

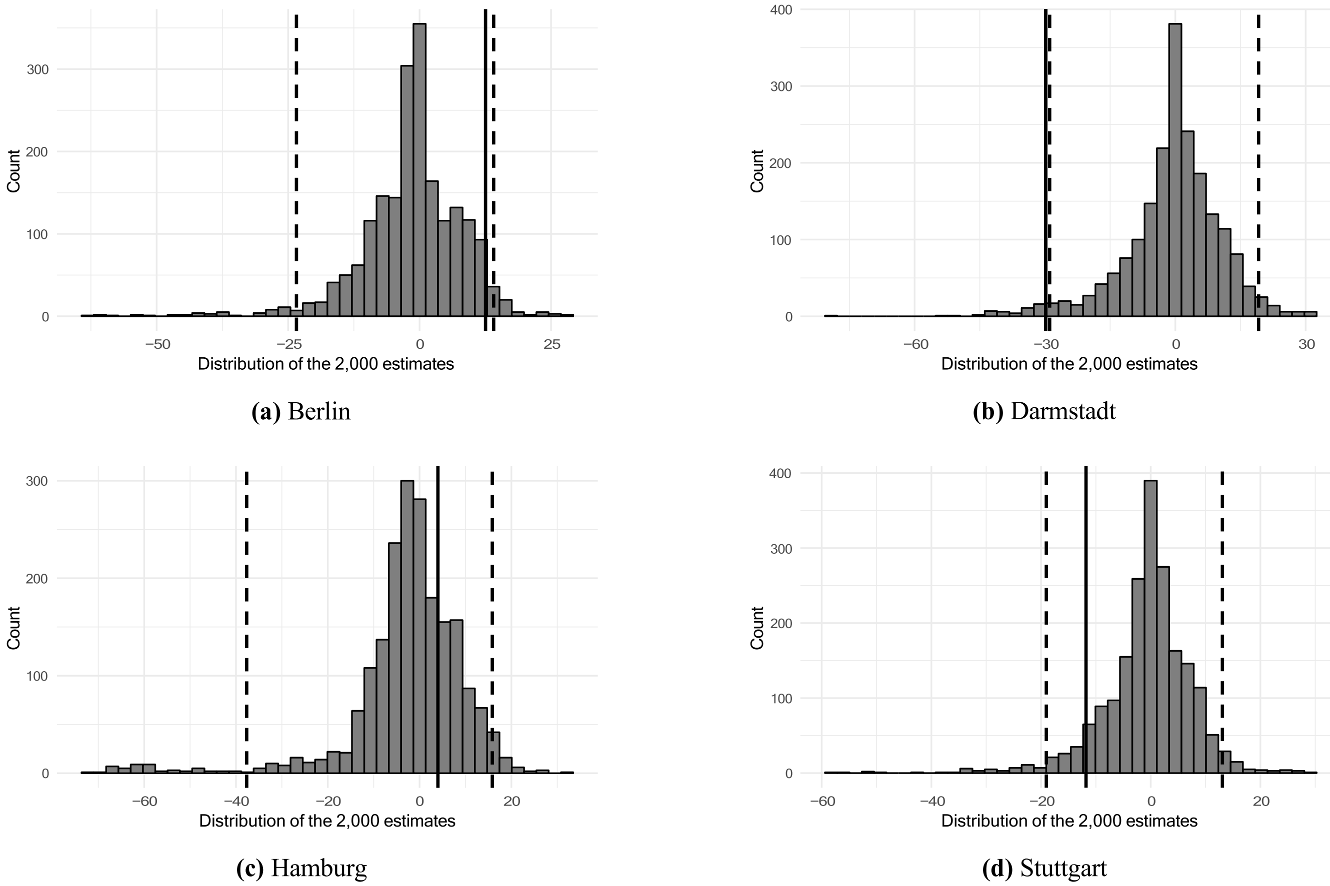


Fig. F5. Bootstrap distributions of 2,000 placebo SDiD treatment effect estimates for each city. The solid vertical line represents the actual SDiD estimate for the treated city, while the dashed vertical lines indicate the 95% confidence interval derived from the empirical distribution of placebo estimates.

Data availability

Data will be made available on request.

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