Environment International 193 (2024) 109067

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

Full length article

Munich's selective diesel vehicle ban and its impact on nitrogen dioxide concentrations: A quasi-experimental study

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ARTICLE INFO

Keywords:
Nitrogen dioxide
Quasi-experimental study
Air quality
Diesel ban
Vehicle emissions

ABSTRACT

Background: The current limit on NO_2 concentrations of 40 μg/m^3, set by the European Union, has been regularly exceeded in Munich, Germany. This limit will likely be reduced towards the WHO recommended target of 10 μg/m3. Against this backdrop, the city implemented a selective diesel vehicle ban within the existing low-emission zone in February 2023, targeting Euro 4 and older diesel vehicles. Our study investigated the effect of Munich's selective diesel vehicle ban on NO_2 concentrations, focusing on the half-year period following its implementation.

Methods: Our study utilized a synthetic control approach (primary analysis) and a controlled interrupted time series approach (secondary analysis). These quasi-experimental methodologies create a 'counterfactual' no-intervention scenario, enabling comparison between observed and counterfactual scenarios to estimate an intervention effect. We employed historical controls, using routine data from multiple monitoring stations located within and outside the low-emission zone for 2014 to 2022, and considered possible confounders.

Results: NO_2 concentrations within Munich's low-emission zone showed overall declining trends from August 2014 to July 2023. Effects of the selective diesel vehicle ban were small and wide confidence intervals indicate large uncertainty in the magnitude and direction of the effect. At Landshuter Allee, the average intervention effect was −2.67 μg/m^3 (95 %-CI = [-12.72; 7.38]), at Stachus it was −2.74 μg/m^3 (95 %-CI = [-9.91; 4.42]), and at Lothstrasse it was −1.03 μg/m^3 (95 %-CI = [-7.75; 5.69]). The secondary analysis confirmed these findings, reinforcing uncertainty about the effect of the intervention.

Conclusion: Our study suggests that Munich's selective diesel vehicle ban had a limited effect on lowering NO_2 concentrations. Possible explanations include the ban's focus on Euro 4 and older diesel vehicles, many exemptions to the selective ban, and unclear enforcement. This highlights that comprehensive approaches and ongoing, well-designed monitoring and evaluation are crucial for addressing urban air pollution and protecting public health.

1. Introduction

Despite significant reductions in concentrations of various air pollutants over the last few decades, air quality remains a considerable concern in many urban areas worldwide. While the majority of research has been concerned with particulate matter (PM) of various sizes, a growing body of evidence indicates that increased exposure to nitrogen dioxide (NO_2) is associated with higher risk of various health outcomes, such as decreased lung function, chronic obstructive pulmonary disease (COPD), lung cancer, and cardiovascular disease (Doiron et al., 2019; Hamra et al., 2015; Yang et al., 2019). Further, it has been shown that short- and long-term exposure to NO_2 is associated with increased mortality rates (Huang et al., 2021; Huangfu and Atkinson, 2020; Orellano et al., 2020; Wang et al., 2021). A systematic review commissioned by the World Health Organization (WHO) found that long-term exposure to an NO_2 concentration as low as 10 μg/m^3 poses an increased risk for all-cause mortality, as well as mortality due to respiratory disease and COPD (Huangfu and Atkinson, 2020). Mounting

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https://doi.org/10.1016/j.envint.2024.109067
Received 12 June 2024; Received in revised form 14 September 2024; Accepted 9 October 2024
Available online 10 October 2024

evidence suggests that there are no safe levels of NO_2 (Khreis et al., 2023). The WHO therefore recommends a target annual average NO_2 concentration of less than 10 μg/m^3 (WHO, 2021). The EU currently sets a binding limit that is higher than what is recommended by the WHO but is likely to reduce the limit in the future to be more in line with WHO recommendations (Council of the EU, 2024; European Commission, 2008). The concern about NO_2 has been more pronounced in densely populated cities, where vehicular emissions, particularly those from diesel-powered vehicles, have been identified as a significant source (Wang et al., 2021). The German Environment Association (*Umweltbundesamt*) estimates that privately-owned diesel vehicles are responsible for 65 % of NO_2 emissions from traffic in Germany. Commercial vehicles (almost exclusively diesel-fueled) account for another 28 % (Umweltbundesamt, 2019).

Like many other metropolitan areas, the city of Munich, Germany, has grappled with air quality challenges related to high concentrations of NO_2. The decision to impose restrictions on diesel vehicles emerged as a response to concerns over frequent air quality violations of EU air quality regulations and ensuing legal action by environmental interest groups. In response to several lawsuits, Munich's city council (*Münchner Stadtrat*) decided to implement additional measures to meet regulatory standards and improve air quality (Schubert, 2023). The initial phase of this initiative, which began in February 2023, focused on banning Euro 4 and older diesel vehicles with lower Euro classifications (phase 1) within the low-emission zone (*Umweltzone*, see Fig. 2) in Munich. However, discussions about further measures have persisted, including a planned extension of these restrictions to Euro 5 diesel vehicles (phase 2). A decision regarding this extension hinges on the assessment of air quality, particularly the concentrations of NO_2, which will be reviewed in 2024 (Landeshauptstadt München, 2024b).

In light of these developments, Munich's selective ban on diesel vehicles presents a unique research opportunity. This study aims to contribute to the scientific evidence and broader discourse on urban air pollution control and its implications for health by investigating the impact of the selective ban on NO_2 concentrations in the half-year period after its implementation. To analyze this impact, we used a quasi-experimental study design, employing a synthetic control (SC) approach as the main analysis and a controlled interrupted time series (cITS) approach as the secondary analysis.

2. Methods

2.1. Intervention

The introduction of a selective diesel vehicle ban in Munich on February 1, 2023, represents a regulatory intervention aimed at addressing air quality concerns. The following provides a detailed description of the specifics of this intervention and the policy process it arose from.

In 2008, the EU directive 2008/50/EG set air quality standards, which included limits for NO_2, namely that the hourly average cannot exceed 200 μg/m^3 more than 18 times per year and that the yearly average cannot exceed 40 μg/m^3 (European Commission, 2008). Air quality measurements in Munich regularly exceeded these thresholds set by the EU, which prompted several environmental interest groups (mainly *Deutsche Umwelthilfe* and *Verkehrsclub Deutschland*) to file lawsuits against the city of Munich (Schubert, 2023). The Deutsche Umwelthilfe filed and won their first lawsuit in 2012, but appeal proceedings have gone back and forth since (Umwelthilfe, 2018). In response to this and with the aim of decreasing NO_2 concentrations, Munich's city council decided on October 26, 2022, to implement a phased approach to selectively ban specific diesel vehicles from the city's low-emission zone (Landeshauptstadt München, 2024a).

This phased approach is outlined in Table 1. The initial phase 1, implemented on February 1, 2023, banned diesel vehicles classified as Euro 4 and below, although it featured many exemptions

Table 1
Overview of the three phases of the selective diesel vehicle ban in the city of Munich.

	Phase 1	Phase 2	Phase 3
Target vehicles (Gerstenberger, 2023; Landeshauptstadt München, 2024b)	Diesel vehicles, Euro category 4 and below (4.6 % of personal vehicles and 28.4 % of heavy commercial vehicles*)	Diesel vehicles, Euro category 5 and below (11.8 % of personal vehicles and 44.6 % of heavy commercial vehicles*)	Diesel vehicles, Euro category 5 and below (11.8 % of personal vehicles and 44.6 % of heavy commercial vehicles*)
Automatic exemptions (Landeshauptstadt München, 2024b; Schubert, 2023)	People who live within the ring road; freight traffic into the low emission zone; people who work night shifts and therefore cannot rely on public transport; craftsmen who work and have a parking permit for within the ring road; people with disabilities.	People who live within the ring road; freight traffic into the low emission zone; people who work night shifts and therefore cannot rely on public transport; craftsmen who work and have a parking permit for within the ring road; people with disabilities.	People who work night shifts and therefore cannot rely on public transport; craftsmen who work and have a parking permit for within the ring road; people with disabilities.
Timing (Landeshauptstadt München, 2024b; Schubert, 2023)	Decided by the city council on October 26, 2022; implemented on February 1, 2023.	Originally planned to be implemented in October 2023. The city council decided in September 2023 to postpone this decision, which is now scheduled for April 24, 2024.	Repealed in September 2023.
Area (Landeshauptstadt München, 2024b)	Within the city of Munich's low emission zone (*Umweltzone*), which comprises the main ring road in Munich and the area within the ring road; It excludes the Brudermühl bridge, which is part of the ring road, for easier crossing of the river Isar.		

*Percentages of vehicles registered in Munich on December 31, 2022.

(Landeshauptstadt München, 2024b). In January 2023, shortly before the implementation of the selective diesel vehicle ban, the city of Munich notified approximately 80,000 private and commercial vehicle owners that they would not be allowed to drive within the low-emission zone starting on February 1, 2023 (Rauch et al., 2023) – this figure does not include commuters living outside of Munich and tourists who may also be affected by the selective ban. There are no data available on what proportion of traffic within the low-emission zone was effectively banned with this policy.

Phase 2 involves banning diesel vehicles classified as Euro 5 and below, with the same exemptions as in phase 1. Phase 3 would go one step further by repealing most exemptions of phases 1 and 2. The decision to move from one phase to another hinges on evaluations of changes in measured NO_2 concentrations since the introduction of the selective ban and forecasts of future NO_2 concentrations (Landeshauptstadt München, 2024a). These evaluations are commissioned by the city and conducted by an independent engineering bureau (Schubert, 2023; Landeshauptstadt München, 2022). The first such evaluation was done in July 2023 and a more extensive one was planned for April 2024 (Landeshauptstadt München, 2024b). Based on the first evaluation, Munich's city council decided in September 2023 to delay phase 2 and repeal phase 3. They plan to revisit the decision regarding the necessity and proportionality of implementing phase 2 in spring

2024 (Landeshauptstadt München, 2024b).

According to the city, the selective diesel vehicle ban is enforced through checks by the police and local traffic authorities. However, with no visible marker indicating which vehicles are banned, this enforcement must be done manually. Thus, it is unclear how often enforcement happens. Further, adherence to the regulation is enforced when drivers are charged with speeding or parking offenses and when applying for local parking permits (Landeshauptstadt München, 2024b). The city does not make data regarding enforcement and adherence available.

2.2. Study design overview

To analyze the impact of the selective diesel vehicle ban on NO_2 concentrations during the first six months after its implementation, our study employed an SC approach in its main analysis and a cITS approach in its secondary analysis. Both approaches allow the creation of a 'counterfactual' scenario, essentially estimating a hypothetical scenario that would have occurred if the intervention had not been introduced, which can then be compared to the observed scenario. The difference between the counterfactual and observed scenarios represents the intervention effect.

These quasi-experimental methodologies make use of serial outcome data over a relatively long period of time, including data from the pre- and post-intervention period, both for an intervention unit and one or multiple control units. This enables the comparison of changes in the outcome for intervention units relative to changes for control units (Craig et al., 2017). For our specific study, we utilized historical controls; this means the intervention unit was the year during which the intervention was implemented ('intervention year'), while the control units were years during which the intervention did not take place ('control years'). This ensured that any observed effect following the introduction of the intervention in 2023 was not due to existing trends in NO_2 concentrations or seasonal variations.

For the main analysis, the SC approach constructed a synthetic control unit by taking a weighted average of the control years in the post-intervention period to create a counterfactual, which was then compared to the observed outcome in the intervention year. This weighted combination allowed for a tailored and data-driven comparison, capturing the intervention's impact over time while addressing potential confounding factors. For the secondary analysis, the cITS approach, we compared each individual control year to the intervention year and subsequently chose an appropriate main control year based on pre-intervention outcome trends and temporal proximity (Lopez Bernal et al., 2018).

2.3. Impact model

For such a quasi-experimental evaluation, it is necessary to determine the impact model a priori (Lopez Bernal et al., 2017). For this study, this meant that we had to consider when an intervention effect could be expected, for which pollutants, and at which air quality monitoring station.

The period between announcement and implementation of the selective diesel vehicle ban was only three months and thus very short. Related to the timing of a potential intervention effect, we assumed that, due to long wait lists for new vehicles and limited availability of used cars, most people who owned diesel vehicles of categories Euro 4 or below – if they were not exempt from the ban – were unable to purchase a replacement vehicle by February 1, 2023 (ADAC, 2024). We also assumed they stopped driving their vehicles within the low-emission zone immediately after the implementation of the intervention and either used alternative means of transport or alternative routes not crossing the low-emission zone. We assumed that this behavior was retained during the months following the intervention. We did not assume any anticipatory effects. Consequently, February 1 marks the beginning of the post-intervention period. Assuming an immediate decline in NO_2 concentrations due to the selective diesel vehicle ban, we expected to see an initial effect right after the implementation and also expected a sustained effect throughout the post-intervention period.

We used the six months prior to the intervention as the pre-intervention period and the six months after the intervention as the post-intervention period (see Fig. 1 for an illustration). Thus, for the intervention year, August 1, 2022 – January 31, 2023 served as the pre-intervention period, and February 1, 2023 – July 31, 2023 as the post-intervention period. The years 2014–2022 served as control years, with each being divided into pre- and post-intervention periods accordingly. We excluded two years, from August 2019 to July 2021 from the analysis, as there were temporary COVID-19 mitigation measures in place that affected traffic volumes and likely resulted in a reduction of NO_2 concentrations (Burns et al., 2021).

Related to specific air pollutants, the selective diesel vehicle ban targets NO_2. We therefore expected reductions in NO_2, if the ban had achieved its intended effects. As the emission abatement of the different Euro classifications targets NO_x (nitrogen oxides, which comprise NO and NO_2), we expected the effect of the intervention on NO_x to be similar or potentially more pronounced than on NO_2. For other pollutants, such as PM_{10} (PM with a diameter of 10 µm or less), however, we expected to see little or no effect in either direction. As diesel-powered vehicles do not emit more PM_{10} than gasoline-powered vehicles (Timmers and Achten, 2016), we did not expect a decrease in concentrations. Newer, heavier cars often emit more PM_{10} through friction mechanisms on tires (Piras et al., 2024). However, as outlined above, we assume that replacing old vehicles with newer ones did not take place to a meaningful extent within the study period. Therefore, we also did not expect an increase in PM_{10}. Thus, for our main comparison, we assessed changes in NO_2 concentrations, while examinations of PM_{10} were conducted as 'placebo pollutant' analyses, as described in section 2.5.2.

Related to the geographical area, we expected the intervention to affect air quality within the low-emission zone, especially in heavily trafficked areas., i.e. Landshuter Allee and Stachus. We expected little or no change in NO_2 for monitoring stations outside of the low-emission zone, i.e. Allach and Johanneskirchen (see Fig. 2 and Panel 1). These are located well beyond areas that may be affected by traffic rerouting due to the diesel ban. We used them for 'placebo sites' analyses, as described in section 2.5.2.

2.4. Data

2.4.1. Outcome

The Bavarian Environmental Administration (*Bayerisches Landesamt für Umwelt*) is responsible for overseeing air quality in Bavaria and makes its measurements from 50 air quality monitoring stations in Bavaria publicly available (Bayerisches Landesamt für Umwelt, 2024). Five of these are located in the greater Munich area and have consistently collected data on NO_2 and NO since 2014: Landshuter Allee, Stachus, Lothstrasse, Allach, and Johanneskirchen (see Fig. 2 and Panel 1). All of these, except for Allach, have also collected data on PM_{10} over the same time period (Bayerisches Landesamt für Umwelt, 2024). Data for the different monitoring stations are available as hourly concentrations; we aggregated these into daily means. The quality and means of measurement of air quality are regulated by a federal law in Germany that includes regulations for the assessment and control of air quality, air pollution control plans, short-term measures, and information and reporting obligations to the European Commission (Bayerisches Landesamt für Umwelt, 2019).

2.4.2. Covariates

There are multiple other factors that may affect NO_2 concentrations, which were incorporated into both quasi-experimental methodologies. These included weather, day of the week and school holiday periods. Weather-related metrics were obtained from the German Weather Service (*Deutscher Wetterdienst*). This included daily average temperature,

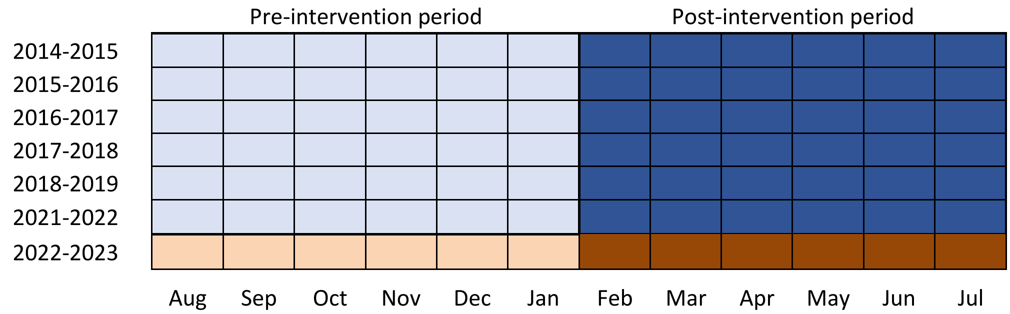

Fig. 1. Graphical illustration of pre- and post-intervention periods. Each row represents either the intervention year (in orange) or a control year (in blue). The columns represent months and are divided into the pre-intervention period (light shading) and the post-intervention period (dark shading). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

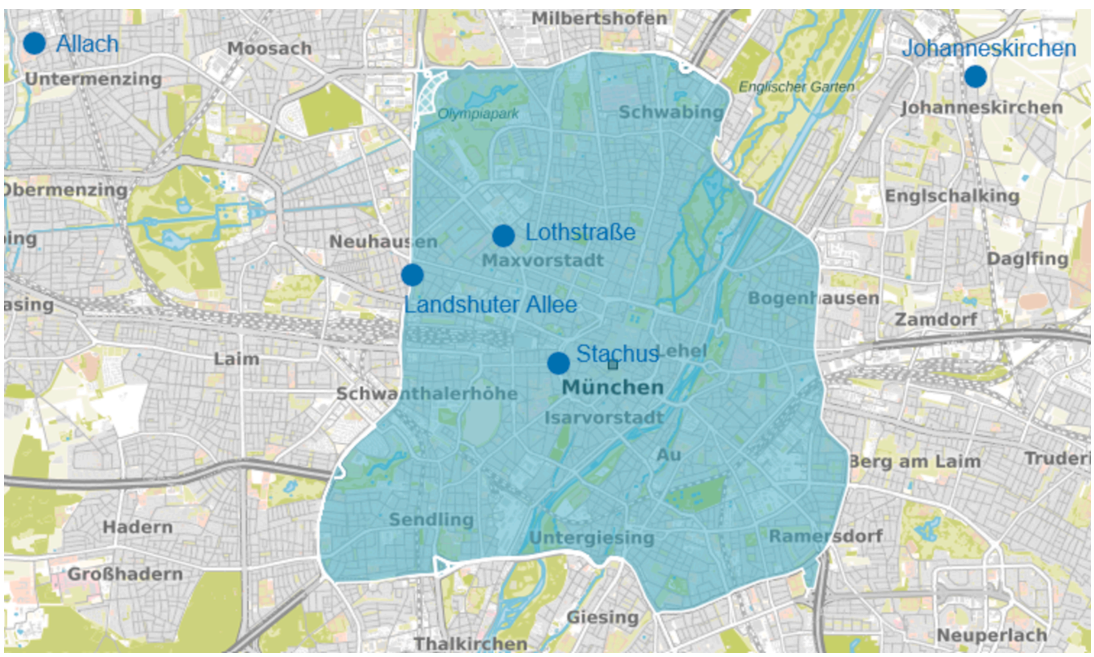

Fig. 2. Low-emission zone in Munich, where driving diesel vehicles categorized as Euro 4 or below has been prohibited since February 1, 2023 (European Commission, 2008)**, and air quality monitoring stations of the Bavarian Environmental Administration located within and outside the low-emission zone (in blue)** (Bayerisches Landesamt für Umwelt, 2024). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Monitoring stations located within the low-emission zone (urban traffic and urban background)

- Landshuter Allee (urban traffic): heavily-trafficked road situated at the edge of the low-emission zone.
- Stachus (urban traffic): large, centrally-located traffic junction.
- Lothstrasse (urban background): centrally located, but not heavily trafficked road.

Monitoring stations located outside the low-emission zone (suburban background)

- Allach: located in a suburban living and business area west of the city center.
- Johanneskirchen: located in a suburban living and business area next to athletic fields east of the city center.

Panel 1. Overview and description of monitoring stations in Munich, operated by the Bavarian Environmental Administration (Bayerisches Landesamt für Umwelt, 2024).

rainfall, air pressure, humidity, wind speed, and sunshine duration, all known to affect concentrations of NO_2 and other pollutants (Deutscher Wetterdienst, 2024). Publicly available data on school holidays were obtained to determine which weekends were holiday weekends (that are likely to be characterized by increased travel activity) and which weekdays were holiday weekdays (that are likely to be characterized by decreased travel activity).

2.5. Statistical analyses

2.5.1. Main analysis

As described in section 2.2., we employed the SC approach, which creates a counterfactual by taking a weighted average of the control units. The weights were determined in such a way that the SC mirrored, as closely as possible, the intervention year with regard to the pre-intervention outcome trend and the covariates. Specifically, we employed a regression-based operationalization of the SC approach that entails multiple stages.

First, an interactive fixed effects model is applied in regressing NO_2 concentrations on the selected covariates and fixed effects of each control year. The resulting regression coefficients provide an understanding and description of how the underlying NO_2 concentrations evolve over each study year.

These coefficients provided a basis for weighting each control year in a manner that closely matches the pre-intervention period of the intervention year. The SC was then essentially constructed by taking the average of these reweighted control years across the full study period, with the post-intervention period representing the counterfactual. This approach to calculating the counterfactual should, in principle, ensure that the influence of time-invarying confounders (i.e. those associated with specific years) as well as time-varying confounders (i.e. those associated with covariates) is minimized. This counterfactual outcome trend was then compared to the observed outcome trend in the intervention year. This enabled the computation of treatment effects, which for the purpose of this study we will call 'intervention effects'. These intervention effects were computed for both individual time points and over the entire post-intervention period, providing insights into how the intervention effect evolved over time and its average impact. This analysis was conducted individually for the three monitoring stations (Stachus, Lothstrasse and Landshuter Allee) within the low-emission zone. Further details on the empirical approach can be found in the original publication on this method (Xu, 2017).

2.5.2. Robustness checks

We conducted various placebo analyses to test that no effect or a much smaller effect could be found where none would be expected, as any such effect could be interpreted as a potential signal that something other than the intervention may have driven effects observed in the main analysis. First, as mentioned in section 2.3., we tested for any effects on PM_{10} concentrations ('placebo pollutant'), which, as described above in section 2.3., we would expect to be much smaller than effects on NO_2 concentrations. Second, we analyzed data from the Allach and Johanneskirchen monitoring stations ('placebo sites'). Third, we moved the intervention date back six months to August 1, 2022 ('placebo intervention date'). Fourth, we eliminated the intervention year from the analyses and randomly selected a control year that then served as the intervention year ('placebo intervention year').

We also conducted a sensitivity analysis. To reduce the noise in the daily NO_2 data, we used a 7-day moving average as the outcome variable. For this analysis, we did not include the day of the week and the holiday variables as covariates.

Unless otherwise specified, we conducted all of these robustness checks using the SC approach and using NO_2 data from Landshuter Allee, Stachus and Lothstrasse.

2.5.3. Secondary analyses

For the cITS approach, we conducted the analysis for each control year individually and chose the main control year based on similarity in pre-intervention outcome trends and temporal proximity. We fitted the linear model using the general least squares method. The regression equation for the cITS had the following form:

$$NO_2 = \beta_0 + \beta_1 \text{ days} + \beta_2 \text{ post} + \beta_3 \text{ days}_{post} + \beta_4 \text{ int} + \beta_5 \text{ int*days} + \beta_6 \text{ int*post} + \beta_7 \text{ int*days}_{post} + \beta_{8\text{-}z}\text{covs}$$

NO_2 represents the outcome (daily averages of the NO_2 concentrations); days is the time in days since the beginning of the pre-intervention period; post is a dummy variable that takes the value of 0 during the pre-intervention period and 1 for the post-intervention period; days_{post} is the time in days since the beginning of the post-intervention period (and takes the value of 0 for the pre-intervention period); int is a dummy variable that takes the value of 0 for the control years and 1 for the intervention year; int*days is an interaction term and its coefficient, β_5, represents the slope difference between the control and intervention year in the pre-intervention period that was used to determine the main control year; int*post is an interaction term and its coefficient, β_6, estimates the immediate level change in NO_2 concentrations in the intervention year relative to the control year; int*days_{post} is another interaction term and its coefficient, β_7, estimates the trend change in NO_2 concentrations in the post-intervention period in the intervention year relative to the control year; covs denote potential covariates. Autocorrelation function and partial autocorrelation function plots were considered to determine the appropriate autocorrelation structure to be modelled (Lopez Bernal et al., 2017; Lopez Bernal et al., 2018).

Additionally, in a post-hoc analysis, we used the SC approach with NO_x as the outcome variable, to assess the effect of the intervention on NO_x.

We conducted all data processing and analyses in R version 4.3.1. For the main analysis, we used the Generalized Synthetic Control Method (gsynth) package (Xu, 2017). For the secondary analysis, we used the Linear and Nonlinear Mixed Effects Models (nlme) package (RDocumentation, 2023).

3. Results

3.1. Descriptive results

Regarding overall trends in NO_2 concentrations within the low-emission zone, Fig. 3 depicts an overall decline in concentrations from August 2014 to July 2023 at the Landshuter Allee, Stachus, and Lothstrasse monitoring stations, which indicates a general improvement in air quality over the study period. Of the three monitoring stations, Landshuter Allee had the highest concentrations throughout, followed by Stachus and Lothstrasse. The monitoring station at Landshuter Allee routinely exceeds the limits set by the EU directive, as the yearly average concentration of NO_2 was above 40 $\mu g/m^3$ for the whole study period, whereas Stachus has not exceeded the limit since 2019 and Lothstrasse, as an urban background monitor, has not exceeded the limit at all during the study period.

3.2. Main analysis: Synthetic control approach

Regarding the impact of the selective diesel vehicle ban, the estimated intervention effects for NO_2 concentrations at different monitoring stations within the low-emission zone, as well as the results of robustness analyses, are summarized in Table 2. The intervention effects represent the differences between the observed NO_2 concentrations and the SC in the post-intervention period. The average intervention effect takes the average of the daily differences over the whole post-intervention period. A negative average intervention effect thus indicates lower NO_2 concentrations than would have been expected in the absence of the selective diesel vehicle ban.

At Landshuter Allee, the average intervention effect for NO_2 was -2.67 $\mu g/m^3$ (95 %-CI = [-12.72; 7.38]). Similarly, at Stachus, the average intervention effect was -2.74 $\mu g/m^3$ (95 %-CI = [-9.91; 4.42]). For Lothstrasse, the average intervention effect was slightly smaller at -1.03 $\mu g/m^3$ (95 %-CI = [-7.75; 5.69]). These findings suggest that

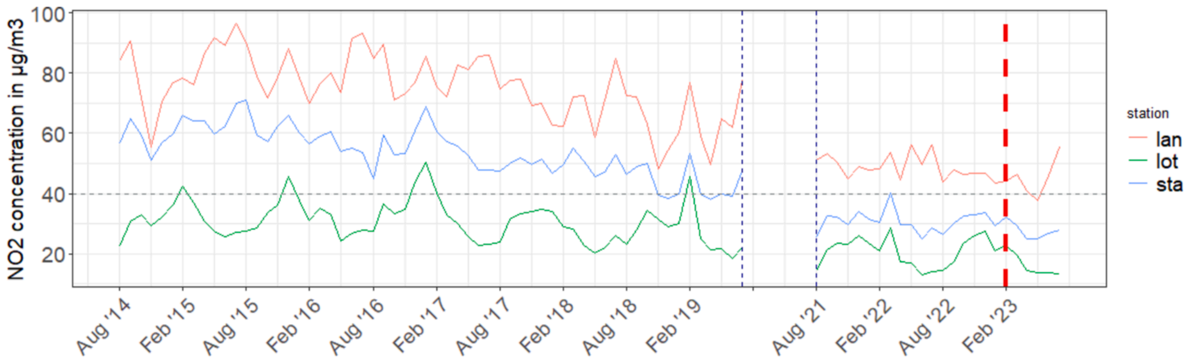

Fig. 3. Monthly average NO_2 concentrations from August 2014 to July 2023 at three monitoring stations within Munich's low-emission zone. Abbreviations: lan: Landshuter Allee; lot: Lothstrasse; sta: Stachus. The blue vertical dotted lines denote the interruption of the study period due to the COVID-19 pandemic from August 2019 to July 2021; the red vertical dotted line denotes the introduction of the intervention, a ban on diesel vehicles categorized as Euro 4 or below within Munich's low-emission zone; the grey horizontal dotted line denotes the limit on NO_2 concentrations set by the European Union. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Summary of results from main analysis and robustness analyses.

	NO_2 – main analysis		PM_{10} – placebo pollutant		NO_2 – placebo intervention date*		NO_2 – placebo intervention year**		NO_2 – 7-day moving average	
Main Sites	**IE**	**95 %-CI**	**IE**	**95 %-CI**	**IE**	**95 %-CI**	**IE**	**95 %-CI**	**IE**	**95 %-CI**
LAN	−2.67	−12.72; 7.38	1.77	−5.28; 8.82	−0.64	−9.63; 8.35	−2.79	−14.55; 8.96	−1.90	−9.34; 5.54
STA	−2.74	−9.91; 4.42	1.30	−5.88; 8.47	2.70	−4.11; 9.5	−5.69	−11.86; 0.48	−2.80	−10.77; 5.16
LOT	−1.03	−7.75; 5.69	0.73	−5.68; 7.14	−0.64	−7.48; 6.2	−0.73	−8.35; 6.89	−2.14	−7.83; 3.54
Placebo Sites										
JOH	−1.27	−5.07; 2.52								
ALL	−0.64	−4.72; 3.44								

Intervention effects denote the average difference between the observed outcome and the synthetic control in the post-intervention period. Abbreviations: LAN: Landshuter Allee, STA: Stachus, LOT: Lothstrasse, JOH: Johanneskirchen, ALL: Allach; CI: Confidence interval; IE: Intervention effect. All values are in µg/m^3. *August 1, 2022 (6 months prior to the actual intervention) was selected as the placebo date. **2018/2019 was the randomly selected placebo intervention year.

there may have been minor reductions in NO_2 concentrations following the implementation of the selective diesel vehicle ban at these monitoring stations. These effects would translate to 5.8 %, 9.4 % and 6.2 % reductions in concentrations, respectively, taking the average NO_2 concentrations of February to July 2023 of the counterfactual as the reference. However, the wide confidence intervals indicate considerable uncertainty in the estimates, and do not exclude the possibility that concentrations did not change. Fig. 4 shows intervention effects and their 95 %-confidence-intervals for each individual day. These daily estimated intervention effects show a high degree of fluctuation, with large confidence intervals indicating uncertainty.

The weights that were assigned to each control year to calculate the counterfactual for the intervention year in the post-intervention period can be found in eTable 1 of the supplementary material.

3.3. Robustness checks

Results from the robustness checks are summarized in Table 2. The estimated average intervention effects observed at the placebo sites that were located outside of the low-emission zone, where no effects were anticipated, revealed marginal reductions in NO_2 concentrations, with confidence intervals indicating uncertainty in the magnitude and direction of effect. Specifically, at Johanneskirchen, the average estimated intervention effect was −1.27 µg/m^3 (95 %-CI = [-5.07; 2.52]), while at Allach, it stood at −0.64 µg/m^3 (95 %-CI = [-4.72; 3.44]).

The results of the placebo pollutant analysis, using PM_{10} as the outcome variable, showed a small increase in concentrations in the post-intervention period of the intervention year compared to the control years, again with confidence intervals indicating uncertainty in the direction of effect. At Landshuter Allee, the intervention effect for PM_{10} was 1.77 µg/m^3 (95 %-CI = [-5.28; 8.82]), while at Stachus, the intervention effect was 1.30 µg/m^3 (95 %-CI = [-5.88; 8.47]), and at Lothstrasse, the intervention effect was 0.73 µg/m^3 (95 %-CI = [-5.68; 7.14]).

Furthermore, the placebo intervention date analysis, which moved the intervention date back to August 1, 2022, yielded intervention effect estimates for NO_2 concentrations smaller in magnitude than in the main analysis, ranging from –0.64 µg/m^3 (95 %-CI = [-9.63; 8.35]) at Landshuter Allee to also –0.64 µg/m^3 (95 %-CI = [-7.48; 6.2]) at Lothstrasse and 2.70 µg/m^3 at Stachus (95 %-CI = [-4.11; 9.5]). For the randomly selected placebo intervention year, from August 2018, to July 2019, the intervention effect estimates are −2.79 µg/m^3 (95 %-CI = [-14.55; 8.96]) at Landshuter Allee, −5.69 µg/m^3 (95 %-CI = [-11.86; 0.48]) at Stachus, and –0.73 µg/m^3 (95 %-CI = [-8.35; 6.89]) at Lothstrasse.

Additionally, a sensitivity analysis using a 7-day moving average of NO_2 concentrations yielded intervention effect estimates that were consistent with those obtained from the main analysis. Given the large weights assigned to the control years in constructing the synthetic control for Landshuter Allee in the main analysis, we were also interested in whether data smoothing would alter these weights. However, both the weights and the estimates remained of similar magnitude, as demonstrated in Table 2 and eTable 2 of the supplementary material. At Landshuter Allee, the intervention effect was −1.90 µg/m^3 (95 %-CI = [-9.34; 5.54]), while at Stachus, the intervention effect was −2.80 µg/m^3 (95 %-CI = [-10.77; 5.16]), and at Lothstrasse, the intervention effect was −2.14 µg/m^3 (95 %-CI = [-7.83; 3.54]).

Overall, the results of the robustness analyses provide additional context for interpreting the findings of the main analysis. The placebo analyses do not show any meaningful effects due to the intervention, thus do not suggest that any unobserved confounders are influencing the main analysis. The results of the sensitivity analysis are in line with the results of the main analysis.

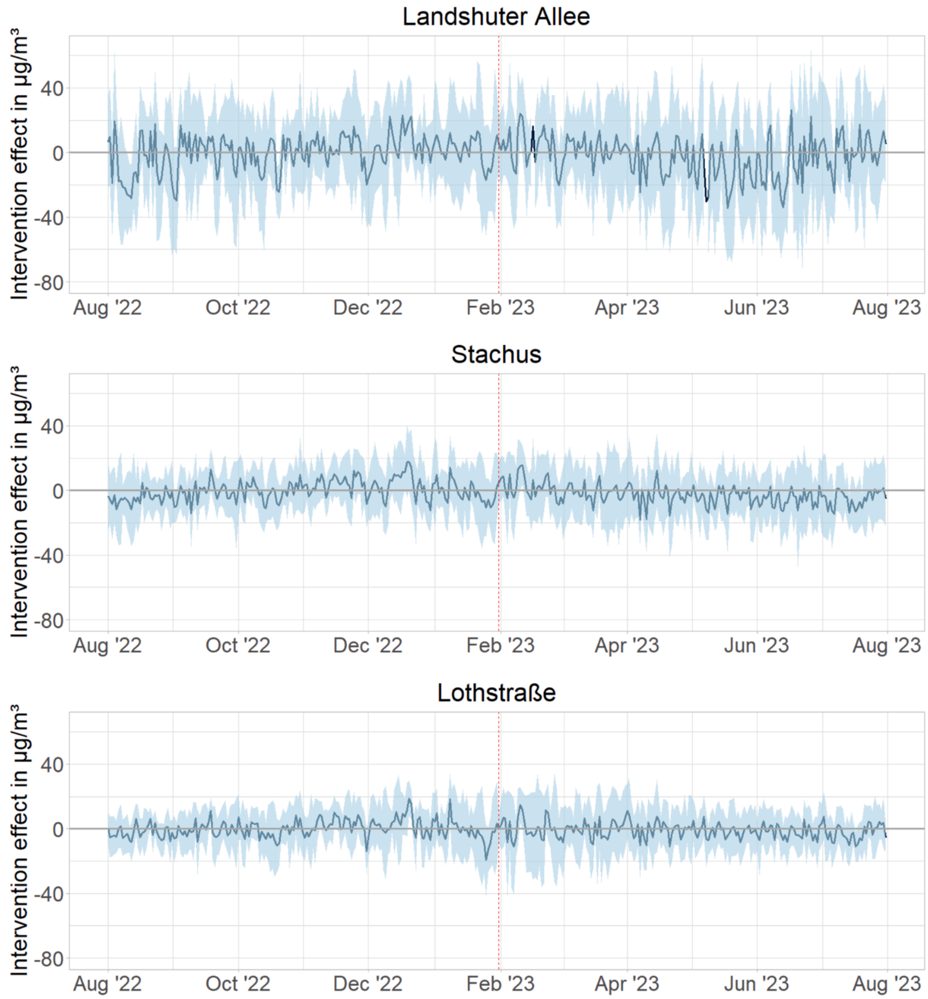

Fig. 4. Daily intervention effects (difference between observed NO_2 concentrations and synthetic control) at Landshuter Allee (urban traffic monitor), Stachus (urban traffic monitor), and Lothstrasse (urban background monitor). The light blue band signifies the 95% confidence interval of the intervention effect. The red dotted line denotes the introduction of the intervention. In the pre-intervention period, i.e. left of the red dotted line, the curve should remain around 0; in the post-intervention period, i.e. right of the red dotted line, if the selective diesel vehicle ban is effective, then curve should lie below 0. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 3
Summary of results from the secondary analyses, a controlled interrupted time series approach and a synthetic control approach with NO_x as outcome variable.

Site	Control year	Level change	95 %-CI	Level change range of all control years	Trend change	95 %-CI	Trend change range of all control years	IE	95 %-CI
Controlled interrupted time series approach: effect on NO_2									
LAN	2021/22	−2.24	−12.13; 7.65	−16.29; 12.41	0.00	−0.09; 0.1	−0.23; 0.00	–	–
STA	2021/22	−1.70	−7.3; 3.91	−10.53; 9.99	0.04	−0.02; 0.1	−0.12; 0.15	–	–
LOT	2021/22	−1.74	−6.72; 3.23	−9.49; 10.71	0.03	−0.02; 0.08	−0.02; 0.11	–	–
Synthetic control approach: effect on NO_x									
LAN	–	–	–	–	–	–	–	−10.15	−61.37; 41.07
STA	–	–	–	–	–	–	–	−5.02	−42.49; 32.46
LOT	–	–	–	–	–	–	–	−4.20	−37.34; 28.94

Abbreviations: LAN: Landshuter Allee, STA: Stachus, LOT: Lothstrasse; CI: Confidence interval; IE: Intervention effect. All level change values are in $\mu g/m^3$, all trend change values are in $\mu g/m^3$ per day, results of the synthetic control are in $\mu g/m^3$ (NO_2 equivalents). We report NO_2 equivalents for NO_x concentrations to standardize the mix of NO and NO_2, as they have different molecular weights. This standardization enables comparison of results with those of other analyses.

3.4. Secondary analyses

For the controlled interrupted time series approach, we selected 2021/22 as the main control year for all monitoring stations. Table 3 summarizes the results of the cITS approach. The level change refers to an immediate shift in NO_2 concentrations following the intervention in the intervention year compared to the control year, while a trend change refers to a post-intervention alteration in the rate of change of NO_2 concentrations over time. Landshuter Allee exhibits a negative level change of −2.24 μg/m^3 (95 %-CI = [-12.13; 7.65]). Both Stachus and Lothstrasse also show a negative level change, albeit smaller in size than at Landshuter Allee. For Stachus, the level change was −1.70 μg/m^3 (95 %-CI = [-7.3 to 3.91]), whereas for Lothstrasse it was –1.74 μg/m^3 (95 %-CI = [-6.72 to 3.23]). As was the case in the main analysis, wide confidence intervals of the estimates in the secondary analysis indicate uncertainties regarding the magnitude and direction of the estimated effects. For all three monitoring stations, the trend change post-intervention was negligible.

In addition to the estimators and confidence intervals for the main control year, Table 3 also provides the range of the estimators for level and trend change observed across all control years. Choosing different control years had a notable impact on the results, as the estimators for level and trend change varied considerably across control years. Detailed results for all control years can be found in eTable 8 in the supplementary material.

Table 3 also displays the results of the post-hoc analysis of the SC approach using NO_x as the outcome. The average intervention effects for all three monitoring stations were larger for NO_x than for NO_2, yet, as for the main analyses, large confidence intervals indicate uncertainty about the size and direction of the effects for this outcome as well. At Landshuter Allee, the average intervention effect for NO_x was −10.15 μg/m^3 (95 %-CI = [-61.37; 41.07]). At Stachus, the average intervention effect was smaller at −5.02 μg/m^3 (95 %-CI = [-42.49; 32.46]). Similarly, for Lothstrasse, the average intervention effect was −4.20 μg/m^3 (95 %-CI = [-37.34; 28.94]).

4. Discussion

4.1. Summary and key findings

Road traffic is a major source of air pollution in cities worldwide, contributing significantly to PM, NO_2 and greenhouse gas emissions, highlighting the urgent need for interventions to mitigate the adverse health effects associated with these pollutants (European Environment Agency, 2016). In light of this, the WHO recommends a target NO_2 average yearly concentration below 10 μg/m^3 (WHO, 2021). While the current EU directive sets a considerably higher threshold of 40 μg/m^3 for NO_2, the EU is likely to tighten these limits, as indicated by the approval by several decision-making bodies at the European level of a provisional political agreement that would bring these limits closer to the WHO recommendations. This agreement seeks to reduce the current limit of 40 μg/m^3 to 20 μg/m^3 by 2030 and further decrease it thereafter (Council of the EU, 2024). In an effort to reduce NO_2 concentrations, the city of Munich introduced a ban on diesel Euro 4 and older vehicles in Munich's low-emission zone on February 1, 2023.

While our findings indicate a modest reduction in NO_2 concentrations following this intervention, wide confidence intervals in both our main and secondary analyses indicate large uncertainties regarding the presence and magnitude of these effects. Additionally, regardless of the confidence intervals, it is questionable whether the reductions we estimated are sufficient to meaningfully mitigate health risks and meet the stringent thresholds set by the WHO and potentially by the EU in the future (Council of the EU, 2024; WHO, 2021).

4.2. Interpretation and contextualization of results

There are several factors that may partially explain the limited impact of the selective diesel vehicle ban in Munich. First, the diesel vehicle ban in Munich focused solely on Euro 4 and older vehicles, despite representing only a small percentage of registered vehicles (Gerstenberger, 2023). As described in Table 1, around 5 % of personal vehicles and 28 % of heavy commercial vehicles that were registered at the time of the intervention in Munich were diesel vehicles categorized as Euro 4 or below. Euro 5 and 6 diesel vehicles represent a much larger share—24 % of personal vehicles and 68 % of commercial vehicles (Gerstenberger, 2023). While vehicles not registered in Munich that travel into the city are also affected by the selective diesel ban, the proportions of Euro 4, 5, and 6 vehicles registered in all of Germany show a similar pattern (KBA, 2023). The selective targeting of only diesel vehicles categorized as Euro 4 and below may have constrained the intervention's effect in reducing NO_2 emissions. Second, the presence of numerous exemptions and the low administrative hurdles to exercise these exemptions further reduced the number of vehicle owners affected by the selective ban and thus may have diminished its impact. Third, real-world emissions from vehicles often exceed Euro classification limits, with only marginal differences observed in real-world measurements between Euro 4, 5, and 6 vehicles (European Environment Agency, 2016; Umweltbundesamt, 2019). Fourth, limiting the diesel vehicle ban to Euro classifications 4 and lower, which are categorized based on NO_x emissions, may not have the desired impact on NO_2, as it is unclear how large the share of NO_2 in NO_x is for the different Euro classifications, especially under real-world driving conditions (European Environment Agency, 2016). Fifth, uncertainties regarding the enforcement of the selective ban, which in turn raises questions about adherence among vehicle owners, may have further decreased the effectiveness of the intervention. The modest – if any – reduction in NO_2 concentrations observed in Munich following the selective diesel vehicle ban suggests that this measure is likely not enough to improve air quality sufficiently.

A recent court ruling underscores this finding. The Bavarian Administrative Court (*BayVGH*) ruled on March 21, 2024, that the city of Munich must expand its selective diesel vehicle ban to include Euro 5 diesel vehicles. The court emphasized the need for the city to take effective measures to reduce air pollution. It focused on two specific monitoring stations where the NO_2 thresholds were exceeded in 2023: Moosacher Strasse, which is located outside of the low emission zone and has been operated by the city of Munich since January 2023, and Landshuter Allee. The court gave the city the option to implement either a zone-based or route-specific ban on Euro 5 diesel vehicles (BayVGH, 2024). On April 24, 2024, Munich's city council decided instead to introduce a speed limit of 30 km/h on the most heavily polluted part of Landshuter Allee and to file a complaint about a clause in the court ruling that an appeal would not be possible.

Possible next steps in Munich could be advancing to phase 2 of the selective ban or exploring measures more comprehensive than a selective diesel ban. Existing research has observed mixed effects of interventions restricting vehicular emission sources and has highlighted the importance of carefully designing, implementing, and evaluating such interventions (Burns et al., 2019). Some studies suggest that more stringent low-emission zones or congestion charging zones, such as London's Ultra Low Emission Zone and Stockholm's congestion pricing scheme, have been able to significantly reduce air pollution in cities (Chamberlain et al., 2023; Johansson et al., 2009; Prieto-Rodriguez et al., 2022). Other studies, however, have shown smaller effects or no effects of such interventions (Burns et al., 2019; Nieuwenhuijsen and Khreis, 2016). Further approaches that could serve as alternatives or complements to interventions restricting vehicles include promoting active travel and public transport use, speed limit regulation or reduction, and restricting parking spaces (Khreis et al., 2023). However, it is crucial to carefully consider not only the likely impact of such interventions on air quality but also their economic and social implications. Longer-term planning and early, transparent communication are also advisable to increase population acceptability and feasibility of implementation of such policies.

4.3. Strengths and limitations

This study employed a quasi-experimental design, leveraging both the SC and cITS approaches. These methods are well-established in evaluating temporal changes due to an intervention by establishing counterfactuals that can be compared to observed outcomes. Combining both of these approaches strengthens the robustness of our study. Historical controls were utilized to ensure that observed changes in NO_2 concentrations were not solely due to seasonal patterns or other confounding factors. This approach adds rigor to the study by providing a comparison against baseline trends over several years, minimizing bias associated with short-term fluctuations (Lopez Bernal et al., 2018).

Potential confounders such as temperature, rainfall, air pressure, humidity, wind speed, sunshine duration, day of the week, and holidays were accounted for in the analyses. Doing so strengthens the validity of the findings by controlling for factors that may influence NO_2 concentrations independently of the intervention.

Robustness checks, including several placebo analyses, enhanced the reliability of our findings by minimizing the possibility that observed effects are not driven by factors unrelated to the intervention.

The study defined hypotheses and analyses a priori and registered a study protocol before data collection, promoting transparency and reducing the risk of selective reporting bias (Leibinger et al., 2024).

However, this study also has limitations. The study relies on available air quality data, which show limitations with regards to the limited number and specific location of monitoring stations. While both Landshuter Allee and Stachus serve as urban traffic monitoring stations that should be capable of detecting meaningful changes in air quality due to traffic, they do not offer a representative picture of the entire low-emission zone area. Further, wind direction may affect measured NO_2 concentrations, depending on the spatial positioning of monitoring stations relative to roadways, potentially facilitating the transport of pollutants toward or away from the monitoring stations.

Additionally, the exclusion of certain years due to COVID-19-related measures that likely influenced air quality may impact the completeness and reliability of the data used in the analysis. The data also feature significant daily variation, which poses challenges to statistical analyses; however, a sensitivity analysis suggested that this did not meaningfully influence results.

While the study assumes that the selective diesel vehicle ban led to reductions in NO_2 concentrations, it cannot directly assess the causal chain linking the intervention to changes in human behavior followed by traffic patterns and, subsequently, air quality. The lack of reliable data on traffic, on the degree of enforcement of and adherence to the selective ban, as well as on exemptions presents a challenge in establishing a clear causal pathway.

Further, despite the known reactivity between ozone and NO_2 (Jaroszyńska-Wolińska, 2010), we did not include ozone as a covariate, as ozone concentrations were not available for all monitoring stations throughout the study duration.

Our study design was not able to detect any rerouting of banned vehicles that may have led to increased concentrations of NO_2 in areas outside of the low-emission zone. This is due to limited data availability, as there are no monitoring stations located in highly trafficked areas outside of the low-emission zone.

The findings of the study may be specific to the context of Munich and may not be generalizable to other cities or regions with different air quality profiles, traffic patterns, or regulatory environments. Therefore, caution should be exercised when extrapolating the results to other settings.

4.4. Conclusions

Our study observed modest reductions in NO_2 concentrations following the introduction of the selective diesel vehicle ban, yet with wide confidence intervals, which suggest small, if any, effects of the selective diesel ban. Selectively targeting Euro 4 and older diesel vehicles, alongside numerous exemptions and enforcement uncertainties, may have limited its impact. These findings suggest a need for more comprehensively designed interventions to effectively mitigate urban air pollution. Decisions on future measures should be informed by careful consideration of observed trends and potential alternatives, balancing environmental and health benefits with economic and social implications as well as feasibility considerations. While there is a growing body of evidence on the effectiveness of various urban air quality interventions, more robust evidence is needed to better understand their impact. As a first step, cities should ensure that monitoring stations are strategically located to capture all main traffic areas, and collect data on NO_2, NO, ozone, and fine particulate matter and, where feasible, ultrafine particulate matter and additional pollutants. Rigorous monitoring and evaluation of air quality interventions and a thorough examination of implementation modalities in the local context, are essential for informing policy decisions and promoting public health – in Munich and elsewhere.

Ethics approval

No human subjects were involved in this research and no ethical clearance was required according to the regulations of the Ethics Committee of Ludwig-Maximilians-Universität München (LMU Munich).

CRediT authorship contribution statement

Anna Leibinger: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Eva Rehfuess:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jacob Burns:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization.

Funding

This research received no external funding.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: ER declares owning a Diesel Euro 4 vehicle. The other 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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2024.109067.

Data availability

Data are publicly available, as outlined in section 2.4.

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