Urban Air Quality and Traffic Policy

A Difference-in-Differences Study of Stockholm Hornsgatan

Fredrik Pears

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Fredrik Pears

Supervisor:	**Jonathan Stråle, Swedish University of Agricultural Sciences, Department of Economics**
Examiner:	Shon Ferguson, Swedish University of Agricultural Sciences, Department of Economics

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Swedish University of Agricultural Sciences
Faculty of Natural Resources and Agricultural Sciences
Department of Economics

Abstract

This study attempts to estimate the causal effect of Sweden's first passenger car low emission zone on street-level PM10 concentrations. This is done by looking at the miljözon klass 2 which was introduced on Hornsgatan in Stockholm in January 2020, using a difference-in-differences design with Malmö's Dalaplan as a control street. Weekly mean PM10 concentrations are compared between the treated and control streets using a data set spanning from 2015 to 2024. The preferred specification yields a DiD coefficient of 1.574 µg/m³ (SE = 0.994), which is statistically insignificant at all conventional significance levels. A placebo test using Sveavägen as an alternative control street produces a similarly insignificant result. The event study reveals considerable pre-treatment coefficient volatility, raising concerns about the validity of the parallel trends assumption and limiting the conclusions that can be drawn from the estimates. Given these identification challenges, the results cannot be interpreted as definitive evidence either for or against the policy's effectiveness. The absence of a detectable effect is, however, consistent with documented enforcement failures. Stockholm's own post-implementation evaluation found that at most five fines were issued in the first year of operation despite widespread violations. This suggests that weak enforcement may have substantially undermined the zone's potential air quality impact. Future research should incorporate multiple treated units and exploit variation in LEZ adoption across Swedish municipalities to enable more credibly identified causal inference.

Keywords: Low emission zone; Miljözon; Difference-in-differences; PM10; Urban air quality; Hornsgatan; Sweden; Environmental Policy

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Abbreviations

Abbreviation	Description
DiD	Difference in Difference
FE	Fixed Effects
LEZ	Low Emission Zone
m/s	Meters per second
mm	Millimeters
$\mu g/m^3$	Micrograms per cubic meter
NO2	Nitrogen Dioxide
NOx	Nitrogen Oxides
PM2.5	Particulate Matter with aerodynamic diameter of 2.5 micrometres or less
PM10	Particulate Matter with aerodynamic diameter of 10 micrometres or less
SLB	Stockholms Luft- och Bulleranalys
SMHI	Sveriges meteorologiska och hydrologiska institut
SUTVA	Swedish University of Agricultural Sciences
ULEZ	Ultra Low Emission Zone
WoY	Week of Year

1. Introduction

Air pollution has long been a central concern within environmental economics due to the substantial social costs it imposes on society. Exposure to particulate matter and other traffic-related pollutants is associated with increased risks of respiratory and cardiovascular disease, reduced cognitive function, and premature mortality. The World Health Organisation estimates 4.2 million premature deaths annually attributable to ambient outdoor air pollution (WHO, 2024). Beyond direct health costs, air pollution imposes broader economic burdens. A 1 $\mu g/m^3$ increase in PM2.5 concentrations reduces European firm-level labour productivity by 0.55% (Dechezleprêtre & Vienne, 2025), and evidence from happiness data suggests that air pollution has a direct and economically significant negative effect on subjective wellbeing beyond its health impacts (Levinson, 2012). These costs reflect a negative externality where motorists driving high-emitting vehicles in urban areas impose costs on others that they do not themselves bear, constituting a market failure that justifies regulatory intervention.

In response to these externalities, a range of policies have historically been introduced with the aim of reducing traffic-related air pollution in urban areas. These include market-based instruments such as carbon taxes, fuel taxes, and congestion pricing, as well as direct regulatory measures such as vehicle emission standards, studded tyre bans, and low emission zones (LEZs). Among these, LEZs have emerged as one of the most widely adopted local policy instruments in Europe. LEZs are geographically defined areas within which access is restricted to vehicles meeting minimum emission standards, with the primary objective of reducing local air pollution concentrations (Delgado-Lindeman et al., 2025). First introduced in Sweden in 1996, LEZs have expanded rapidly across the continent. Growing from 228 in 2019 (Azdad et al., 2022) to 363 by October 2024, with Western and Central Europe hosting the majority and countries such as Germany, Italy, and France leading in terms of both number and distribution (Delgado-Lindeman et al., 2025)

This study explores the effectiveness of LEZs by investigating the introduction of a new LEZ in Sweden. A difference-in-differences design is employed exploiting the January 2020 policy introduction as a quasi-experimental treatment date. The design uses a street in Malmö, Dalaplan, as a control street and makes use of datasets spanning from 2015 to 2024. The preferred specification includes meteorological controls for wind speed, precipitation, and minimum and maximum temperature, alongside week-of-year, year, and location fixed effects. A placebo test using Sveavägen as an alternative control street is conducted to assess the robustness of the findings. Through this the study aims to answer the question: What was the causal effect of the introduction of miljözon klass 2 on Hornsgatan on street-level PM10 concentrations?

The evidence in the existing literature on LEZ effectiveness is mixed. Studies using causal methods find meaningful reductions in air pollution and associated health benefits in some settings. Using a difference-in-differences approach, London's LEZ is found to have significantly reduced PM10 by 12% of the baseline mean, and the subsequent ULEZ reduced NO2 by 12.4% and PM10 by 27% (Beshir & Fichera, 2022). German LEZs have also been found to generate small but statistically significant reductions in cardiovascular and respiratory disease (Pestel & Wozny, 2021). However, earlier evaluations relying on descriptive rather than causal methods find mixed results, with most studies failing to find clear effects on PM10 and NO2 when confounding factors are not adequately controlled for (Holman et al., 2015). This suggests that the effectiveness of LEZs is highly context-dependent, and that causal evaluation using quasi-experimental methods is necessary to draw reliable conclusions about their impact.

Sweden's own LEZ framework was significantly expanded in January 2020 when new legislation introduced a tiered class system called miljözon klass 1, 2, and 3. This legislation allows municipalities to restrict passenger cars for the first time. The legislation was structured as enabling rather than mandatory, giving municipalities the option to adopt the new classes voluntarily (Transportstyrelsen, 2024; Säfström, 2019). As a result, the new policy has had limited uptake, the sole implementation of a miljözon klass 2 in Sweden is on Hornsgatan in Stockholm's Södermalm district, introduced on January 15, 2020 (Burman & Johansson, 2020). Hornsgatan has a long history of air quality problems, successive interventions include the original implementation of an LEZ from 1996, the congestion tax from 2007, and a studded tyre ban from 2010. These implementations have been introduced on or around the street in response to persistent exceedances of environmental quality norms (Johansson et al., 2011; Säfström, 2019). Despite its unique status as Sweden's only passenger car LEZ and its direct policy relevance, no causal evaluation of the zone's air quality effects has been published to date. Stockholm's own post-implementation evaluation found that the zone reduced nitrogen oxide concentrations by only 2% compared to a zero alternative in 2020 (Burman & Johansson, 2020). This was far below the 11% reduction theoretically achievable under full compliance. Enforcement failures were identified as the primary explanation, as police reported issuing at most five fines in the entire first year of operation (Säfström, 2021). However this evaluation is descriptive in nature and cannot separate the causal effect of the LEZ from concurrent trends, seasonal variation, or the

COVID-19 pandemic, which independently reduced traffic volumes across Swedish cities in the same year.

This study contributes to the existing literature by providing the first causal evaluation of Sweden's miljözon klass 2. Following standard practice in the causal LEZ literature (e.g. Margaryan, 2021; Pestel & Wozny, 2021), the study combines a DiD specification with an event study to assess the parallel trends assumption underlying the design, providing the methodological transparency necessary to interpret the resulting estimates. The results show a DiD coefficient that is positive but statistically insignificant across all specifications, including a placebo test using an alternative control street. However, the event study reveals considerable pre-treatment volatility in the estimated coefficients, indicating that the parallel trends assumption may not be fully satisfied. As a result, the findings cannot be interpreted as conclusive evidence either for or against the effectiveness of the zone. Nonetheless, the absence of a detectable effect is consistent with the weak enforcement of the zone documented by Stockholm's own post-implementation evaluation, and the study highlights enforcement capacity as a central consideration for the design and evaluation of future LEZs in Sweden and elsewhere.

The remainder of the paper is structured as follows. Section 2 provides background on LEZs and the specific context of Hornsgatan. Section 3 describes the data and empirical methodology. Section 4 presents the results. Section 5 discusses the findings and their implications. Section 6 concludes.

2. Previous Literature

The specific design of LEZs varies substantially across national contexts in terms of geographic scope, vehicle types covered, emission standards applied, and the stringency of enforcement. Early evaluations of LEZ effectiveness largely relied on descriptive methods comparing pollution levels before and after introduction without adequately accounting for confounding factors such as weather, traffic trends, and broader fleet renewal (Holman et al., 2015). Evidence on the efficacy of LEZs to improve urban air quality across Denmark, Germany, the Netherlands, Italy, and the UK has produced mixed results. German LEZs may have reduced PM10 and NO2 concentrations by a few percent, but elsewhere no clear effects on PM10 and NO2 were observed, with most studies not taking confounding factors into account adequately (Holman et al., 2015). These mixed findings reflect the variation in LEZ effectiveness across contexts as well as the methodological limitations of descriptive evaluations that cannot credibly separate policy effects from concurrent trends. The conclusion drawn by Holman et al. (2015) is that most LEZ studies lack adequate controls for confounding which directly motivates the quasi-experimental approach adopted in the present study.

More recent studies applying causal methods have found clearer and more consistent evidence of air quality improvements. Using a difference-in-differences (DiD) approach with linked survey and administrative data, London's LEZ is found to have significantly reduced PM10 by 12% of the baseline mean, and the subsequent Ultra Low Emission Zone (ULEZ) reduced NO2 by 12.4% and PM10 by 27% (Beshir & Fichera, 2022). Evidence from Germany similarly finds positive effects. Pestel and Wozny (2021) exploit variation in the timing and spatial distribution of LEZ introductions across German cities since 2008, finding that LEZs reduce levels of air pollution and generate small but statistically significant reductions in diagnoses of circulatory and chronic lower respiratory diseases. Margaryan (2021) corroborates these findings using a complementary dataset, finding a 2–3% reduction in cardiovascular disease patients attributable to German LEZs, with effects concentrated among those aged 65 and above. The finding that German LEZs generate statistically significant reductions in cardiovascular and respiratory health outcomes is consistent across both studies despite their use of different datasets and slightly different DiD specifications, strengthening confidence in the causal interpretation of these effects.

Evidence from Japan provides further support. A study of Greater Tokyo's LEZ uses a matching approach to construct a comparable control group before applying a DiD design, finding reductions in hourly particulate matter concentrations and the incidence of low birthweights. This suggests that LEZinduced air quality improvements have detectable effects on birth outcomes in addition to the cardiovascular and respiratory effects documented in the European literature (Nishitateno & Burke, 2024).

In Spain, a study of Madrid's LEZ introduced in 2018 uses a DiD design and finds statistically significant reductions in NO_2 concentrations in the years following implementation. The study also documents a significant increase of 0.20 standard deviations in university admission exam scores among high schools located within the zone. This is an innovative finding that connects air quality improvements to cognitive outcomes and academic performance (Valdés et al., 2025).

The literature reviewed above highlights two methodological lessons that inform the present study. First, descriptive evaluations consistently produce unreliable estimates because they cannot adequately control for confounding trends. This motivates the use of a DiD design with a control street, meteorological controls, and fixed effects. Second, the magnitude of estimated LEZ effects varies substantially across contexts depending on enforcement, zone design. A further methodological challenge noted in the literature is that LEZs do not impact non-exhaust PM emissions from traffic, such as road surface wear and brake dust. This may be an equally or more important source of PM_{10} than exhaust emissions, meaning that the scope for LEZs to reduce measured PM_{10} concentrations is inherently limited even under full compliance (Holman et al., 2015).

3. Background

Low emission zones (LEZs) are geographically defined areas within which access is restricted to vehicles meeting minimum emission standards, with the primary objective of reducing local air pollution concentrations (European Commission, n.d.). The restrictions vary considerably across cities and countries, but the zones are typically implemented in dense urban areas where traffic-related air pollution is most concentrated and where population exposure is highest, such as city centres and heavily trafficked corridors (European Commission, n.d.).

The environmental zones introduced in Sweden in 1996 can be considered the first LEZ programme in Europe. Following the Swedish example, low emission zones were implemented in a few cities in Germany, the Netherlands, northern Italy, and London in 2007–2008, and since then the number of LEZs has been steadily increasing (Holman et al., 2015; Delgado-Lindeman et al., 2025). The number of active LEZs in Europe grew from 228 in 2019 to 320 by June 2022 (Azdad et al., 2022) and 363 by October 2024 (Delgado-Lindeman et al., 2025). Initially focused on trucks and buses, LEZs have progressively expanded to encompass all motorised vehicle types, with access restrictions becoming increasingly stringent across European cities (Delgado-Lindeman et al., 2025)."

The Swedish LEZ system, known as *miljözoner*, has evolved considerably since its introduction in 1996. From 1 January 2020, municipalities gained the ability to introduce miljözon klass 1, 2, or 3, as a measure to improve air quality in specific areas (Transportstyrelsen, 2024). This tiered system expanded the scope of Swedish LEZs from heavy vehicles alone to include passenger cars for the first time. Klass 1 restricts heavy buses and trucks, this is equivalent to the original LEZs in Sweden from 1996. Klass 2 restricts passenger cars, light buses, and light goods vehicles, requiring petrol vehicles to meet Euro 5 or Euro 6 standards and diesel vehicles to meet Euro 6 (Transportstyrelsen, 2024). Class 3 covers only electric vehicles, fuel cell vehicles, and gas vehicles, with gas vehicles required to meet Euro 6 standards. The sole implementation of a class 2 zone in Sweden is on Hornsgatan in Stockholm, introduced on January 15, 2020 (Burman & Johansson, 2020; Säfström, 2019). This makes it a unique case for evaluating the causal air quality effects of this policy instrument._

Hornsgatan is a heavily trafficked street running through Stockholm's Södermalm district and has long had issues with air pollution (Burman & Johansson, 2020). This has led to many policies being implemented with the aim of mitigating the effects of air pollution in the area. Hornsgatan was, as early as 1996, part of the first Swedish LEZ system restricting trucks and buses. Additionally, Stockholm introduced a congestion tax in 2007 which levies a charge on most vehicles entering and exiting the city centre. Although the implementation was city wide with the primary goal of decreasing traffic congestion, it still improved Hornsgatan's air quality due to reduced traffic. Stockholm also introduced a ban on the use of studded tyres on Hornsgatan in 2010. This was in response to levels of PM10 exceeding the Environmental quality standard (Johansson, Norman & Burman, 2011). The studded tyre percentage decreased, as did total traffic, leading to a decrease of PM10 of almost 20% (Johansson, Norman, & Burman, 2011). Finally, the miljözon klass 2 tightening was introduced in 2020 (Burman & Johansson, 2020).

The introduction of miljözon klass 2 on Hornsgatan was motivated by the persistent exceedance of environmental quality norms for nitrogen dioxide and particulate matter. As documented in the pre-implementation report, the daily mean value for nitrogen dioxide was exceeded on 13 days in 2018, against a legal maximum of 7 days per year, and the hourly mean value was exceeded 185 hours against a maximum of 175 hours (Säfström, 2019). The zone was therefore introduced explicitly as a regulatory response to a documented air quality problem on a specific street. Stockholm's own post-implementation evaluation estimated that under full compliance, nitrogen oxide concentrations would decrease by 11% relative to a zero alternative. The actual reduction measured was, however, only 2%. The evaluation high-lights that measurements coincided with the COVID-19 pandemic which caused a roughly 30% reduction in traffic and therefore cannot be considered representative of normal conditions (Säfström, 2021). The report also documents that police estimated at most five fines had been issued for class 2 violations in the entire first year of operation, due to enforcement being limited to incidental checks during other operations rather than targeted surveillance (Säfström, 2021). These official evaluations are descriptive in nature and cannot separate the causal effect of the LEZ from concurrent trends, seasonal variation, or the confounding effects of COVID-19, motivating the difference-in-differences design adopted in the present study.

While the primary regulatory motivation for the zone concerned nitrogen dioxide, PM10 is used as the outcome variable in this study as a broader indicator of street-level air quality. Hornsgatan has a well-documented history of PM10 exceedances making it a relevant and historically significant air quality indicator for this street specifically. It should however be acknowledged that PM10 on Hornsgatan is substantially driven by non-exhaust sources such as road surface wear and brake dust, meaning the link between Euro emission class restrictions and PM10 is more indirect than for nitrogen oxides. Any detected effect on PM10 would therefore likely reflect reduced traffic volumes or broader traffic composition changes rather than a direct exhaust emission reduction. Both the Hornsgatan and Dalaplan monitoring stations report continuous PM10 measurements, and Malmö's

Dalaplan is used as the control street, exploiting the January 2020 introduction of the zone as a quasi-experimental treatment date.

4. Method and Data

The primary empirical challenge in evaluating the effect of the Class 2 Low Emission Zone (LEZ) on PM10 concentrations is finding what PM10 levels on Hornsgatan would have been in the absence of the policy. To address this, a Difference-in-Differences (DiD) framework is employed, which has become a standard quasi-experimental approach in environmental and urban economics (Angrist & Pischke, 2009).

The DiD estimator is a quasi-experimental method used to estimate the causal effect of a policy intervention by comparing the change in outcomes over time between a treated group and an untreated control group (Angrist & Pischke, 2009). The core intuition is that while the treated and control units may differ in their baseline levels of the outcome variable, they are assumed to follow parallel trends in the absence of treatment. This means that any post-treatment divergence between the two groups can be attributed to the policy rather than pre-existing differences. This is the so-called parallel trends assumption, which needs to hold for a causal interpretation of the results.

The baseline DiD estimator can be expressed as:

$$\delta_{DiD} = \left(\bar{Y}_{treated,post} - \bar{Y}_{treated,pre}\right) - \left(\bar{Y}_{control,post} - \bar{Y}_{control,pre}\right)$$

Where $\bar{Y}$ denotes the mean outcome for each group in each period. The first term captures the change in the outcome for the treated unit over time. Whilst the second term shows how much of that change would have occurred anyway in the absence of treatment, as estimated from the control unit.

4.1 Choice of Control Street

The selection of an appropriate control street is critical to the validity of the DiD design. For Dalaplan to serve as a credible control, it must satisfy two broad criteria: it must be comparable to Hornsgatan in terms of the characteristics that drive PM10 concentrations, and it must be unaffected by the treatment. Dalaplan is a heavily trafficked urban street in central Malmö, classified as an urban traffic monitoring station by the national air quality database, making it structurally comparable to Hornsgatan in terms of traffic exposure and street-level pollution dynamics. Malmö also does not operate a class 2 passenger car LEZ, this means that Dalaplan was not subject to the treatment during the study period. The use of a control street in a different city, rather than a neighbouring Stockholm street such as Sveavägen, is motivated by the risk of spillover effects. If the introduction of the LEZ on Hornsgatan displaced non-compliant vehicles onto adjacent

Stockholm streets, a Stockholm-based control street could be indirectly affected by the treatment, violating the control group's untreated status. By using Dalaplan in Malmö, which is geographically remote from the treated area, this spillover concern is substantially mitigated. A robustness check using Sveavägen as an alternative Stockholm-based control is nonetheless conducted and reported in column (6) of Table 1, allowing assessment of whether the choice of control street materially affects the findings.

4.2 Stable Unit Treatment Value Assumption

The DiD estimator relies on the Stable Unit Treatment Value Assumption (SUTVA), which requires that the potential outcomes of one unit are not affected by the treatment status of another unit (Rubin, 1980). In the present context, SUTVA requires two things to hold. First, the treatment received by Hornsgatan must be well-defined and consistent: the class 2 LEZ applies uniformly to the full length of Hornsgatan covered by the local traffic regulation, and its introduction date of 15 January 2020 is clearly defined, satisfying this requirement. Second, the introduction of the LEZ on Hornsgatan must not affect PM10 concentrations on Dalaplan, the control street.

Two potential channels could threaten this second requirement. The first is traffic displacement, whereby non-compliant vehicles rerouted from Hornsgatan increase traffic and PM10 elsewhere. Displacement onto Dalaplan itself can be ruled out given the geographic distance between Stockholm and Malmö. However, a partial violation cannot be excluded at the local Stockholm level, since displaced vehicles may have increased traffic and PM10 on nearby Stockholm streets such as Sveavägen. This is the main motivation for using Dalaplan rather than a Stockholm street as the control, as discussed above, and any remaining local displacement effects would in any case be captured by the Sveavägen placebo test.

The second potential channel is an information spillover, whereby awareness of the Hornsgatan LEZ among drivers elsewhere in Sweden could indirectly affect behaviour in Malmö (Clarke, 2017). This is unlikely to be empirically relevant in the present setting: miljözon klass 2 has not been adopted in Malmö, and there is no plausible mechanism by which awareness of restrictions applying exclusively to a specific street in Stockholm would alter driving behaviour on Dalaplan. Even if such a spillover existed, it would most likely bias the DiD estimate toward finding a larger effect of the LEZ than truly exists, rather than toward the null result observed here.

4.3 DiD Specification

In the present study, the regression-based DiD specification is estimated as follows:

$$PM10_{it} = \alpha + \beta_1 DiD_{it} + \beta_2 Precipitation_{it} + \beta_3 Windspeed_{it} + \beta_4 TempMin_{it} + \beta_5 TempMax_{it} + \gamma_i + \delta_t + \varphi_{woy} + \varepsilon_{it}$$

Where $PM10_{it}$ is the weekly mean PM10 concentration in µg/m³ for street i in week t. DiD_{it} is the interaction term $Treated_i \times Post_t$, equal to 1 for Hornsgatan in the post-treatment period (from 15 January 2020 onwards) and 0 otherwise. This is the key coefficient of interest β_1, which captures the causal effect of the LEZ on PM10 concentrations, given that the identifying assumptions discussed above hold. γ_i are the location fixed effects, which controls for all time-invariant differences between Hornsgatan and Dalaplan. δ_t denotes year fixed effects, absorbing common year-to-year shocks affecting both streets. These will e.g. absorb the effect of Covid 19 on traffic, to the extent that the effects are the same in Malmö and Stockholm. φ_{woy} denotes week-of-year fixed effects, absorbing seasonal patterns in PM10 concentrations that recur systematically across years. The meteorological controls, wind speed, precipitation, minimum temperature, and maximum temperature, are included to account for week-specific weather variation that affects PM10 concentrations independently of the LEZ. ε_{it} is the error term. The data covers the period from January 1st 2015 to December 31st 2024, providing five years of pre-treatment observations and five years of post-treatment observations. Standard errors are heteroskedasticity-robust throughout (Huber, 1967; White, 1980).

4.4 Event Study

The validity of the DiD estimator rests entirely on the parallel trends assumption. The parallel trends assumption is that in the absence of the LEZ the PM10 concentrations on Hornsgatan and Dalaplan would have evolved along parallel trajectories over time. This assumption is fundamentally untestable for the post-treatment period, since we cannot observe the counterfactual. However, it can be assessed empirically in the pre-treatment period by testing whether the two streets exhibited parallel trends prior to January 2020 (Angrist & Pischke, 2009).

This is evaluated through an event study specification, which replaces the single DiD coefficient with a series of period-specific estimates:

$$PM10_{it} = \alpha + \sum_{k=1, k\neq 65}^{130} \beta_k (Treated_i \times 1[month = k]) + \beta_w Windspeed_{it} + \beta_p Precipitation_{it} + \beta_{Tmin} TempMin_{it} + \beta_{Tmax} TempMax_{it} + \gamma_i + \delta_t + \varphi_{woy} + \varepsilon_{it}$$

Where k indexes four-week periods from $k = 1$ (January 2015) to $k = 130$ (December 2024), constructed using the ceiling function applied to the week number such that each period contains approximately four weekly observations. This construction avoids the complications arising from partial calendar months at the boundaries of the data period and around the treatment date and is preferred to standard calendar month aggregation for this reason. The period $k = 65$ is the four-week period immediately preceding the treatment date of January 15, 2020. This period is omitted as the reference category, normalising all event study coefficients relative to the pre-treatment baseline.

β_k are the event study coefficients of interest. For pre-treatment periods $k < 65$, these coefficients capture the differential trend between Hornsgatan and Dalaplan prior to the introduction of the zone, after controlling for the fixed effects and meteorological control variables. Under the parallel trends assumption, pre-treatment coefficients should be statistically indistinguishable from zero, indicating no systematic pre-existing divergence between the two streets. Significant or systematically non-zero pre-treatment coefficients would indicate a violation of this assumption and would undermine the causal interpretation of the DiD estimate. For post-treatment periods $k > 65$, the coefficients trace the dynamic treatment effect of miljözon klass 2 on PM10 concentrations in each period following implementation, allowing assessment of whether any effect was immediate or gradual, and whether it persisted or dissipated over the post-treatment period. Year fixed effects are included with 2019 omitted as the reference year, consistent with the main specification. Location and week-of-year fixed effects are included throughout. Standard errors are heteroskedasticity-robust.

4.5 Time Fixed Effects

A key methodological challenge in the setting is the choice of time fixed effects. Ideally weekly fixed effects would be included to absorb all common weekly shocks including seasonal variation and the Covid-19 pandemic. However, with only two locations, including both weekly fixed effects and monthly treatment interaction dummies leads to perfect multicollinearity since each treated dummy is perfectly collinear with the combination of weekly fixed effects and location fixed effects.

To address this yearly, fixed effects are used instead, to control for year-specific common shocks and week of year fixed effects to control for recurring seasonal patterns in PM10 concentrations. Together these capture both year-specific variation and seasonal cyclicality without inducing perfect multicollinearity.

4.6 Data

All datasets used in the econometric specification are sourced from Sweden's Meteorological and Hydrological Institute (SMHI). The dataset can be divided into two categories: meteorological control variables and air quality outcome variables. All datasets cover the period from 1 January 2015 to 31 December 2024, providing a dataset including five years of pre-treatment and five years of post-treatment observations.

Meteorological data is obtained from two weather stations selected on the basis of geographic proximity to the respective air quality monitoring stations. Weather conditions in Stockholm, used for Hornsgatan and Sveavägen, are drawn from the Stockholm-Bromma Flygplats station. Weather conditions in Malmö, used for Dalaplan, are drawn from the Malmö A station. The meteorological variables included are wind speed, precipitation, and minimum and maximum temperature. Wind speed is measured at station level as the average local wind speed over a ten-minute duration, recorded once per hour, and reported in metres per second (m/s). Precipitation is measured as the accumulated liquid equivalent in millimetres (mm) recorded hourly. Minimum and maximum temperature are measured twice daily at station level, once at 06:00 and once at 18:00, the minimum and maximum values of the two daily readings are then recorded in degrees Celsius. Minimum and maximum temperature are included rather than daily mean temperature to capture the effects of extreme cold on vehicle cold-start emissions and of high temperatures on atmospheric chemistry affecting PM10 concentrations. All meteorological variables are aggregated to weekly values prior to estimation. Wind speed and minimum and maximum temperature are aggregated as weekly means, while precipitation is aggregated as the weekly sum to reflect the total accumulated rainfall over each period.

Air quality data are obtained from three street-level monitoring stations: Stockholm Hornsgatan 108 Gata, Malmö Dalaplan, and Stockholm Sveavägen 59 Gata. The outcome variable, PM10 concentration, is measured in micrograms per cubic metre (µg/m^3) at an hourly frequency. Hourly observations are aggregated to weekly mean values prior to estimation, consistent with the aggregation applied to the meteorological control variables.

5. Results

Table 1 presents the DiD estimates across six specifications, progressively adding meteorological controls. The baseline specification in column (1) includes week-of-year, year, and location fixed effects without any weather controls, yielding a DiD coefficient of 0.923 µg/m³ (SE = 1.056). Controls are added sequentially with wind speed in column (2), precipitation in column (3), minimum temperature in column (4), and maximum temperature in column (5). The DiD coefficient remains positive and statistically insignificant throughout, ranging from 0.923 to 1.574 µg/m³. The preferred specification in column (5), which includes the full set of meteorological controls alongside all fixed effects, yields a DiD coefficient of 1.574 µg/m³ (SE = 0.994). This corresponds to approximately 8.5% of the sample mean PM10 concentration of 18.46 µg/m³. This coefficient is statistically indistinguishable from zero at all conventional significance levels, indicating no detectable causal effect of miljözon klass 2 on weekly mean PM10 concentrations on Hornsgatan relative to Dalaplan.

Tabell 1: Difference-in-Differences Estimates of the Effect of Miljözon Klass 2 on Weekly Mean PM10 Concentrations (µg/m³)

Variables	(1)	(2)	(3)	(4)	(5) Preferred specification	(6) Placebo test
DiD	0.923 (1.056)	1.347 (1.073)	1.172 (1.049)	1.420 (1.030)	1.574 (0.994)	-1.059 (0.903)
Windspeed		-1.427*** (0.414)	-0.808* (0.420)	-1.808*** (0.425)	-0.924** (0.409)	
Precipitation			-26.27*** (2.948)	-26.32*** (2.967)	-15.47*** (3.062)	
Temperature(min)				0.803*** (0.112)	-0.494** (0.194)	
Temperature (max)					1.491*** (0.203)	
Mean PM10 concentration	18.438	18.438	18.456	18.463	18.463	18.829
Observations	1,036	1,035	1,032	1,031	1,031	1,031
R-squared	0.355	0.363	0.393	0.423	0.470	0.598
WoY FE	YES	YES	YES	YES	YES	YES
Year FE	YES	YES	YES	YES	YES	YES
Location FE	YES	YES	YES	YES	YES	YES

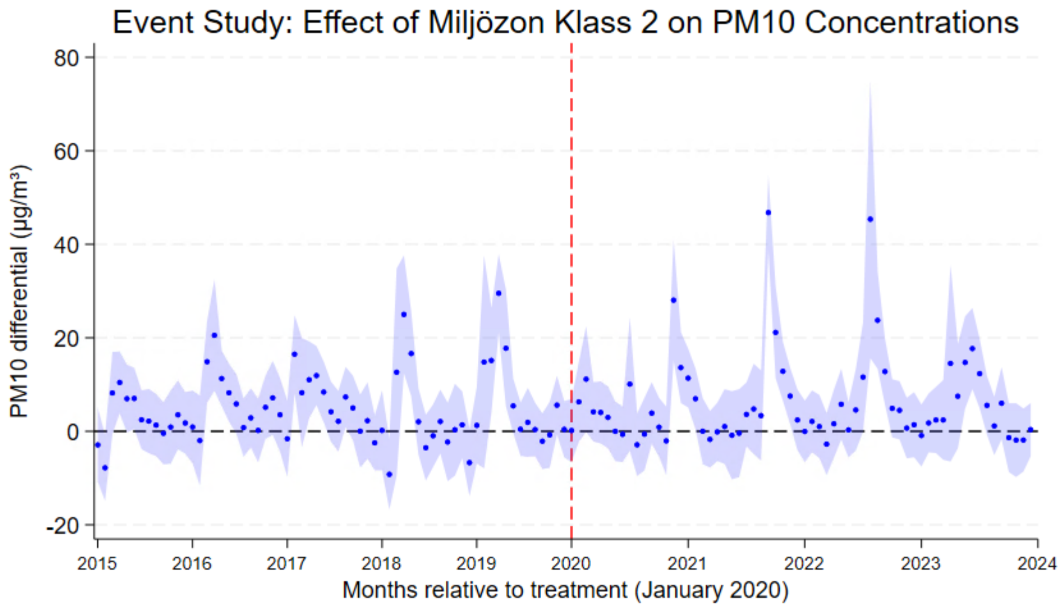
Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Columns (1)–(5): Hornsgatan (treated) vs Dalaplan (control). Column (6): Hornsgatan vs Sveavägen (placebo)

The meteorological controls perform as theoretically expected. Wind speed is negatively associated with PM10 concentrations (−0.924**, SE = 0.409), consistent with higher wind speeds dispersing particulate matter at street level. Precipitation is strongly negatively associated with PM10 (−15.47***, SE = 3.062), reflecting the well-documented washout effect of rainfall on airborne particles. The temperature coefficients show opposing signs, where minimum temperature is negatively associated with PM10 (−0.494**, SE = 0.194) while maximum temperature is positively associated (1.491***, SE = 0.203). This suggests a nonlinear relationship between temperature and particulate concentrations consistent with the role of atmospheric mixing and cold-start vehicle emissions. The R^2 increases substantially from 0.355 in the baseline specification to 0.470 in the preferred specification, confirming that meteorological conditions are important determinants of weekly PM10 variation.

The placebo test in column (6) replaces Dalaplan with Sveavägen, a comparable inner-city Stockholm street not subject to the class 2 LEZ. The DiD coefficient is −1.059 (SE = 0.903), also statistically insignificant. The consistency of the null result across both control streets provides reassurance that the finding is not driven by an idiosyncratic feature of the Hornsgatan–Dalaplan comparison.

Figure 1 presents the event study estimates, plotting the monthly treatment-control differential in PM10 concentrations relative to the four-week reference period immediately preceding the treatment date. Two features of the plot are noteworthy. First, the post-treatment coefficients show no systematic downward shift following the introduction of the zone in January 2020, consistent with the null result in Table 1. Second, and more importantly for identification, the pre-treatment coefficients display considerable volatility and do not consistently cluster around zero throughout the 2015–2019 period. Under the parallel trends assumption, pre-treatment coefficients should be statistically indistinguishable from zero, indicating that Hornsgatan and Dalaplan were evolving in parallel before the policy was introduced. The observed pre-treatment volatility raises concerns about whether this assumption is fully satisfied, and suggests that the results should be interpreted with caution.



Figur 1: Event study estimates of the effect of miljözon klass 2 on PM10 concentrations on Hornsgatan relative to Dalaplan.. The red dashed line indicates the introduction of the zone in January 2020. The omitted reference period is the four-week period immediately preceding the treatment date. Shaded areas represent 95% confidence intervals. Standard errors are heteroskedasticity-robust.

6. Discussion

6.1 Biases and Measurement Errors

Several potential sources of bias and measurement error should be acknowledged when interpreting the findings of this study.

6.1.1 Parallel trends violation

As documented in the event study, the pre-treatment coefficients display considerable volatility and do not consistently cluster around zero throughout the 2015–2019 period. This raises concerns that the parallel trends assumption which is the core identifying assumption of the DiD design may not be fully satisfied. If Hornsgatan and Dalaplan were already diverging in PM10 trends before the introduction of the LEZ for reasons unrelated to the policy, the DiD estimate may be biased in an indeterminate direction. This is the most significant identification concern in the study and means the null result cannot be interpreted as definitive evidence of policy ineffectiveness.

6.1.2 Non-random treatment selection

Hornsgatan was deliberately chosen for the class 2 LEZ because it had the worst air quality record in Stockholm, which is the opposite of random assignment. This creates a potential mean reversion concern: if PM10 on Hornsgatan was already on a declining trajectory due to regression to the mean, the DiD estimator may understate a true treatment effect by attributing part of the pre-existing decline to the counterfactual trend estimated from Dalaplan. The long pre-treatment period from 2015 to 2019 partially mitigates this concern by allowing a thorough assessment of pre-trends, but cannot fully resolve it.

6.1.3 Single treated unit

The design relies on a single treated street, Hornsgatan, which limits the precision of the DiD estimates. This in turn means that the results are sensitive to any idiosyncratic shock specific to Hornsgatan that happened to coincide with January 2020. With a single treated unit it is not possible to average out such idiosyncratic variation, which standard DiD designs with multiple treated units would allow. This constraint is inherent to the context of the Swedish LEZ landscape since Hornsgatan is the only street with a class 2 passenger car LEZ.

6.1.4 Outcome variable mismatch

As discussed in the background section, the class 2 LEZ was primarily designed to reduce NOx and NO2 through exhaust emission restrictions, while PM10 on Hornsgatan is substantially driven by non-exhaust sources such as road surface wear and brake dust that are not directly targeted by Euro emission class standards. A null result on PM10 is therefore not necessarily inconsistent with the policy having achieved its primary intended effect on nitrogen oxides. A more direct test of the policy mechanism would use NO2 as the primary outcome variable, though data limitations and parallel trends concerns precluded this approach in the present study.

6.1.5 Weather station proximity

The meteorological controls are drawn from Stockholm-Bromma Flygplats for the Stockholm streets and Malmö A for Dalaplan. These stations may not perfectly represent local weather conditions at street level, particularly wind speed, which can vary considerably between an open airport environment and a dense urban environment such as Hornsgatan. Measurement error in the weather controls could attenuate their estimated coefficients and leave residual weather-driven variation in PM10 that is not fully absorbed, potentially inflating the standard error of the DiD estimate.

6.1.6 COVID-19 confound

The treatment date of January 2020 closely coincides with the onset of the COVID-19 pandemic, which reduced traffic volumes and ambient pollution across Swedish cities from March 2020 onwards (Malmqvist et al., 2024). While the DiD design differences out any symmetric COVID-19 effect, differential impacts on inner-city Stockholm and central Malmö cannot be fully excluded. Year fixed effects absorb some of this variation, but within-year differential effects, particularly in spring 2020, may remain in the residual. This confounder is most acute for the immediate post-treatment period and means estimates for 2020 specifically should be interpreted with particular caution.

6.2 Interpretation of Estimated Variables

Given the identification concerns discussed in section 6.1, particularly the pre-treatment coefficient volatility observed in the event study and the reliance on a single treated unit. The following estimates should be interpreted with considerable caution.

The preferred specification yields a DiD coefficient of 1.574 µg/m³ (SE = 0.994), positive but statistically insignificant at all conventional levels. To provide a sense of scale, this corresponds to approximately 8.5% of the sample mean PM10 concentration of 18.46 µg/m³ (Table 1). This would be a moderate effect were it significant. In this case however, it is inappropriate to draw strong conclusions from this coefficient in either direction. The result is neither evidence that the LEZ had no effect on PM10 concentrations, nor evidence that it did, and the wide confidence intervals mean a true effect of meaningful magnitude cannot be ruled out.

The positive sign of the coefficient warrants brief comment. While it might superficially suggest that PM10 increased on Hornsgatan relative to Dalaplan following the introduction of the zone, this interpretation is not warranted given the statistical insignificance of the estimate. The sign is more likely driven by the pre-existing divergence between the two streets visible in the event study than by any genuine post-treatment effect.

The meteorological controls, by contrast, are more reliably interpretable since they are estimated from the full panel rather than from a single policy discontinuity, and their signs and magnitudes align with established mechanisms in the air quality literature. Wind speed (−0.924**, SE = 0.409) and precipitation (−15.47***, SE = 3.062) both reduce PM10 significantly, consistent with dispersion and wet deposition removing particulate matter from the atmosphere. The latter effect being particularly large suggests that rainfall events are among the strongest short-term determinants of weekly PM10 variation. The temperature coefficients show opposing signs, with minimum temperature negatively associated with PM10 (−0.494*, SE = 0.194) and maximum temperature positively associated (1.491***, SE = 0.203). While this pattern is statistically robust, the underlying mechanism is not immediately obvious and is not central to the interpretation of the main DiD result.

The increase in R^2 from 0.355 in the baseline specification to 0.470 in the preferred specification confirms that these meteorological conditions account for a meaningful share of weekly PM10 variation, underscoring the importance of controlling for weather in any causal evaluation of air quality policy. However, this improved precision does not resolve the identification challenges discussed in section 6.1: the DiD coefficient's causal interpretation continues to rest entirely on the parallel trends assumption, which remains imperfectly satisfied regardless of how well the controls perform.

6.3 Connection to Earlier Literature

The null result found in this study is consistent with a growing body of evidence suggesting that the effectiveness of LEZs is highly contingent on enforcement capacity and the specific pollutant being targeted. Holman et al. (2015) document mixed results across five European countries, noting that most LEZ evaluations fail to find clear effects on PM10 and NO2 when confounding factors are not adequately controlled for. The present study adds to this literature by providing a quasi-experimental evaluation of a passenger car LEZ using a DiD design, finding no significant PM10 effect, a result that is robust across both control streets examined.

The findings are most directly comparable to the official post-implementation evaluation conducted by Stockholm city (Säfström, 2021). They found that the actual reduction in nitrogen oxide concentrations in 2020 was approximately 2% compared to a zero alternative which was far below the 11% theoretically achievable under full compliance. While that evaluation focused on NOx rather than PM10, and while the identification challenges discussed in section 6.1 mean that the present study's null result cannot be given a definitive causal interpretation, both findings are consistent with the zone's real-world impact falling substantially short of its potential. To the extent that the null result is informative, weak enforcement represents the most plausible explanation. The report documents that at most five fines were issued in the entire first year of operation despite widespread violations (Säfström, 2021). This figure illustrates the gap between the zone's formal regulatory ambition and its practical implementation. This is consistent with the broader literature suggesting that enforcement capacity is a critical moderating factor in LEZ effectiveness (Delgado-Lindeman et al., 2025), and with the contrast between the weak effects found in manually enforced zones and the large effects estimated for London's automated ULEZ (Beshir & Fichera, 2022). A zone that is not actively enforced cannot be expected to generate a detectable change in air quality regardless of its formal design. It is important to mention that whether this explains the present study's null result, or whether pre-existing trend differences between Hornsgatan and Dalaplan are the primary driver, cannot be determined from the available evidence.

In a broader policy context, this finding has implications for the design of future LEZs in Sweden and elsewhere. The contrast between the weak enforcement of Hornsgatan's class 2 zone and the 98% compliance rate observed for the class 1 heavy vehicle zone on the same street (Säfström, 2021) suggests that enforcement capacity is a critical determinant of LEZ effectiveness. Heavy vehicle compliance is easier to achieve partly because the fleet of non-compliant trucks and buses is smaller and more identifiable, and partly because commercial operators face stronger institutional incentives to comply. Passenger car enforcement requires either automated camera systems as used in London's ULEZ or targeted police operations, neither of which has been implemented on Hornsgatan. The findings therefore lend support to the argument that LEZ design and enforcement infrastructure are as important as the formal regulatory standard itself.

From a social equity perspective, it is also worth noting that the residents of Södermalm, where Hornsgatan is located, have been exposed to PM10 concentrations exceeding environmental quality norms for many years. This has motivated successive interventions including the studded tyre ban in 2010 and the class 2 LEZ in 2020 (Johansson et al., 2011; Säfström, 2019). The null result of this study suggests that these residents have not yet experienced the air quality improvement the class 2 zone was designed to deliver, reinforcing the public health motivation for stronger enforcement. The WHO (2024) estimates 4.2 million premature deaths annually attributable to ambient air pollution globally, and even modest local improvements in PM10 concentrations carry meaningful health benefits at the population level. This makes the enforcement gap documented here a matter of public health concern rather than merely a regulatory technicality.

The experience of Hornsgatan also illustrates the challenge of evaluating policies introduced during the COVID-19 pandemic, as discussed in section 6.1. While the DiD design differences out any common COVID-19 effect affecting both

Hornsgatan and Dalaplan equally, differential impacts on inner-city Stockholm versus central Malmö cannot be fully ruled out.

6.4 Future Research

While the limitations discussed in section 6.1 are inherent to the present design given the available data and time constraints, several concrete extensions would substantially strengthen the identification strategy with additional resources. First, the reliance on a single treated unit could be addressed by constructing a synthetic control for Hornsgatan. This is done by combining multiple untreated streets into a weighted composite that more closely matches Hornsgatan's pre-treatment PM10 trajectory than any single control street can (Abadie et al., 2010). This would directly address both the parallel trends violation documented in the event study and the single-unit precision problem, since the synthetic control is explicitly constructed to minimise pre-treatment divergence. An additional improvement would be to expand the set of control streets beyond Dalaplan and Sveavägen by incorporating additional urban traffic monitoring stations from other Swedish or Scandinavian cities. This would allow the parallel trends assumption to be assessed across a richer set of comparisons and would provide the multiple control units that a synthetic control approach requires. Third, extending the analysis to include NO2 as an outcome variable would allow a more direct test of the policy's intended mechanism, since the class 2 zone restricts vehicles by exhaust emission standard and therefore targets NOx and NO2 directly, whereas PM10 is only indirectly affected through non-exhaust sources as discussed in section 6.1. Combining an NO2 specification with a synthetic control design, rather than the simple two-street DiD employed here would a concrete direction for a more definitive causal evaluation of miljözon klass 2. This would directly address the three most significant limitations of the present study: the single treated unit, the parallel trends violation, and the outcome variable mismatch.

7. Conclusion

This study applies a difference-in-differences design to estimate the causal effect of Sweden's first passenger car low emission zone, the introduction of miljözon klass 2 on Hornsgatan, Stockholm, on street-level PM10 concentrations. By using Malmö's Dalaplan as a control street and exploiting the January 2020 policy introduction as a quasi-experimental treatment date. The preferred specification yields a DiD coefficient of 1.574 $\mu g/m^3$ (SE = 0.994), which is positive and statistically insignificant at all conventional significance levels. A placebo test using Sveavägen as an alternative control street produces a similarly insignificant result, providing some reassurance that the finding is not driven by the specific choice of control street.

However, the results of this study should be interpreted with considerable caution. The event study reveals substantial pre-treatment coefficient volatility, raising concerns about whether the parallel trends assumption is fully satisfied. Combined with the reliance on a single treated unit and the mismatch between the policy's primary mechanism, which targets exhaust emissions and NOx, and the chosen outcome variable of PM10, which is substantially driven by non-exhaust sources on Hornsgatan, the estimates are too imprecise and the identification too uncertain to support strong conclusions in either direction. The result cannot be taken as definitive evidence that the policy had no effect, nor as evidence that it did.

The most empirically well-documented explanation for the absence of a detectable effect is the weak enforcement of the zone. Stockholm's own post-implementation evaluation found that at most five fines were issued in the entire first year of operation, despite widespread violations, as police cited insufficient resources for targeted enforcement (Säfström, 2021). Under these conditions, the fleet composition on Hornsgatan only changed slightly, from 77% to 82% of passenger cars meeting Euro 5/6 standards in 2020. This falls short of the full compliance scenario under which the official evaluation projected an 11% reduction in nitrogen oxide concentrations. A zone that is not enforced cannot be expected to generate a detectable improvement in air quality regardless of its formal regulatory ambition.

Future research should seek to address the limitations of this study by incorporating multiple treated streets and control units to strengthen identification and improve the precision of causal estimates. The staggered adoption of class 1 miljözoner across Swedish municipalities offers potential variation that could be exploited in a more credibly identified design. Furthermore, the ongoing introduction of miljözon klass 3 in Stockholm may in time provide an opportunity for a cleaner causal evaluation in a setting with stronger enforcement mechanisms and a more direct connection between the policy instrument and the targeted pollutants. Until such evaluations are available, the effectiveness of Sweden's passenger car LEZ programme remains an open empirical question.

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