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Effects of Low Emission Zones on Air Quality, New Vehicle Registrations, and Birthweights: Evidence from Japan*

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Abstract

During the early 2000s, five prefectures in Japan introduced a Low Emission Zone (LEZ) policy that banned highly polluting diesel trucks and buses from entering. This paper analyzes effects of this policy intervention on air quality, new vehicle registrations, and birthweights. To do so we use a matching approach to construct a control group that is comparable to the designated areas in terms of pollution levels and road traffic volumes of regulated vehicles and apply a difference-in-differences (DD) design. We find that the LEZs led to a reduction in hourly suspended particulate matter concentrations and to reduced incidence of low birthweights in the treated prefectures relative to the control group, holding the gestational period and other controls constant. Evidence also suggests that the LEZs led to an increase in new registrations of trucks and buses, but not of passenger cars, which were exempt from the regulations. Our paper is the first to study such a large-scale LEZ intervention and to provide evidence linking LEZs to reduced incidence of low birthweights.

Keywords: Low emission zone; Urban air pollution; Birthweight

JEL codes: Q53, R48, I18

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1. Introduction

Motor vehicles are a major source of urban air pollution around the world. Tightened fuel economy standards and regulations of fuel content are among factors that have contributed to improvements in air quality over recent decades. Nevertheless, many cities in developed countries continue to face serious air pollution problems. In 2018, 2,165 cities in high-income countries (excluding the Arab oil-producing countries) exceeded air quality guidelines in terms of annual mean particulate matter 2.5 ($PM_{2.5}$) concentration (10 μg/m^3) (World Health Organization, 2020). Examples include Milan (30 μg/m^3), Paris (20), Berlin (21), Tokyo (17), London (15), and Los Angeles (13).

Low Emission Zones (hereafter, LEZs) – geographically defined areas for which the most polluting vehicles in the fleet are restricted from entering – have been an important measure taken to improve local air quality in European cities.[1] Since the first implementation in Sweden in 1996, the LEZ approach has spread, with 184 LEZs being recorded across Europe as of January 2021 (Sadler Consultants Ltd., 2021). LEZs vary substantially in terms of implementation dates, the sizes of designated areas, applicable vehicles, the stringency of emission standards, and the monitoring systems used (Holman et al., 2015). The main aim has been to reduce emissions of pollutants including PM and nitrogen dioxide (NO_2) in city areas in order to protect human health.

LEZs have often divided public opinion in Europe. An IPSOS survey showed that large proportions of citizens in Germany (43%), Belgium (40%), and France (40%) opposed LEZs (European Federation for Transport and Environment, 2019). The unpopularity emanates mainly from fairness issues and the fact that the restrictions require some

[1] See Wolff and Perry (2010) for an overview of air pollution policies in Europe.

vehicle owners to implement vehicle retrofits or upgrade to an alternative vehicle, imposing a financial burden. The effectiveness of LEZs in improving air quality and public health has also been questioned (Boogaard et al., 2012; Ellison et al., 2013; Ferreira et al., 2015; Santos, 2019). Madrid's LEZ was reversed within a year of its introduction (Lebrusán and Toutouh, 2020).

It is perhaps less well known that Japan has also pursued the LEZ approach, and at a large scale. With the aim of reducing ambient concentrations of suspended particulate matter (SPM),[2] LEZs were introduced in Tokyo, Saitama, Kanagawa, and Chiba in October 2003 and Hyogo in October 2004. The LEZs banned diesel trucks and buses that violated PM emission standards specified by prefectural governments from entering designated areas, except those for which a diesel particulate filter designated by the prefectural governments was installed. Japan's LEZs were unprecedented in that they were implemented prefecture-wide, or municipality-wide in the case of Hyogo. Prior studies of Japan's LEZs have analyzed their effectiveness in reducing PM emissions from road transport (Ishii and Tsukigawa, 2004; Rutherford and Ortolano, 2008) and carried out ex-ante estimates of costs and benefits (Iwata et al., 2020). However, little is known about how much Japan's LEZs have contributed to improvements in ambient air quality and public health.

The goal of this paper is to estimate the effects of Japan's LEZs on ambient SPM concentrations, the number of new vehicle registrations by vehicle type, and birthweights. We use a matching approach to construct a control group that is

[2] SPM is defined as airborne particles with a diameter less than or equal to 10 micrometers (PM_{10}).

comparable to the designated areas in terms of pollution levels and road traffic volumes of regulated vehicles and apply a difference-in-differences (DD) design. Our analysis utilizes hourly air pollution data at the monitor level and birthweight data for each birth over 2000–2008. For the vehicle registration analyses we use administrative data on new vehicle registrations for 1999–2008.

Birthweights are an important variable to study as there is increasing evidence of long-term effects of poor health at birth on future health and educational outcomes (Currie, 2009). Given concern about declining birthweights in some developed countries, the impact of atmospheric pollution on birthweights is of substantial interest. Over 2000–2019, the share of live births with low birthweights (< 2,500 grams) increased by 1.1 percentage points in France, 0.4 percentage points in Italy, 0.8 percentage points in Japan, and 0.7 percentage points in the United States (Organization for Economic Co-operation and Development, 2022a).[3]

Our results suggest that the LEZs on average led to a 5.4% reduction in the hourly mean SPM concentration for roadside monitors in Tokyo, Saitama, Kanagawa, Chiba, and Hyogo relative to the control group over October 2003–December 2008. The pollution-reducing effects are heterogeneous across prefectures, with the largest proportional effect found for Tokyo (11%). Event-study estimates suggest that the effects increased for several years after the LEZs were implemented. The LEZs also contributed to improvements in background air quality (in terms of SPM) away from roadsides, implying reduced exposure to air pollution among the general population.

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[3] Some other countries such as Germany and United Kingdom experienced reductions in this share over the period.

We find that on average the annual number of registrations of new trucks and buses in the LEZ prefectures increased by 23–28% per annum during 2003–2008 relative to the control group. However the estimated number of replacements during 2003–2008 accounted for only about 2–4% of the stock of regulated diesel trucks and buses, consistent with a conclusion that most owners of non-compliant vehicles responded to the policy by installing a diesel particulate filter. A placebo test confirms that the LEZs did not affect new vehicle registrations of passenger cars, which were not subject to the regulations. The results suggest that the compliance costs of replacing non-compliant vehicles and installing diesel particulate filters amounted to around US$2.5 billion in year-1997 dollars.

An important finding is that the LEZs appear to have reduced the incidence of low birthweights, holding gestational age and other factors constant. Evidence suggests that the implementation of the LEZs led to a 0.14% (around 4.2 g) increase in birthweights on average over October 2003–December 2008 for newborn babies inside the LEZs relative to those outside the LEZs, all else equal. The results also suggest that of the 944,178 births that we observe in LEZs for October 2003–September 2008, about 2,360 births switched from being below 2,500 g to above, all else equal. The health effects are largest for Tokyo and Saitama. The largest treatment effects emerge 4–5 years after the implementation of the LEZs, which corresponds to the timing of the effects on ambient air pollution.

To check the robustness of our results, we examine the potentials for pollution leakages and compositional changes in parental characteristics in the treatment and control groups before and after the implementation of LEZs. We do not find noticeable evidence that these factors are a threat to our identification strategy. In addition, we find that our baseline estimates are relatively robust to alternative specifications that control for anticipation effects and day fixed effects, and that cluster standard errors at a higher (prefecture) level.

Our paper relates closely to the rapidly growing literature analyzing the effectiveness of LEZs, especially in Europe.[4] Analyzing a monitor-day panel with DD regressions, Wolff (2014) investigated the effects of LEZs on vehicle replacements and air quality in Germany. Several subsequent articles have explored the health effects of German LEZs, analyzing effects on health outcomes including birthweights and the occurrence of stillbirths (Gehrsitz, 2017), pharmaceutical expenditures for asthma and heart diseases (Rohlf et al, 2020), outpatient and inpatient health (Margaryan, 2021), and hospital shares of diagnosed ischemic heart diseases and chronic lower respiratory diseases (Pestel and Wozny, 2021), and the number of medical prescriptions and costs of prescriptions per child (Klauber et al., 2021). Zhai and Wolff (2021) examined the environmental effect of London's LEZ, finding that it led to worse air quality during the initial phase due to an increase in inflows of heavy gross vehicles and temporarily-exempted light goods vehicles.

Our paper also relates to a broader literature studying other types of traffic-related policy interventions.[5] Currie and Walker (2011) investigated the environmental and health impacts of the E-ZPass in Pennsylvania and New Jersey, finding that its adoption

[4] See Appendix A for a summary of prior research.
[5] See Appendix B for a summary of this prior research.

led to reduced NO_2 concentrations and lowered the incidences of premature births and low birthweights. He et al (2019) analyzed a newly-built beltway in São Paulo designed to keep heavy diesel trucks away from congested truck routes, finding that the intervention reduced congestion, air pollution, and cardiovascular and respiratory admissions around the original truck routes. Simeonova et al (2019) studied the impacts of Stockholm's Congestion Pricing Zone (CPZ), finding that it led to improved air quality in designated areas and a reduction in acute asthma episodes among children aged under 5 years. Green et al (2020) studied congestion pricing in London and found evidence of improvements in air quality and a reduction in pollution per mile driven.

Studying Japan's LEZs offers substantial potential to contribute to our understanding of the environmental and health impacts of LEZs and traffic-related policies more generally. A key contribution of this study is the focus on what is the world's largest set of LEZs. A unique feature of Japan's LEZs is that the entire prefecture was designated as an LEZ in all cases other than Hyogo. As will be discussed, the covered areas are much larger than the Greater London LEZ (1,500 km^2), the largest in Europe. Other LEZs in Europe are typically small: 8.2 km^2 for Milan, 20 km^2 for Amsterdam, and 44 km^2 for Munich. Despite the widespread use of LEZs, air pollution levels in Europe have often still exceeded European Union (EU) air quality limits, with France, Germany, and Italy facing legal action from the EU Commission over their failure to comply (Abnett, 2020). More ambitious LEZs are one potential policy option.

The second key contribution of the current paper is to use the largest sample of births to date (in terms of the absolute number) to examine the effects of LEZs on the incidence of low birthweights per gestational age, finding evidence of detectable effects.[6] Prior research has revealed that traffic-related policy interventions, including LEZs, are effective in improving air quality and protecting public health for the current generations (He et al., 2019; Simeonova et al., 2019; Rohlf et al, 2020; Margaryan, 2021; Pestel and Wozny, 2021; Klauber et al., 2021). However, relatively little is known about the effect on fetal health. Currie and Walker (2011) found that the E-Zpass reduced the incidence of low birthweights in the United States, whereas Gehrsitz (2017) found no significant evidence that LEZs had an influence on birthweights in Germany.

The remainder of this paper is structured as follows. Section 2 provides information on Japan's LEZs, followed by a description of the data in Section 3. In Section 4 we document our method for selecting the treatment and control groups and show the temporal trends of the outcome and other variables. Section 5 presents empirical evidence on the effects of LEZs on air pollution, new vehicle registrations, and birthweights. Section 6 examines the robustness of our baseline estimates. Section 7 concludes.

2. Low Emission Zones in Japan

Japan has introduced three major vehicle emission policies. The first is a fuel economy standard applied to all newly-sold motor vehicles. The standard on PM was introduced in 1993 and set at 0.43 g/km for standard trucks and buses. It has been tightened over time and is currently 0.007 g/km. The second is an automobile NOx/PM control (ANPC) that has banned vehicles that did not meet national emission standards from being registered in designated municipalities. The ANPC was introduced in some

[6] We use this term to refer to the effect on low birthweights while controlling for gestational age.

municipalities in Tokyo, Saitama, Chiba, Kanagawa, Osaka, and Hyogo in June 1992. In June 2001 its coverage was expanded to some municipalities in Aichi and Mie and additional municipalities in Saitama and Hyogo.[7]

The third vehicle emission policy, analyzed in this paper, is the use of Low Emission Zones (LEZs). Despite tightened fuel economy standards and the ANPC, air quality in Tokyo remained poor in the 1990s: as of 1998, around 90% of air pollution monitors in Tokyo violated the national SPM standard.[8] Over 1996–2000 more than 500 patients with respiratory diseases filed lawsuits against the national government, the Tokyo metropolitan government, Tokyo Expressway Public Corporation, and carmakers. The plaintiffs argued that the defendants had responsibility for air pollution not only at roadsides but also in background areas (Tokyo Metropolitan Government, 2003). The judges recognized that PM pollutants, particularly diesel exhaust particles, were responsible for health damages and ordered the defendants, including the Tokyo metropolitan government, to implement measures to reduce PM emissions from road transport.

In response to these developments, the Tokyo metropolitan government enacted the Tokyo Metropolitan Environmental Protection Ordinance in December 2000. The key measure was the introduction of an LEZ that applied to the entire prefecture (2,200 km^2). The implementation date was set as October 2003. The LEZ banned the entry of diesel trucks and buses that violate the PM emission standards specified by the prefectural government. Trucks and buses were targeted given they were major sources

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[7] See Nishitateno and Burke (2020, 2021) for details on the ANPC.

[8] The national air quality standard for SPM has required that the 98th-percentile of the daily-mean SPM concentration be below 100 $\mu g/m^3$ throughout the year.

of PM emissions from motor vehicles (Tokyo Metropolitan Government, 2003). The PM emission standards were equivalent to the 1997 levels of the national fuel economy standard: 0.08 g/km for gross vehicle weights of less than 1.7 tons, 0.09 g/km for 1.7–2.5 tons, and 0.25 g/kWh for more than 2.5 tons. From 1 April 2006 the standards were tightened to the 2003 national fuel economy standard levels: 0.052 g/km for gross vehicle weights of less than 1.7 tons, 0.06 g/km for 1.7–2.5 tons, and 0.18 g/kWh for more than 2.5 tons. Passenger cars were not subject to the regulation.

For all non-compliant vehicles, bans came into effect seven years after the year of initial registration. The LEZ thus went into immediate effect for non-compliant trucks and buses first registered before October 1996 and in a staggered way over time for other vehicles. Only compliant vehicles, including those for which a diesel particulate filter designated by the prefectural government had been installed, could legitimately enter the LEZs. Once a particulate filter was properly installed, a sticker was issued that was required to be placed on the side of the vehicle. Implementation of the LEZ was monitored by on-road-oversight, cameras, and anonymous tip-offs. On-site inspections of truck and bus companies were carried out. Those not in compliance could be ordered to pay a fine of up to 500,000 Japanese yen (US$5,000).

There is substantial demand for truck freight transport on an intra-metropolitan basis in Japan (Tokyo Metropolitan Area Transport Planning Council, 2005). To ensure that the Tokyo LEZ would work effectively, the Tokyo metropolitan government requested three neighboring prefectures – Saitama, Kanagawa, and Chiba – to also introduce LEZs. Given that those prefectures were also tackling vehicular air pollution, all agreed to introduce LEZs in almost identical manners as the Tokyo LEZ in terms of PM emission standards, implementation dates (October 2003), and targeted vehicles (trucks and buses). These prefectures also designated their entire areas as LEZs: 3,800 km^2 for Saitama, 2,400 km^2 for Kanagawa, and 5,100 km^2 for Chiba, meaning that the world's largest overall LEZ (13,500 km^2 in total) was formed (Figure 1). This was 9 times larger than the Greater London LEZ (1,500 km^2), the largest in Europe. As of 2003, Japan's four LEZ prefectures had a population of about 36 million people (about 30% of Japan's total), a gross domestic product (GDP) of about US$ 1.6 trillion (about 32% of national GDP), and 14 million registered four-wheel motor vehicles (about 19% of the national total).[9]

[9] Although Japan's four LEZs formed the world's largest LEZ in terms of the area coverage, driving restrictions were applied to trucks and buses only, accounting for only about 20% of the four-wheel motor vehicle fleet. German LEZs, for example, have applied to all motor vehicles.

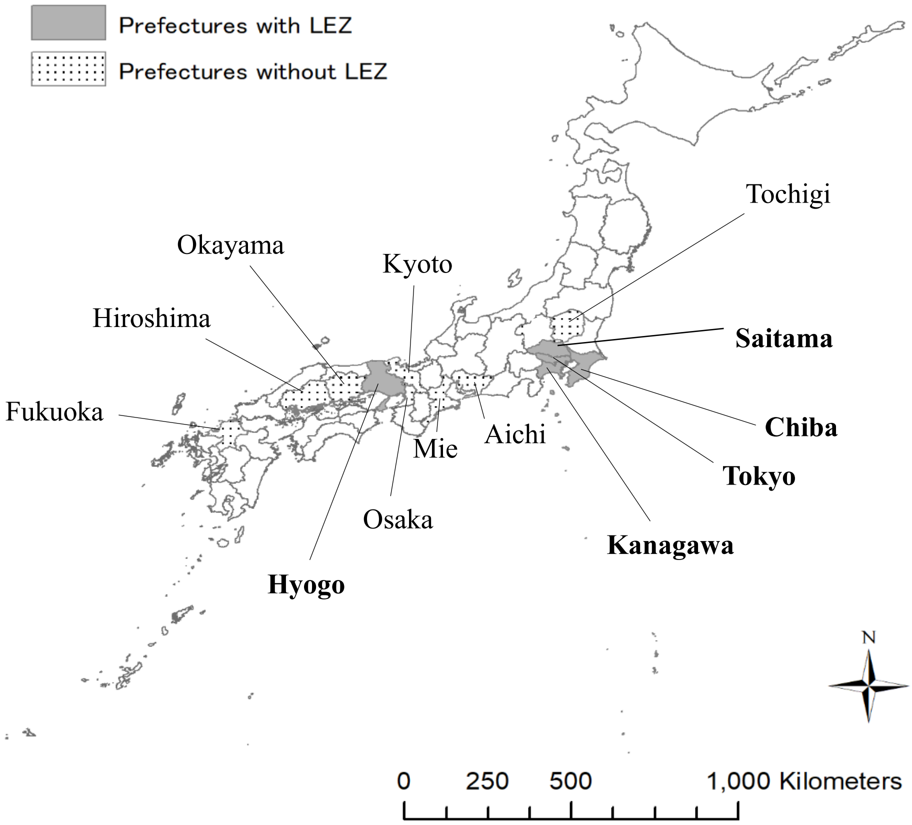

Figure 1. Low Emission Zones in Japan as of December 2008

Notes: LEZs were introduced in Tokyo, Saitama, Kanagawa, and Chiba in October 2003. In these four prefectures the entire prefecture was designated. An LEZ was then introduced in Hyogo in October 2004, restricting access of non-compliant vehicles in six municipalities (3% of the area of the prefecture). The dotted areas show the control group in this study. For other areas, either data on air pollution are unavailable or all roadside monitors are dropped in the matching process.

An LEZ was subsequently introduced in Hyogo on 1 October 2004. This restricted non-compliant trucks and buses from entering six of Hyogo's municipalities (Nada, Higashinada, Amagasaki, Nishinomiya, Itami, and Ashiya), representing a total area of 260 km^2, or about 3% of the area of the prefecture.[10]

The LEZ prefectures also introduced incentives for owners to replace their non-compliant vehicles with clean trucks and buses in the form of subsidies, low-interest loan, and tax reductions. For example, in the case of Tokyo the purchase of hybrid

[10] Osaka introduced an LEZ in 1 January 2009. This is not analyzed in this paper because the implementation date falls outside the sample period.

trucks was subsidized by around US$1,600–5,700 per vehicle, depending on vehicle weight. For a new purchase of a hybrid bus, the maximum subsidy was US$25,000 per bus. Replacements with natural gas trucks and buses were also supported by subsidies of US$1,000–2,000 per vehicle. Such favorable treatment was limited to small and medium-sized enterprises that registered their vehicles in Tokyo.[11]

The number of affected vehicles was large. As of March 2003, the number of registered diesel trucks that had been first registered before 1996 in the five LEZ prefectures (including Hyogo) was 512,000, accounting for 33% of the trucks registered in those prefectures. Likewise, the number of regulated diesel buses was 19,300, accounting for 43% of the buses registered in the five prefectures.

Inflows and outflows of vehicles to LEZs were not monitored by cameras. However, on-road monitoring and on-site inspections indicated that compliance was high (Ministry of Environment, 2013). For example, the Tokyo metropolitan government undertook on-road monitoring during October 2003–September 2005, finding that 12,502 out of 12,782 relevant vehicles were compliant (a compliance rate of 98%). Based on similar on-road monitoring, compliance rates were 92% in Saitama, 97% in Chiba, and 100% in Hyogo. Data for Kanagawa are not available. Data from the Ministry of Economy, Trade and Industry (2008) suggest that about 70 percent of replaced vehicles under the intervention were scrapped and about 28 percent exported overseas. Thus, pollution leakage due to vehicle transfers to non-LEZ areas appears not to be a major issue.

[11] https://www.kankyo.metro.tokyo.lg.jp/vehicle/air_pollution/diesel/faq.html#cms9.

3. Data

Our initial analysis is based on a two-dimensional monitor-hour panel dataset constructed using hourly air pollution and meteorological data for January 2000–December 2008.[12] Ambient SPM concentration is used as a key measure of air quality and a proxy of the broader air quality situation. Data were obtained from the environmental statistics database compiled by the National Institute for Environmental Studies (NIES). Access to hourly pollution readings is limited to 21 prefectures, including the five that implemented LEZs by 2008 (Tokyo, Saitama, Kanagawa, Chiba, and Hyogo) and 16 that did not (Miyagi, Ibaragi, Tochigi, Gunma, Yamanashi, Aichi, Mie, Kyoto, Osaka, Nara, Wakayama, Okayama, Hiroshima, Tokushima, Yamaguchi, and Fukuoka). This is because Japan's Air Pollution Control Act did not require all 47 prefectures to report hourly readings until 2009. The sample of roadside monitors includes those located within 20 meters of a main road. We also collected air pollution data from background monitors to examine if the impacts of LEZs spread beyond roadside areas.

The analysis controls for meteorological variables including temperature, precipitation, wind speed, pressure, and humidity as measured at meteorological stations, with data coming from the Japan Meteorological Agency (JMA). We use geographical information systems (GIS) to match the nearest meteorological station to each air pollution monitor.

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[12] We avoid extending beyond 2008 in order to minimize potential estimation bias emanating from two major events: the global financial crisis, which severely affected Japan's economy in 2009 in particular and had heterogeneous impacts across prefectures, and the Great East Japan earthquake and nuclear accident of March 2011, which had larger implications for some locations.

Traffic data are from the 2010 PAREA-Traffic dataset of Japan Asia Group. 2010 is the earliest available year for this dataset. As will be explained below we use these data in selecting a control group. This dataset provides a shapefile for the data from the Road Traffic Census conducted by the Ministry of Land, Infrastructure, Transport and Tourism (MLITT), allowing the identification of a census point around each air pollution monitor. The dataset covers around 44,000 census points across Japan and provides data on the number of lanes, speed limits, daily traffic volumes by vehicle type, and average driving speed during the census period. The census is conducted on a weekday during September–November, excluding Mondays, Fridays, public holidays, and days with an abnormal weather event such as a typhoon. Traffic volumes were measured by either manual surveys or traffic counters. Average daily driving speed was as measured by test cars.

To estimate the effects of the LEZs on new vehicle registrations, we constructed a prefecture-year-vehicle size (three-dimensional) panel for 1999–2008. Vehicle registration data are from the Automobile Inspection & Registration Information Association (AIRIA). The AIRIA provides administrative data on vehicle registrations on an annual basis, disaggregated by dimensions including vehicle type, first registration year, and registration location (prefecture only). We also used the System of Social and Demographic Statistics compiled by the Ministry of Internal Affairs and Communications (MIAC) to obtain prefecture-level control variables such as population, per capita income, and the unemployment rate.

To estimate the effects of the LEZs on birthweights we constructed a dataset of 2.2 million births over January 2000–December 2008. To do so we requested access to confidential data on birth certificates from the Ministry of Health, Labor and Welfare (MHLW) based on Article 33 of the Statistics Act in Japan. The Family Registration Law requires all Japanese citizens to submit a birth certificate within 14 days to each municipal government. We were able to obtain microdata on the date of birth, birthweight, gestation period, gender, type of birth (single or multiple), birth order, ages of the mother and father, nationalities of the mother and father, household head's job, and parents' residential locations. The municipality that the parents resided in when they submitted a birth certificate for their newborn baby is also available. For privacy reasons, exact home addresses are not.

Our analysis uses data from two administrative levels: prefectures and municipalities. Prefectures are the larger geographical unit in Japan and are largely responsible for monitoring air quality, implementing LEZs, and promoting environmentally-friendly vehicles. Some municipalities also undertake local air pollution measures and provide additional (typically quite limited) monetary support for vehicle replacements. Municipalities also focus on dealing with local public needs, including for example providing municipality-based programs for pregnant women.

4. Sample

4.1. Differences in underlying characteristics

Over the sample period, data are available for 125 and 150 roadside monitors in and outside the LEZs, respectively. The two groups differ in some underlying characteristics. The first is pre-trends in air pollution. Figure 2 shows the unadjusted time trends of the monthly-averaged SPM concentration. We use monthly rather than hourly data here for visual simplicity. We see that there are some noticeable differences in pre-SPM levels and their temporal trends between roadside monitors in and outside the LEZs.

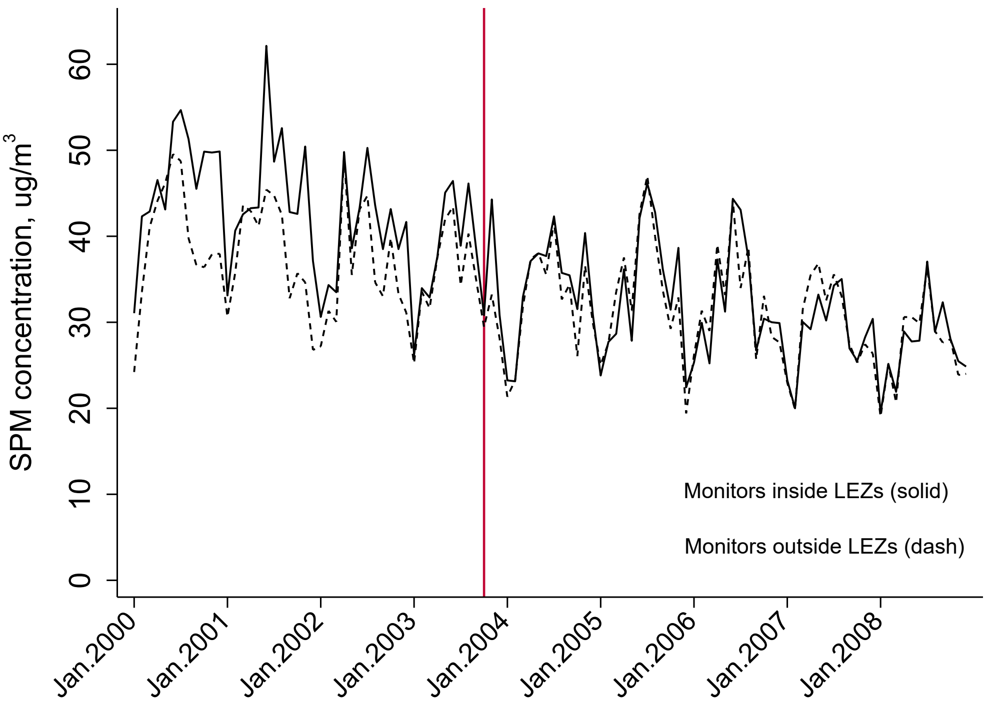

Figure 2. Monthly-Averaged SPM Concentration

Notes: The monthly-averaged SPM concentration is calculated based on hourly SPM readings with the unmatched sample including 125 roadside monitors inside LEZs and 150 roadside monitors outside LEZs. The red vertical line shows the date of implementing the LEZs in Tokyo, Saitama, Kanagawa, and Chiba. Hyogo's implementation date was October 2004.

The second difference is in traffic volumes for regulated vehicles (diesel trucks and buses). Table 1 shows a summary of road traffic conditions within a kilometer radius of each roadside monitor in 2010. While the average number of lanes, average speed limit, and average driving speed between the two groups are similar, there are noticeable differences in average daily traffic volumes, particularly for trucks and buses. Appendix C shows that similar differences can be observed when daily traffic volumes are measured using either a 500-meter or 5-kilometer radius from each roadside monitor. We are concerned that substantial differences in traffic volumes of regulated vehicles would also have existed prior to the treatment.

Table 1 —Road Traffic within a 1-Kilometer Radius of a Roadside Monitor

	Monitors inside LEZs	Monitors outside LEZs
Average number of lanes	3.7	3.5
Average speed limit, km/hour	49	47
Average traffic volume per day		
Passenger cars	25,912	21,025
Trucks and buses	7,031	3,612
All cars	32,943	24,637
Average driving speed, km/hour		
Peak hours	26	25
Off-peak hours	29	28

Notes: This table is based on the Road Traffic Census conducted during September–November 2010. Peak hours are 7–9am and 5–7pm. Off-peak hours are others. The sample includes 125 roadside monitors inside LEZs and 150 roadside monitors outside LEZs. Averages are taken across roadside monitors.

4.2. Matching

To make an apples-to-apples comparison, one natural way to construct a control group is to find a sample comparable to the treatment group in both (a) pre-intervention pollution levels and (b) pre-intervention road traffic volumes of regulated vehicles. However, as mentioned the earliest available year for the Road Traffic Census data is 2010. Therefore, we use the post-intervention road traffic volumes of regulated vehicles, making the assumption that cross-sectional variation in road traffic volumes of regulated vehicles around roadside monitors for 2010 was similar to that for the pre-treatment period (2000–2003). We will also explore alternative control group selection approaches below.

The use of matched samples is motivated by concern over the parallel trends assumption: our worry is that initial conditions may be correlated with future trends. For example, people might migrate from rural to (more polluted) urban areas to seek a better job.[13] On the other hand, it is also possible that local governments in polluted areas have undertaken local pollution measures in addition to the LEZs (such as traffic flow

[13] During the 2000s the population indeed grew faster in the LEZ prefectures than the other prefectures.

controls). Balancing the underlying characteristics between the LEZs and non-LEZs may help to alleviate the implications of such effects on our ability to accurately identify the effects of the LEZs.[14] Similar approaches have been employed by Smith and Todd (2005), Girma and Görg (2007), Chabé-Ferret and Subervie (2013), Hirota and Yunoue (2017), and Deryugina et al (2020).

We selected the estimation sample via the following steps. First, we used a logit model to estimate the propensity score of being "treated" for all available roadside monitors based on the average hourly SPM levels during the pre-intervention period and the average daily traffic volume of trucks and buses within a kilometer of each roadside monitor in 2010. Second, we constructed different sample groups by using various matching algorithms including balancing the propensity score, one-to-one matching, and kernel matching. We also compare against the matching approaches based on pre-pollution levels of Wolff (2014) and based on municipality characteristics of Green et al (2020). Third, we examine which matching approaches work best in balancing the samples of monitors between the control and treatment monitors. We pick the most balanced in terms of the pre-intervention SPM levels and road traffic volumes of regulated vehicles and use this as our preferred sample for all analyses.

Table 2 reports the average pre-SPM levels, road traffic volumes of regulated vehicles, and propensity scores for LEZ and non-LEZ monitors. Their differences are also shown. Panel A shows the unmatched sample averages, used as a benchmark. Panel B shows the matching results obtained by balancing propensity scores. We ordered the non-LEZ

[14] Ryan et al. (2019) illustrated via simulations that DD estimation with a matched sample can perform well at dealing with non-parallel trends in the context of a health policy intervention.

monitors from the highest (0.85) to the lowest (–0.06) propensity score and sequentially excluded monitors with the lowest propensity scores until the average propensity score for non-LEZ monitors reached the level for the LEZ monitors (0.59). The sample of 125 LEZ monitors was held fixed in this process. The resulting sample has 34 non-LEZ monitors. Importantly, differences in both pre-SPM levels and road traffic volumes substantially reduced using this approach. Tests fail to reject the null hypotheses of no difference between LEZ and non-LEZ monitors for the two underlying characteristics.[15]

We find that the pre-SPM levels and road traffic volumes of regulated vehicles remain balanced between LEZ and non-LEZ monitors, even when using alternative threshold value set at ±5% of 0.59. With a lower threshold value of 0.56, 50 non-LEZ monitors are chosen. Their average pre-SPM levels and road traffic volumes are 43 μg/m^3 and 5,723 per day, which are again statistically indistinguishable from those for the LEZ monitors. With a higher threshold value of 0.62, the number of non-LEZ monitors is 30. Their average pre-SPM levels and road traffic volumes are 44 μg/m^3 and 7,012 per day. Again, statistical tests fail to reject the null hypotheses of no difference in average pre-SPM levels and road traffic volumes between LEZ and non-LEZ monitors. This may to some extent alleviate concerns over possible imbalances of samples due to the use of post-intervention traffic data.

Panels C and D of Table 2 show the results for the alternative approaches of one-to-one

[15] Alternatively, we could balance the distributions of the propensity score of treatment and control groups by keeping only LEZ and non-LEZ monitors within an overlapping range of their propensity scores. We do not follow this approach because it fails to equalize the average propensity score and balance the pre-SPM levels and road traffic volumes. Results are available on request.

matching and kernel matching.[16] In both methods we impose a common support condition to satisfy the overlap assumption, dropping LEZ monitors whose propensity score is higher than the maximum or lower than the minimum score among non-LEZ monitors. Although their differences reduce somewhat, these approaches fail to adequately balance the sample averages for pre-SPM levels and road traffic volumes.

In studying the effect of congestion pricing in London, Green et al (2020) used an alternative approach of employing propensity score matching to select a sample at a more aggregated level. Their propensity score was estimated through a probit specification on the basis of annual observable factors at the local authority level, such as vehicle-miles travelled, population, unemployment rates, and weather measures so that the sample of treatment and control observations falls in the overlapping ranges of the estimated propensity scores. Similar to Green et al (2020), we analyze municipality-level data. To estimate propensity scores, we also collected data on annual vehicle ownership rates, population, unemployment rates, temperature, precipitation, wind speed, pressure, and humidity as of 2000. Panel E of Table 2 shows the results using the method of Green et al (2020). This approach fails to balance the sample averages for both pre-SPM levels and road traffic volumes.

[16] One-to-one matching finds a single non-LEZ monitor with the closest propensity score for each LEZ monitor and matches each LEZ monitor. In kernel matching, each LEZ monitor is matched with a weighted average of all non-LEZ monitors, with the weights inversely proportional to the distance between the propensity scores of the treated and control groups. We use the Epanechnikov kernel function with a bandwidth parameter of 0.06.

Table 2 —Matched Samples

	A. No matching			B. Balancing propensity scores			C. One-to-one matching		
	Inside LEZ	Outside LEZ	Diff.	Inside LEZ	Outside LEZ	Diff.	Inside LEZ	Outside LEZ	Diff.
Average pre-SPM concentration level, μg/m^3	42.78	36.90	5.88***	42.78	43.59	–0.81	41.61	40.73	0.88
Average traffic volumes of regulated vehicles per day	7,031	3,612	3,418***	7,031	6,393	637	5,548	4,213	1,335**
Average propensity score	0.59	0.37	0.22***	0.59	0.59	0	0.54	0.48	0.07**
Number of roadside monitors	125	150		125	34		117	47	
	D. Kernel matching			E. Matching by municipality characteristics			F. Within 38–40 μg/m^3 of pre-SPM levels		
	Inside LEZ	Outside LEZ	Diff.	Inside LEZ	Outside LEZ	Diff.	Inside LEZ	Outside LEZ	Diff.
Average pre-SPM concentration level, μg/m^3	41.61	37.37	4.23***	42.86	37.53	5.33***	39.63	39.33	0.30
Average traffic volumes of regulated vehicles per day	5,548	3,687	1,861***	7,681	4,012	3,669***	6,520	4,537	1,983**
Average propensity score	0.54	0.38	0.17***	0.71	0.37	0.34***	0.51	0.45	0.06**
Number of roadside monitors	117	145		83	54		25	39	

Notes: This table reports the results of balancing tests. ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively. Averages are across monitors.

Prior research in the LEZ literature utilizes alternative approaches. Wolff (2014) obtained a group of cities with average pre-treatment pollution levels within a fixed range (for all cities). Building on his approach, we explored setting a fixed range of 38–40 μg/m^3 (equal to ±1 μg/m^3 of the average hourly SPM levels during the pre-intervention period).[17] Panel F of Table 2 shows the matching results. This approach has two shortcomings in our application. First, it comes at a cost of discarding a large share of the sample. Second, the approach does not balance the road traffic volumes of regulated vehicles.

Our approach of balancing propensity scores is able to generate treatment and control samples with similar pre-trends. Specifically, pre-intervention treatment effects are statistically indistinguishable from zero for roadside monitors, increasing confidence that the parallel trends assumption is met (Panel A, Figure 4). That pre-treatment effects are not visible after controlling for the variables included in our estimation is seen in panel A of Appendix D, which plots the monthly-averaged residuals for hourly SPM concentration from a regression that controls for hourly meteorological variables, monitor fixed effects, month fixed effects, hour-of-day fixed effects, and national holiday and weekend dummies.

On the other hand, there is evidence of pre-trends when alternative matching approaches are employed. For example, Appendix F shows event-study estimates based on Green et al (2020)'s matching approach using pre-treatment variables. The point estimate one year prior to the intervention is –2.5 at the 1% level. We thus use the approach based on

[17] The matching results are consistent even when wider ranges, such as 37–41 μg/m^3 and 36–42 μg/m^3, are applied.

balancing the propensity scores for the main estimates. In this setting, this approach is superior from the viewpoints of sample balance, size, and in terms of an absence of pre-trends. It does have the disadvantage of using post-treatment data, but this is only for matching and does not affect any other aspect of the analysis.

We thus proceed to use our above-detailed propensity score method as our preferred approach. Using the matched roadside monitors, we classify the treatment and control groups as summarized in Table 3. The treatment group includes 125 roadside monitors in 92 municipalities across Tokyo, Saitama, Kanagawa, Chiba, and Hyogo. The 34 roadside monitors in the control group are in 30 municipalities that did not implement an LEZ (Figure 1). Note that municipalities in Hyogo prefecture are included in both groups as Hyogo has both designated and non-designated areas. For the prefecture-level analysis, Hyogo is included in the treatment group.

Table 3 —Treatment and Control Groups

Prefectures	Number of municipalities	Number of monitors	
		Roadside	Background
Treatment group			
Tokyo	28	39	24
Saitama	17	23	32
Kanagawa	25	31	37
Chiba	17	23	78
Hyogo	5	9	20
Total	92	125	191
Control group			
Kyoto	1	1	0
Osaka	14	16	25
Hyogo	3	3	0
Okayama	1	1	6
Hiroshima	4	4	13
Aichi	3	5	5
Mie	1	1	1
Tochigi	1	1	1
Fukuoka	2	2	1
Total	30	34	52

Notes: The treatment group is subject to an LEZ, while the control group is not. Hyogo has areas included in both the treatment and control groups. For the prefecture-level analysis, Hyogo is in the treatment group.

The last column of Table 3 shows the number of background monitors in our sample, chosen in the following manner. First, we identified all background monitors in the selected municipalities using our balancing propensity score method explained above. Second, we used a logit model to estimate the propensity score of being treated for all available background monitors based on the average hourly SPM levels during the pre-intervention period. Lastly, we constructed the sample group such that the estimated propensity scores balance between the treatment and control groups. Through this process, 12 control group background monitors were dropped.[18]

4.3. Descriptive statistics

Table 4 shows the sample averages during the pre- and post-intervention periods, and their differences, for the treatment and control groups. We see that average hourly SPM concentration fell by 11 μg/m^3 in the treatment group, relative to 8 μg/m^3 in the control group, for roadside monitors. Such differential temporal trends can be observed for background monitors as well. The treatment group experienced greater increases in new registrations of the regulated vehicles (trucks and buses) relative to the control group. Thus, simple difference-in-difference calculations provide evidence of treatment effects on SPM.

[18] We took this matching approach for background monitors, because our balancing propensity score method fails to equalize both levels and trends of air pollution during the pre-intervention period for treatment and control background monitors.

Table 4 —Descriptive Statistics

	Treatment group			Control group		
	Before	After	Diff.	Before	After	Diff.
A. Monitor-hour data						
SPM concentration (roadside), μg/m^3	43.0	31.7	–11.3	43.6	35.3	–8.3
SPM concentration (background), μg/m^3	34.9	27.8	–7.1	34.9	29.1	–5.8
Temperature, degrees Celsius	16.0	15.9	–0.1	17.0	16.8	–0.2
Precipitation, millimeters	0.2	0.2	0	0.1	0.1	0
Wind speed, meters per second	3.2	3.1	–0.1	2.9	2.8	–0.1
Pressure, hectopascal	1,005	1,006	1	1,007	1,007	0
Humidity, %	65.9	65.3	–0.6	64.6	64.4	–0.2
B. Birth data						
Birthweight, grams	3,027	3,008	–19	3,025	3,009	–16
Dummy variable if birthweight is						
< 2,500 grams	0.086	0.093	0.007	0.087	0.094	0.007
< 1,500 grams	0.006	0.007	0.001	0.007	0.008	0.001
Gestation period, weeks	275.30	274.77	–0.53	275.41	275.03	–0.38
Single birth	0.980	0.978	–0.002	0.979	0.977	–0.002
Male	0.5135	0.5138	0.0003	0.5147	0.5119	–0.0028
Birth order	1.615	1.618	0.003	1.672	1.696	0.024
Father's age	32.23	32.97	0.74	31.17	31.88	0.71
Mother's age	30.01	30.91	0.90	29.14	29.99	0.85
Father's nationality						
Japan	0.9758	0.9726	–0.0032	0.9794	0.9778	–0.0016
South Korea	0.0058	0.0053	–0.0005	0.0102	0.0081	–0.0021
China	0.0052	0.0065	0.0013	0.0036	0.0050	0.0014
Philippines	0.0005	0.0007	0.0002	0.0004	0.0004	0
Thailand	0.0001	0.0002	0.0001	0.0001	0.0001	0
United States	0.0025	0.0029	0.0004	0.0006	0.0007	0.0001
United Kingdom	0.0009	0.0011	0.0002	0.0003	0.0003	0
Brazil	0.0009	0.0008	–0.0001	0.0023	0.0026	0.0003
Peru	0.0007	0.0006	–0.0001	0.0006	0.0009	0.0003
Other	0.0075	0.0091	0.0016	0.0026	0.0039	0.0013
Mother's nationality						
Japan	0.9720	0.9745	0.0025	0.9785	0.9758	–0.0027
South Korea	0.0061	0.0045	–0.0016	0.0092	0.0077	–0.0015
China	0.0082	0.0090	0.0008	0.0049	0.0072	0.0023
Philippines	0.0059	0.0050	–0.0009	0.0027	0.0034	0.0007
Thailand	0.0009	0.0006	–0.0003	0.0003	0.0003	0
United States	0.0007	0.0006	–0.0001	0.0002	0.0001	–0.0001
United Kingdom	0.0004	0.0003	–0.0001	0.0001	0.0001	0
Brazil	0.0010	0.0007	–0.0003	0.0021	0.0024	0.0003
Peru	0.0006	0.0005	–0.0001	0.0006	0.0008	0.0002
Other	0.0042	0.0044	0.0002	0.0014	0.0023	0.0009
Household head's job						
Farmer	0.003	0.002	–0.001	0.004	0.003	–0.001
Self-employed	0.076	0.073	–0.003	0.085	0.084	–0.001
Employed	0.791	0.792	0.001	0.767	0.763	–0.004
Others	0.086	0.076	–0.010	0.093	0.083	–0.010
Unemployed	0.013	0.011	–0.002	0.019	0.017	–0.002
C. Prefecture-year data						
New registration of trucks	13,132	16,232	3,100	7,881	8,628	747
New registration of buses	331	485	154	168	214	46
New registration of passenger cars	101,457	93,889	–7,568	58,888	54,572	–4,316
Population, million	7.8	8.0	0.2	4.0	4.1	0.1
Per capita income, million yen	4.1	3.9	–0.2	3.5	3.3	–0.2
Unemployment rate, %	5.0	5.8	0.8	4.9	5.9	1.0

Notes: This table presents the sample averages during the pre- and post-intervention periods, and their differences, for the treatment and control groups. Before is from January 2000 to September 2003, and After is from October 2003 to December 2008. For Hyogo, Before is from January 2002 to September 2004, and After is from October 2004 to December 2008.

On the other hand, average birthweight in the treatment group fell by 19 g, relative to 16 g in the control group. A differential temporal trend can also be observed for the gestation period; the treatment group had experienced a decreased gestation period by 0.53 weeks, which is larger than that for the control group (0.38 weeks). Our worry is that some unobservable factors, such as differential growth of cesarean sections among regions, might generate divergent trends of birthweight between the treatment and control groups through the gestation period. A full discussion will be provided in the next section.

5. Difference-in-Difference Analyses

5.1. Specifications

Drawing on a difference-in-difference (DD) research design, we estimate the following initial specification:

$$SPM_{i,t} = \alpha_0 + \alpha_1(Treated_i \times Post_t) + \boldsymbol{\gamma X}_{i,t} + \varepsilon_{i,t} \qquad (1)$$

where *SPM* is ambient SPM concentration in μg/m^3, *i* is pollution monitor, and *t* is hour. *Treated* is a dummy taking the value one if a unit is located inside an LEZ and zero otherwise. *Post* is a dummy indicating the period after an LEZ was implemented: October 2003 onwards for Tokyo, Saitama, Kanagawa, and Chiba and October 2004 onwards for Hyogo. ***X*** is a vector of determinants of outcome variables. ε is an error term. Our interest is in identifying α_1, the effect of the treatment.

Equation (1) is estimated separately for both roadside and background monitors. ***X*** includes hourly meteorological conditions, monitor fixed effects, month fixed effects, hour-of-day fixed effects, and national holiday and weekend dummies. The monitor fixed effects account for time-invariant factors relevant for air pollution levels (e.g. topography). The month fixed effects control for any national-level monthly changes during the sample period such as the tightening of the national fuel economy standard and reductions in the sulfur content of light fuel oil. The hour-of-day fixed effects capture regular within-day patterns such as due to peak and off-peak hours.

The specification for analyzing the effect of the LEZs on new vehicle registrations (*Vehicle*) is:

$$\ln Vehicle_{i,t,s} = \alpha_0 + \alpha_1(Treated_i \times Post_t) + \boldsymbol{\gamma X}_{i,t,s} + \varepsilon_{i,t,s} \tag{2}$$

where subscripts *i*, *t*, and *s* are prefecture, year, and vehicle size (standard or heavy) and ln is the natural logarithm. This three-dimensional specification is estimated separately for new registrations of trucks, buses, and passenger cars. For the latter, we expect that there is no effect as they were not subject to LEZ rules. The post-period in this annual specification is after the year 2003 for Tokyo, Saitama, Kanagawa, and Chiba, and after the year 2004 for Hyogo. $\boldsymbol{X}$ includes prefecture-level controls such as population, per capita income, and the unemployment rate. Prefecture, year, and vehicle-size fixed effects are also included.

Our analysis of the effect of LEZs on birthweights uses a dataset of all births (*j*). We estimate the equation:

$$Birthweight_j = \alpha_0 + \alpha_1(Treated_m \times Post_d) + \boldsymbol{\gamma X}_{j,m,d} + \varepsilon_j \tag{3}$$

where the dependent variable is the log birthweight or a binary variable taking the value one for a birthweight below either 2,500 g or 1,500 g.[19][20] m is municipality and d is day. $\boldsymbol{X}$ includes the gestation period in weeks, gender, type of birth (single or multiple), the birth order, the ages of the mother and father, the nationalities of the mother and father, the household head's job, municipality fixed effects, and month fixed effects.

The reason for controlling for the gestation duration is that there has been an overall increase in the prevalence of cesarean sections in Japan and also a decrease in gestation durations and birthweights over time (Kato et al., 2021). Specifically, the cesarean section rate rose from 17.4% in 1999 to 23.3% in 2008, with differential growth rates by prefecture (Kawamura and Ogura, 2013; Maeda et al., 2018; Yuda, 2018). The simple DD interpretation in Table 4 suggested divergent trends for the gestation period between the treatment and control groups, perhaps because LEZ prefectures experienced a faster increase in the popularity of cesarean sections than non-LEZ prefectures for reasons unrelated to the LEZs themselves.[21] This would be important to control for.

Birthweights are a function of both fetal growth per gestational age and the gestation duration (Glinianaia et al., 2004). In Equation (3), α_1 can be interpreted as a treatment effect on fetal growth per gestational age given that the gestation period has been included in the control set. Analysis of birthweights adjusted for gestation duration is common in epidemiological research, with examples including the studies of Morello-Frosch et al (2010) and Pedersen et al (2013). Our approach helps to reduce omitted

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[19] We focus on the log birthweight as the dependent variable, rather than the level of birthweight, as the R^2 for the model with the log birthweight is 20% higher than that with the level of birthweight (Table 7). The sign and significance levels are the same either way.
[20] Gestation age could be analyzed as an outcome variable (Currie and Walker, 2011). However, we use this variable as a control in this study to account for the upward trend in cesarean sections in Japan, as will be discussed below.
[21] Appendix G shows suggestive evidence.

variable biases, but also means that the total effect of LEZs on birthweights (effects on fetal growth per gestational age plus effects on gestation duration) cannot be estimated. Our estimates should be regarded as potentially a lower bound of the policy effect.

To account for potential serial correlation, standard errors are clustered at the municipality level in the air quality and birthweight analyses. Clustering is at the prefecture level in the new vehicle registration analysis given that this is the smallest geographical unit in this analysis (Bertrand et al., 2004).

We also estimate additional specifications to examine how treatment effects differ among prefectures and evolve over time. For the pollution analysis, we estimate:

$$SPM_{i,t} = \alpha_0 + \sum_{p=Tokyo}^{Hyogo} \alpha_1^p \left(Treated_i^p \times Post_t\right) + \boldsymbol{\gamma X}_{i,t} + \varepsilon_{i,t} \tag{4}$$

$$SPM_{i,t} = \alpha_0 + \sum_{year=-2}^{+5} \alpha_1^{year} \left(Treated_i \times Post_t^{year}\right) + \boldsymbol{\gamma X}_{i,t} + \varepsilon_{i,t} \tag{5}$$

Superscript *p* in Equation (4) stands for the five prefectures that implemented LEZs: Tokyo, Saitama, Kanagawa, Chiba, and Hyogo. The other elements are identical to Equation (1). α_1^p captures the pollution-reducing effects of the LEZs by prefecture. Superscript *year* in Equation (5) stands for years relative to LEZ implementation. For example, year = +1 means the year following the intervention: October 2003–September 2004 for Tokyo, Saitama, Kanagawa, and Chiba, and October 2004–September 2005 for Hyogo. In estimating Equation (5) we limit our sample to October 2000–September 2008. The reference period is October 2000–September 2001. α_1^{year} indicates the extent to which outcomes in treated areas, relative to the initial pre-intervention period, differ from those of the control group. In analyzing the effects on new vehicle registrations, the reference period is the year 1999.[22]

5.2. Effects of the LEZs on air pollution

Table 5 reports the estimation results for Equation (1) using a monitor-hour panel dataset. Column 1 finds a point estimate for Treated × Post of –2.3 – significantly different from zero at the 1% level, with a 95% confidence interval ranging from –3.7 to –0.9. This suggests that the implementation of the LEZs on average led to a reduction in hourly ambient SPM concentrations of 2.3 μg/m^3 during the post-intervention period for roadside monitors inside the LEZs relative to roadside monitors outside the LEZs. Given that the mean pre-intervention SPM level for the LEZ monitors was 43 μg/m^3, the pollution-reducing effect of the LEZs is equivalent to about a 5.4% reduction on average. The result also suggests that about 20% of the reduced SPM concentration during October 2003–September 2008 inside LEZs was attributable to the intervention.

[22] Given that treatment is rolled out over time, a Goodman-Bacon decomposition (2021) could potentially be applied to our analyses. However this approach relies on the assumptions that average treatment effects for each timing group do not change over time. We instead find evidence that treatment effects on air pollution and birthweights vary by prefecture (Figures 3 and 4) and over time (Figures 7 and 8). We thus decided not to employ this approach.

Table 5 —Estimated Effect of the LEZs on Air Pollution

Dependent variable: Hourly ambient concentration of SPM		
	Roadside monitors (1)	Background monitors (2)
Treated × Post	–2.320***	–1.319**
	(0.697)	(0.542)
R^2	0.21	0.16
Monitor fixed effects	Yes	
Month fixed effects	Yes	
Control variables	Yes	
Monitors inside LEZs	125	191
Monitors outside LEZs	34	52
Observations	11,371,701	16,913,730
Pre-LEZ mean	43	35

Notes: This table shows the estimation results for Equation (1) for both roadside and background monitors. Each specification uses an hourly panel dataset at the monitor level for 1 January 2000–31 December 2008. The set of monitors outside LEZs is selected by propensity score matching. The control variables include hourly meteorological conditions (temperature, precipitation, wind speed, pressure, and humidity), hour-of-day fixed effects, and national holiday and weekend dummies. Standard errors are robust to heteroscedasticity and clustered at the municipality level. The pre-LEZ mean is for pollution monitors located within LEZs.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Column 2 of Table 5 finds that in point estimate terms the pollution-reducing effect in background areas is smaller than that in roadside areas. This is as expected given that background monitors are more distant from sources of automobile emissions. This finding is consistent in alternative specifications and samples (Tables 10 and 11). Nonetheless, the effect in background areas is still sizeable. The result suggests that the LEZs improved air quality in background areas by about 3.8% relative to the pre-SPM level (35 μg/m^3). The evidence thus indicates that the LEZs led to a reduction in population exposure to air pollution inside the LEZs.

An important issue is that other vehicular control policies such as the ANPC may have also affected pollution levels. However, the ANPC was introduced in June 1992, well before the LEZs were implemented, and designation statuses for the ANPC did not switch during our sample period. Nishitateno and Burke (2020) also found that the effect of the ANPC on the local annual NO_2 concentration was quite stable over 2000–

2008. Monitor fixed effects help to control for effects of the ANPC in the time period of our analysis.

Figure 3 presents estimation results for Equation (4). Panel A shows that the largest effect for roadside areas was in Tokyo, where hourly SPM concentration was reduced by 5.1 μg/m^3 (11%) as a result of its LEZ. This is perhaps related to the fact that the initial pollution level was higher in Tokyo than in the other LEZ prefectures. The average pollution reductions for Saitama, Kanagawa, and Chiba were about 2.3 μg/m^3 (5%), 2.1 μg/m^3 (5%), and 1.0 μg/m^3 (2.5%), respectively. Panel B shows that the pollution reduction in background areas ranges from 0.9 μg/m^3 (2.6%) for Kanagawa to 2.3 μg/m^3 (6.1%) for Saitama.

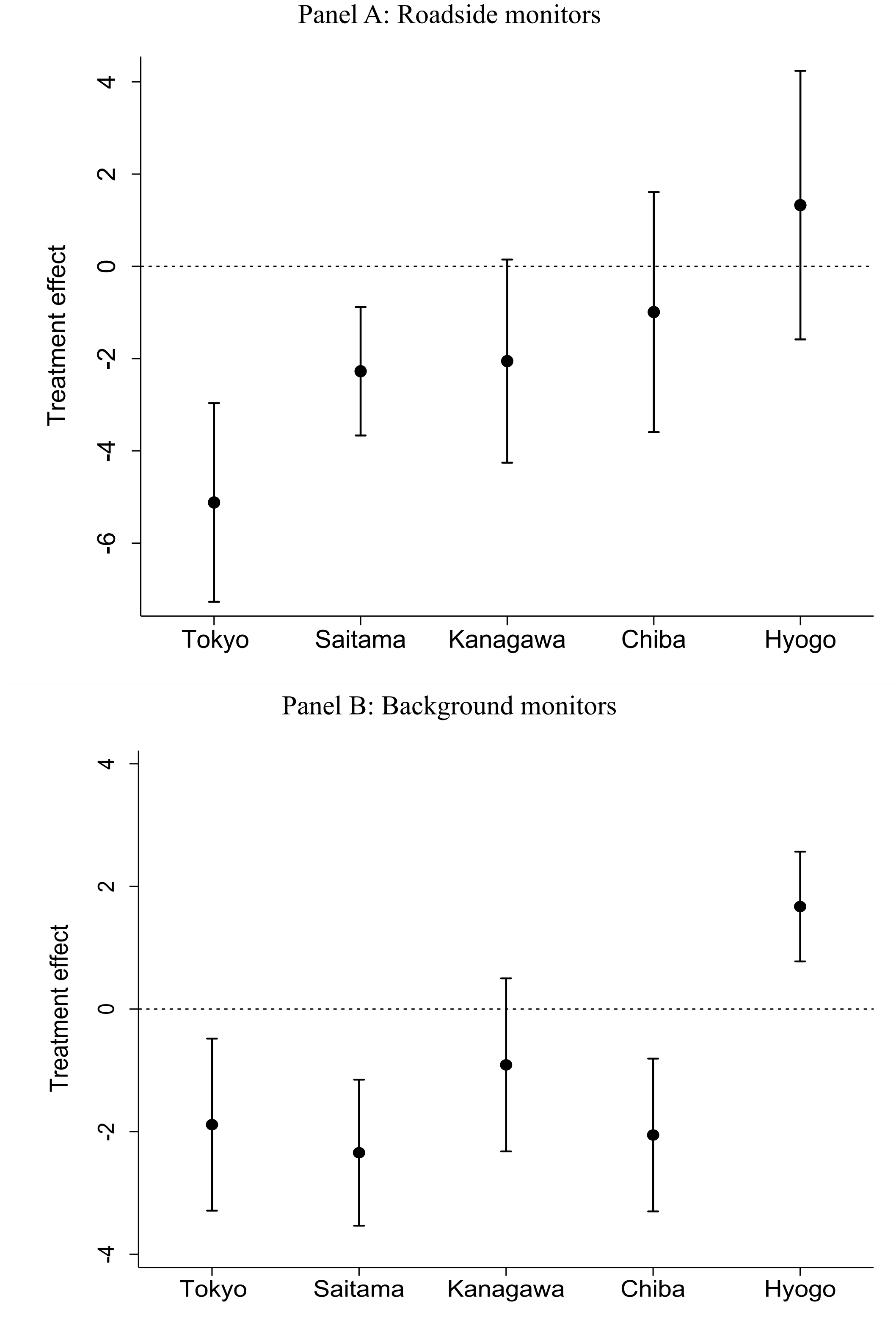


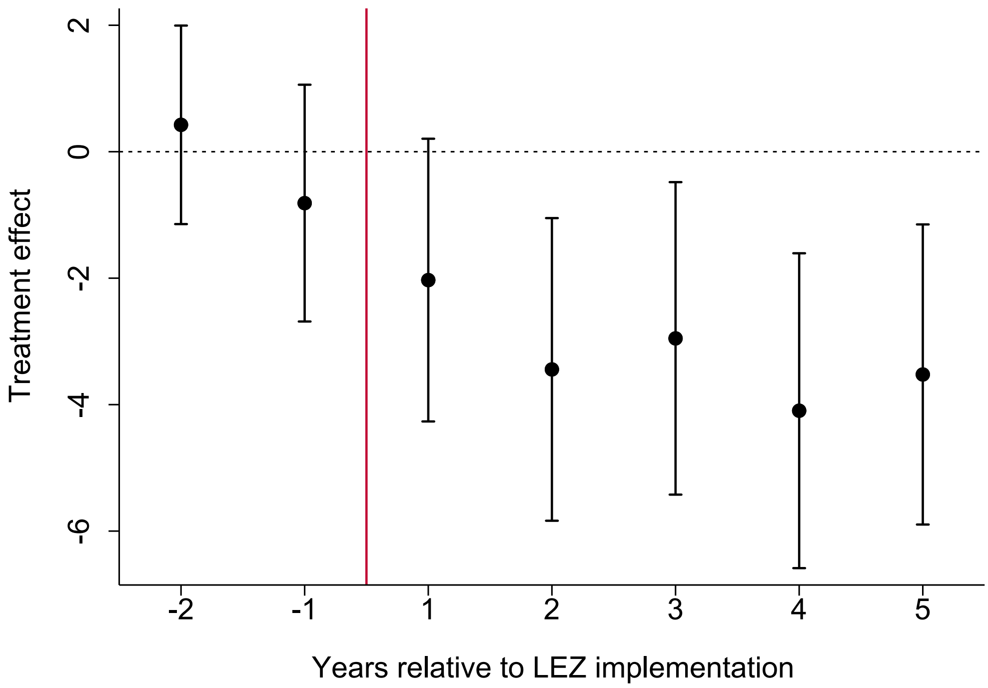
Figure 3. Pollution-Reducing Effect by Prefecture

Notes: The figure plots the result of estimating Equation (4) for a monitor-hour panel dataset for 1 January 2000–31 December 2008. The circles show the point estimates and the bands represent the 95% confidence intervals. The unit of treatment effects is $\mu g/m^3$.

Interestingly, we find a point estimate of 1.3 for roadside monitors and 1.7 for background monitors in Hyogo, suggesting that improvements in air quality in Hyogo's designated municipalities were slower relative to the control group. This may be because pre-treatment pollution levels in Hyogo's designated areas (37 and 30 μg/m^3 for roadside and background monitors) were lower than those in the control group (44 and 35 μg/m^3 for roadside and background monitors). In addition, Hyogo introduced its LEZ in a relatively limited area, without cooperating with neighboring prefectures such as Osaka, the second largest prefectural economy. This was a quite different policy setting from Tokyo metropolitan area, where the neighboring four prefectures (Tokyo, Saitama, Kanagawa, and Chiba) cooperated to form the massive neighbouring LEZs. There might have been some challenges in preventing polluting trucks and buses from entering designated areas in the Hyogo LEZ.

Figure 4 presents the results for estimating Equation (5). We see that the treatment effect gradually increased during the post-intervention period in point estimate terms. Panel A suggests that the mean hourly SPM in roadside areas was about 2 μg/m^3 lower during the year after the intervention relative to three years before the intervention. The event-study estimate increased to –4.1 μg/m^3 and –3.5 μg/m^3 during four and five years after the intervention, respectively. Panel B indicates that a similar temporal pattern of the treatment effect is found for background areas.

Panel A: Roadside monitors



Panel B: Background monitors

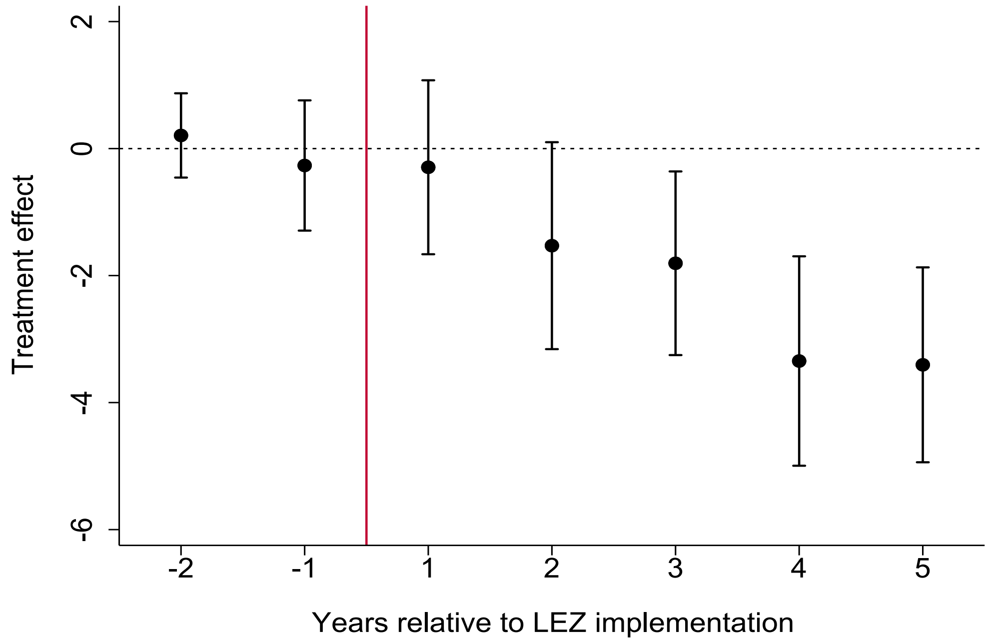


Figure 4. Event-Study of Air Pollution

Notes: The figure plots the result for estimating Equation (5) for a monitor-hour panel for 1 October 2000–31 September 2008. The circles show the point estimates and the vertical bands represent the 95% confidence intervals. The unit of treatment effects is μg/m^3.

5.3. Effects of the LEZs on new vehicle registrations

Table 6 reports estimates of Equation (2) for a three-dimensional panel by prefecture, year, and vehicle size. Column 1 shows that the LEZs increased annual registrations of new diesel trucks by about 28% on average during 2003–2008 in Tokyo, Saitama, Kanagawa, Chiba, and Hyogo relative to the control prefectures.[23] Given that the mean annual new registrations of diesel trucks in the LEZ prefectures over 1999–2002 was 13,132, the effects of the LEZs on new vehicle replacements amount to about 3,700 vehicles per annum on average for the LEZ prefectures. We also find that the LEZs increased annual registrations of new diesel buses by about 23% (76 per annum) (Column 2).

Table 6 —Estimated Effects of LEZs on Log New Vehicle Registrations

Dependent variables	Ln annual new vehicle registrations for:		
	Trucks	Buses	Passenger cars
	(1)	(2)	(3)
Treated × Post	0.248**	0.207**	–0.007
	(0.089)	(0.084)	(0.010)
R^2	0.97	0.91	0.97
Prefecture fixed effects		Yes	
Year fixed effects		Yes	
Vehicle-size fixed effects		Yes	
Control variables		Yes	
Prefectures with LEZs		5	
Prefectures without LEZs		8	
Observations		260	
Pre-LEZ mean	13,132	331	101,457

Notes: This table shows the estimation results for Equation (2). All specifications use a three-dimensional panel by prefecture, year, and vehicle size over 1999–2008. Control variables include population, per capita income, and the unemployment rate. Standard errors are robust to heteroscedasticity and clustered at the prefecture level. The pre-LEZ mean is for prefectures that implemented an LEZ.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Column 3 of Table 6 reports that the effect of the LEZs on passenger car registrations is indistinguishable from zero. This is as expected given that they were not covered by the policy. The finding reduces concerns over the effects of potentially confounding trends.

[23] The formula $100 * [\exp(\text{coefficient}) - 1]$ is applied to log-linear coefficients to calculate the exact percentage change.

Careful attention should be paid to interpreting the results in Table 6. They suggest that the total sums of diesel trucks and buses replaced due to the policy over 2003–2008 across the treatment prefectures were about 22,200 (3,700×6 years) and 456 (76×6 years), accounting for only 2–4% of the regulated diesel trucks and buses.[24] This implies that most owners of non-compliant vehicles probably responded to the policy by installing a diesel particulate filter. Data on filter installations are however not available.

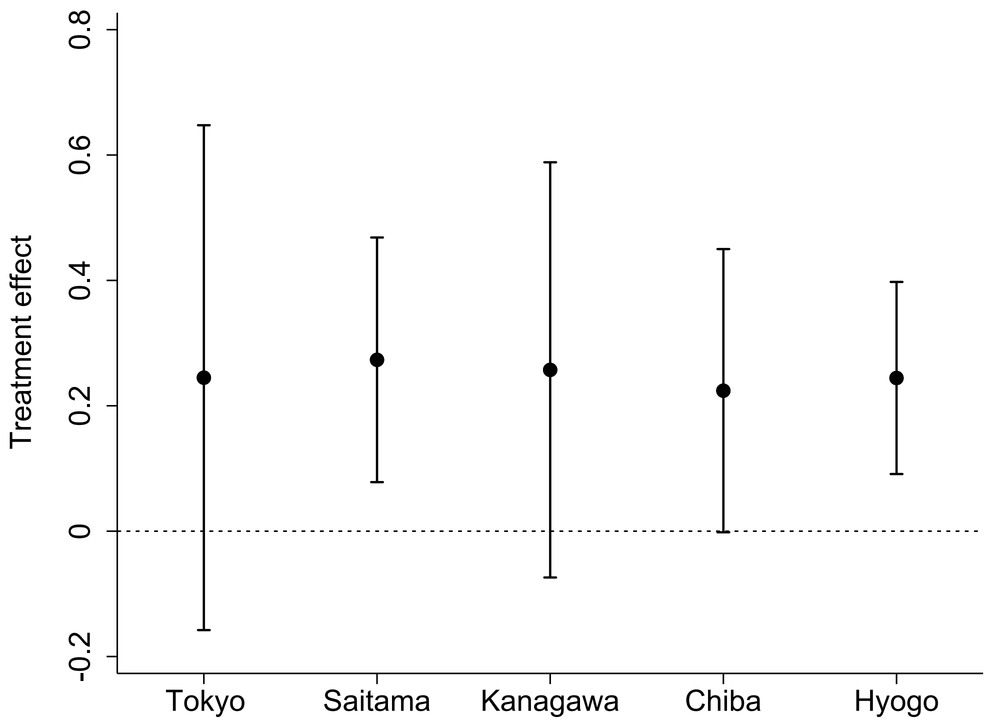
Implementing vehicle retrofits as a response to the policy makes sense, as the cost was cheaper than buying a new vehicle and the majority of regulated vehicles were relatively young. For example, the average prices of standard truck and diesel particulate filters were US$45,500 and US$2,400 in 2005, respectively. Two thirds of regulated trucks in the LEZ prefectures were used for less than 11 years, which was the average usage period for trucks as of 2003 (Japan Trucking Association, 2007). It is thus indeed likely that only some owners of old regulated vehicles would have chosen to purchase a new vehicle rather than retrofit their existing vehicle as a result of the LEZs, as suggested by Table 6.[25]

Figure 5 presents estimation results for new vehicle registrations by prefecture. We see that the effects of LEZs on new registrations of regulated vehicles (trucks and buses) relative to the control group are similar among LEZ prefectures (Panels A and B). Panel C shows that LEZ prefectures experienced differential time trends for effects on new registrations of passenger cars.

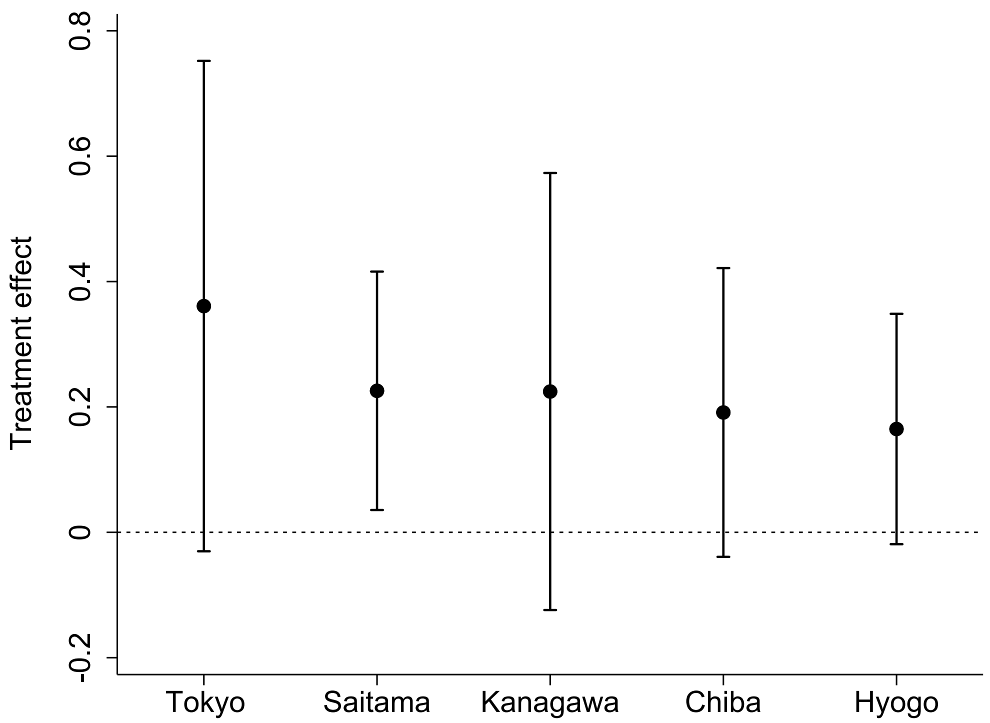
[24] These % shares of diesel trucks and buses replaced due to the policy are obtained by using the total number of regulated vehicles as of 2003; 512,000 for trucks and 19,300 for buses.

[25] Another mechanism leading to the installation of diesel particulate filters was subsidies provided by the LEZ prefectural governments. For example, the Tokyo metropolitan government gave a subsidy to cover up to one quarter of the costs of a diesel particulate filter: https://www.mlit.go.jp/jidosha/sesaku/environment/fukyu/dpf_toriatsukai.pdf

Panel A: Trucks



Panel B: Buses



Panel C: Passenger cars

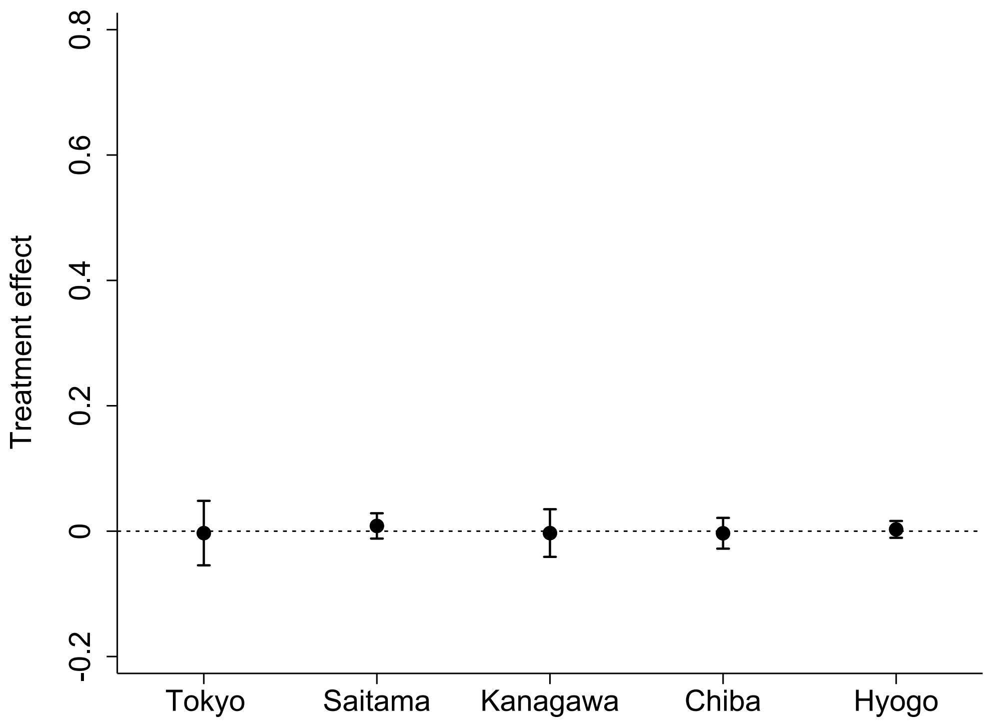


Figure 5. Effects on Log New Vehicle Registrations by Prefecture

Notes: The figure plots results by prefecture for a three-dimensional panel by prefecture, year, and vehicle size over 1999–2008. The circles show the point estimates and the vertical bands represent the 95% confidence intervals.

Figure 6 presents estimation results for new vehicle registrations by year. Panel A shows that the effect of LEZs on replacements of non-compliant trucks peaked in the year that the LEZs were implemented and gradually declined over time. This is consistent with the fact that the LEZs went immediately into effect for a large share of targeted vehicles and in a staggered way over time for other vehicles. Panel B shows that most replacements of non-compliant buses as a response to the policy occurred during the initial post-intervention period. No treatment effects are observed for passenger cars (Panel C).

Panel A: Trucks

Panel B: Buses

Panel C: Passenger cars

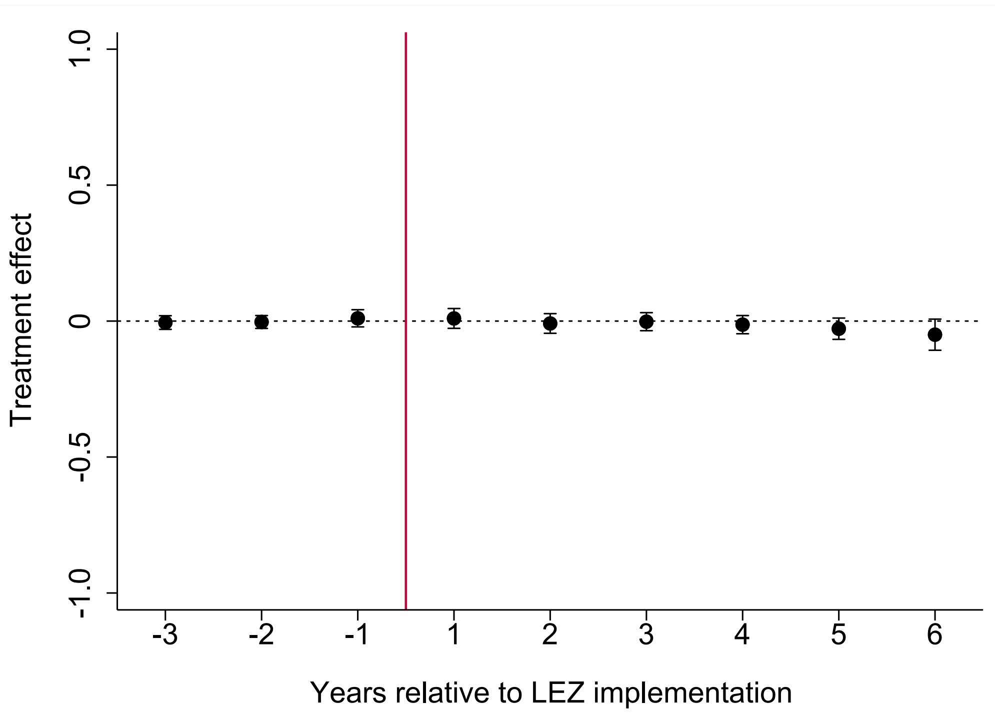


Figure 6. Event-Study of Log New Vehicle Registrations

Notes: The figure plots the result for estimating effects by year using a three-dimensional panel by prefecture, year, and vehicle size over 1999–2008. The circles show the point estimates and the bands represent the 95% confidence intervals.

The estimates, together with the ratio of standard to heavy trucks (48:52) and the average prices of standard and heavy trucks (US$45,500, US$120,000) from the Japan Trucking Association (2007), can be used to calculate that the aggregate costs of replacements for diesel trucks were approximately US$1.3 billion in year-1997 dollars. Likewise, the baseline estimate above, together with the ratio of standard to heavy buses (27:73) and the average prices of standard and heavy buses (US$181,000, US$391,000) from the Ministry of Land, Infrastructure, Transport and Tourism (2017), suggest that the aggregate costs of replacements for diesel buses were about US$0.1 billion. Thus, total vehicle replacement costs were in the order of US$1.4 billion in year-1997 dollars.

Assuming that other non-compliant trucks and buses installed a diesel particulate filter, the total number of filters installed due to the policy in the LEZ prefectures was about 515,000. The average price for the diesel particulate filter was US$2,400, suggesting that the installation costs amounted to about US$1.1 billion. Including the vehicle replacement costs estimated above, the total compliance costs could be around US$2.5 billion in year-1997 dollars.

5.4. Effects of the LEZs on birthweights

Table 7 reports estimates for Equation (3) for birthweight outcomes. Note that all specifications analyze the same sample with 2,246,828 observations and include municipality fixed effects, month fixed effects, and control variables. Columns 1 and 2 present specifications using dummy variables that take the value one for birthweights below 2,500 g or below 1,500 g. The results suggest that the LEZs reduced the probability of birthweights below 2,500 g or 1,500 g by 0.25 and 0.07 percentage points respectively, conditioning on the gestation period and the other controls. We now take the difference between the actual numbers of newborn babies with a birthweight below 2,500 g or 1,500 g in the treatment group and the counterfactual for each one-year period after the policy during October 2003–September 2008. Doing so suggests that of the 944,178 births in LEZs over October 2003–September 2008, about 2,360 births below 2,500 g and about 661 births below 1,500 g switched to being above these birthweight thresholds. This calculation holds the control variables, including the gestation period, constant.

Column 3 of Table 7 presents specification with continuous birthweight variables in the natural logarithm, finding a point estimate for Treated × Post of 0.0014 – significantly different from zero at the 10% level. This suggests that the implementation of the LEZs led to about a 0.14% increase in birthweights on average over the post-intervention period for the newborn babies inside the LEZs relative to the newborn babies outside the LEZs, conditioning on the gestation period and the other controls. Given that the mean pre-treatment birthweight inside LEZs was 3,027 g, the LEZs thus increased birthweights by about 4.2 g on average relative to the control group, all else equal. Column 4 reports the results with the level of birthweight, suggesting that the effect of LEZs on birthweight was 3.2 g.

Table 7 —Estimated Effects of LEZ on Birthweight Outcomes

Dependent variables:	Dummy if birthweight is below:		Ln birthweight	Birthweight
	2,500 g	1,500 g		
	(1)	(2)	(3)	(4)
Treated × Post	–0.0025**	–0.0007*	0.0014*	3.2198*
	(0.001)	(0.0003)	(0.0007)	(1.8058)
R^2	0.27	0.24	0.48	0.40
Municipality fixed effects	Yes			
Month fixed effects	Yes			
Control variables	Yes			
Births inside LEZs	1,723,791			
Births outside LEZs	523,037			
Observations	2,246,828			
Pre-LEZ mean	0.0864	0.0063	3,027	3,027

Notes: The table shows the results for estimating Equation (3). All specifications use birth data over 1 January 2000–31 December 2008. Control variables include the gestation period, gender, type of birth (single or multiple), birth order, ages of mother and father, nationalities of mother and father, and household head's job. Standard errors are robust to heteroscedasticity and clustered at the municipality level. The pre-LEZ mean is for births inside LEZs.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

The results contrast to those of Gehrsitz (2017), who found no effects of LEZs on birthweights in Germany. There are at least a couple of potential contributing explanations. First, Gehrsitz (2017) analyzed the overall effect on birthweights without conditioning on gestational age. Potentially differential trends in the rate of cesarean section deliveries due to reasons other than the LEZs were not considered.[26] Second,

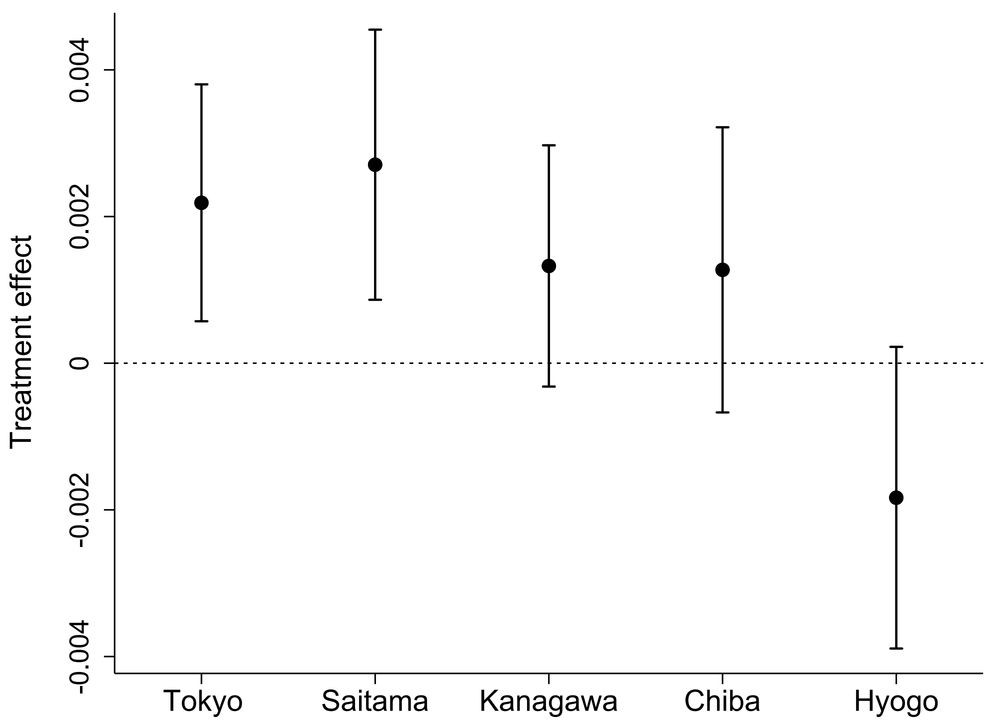
[26] During his sample period (2005–2012), the rate of cesarean sections per 1,000 live births in

the treatment group used by Gehrsitz (2017) includes births outside LEZs but within the same city as an LEZ. This could potentially lead to underestimation of the health effect of LEZs, especially because drivers of non-compliant vehicles might increase their driving outside LEZs but within the same city.

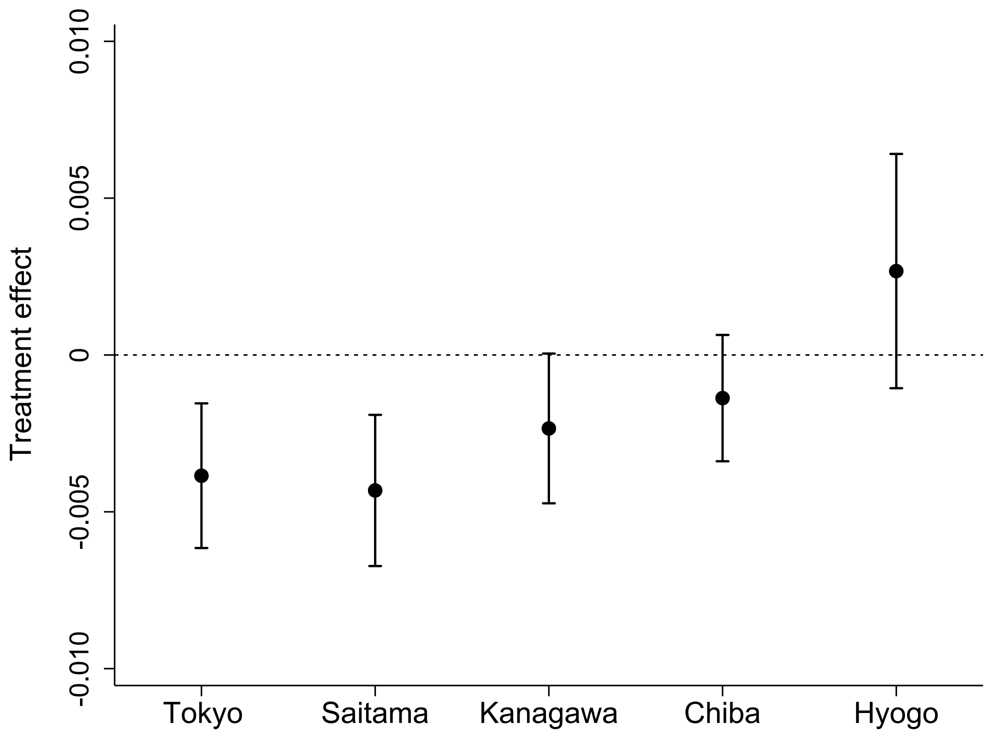
Figure 7 presents estimation results for birth outcomes by prefecture. Panel A shows that the largest effects are for Tokyo and Saitama, suggesting that birthweights on average increased by 0.2% and 0.3% due to the LEZ intervention (all else equal), respectively. Similar evidence is found when low birthweight dummies are used as a dependent variable (Panels B and C). Importantly, this accords with the fact that Tokyo and Saitama experienced a larger pollution reduction compared to other prefectures (Figure 3).

Germany increased from 263 to 309 (Organization for Economic Co-operation and Development, 2022b).

Panel A: Ln birthweight



Panel B: Birthweight < 2,500 g



Panel C: Birthweight < 1,500 g

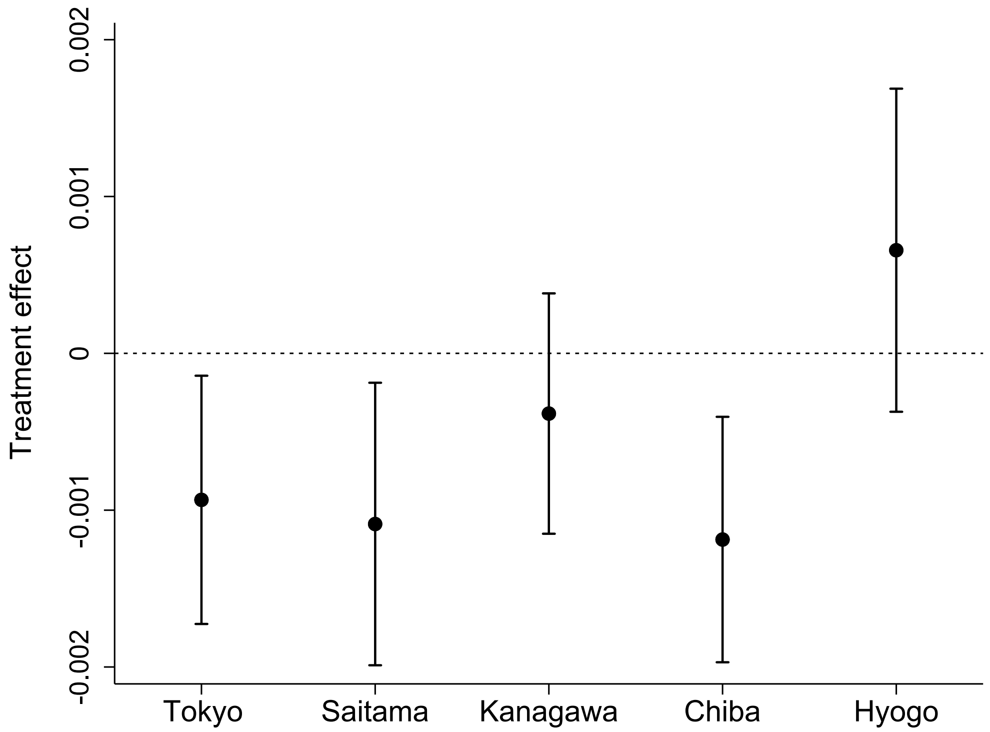
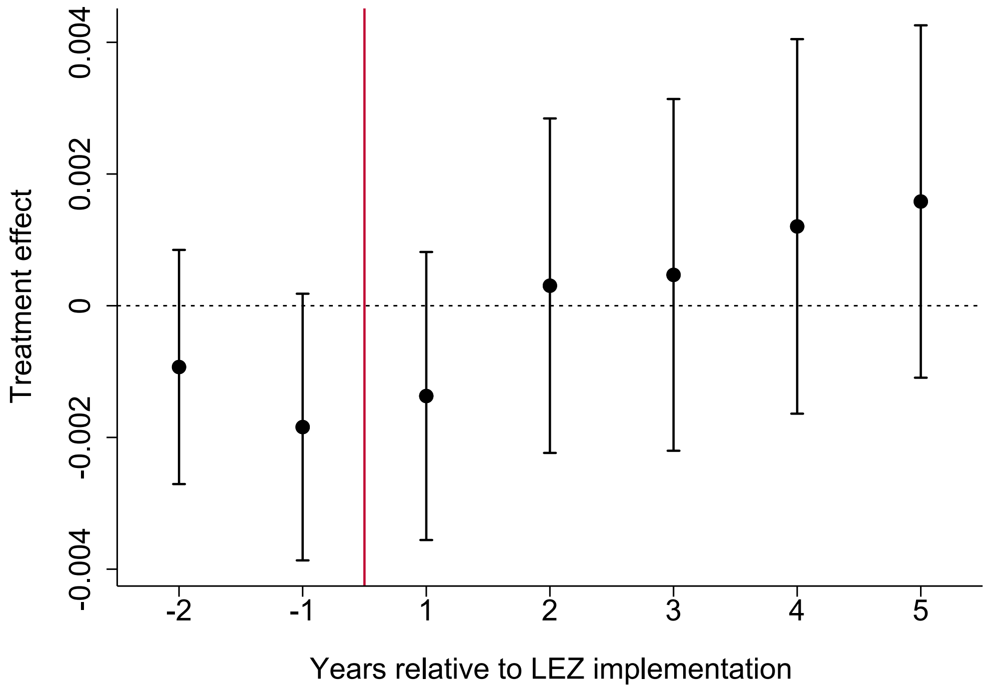


Figure 7. Conditional effects on Birthweights by Prefecture

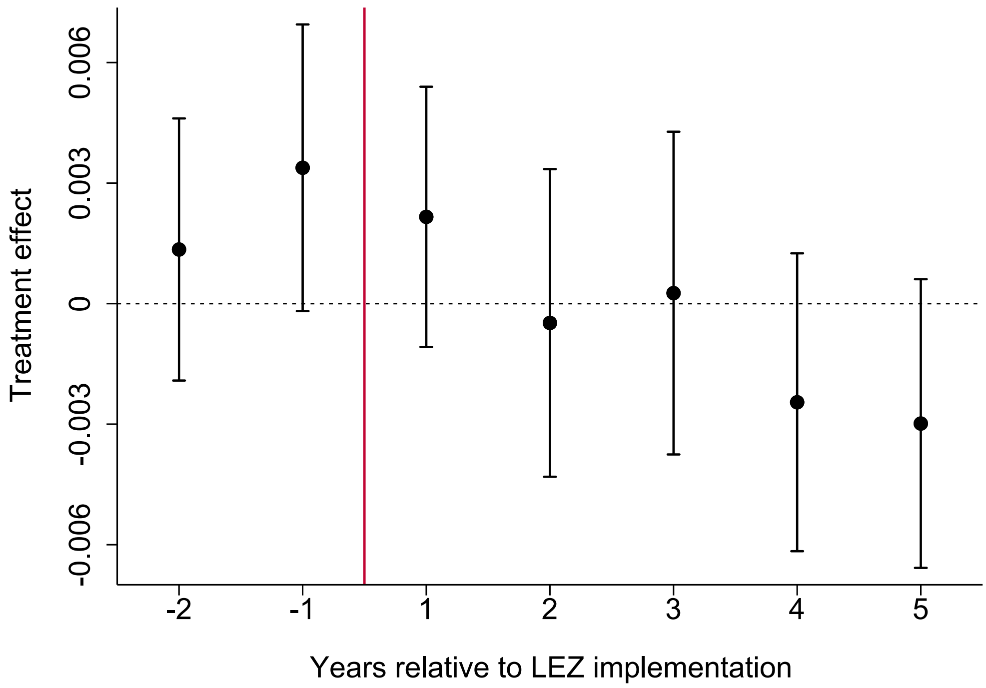
Notes: The figure plots the result for birthweight outcomes by prefecture using a birth dataset for 1 January 2000–31 December 2008. The circles show the point estimates and the bands represent the 95% confidence intervals. The effects are conditional on the controls including the gestational period.

Figure 8 presents estimation results for birthweight effects by year. Interestingly, the time patterns of the effects on birthweights mirror the dynamics of the effects on air pollution (Figure 4). Panel A suggests that the largest effects occurred 4–5 years after the LEZs were implemented, although the point estimates for individual years are statistically insignificant. That the effects on birthweights are large during the later post-intervention period is also evident in Panels B and C where the low birthweight dummies are used as an outcome variable. We find that the effects at 4–5 years later are statistically significant for the incidence of low birthweights below 1,500 g.

Panel A: Ln birthweight



Panel B: Birthweight < 2,500 g



Panel C: Birthweight < 1,500 g

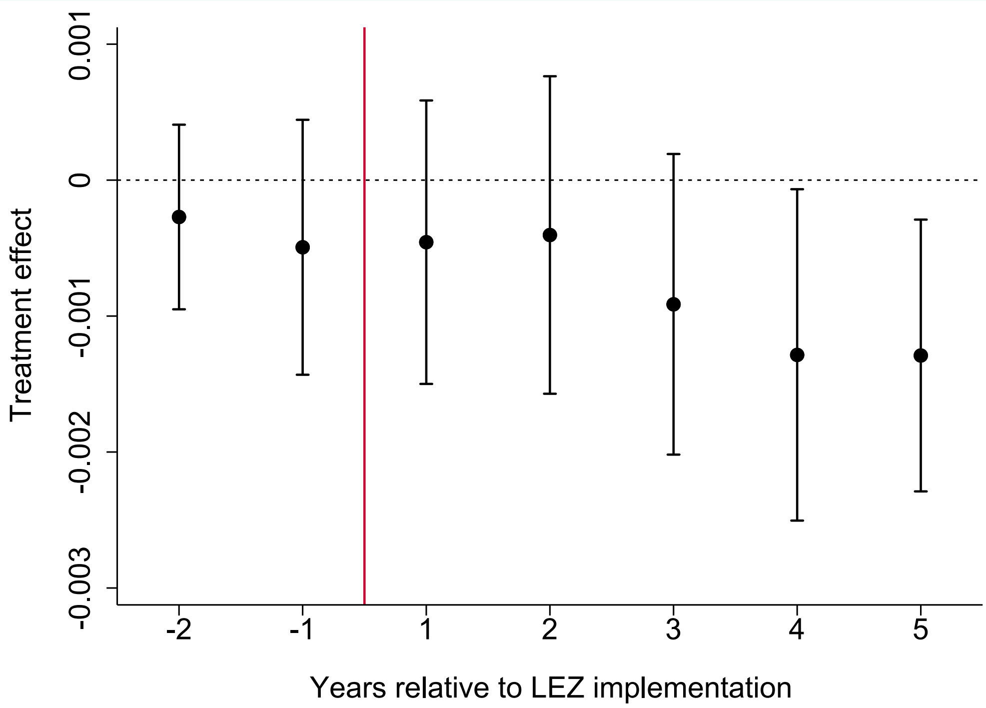


Figure 8. Event Study of Birthweight Outcomes

Notes: The figure plots the result for log birthweights for a birth dataset over 1 October 2000–31 September 2008. The circles show the point estimates and the bands represent the 95% confidence intervals. The effects are conditional on the controls including the gestational period.

6. Robustness analyses

6.1. Potentials for spatial spillovers

Spatial spillovers could bias our estimates. On the one hand, new low-emission vehicles that comply with LEZ standards are sometimes driven outside the LEZs, which would mean that our method would underestimate the effect of the LEZs. On the other, it is possible that truck and bus companies relocated their businesses outside the LEZs, which would mean that our method would overestimate the pollution-reducing effects of the policy. To gauge the extent and scope of potential spatial leakages, we estimate the following specification for a restricted sample of roadside monitors outside LEZs:

$$SPM_{i,t} = \beta_0 + \beta_1(Neighbor_i \times Post_t) + \boldsymbol{\gamma}\boldsymbol{X}_{i,t} + \varepsilon_{i,t} \tag{6}$$

where *Neighbor* is a dummy variable taking the value one if a non-LEZ monitor is located within 50 kilometers from either Chiyoda ward in Tokyo or Higashinada ward in Hyogo and zero for the remaining non-LEZ monitors. These two municipalities were chosen based on the centroid of the two LEZ policy areas. To examine the potential for more widespread spillovers, we also use a dummy variable for whether a non-LEZ monitor is located in a prefecture adjacent to an LEZ. Furthermore, we estimate a specification that controls for the geographical distance from either Chiyoda ward in Tokyo or Higashinada ward in Hyogo (whichever is closer). The other elements are identical to Equation (1). The coefficient β_1 captures the net spillover effect.

Table 8 reports the results. Column 1 suggests that the non-LEZ monitors near the LEZs experienced an increase in SPM levels before and after the intervention of about 0.6 μg/m^3 relative to the remaining non-LEZ monitors. However the estimate is statistically indistinguishable from zero. Column 2 shows that the result is similar even when the scope of the neighbor dummy is more widely defined to cover all non-LEZ monitors located in prefectures adjacent to the LEZs. Column 3 implies that the magnitude of the reduction in SPM levels before and after the intervention is disproportional to the geographical distance from the nearest LEZ. Again, the estimate is not statistically significant. These results reassure us that our baseline estimates are not suffering from a violation of the stable unit treatment value assumption.

Table 8 —Examination of Spillover Effects

Dependent variable: Hourly ambient concentration of SPM			
	(1)	(2)	(3)
Neighbor × Post	0.596	0.412	
	(1.013)	(1.107)	
Ln distance × Post			0.034
			(0.437)
R^2	0.20	0.20	0.20
Observations		2,397,645	

Notes: The table shows estimation results for Equation (6) using different measures of proximity to the LEZs for a sample of roadside monitors outside LEZs. All specifications use hourly panel data at the monitor level for 1 January 2000–31 December 2008 and control for hourly meteorological conditions, monitor fixed effects, month fixed effects, hour-of-day fixed effects, and national holiday and weekend dummies. Column 1 uses a dummy variable for if a non-LEZ monitor is located within 50 kilometers from the center of the nearest LEZ. Column 2 uses a dummy variable for if a non-LEZ monitor is located in a prefecture adjacent to an LEZ. Column 3 uses the geographical distance from the center of the nearest LEZ in the interaction term. Standard errors are robust to heteroscedasticity and clustered at the prefecture level.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

6.2. Potential for sorting

The validity of our DD research design for the analysis of birthweights relies on the assumption that no parents move to LEZs to seek for better birth outcomes. To examine this assumption, we estimate the following specification for parental characteristics (*Parent_Char*):

$$Parent\_Char_j = \varphi_0 + \varphi_1(Treated_m \times Post_d) + \delta_m + \rho_d + \varepsilon_j \qquad (7)$$

where δ_m and ρ_d are municipality fixed effects and month fixed effects, respectively. Parental characteristics include ages of the mother and father, nationalities of the mother and father, and the household head's job. We run a separate regression based on Equation (7) for each characteristic. Table 9 reports the results. We find no evidence of compositional changes for most of the observable parental characteristics before and after the implementation of LEZs. Although some coefficients are statistically significant, their magnitudes are negligibly small.[27] The results alleviate concerns over

[27] Appendix E reports the difference-in-difference estimation results for inflows, outflows, and net inflows of migration, using a municipality-year panel dataset. Due to data limitations, we

estimation bias due to residential sorting.

Table 9 —Estimated Effects of LEZ on Parental Characteristics

	Coefficient	Standard error	R^2
Ln father's age	–0.0014	(0.0011)	0.0280
Ln mother's age	–0.0008	(0.0009)	0.0330
Father's nationality dummies			
Japan	–0.0007	(0.0006)	0.0133
South Korea	0.0014***	(0.0004)	0.0060
China	–0.0005	(0.0003)	0.0044
Philippines	0.0001	(0.0001)	0.0007
Thailand	0.0000	(0.0000)	0.0002
United States	0.0002*	(0.0001)	0.0111
United Kingdom	–0.0001	(0.0001)	0.0078
Brazil	–0.0002	(0.0002)	0.0052
Peru	–0.0003**	(0.0001)	0.0027
Others	–0.0001	(0.0002)	0.0075
Mother's nationality dummies			
Japan	0.0008	(0.0008)	0.0090
South Korea	0.0005	(0.0004)	0.0057
China	–0.0002	(0.0005)	0.0049
Philippines	–0.0005	(0.0004)	0.0025
Thailand	–0.0002**	(0.0001)	0.0005
United States	0.0000	(0.0001)	0.0074
United Kingdom	–0.0001*	(0.0001)	0.0060
Brazil	–0.0003	(0.0002)	0.0050
Peru	–0.0002	(0.0002)	0.0030
Others	0.0001	(0.0003)	0.0056
Household head's job dummies			
Farmer	0.0005	(0.0003)	0.0048
Self-employed	–0.0027*	(0.0015)	0.0060
Employed	0.0089	(0.0057)	0.0207
Others	0.0025	(0.0026)	0.0033
Unemployed	0.0000	(0.0005)	0.0021

Notes: The table shows the results for estimating Equation (7) for each parental characteristic, separately. All estimations are based on birth data for 1 January 2000–31 December 2008. Observations = 2,246,828. Municipality fixed effects and month fixed effects are controlled for. Standard errors are robust to heteroscedasticity and clustered at the municipality level.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

6.3. Alternative specifications

Table 10 reports the results for alternative specifications for both the air pollution and birthweight analyses. Column 1 re-presents our baseline estimates. Column 2 shows estimates when anticipation effects are taken into account. There were lags between the

analyze total migration. We find no evidence that the implementation of LEZs caused inter-municipality migration.

enactments and implementations of the LEZs: 33 months for Tokyo, 19 months for Chiba, 18 months for Saitama, and 12 months for Kanagawa and Chiba. Owners of non-compliant vehicles may have responded in advance of implementation by either switching to a complaint vehicle or installing a diesel particulate filter. If such anticipatory actions are not taken into account, our DD estimates could be biased upward.

Table 10 —Alternative Specifications

	Baseline estimates (1)	Anticipation effects (2)	Day fixed effects (3)	Clustering at the prefecture level (4)
A. Dependent variable: Hourly ambient concentration of SPM for roadside monitors				
Treated × Post	–2.320***	–2.780***	–2.325***	–2.320**
	(0.697)	(0.807)	(0.698)	(0.922)
R^2	0.21	0.21	0.44	0.21
Observations	11,371,701			
B. Dependent variable: Hourly ambient concentration of SPM for background monitors				
Treated × Post	–1.319**	–1.379**	–1.283**	–1.319*
	(0.542)	(0.653)	(0.536)	(0.712)
R^2	0.16	0.16	0.42	0.16
Observations	16,913,730			
C. Dependent variable: Ln birthweight				
Treated × Post	0.0014*	0.0012	0.0014*	0.0014
	(0.0007)	(0.0009)	(0.0007)	(0.0009)
R^2	0.48	0.48	0.49	0.48
Observations	2,246,828			
D. Dependent variable: Dummy if birthweight is below 2,500 g				
Treated × Post	–0.0025**	–0.0020*	–0.0024**	–0.0025**
	(0.0010)	(0.0011)	(0.0009)	(0.0011)
R^2	0.27	0.27	0.27	0.27
Observations	2,246,828			
E. Dependent variable: Dummy if birthweight is below 1,500 g				
Treated × Post	–0.0007*	–0.0008**	–0.0006*	–0.0007
	(0.0003)	(0.0004)	(0.0003)	(0.0004)
R^2	0.24	0.24	0.24	0.24
Observations	2,246,828			

Notes: Column 1 re-presents our baseline estimates from Tables 5 and 7. Columns 2–4 show the estimation results for Equations (1) and (3) with alternative specifications. Standard errors are robust to heteroscedasticity and clustered at the municipality level for Columns 1–3 and at the prefecture level for Column 4.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Following Malani and Reif (2015), we construct a finite dummy variable to capture anticipation effects during the 12 months before an LEZ was implemented, $\sum_{j=1}^{12} \delta_k D_{p,t-k}$. k is a monthly leading indicator, p is prefecture, and t is the implementation date of the LEZ. In the case where $k = 1$, for example, the dummy variable takes 1 if the month of the year is September 2003 for Tokyo, Saitama, Kanagawa, and Chiba, and September 2004 for Hyogo. Twelve months was chosen because (i) owners of non-compliant vehicles had little incentive to replace their polluting cars during the early period of the ordinance, and (ii) the Tokyo government undertook a "Diesel Vehicle Cleanup Project" to prepare for the implementation of its LEZ during the year prior to implementation.

Column 3 of Table 10 shows the result with day fixed effects controlled for instead of month fixed effects to account for additional unobservable factors at the daily frequency. Column 4 displays results where standard errors are clustered at the prefecture level rather than the municipality level. Our concern is that model errors for air pollution and birthweight in the same prefecture might be correlated due to common shocks such as prefectural government policies, resulting in misleadingly smaller standard errors.

The results show that overall, our baseline estimates are robust to alternative specifications. Contrary to expectations, Column 2 of Table 10 suggests that the point estimates in the SPM specifications become larger when anticipation effects are controlled for. Since only Hyogo has the different pre-period to create the finite dummy variable, there is perhaps not enough variation to credibly identify anticipation effects.

6.4. Alternative matched samples

Table 11 shows results using alternative matched samples. Columns 1–3 find similar results to our baseline estimates (Column 1, Table 10). The exception is that the use of the matched samples based on municipality characteristics generates larger pollution-reducing effects in roadside areas (–4.067) (Column 3).

Table 11 —Alternative Samples

	One-to-one matching	Kernel matching	Matching by municipality characteristics	Within 38–40 $\mu g/m^3$ of pre-SPM levels
	(1)	(2)	(3)	(4)
A. Dependent variable: Hourly ambient concentration of SPM for roadside monitors				
Treated × Post	–2.392***	–3.529***	–4.067***	–0.962
	(0.705)	(0.617)	(0.852)	(0.829)
R^2	0.19	0.19	0.20	0.17
Observations	10,825,235	16,602,825	10,620,313	3,807,910
B. Dependent variable: Hourly ambient concentration of SPM for background monitors				
Treated × Post	–0.841	–1.241**	–1.295*	0.148
	(0.648)	(0.546)	(0.681)	(0.865)
R^2	0.16	0.16	0.16	0.15
Observations	13,416,086	14,786,521	11,750,289	3,514,418
C. Dependent variable: Ln birthweight				
Treated × Post	0.0011	0.0012	0.0011	–0.0006
	(0.0009)	(0.0007)	(0.0009)	(0.0010)
R^2	0.48	0.49	0.48	0.48
Observations	1,701,466	1,909,501	1,372,480	456,818
D. Dependent variable: Dummy if birthweight is below 2,500 g				
Treated × Post	–0.0029**	–0.0021**	–0.0024**	0.0006
	(0.0012)	(0.0009)	(0.0011)	(0.0017)
R^2	0.27	0.27	0.27	0.27
Observations	1,701,466	1,909,501	1,372,480	456,818
E. Dependent variable: Dummy if birthweight is below 1,500 g				
Treated × Post	–0.0003	–0.0004	–0.0003	0.0000
	(0.0004)	(0.0003)	(0.0004)	(0.0004)
R^2	0.24	0.24	0.24	0.24
Observations	1,701,466	1,909,501	1,372,480	456,818

Notes: Columns 1−4 show the estimation results for Equations (1) and (3) with alternative matched samples. Standard errors are robust to heteroscedasticity and clustered at the municipality level. ***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

In contrast, Column 4 of Table 11 shows that the use of a matched sample based on a fixed range of pre-SPM levels generates smaller effects on air pollution in both roadside areas (–0.962) and background areas (0.148), and ones that are statistically indistinguishable from zero. In addition, the use of this matched sample leads to negative health effects of LEZs (Panels C and D), although the estimates are not statistically significant. These results remain the same even if we use a wider range of pollution level, for example 38–42 μg/m^3 or 37–43 μg/m^3.

The matching approaches employed by Wolff (2014) and Green et al (2020) generate different estimates from our baseline estimates. The reason for this is perhaps the smaller samples generated under these approaches. It is also possible that omitted variables are more likely to be affecting the estimation in columns 3 and 4 of Table 11 given that the control group sample selection does not take vehicle numbers into account.

7. Conclusion

Residents in metropolitan cities continue to inhale polluted air. To improve air quality and public health, many European cities have introduced Low Emission Zones (LEZs). Yet reliable estimates of the effects on birthweights have been scarce. Analyzing the case of Japan, this paper provides the first evidence of environmental and health impacts of LEZs for a country outside Europe. Japan's key LEZs were prefecture-wide implementations that were unprecedented in scale. In this paper we examined how much the introduction of a large-scale LEZ is effective in reducing ambient SPM concentrations and incidences of low birthweights, conditioning on sets of key controls. We also investigated how owners of non-compliant vehicles responded to the intervention.

We used a matching approach to construct a control group that is comparable to the designated areas in terms of pollution levels and road traffic volumes of regulated vehicles and apply a difference-in-differences (DD) design. We analyzed hourly air pollution data at the monitor level and daily birthweight data at the birth level for 2000–2008. For the vehicle registration analyses we used administrative data on new vehicle registrations for 1999–2008.

The results suggest that the LEZs contributed to improvements in air quality in not just roadside but also background areas within cities relative to the control group, implying reduced population exposure to air pollution. This makes sense, because Japan's key LEZs were introduced prefecture-wide. Our main finding is that the LEZs also improved fetal health. Evidence suggests that in the absence of the LEZs, about 2,360 additional babies would have been born below (rather than above) 2,500 g in the treated prefectures over October 2003–September 2008 holding the gestational periods constant. We also found evidence that some owners of non-compliant vehicles responded to the regulations by purchasing new vehicles.

The implementation of LEZs is costly. Our study found that in the case of Japan the compliance costs of replacing non-compliant vehicles and installing diesel particulate filters amounted to around US$2.5 billion in year-1997 dollars. We have identified benefits in terms of birthweights from the intervention. We have not analyzed other effects such as potentially reduced infant mortality and stillbirths, because we gained access to confidential data on birthweight only. It is also challenging to quantify the long-term effects of improved health at birth on future health and educational outcomes.[28] The LEZs may also have improved health outcomes for children, adults,

[28] McFarland et al. (2022) investigate the impacts of exposure to high-level lead during early

and the elderly that are worthy of examination.

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Appendix A. Previous Research on Low Emission Zones

Authors	Locations	Targeted vehicles	Effects	Data	Methods	Selection of control groups
Wolff (2014)	German cities	All vehicles (except emergency and other work-related vehicles)	PM concentration fell by 9% Share of clean vehicles increased more in cities with LEZ or near LEZ	Daily panel at the monitor level for 2005–2008 Cross-section at the county level for 2010	DD OLS	Similar pre-pollution levels
Gehrsitz (2017)	German cities	All vehicles	PM concentration fell by 8% Stillbirth reduced by 16%, but no effect is found for birthweights	Daily panel at the monitor level for 2005–2012 Daily pooled cross section at the birth level for 2005–2012	DD	Non-LEZ cities but introduced LEZ during the sample period
Rohlf et al (2020)	German cities	All vehicles	PM concentration fell by 6% Pharmaceutical expenditure for asthma and heart diseases by 3–4%	Quarterly panel at the county level for 2006–2013	DD	Similar pre-trends
Klauber et al (2021)	German cities	All vehicles	PM concentrations fell by 5% A LEZ-caused decrease in PM concentration reduced the number of medical prescriptions and the costs of prescriptions for children	Quarterly panel at the county level for 2006–2012	DD IV	Similar pre-trends
Margaryan (2021)	German cities	All vehicles	PM concentration fell by 3% Share of high emission vehicles in car fleet fell by 0.3 percentage points Number of patients with cardiovascular disease decreased by 3% with the larger effects for the elder	Monthly panel at the monitor level for 2004–2016 Yearly panel at the city level for 2007–2016 Yearly panel at the area level for 2004–2017	DD	Similar pre-trends
Pestel and Wozny (2021)	German cities	All vehicles	PM and NO_2 concentrations fell by 6% Hospital's share of diagnosed ischemic heart diseases and chronic lower respiratory diseases decreased by 0.2–0.5 percentage points	Yearly panel at the monitor level for 2006–2016 Yearly panel at the hospital level for 2006–2016	DD	Similar pre-trends
Zhai and Wolff (2021)	Greater London	Light/heavy goods vehicles, trucks, and buses	PM concentration increased during the initial phase by 15% and fell by 6% during the later phase	Daily panel at the monitor level for 2005–2010	DD	Over 180 miles away from London

Note: DD and IV stand for difference-in-difference design and instrumental variable approach, respectively.

Appendix B. Previous Research on Other-Traffic-Related Policy Interventions

Authors	Interventions	Targeted vehicles	Effects	Data	Methods	Selection of control groups
Currie and Walker (2011)	E-Zpass in Pennsylvania and New Jersey	All vehicles	NO_2 concentration fell by 11% Incidences of prematurity and low birthweight decreased by 7–11%	Daily panel at the monitor level for 1994–2003 Daily pooled cross section at the birth level for 1994–2003	DD	Close to highway, but between 2 km and 10 km of a toll plaza
He et al (2018)	Newly-built beltway in Sao Paulo	Heavy diesel trucks	Congestions near the original truck route fell NO_2 concentration near the original truck route fell Cardiovascular and respiratory admission rates near the original truck route decreased	Hourly panel at the segment level for 2008–2013 Daily panel at the monitor level for 2008–2013 Monthly panel at the zip code area level for 2008–2013	DD	Far from the original truck route
Simeonova et al (2019)	Congestion Pricing Zone (CPZ) in Stockholm	All vehicles, but emergency vehicles, buses, hybrid or electric cars, and motorcycles	PM and NO_2 concentrations fell by 14–19% Acute asthma episodes per 10,000 children younger than 5 years old fell by 9.6	Monthly panel at the municipality level for 2004–2010 Monthly panel at the municipality level for 2004–2010	DD	Similar pre-trends
Green et al (2020)	CPZ in London	All vehicles, but motorcycles, bicycles, buses, and taxi	PM and CO concentrations fell by 8–20% Total miles driven for cars/taxi, light/heavy goods vehicles fell, and those for bicycles, motor cycles and buses increased	Hourly panel at the monitor level for 2000–2007 Yearly panel at the county level for 2000–2007	DD	Propensity scores calculated based on socioeconomic characteristics at the local authority level

Note: DD stands for difference-in-difference design.

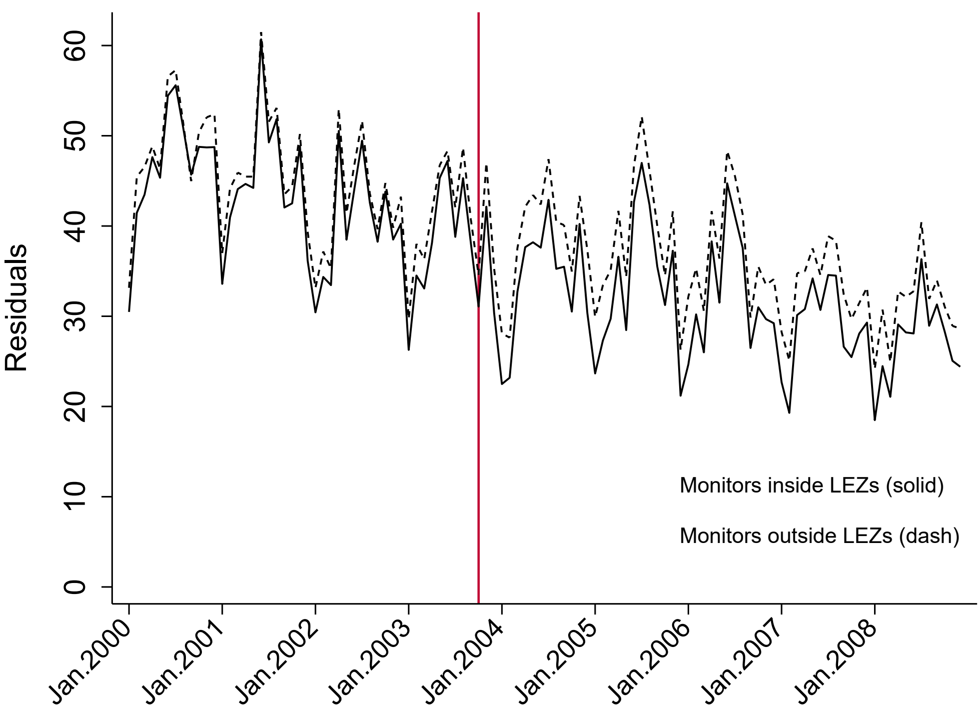
Appendix C. Road Traffic within 500m and 5km of Roadside Monitors

Radius from roadside monitor within:	500m		5km	
	Inside monitors (82)	Outside monitors (115)	Inside monitors (141)	Outside monitors (165)
Average number of lanes	3.9	3.7	3.2	3.2
Average speed limits, km/hour	51	48	48	48
Average traffic volume per day				
Passenger cars	30,493	23,682	22,285	18,898
Trucks and buses	8,235	4,569	5,697	3,526
All cars	38,728	28,251	27,982	22,425
Average driving speed, km/hour				
Peak hours	27	26	26	28
Off-peak hours	32	28	30	31

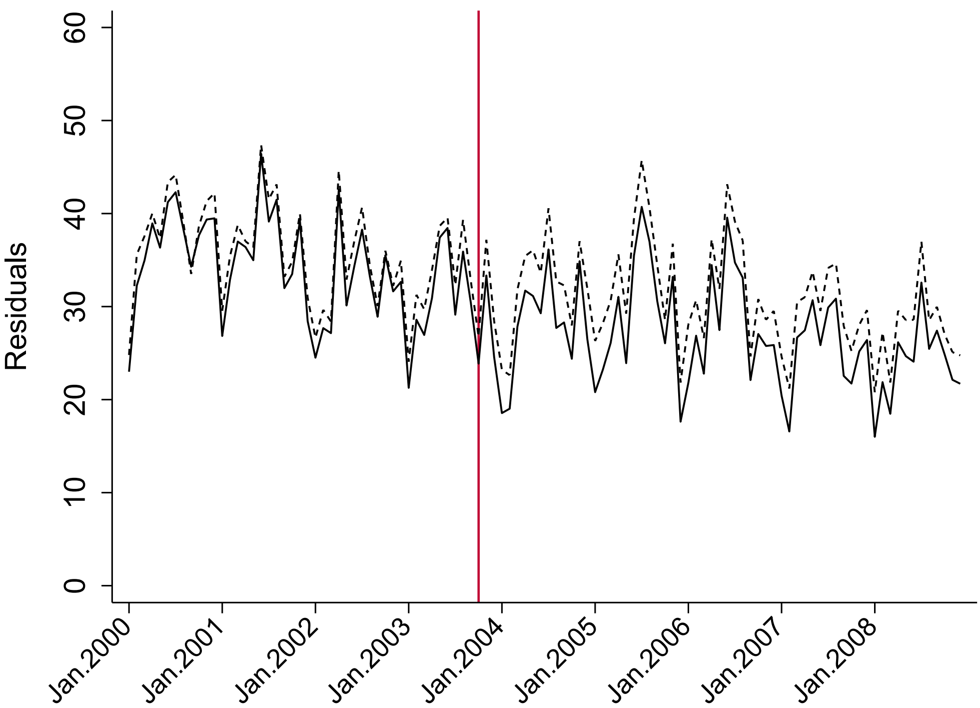
Notes: This table is tabulated based on the Road Traffic Census conducted during September–November 2010. Peak hours are 7–9am and 5–7pm. Off-peak hours are the rest. The number in parentheses indicates the number of roadside monitors. Averages are across monitors.

Appendix D. Adjusted Monthly-Averaged SPM Concentrations

Panel A: Roadside monitors



Panel B: Background monitors



Notes: The figure plots the monthly-averaged residuals for hourly SPM concentration from regression that controls for hourly meteorological variables, monitor fixed effects, month fixed effects, hour-of-day fixed effects, and national holiday and weekend dummies.

Appendix E. Examination of Migrations

Dependent variables:	Inflows of migration (1)	Outflows of migration (2)	Net inflows of migration (3)
Treated × Post	–32.433	239.521	–209.361
	(217.452)	(219.838)	(181.847)
R^2	0.99	0.99	0.72
Municipality fixed effects		Yes	
Year fixed effects		Yes	
Municipalities inside LEZs		92	
Municipalities outside LEZs		30	
Observations		920	
Pre-LEZ mean	15,061	15,179	–118

Notes: This table shows the difference-in-difference estimation results for inflows, outflows, and net inflows of migration. All specifications use a municipality-year panel dataset. Standard errors are robust to heteroscedasticity and clustered at the municipality level. The pre-LEZ mean is for municipalities within LEZ prefectures.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Appendix F. Event-Study with Matched Sample using Pre-Treatment Variables

Notes: The figure plots the result for estimating Equation (5) for a monitor-hour panel for 1 October 2000–31 September 2008. The circles show the point estimates and the vertical bands represent the 95% confidence intervals. The unit of treatment effects is µg/m^3. The sample is chosen by Green et al (2020)'s matching approach that use data on annual vehicle ownership rates, population, unemployment rates, temperature, precipitation, wind speed, pressure, and humidity as of 2000.

Appendix G. Effect of LEZs on Gestation Period

Dependent variables:	Ln gestation period	Gestation period
Treated × Post	–0.0007**	–0.1825**
	(0.0003)	(0.077)
R^2	0.09	0.10
Municipality fixed effects	Yes	
Month fixed effects	Yes	
Control variables	Yes	
Births inside LEZs	1,723,791	
Births outside LEZs	523,037	
Observations	2,246,828	

Notes: All specifications use birth data over 1 January 2000–31 December 2008. Control variables include gender, type of birth (single or multiple), birth order, ages of mother and father, nationalities of mother and father, and household head's job. Standard errors are robust to heteroscedasticity and clustered at the municipality level. The pre-LEZ mean is for births inside LEZs.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.