Department of Policy and Planning Sciences

Discussion Paper Series

No.1370

Benefits of Heavy-Duty Diesel Emission Regulations: Evidence from the World's Largest Low Emission Zone

by

Cheolmin KANG, Mitsuru OTA, AND Koichi USHIJIMA

September 2020

UNIVERSITY OF TSUKUBA
Tsukuba, Ibaraki 305-8573
JAPAN

Benefits of Heavy-Duty Diesel Emission Regulations: Evidence from the World's Largest Low Emission Zone

CHEOLMIN KANG[1], MITSURU OTA[2], AND KOICHI USHIJIMA[3]

[1]Faculty of Political Science and Economics, Waseda University, 1-104 Totsukamachi, Shinjuku, Tokyo, 169-8050, JAPAN (kang@aoni.waseda.jp)

[2]Faculty of Engineering, Information and Systems, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan (ota@sk.tsukuba.ac.jp)

[3]Faculty of Engineering, Information and Systems, University of Tsukuba, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8573, Japan (ushijima@sk.tsukuba.ac.jp).

Ushijima especially thanks Yoshifumi Konishi. We also thank Ryo Kanbayashi, Kentaro Nakajima, Shin-ichiro Okushima, Ryuichi Tanaka, Morito Tsutsumi, and the seminar participants at Kyoto University, Nagoya University, and GRIPS for helpful comments. This study was supported by the Joint Research Program No. 881 at CSIS, University of Tokyo for the use of data. The study was supported by JSPS KAKENHI (Grant numbers 16K17108 and 20K01602) and by the Murata Science Foundation.

We examined the impacts of heavy-duty diesel emission regulations on air quality, land prices, and infant health in the Tokyo metropolitan area. The estimation results show that the greater the traffic volume of heavy-duty diesel vehicles before the introduction of the low emission zone, the more all the focal outcomes were improved even after controlling for the traffic volume of non-regulated gasoline vehicles. By contrast, the concentrations of non-regulated air pollutants remained unaffected. Calculations based on the hedonic approach show that the benefit of air quality improvement in the metropolitan area is about 14 times the cost. (JEL I12, J13, L62, Q52, Q53, Q58, R23)

Diesel engines have excellent thermal efficiency, durability, and torque (output = torque × engine speed). They are used in trucks and buses, called heavy-duty diesel vehicles, which are the primary means of land transportation worldwide.[1] Diesel vehicle emissions, however, are notorious as a cause of air pollution, because they contain high levels of particulate matter (PM), including suspended particulate matter (SPM), and nitrogen oxides (NO_x).[2] These air pollutants cause long-term and short-term health problems.[3] Anenberg et al. (2017) suggest that about 174,000 premature deaths could be avoided in the 20 years to 2040 by global elimination of

[1] In Europe, diesel engines are also used in passenger cars. In the United States and Japan, the majority of passenger cars are gasoline powered.

[2] PM is a generic term for grains of various types, properties, and sizes; those that are suspended in the atmosphere are called SPMs; NO_x is a precursor to PM and ozone. Diesel cars produce seven times as many secondary organic aerosols as passenger cars do (Gentner et al. 2012). Secondary organic aerosols are the main contents of PM.

[3] The survey papers are Currie et al. (2014) and Parry, Walls, and Harrington (2007). There are many other studies, such as Anderson (2019), Arceo, Hanna, and Oliva (2015), Chay and Greenstone (2003), Currie et al. (2009, 2015), Currie, Greenstone, and Meckel (2017), Currie and Neidell (2005), Currie, Neidell, and Schmieder (2009), Currie and Walker (2011), Gehrsitz (2017), Graff Zivin and Neidell (2018), Greenstone and Hanna (2014), Hanna and Oliva (2015), Isen, Rossin-Slater, and Walker (2017), Jans, Johansson, and Nilsson (2018), Knittel, Miller, and Sanders (2016), Marcus (2017), De la Mata and Garcés (2019), Moretti and Neidell (2011), Neidell (2011), Schlenker and Walker (2016).

emissions of diesel-related air pollutants. Indeed, many air pollutants are emitted by diesel vehicles, with NO_x, for example, accounting for 20% of anthropogenic emissions (Anenberg et al. 2017). Not surprisingly, air pollution from diesel vehicle emissions is more severe in urban areas with high traffic volumes. [4]

Over 250 European cities are working to mitigate health risks from emissions by creating low emission zones (LEZs) where the passage of some polluting vehicles is restricted. When implementing traffic regulations, such as LEZ, it is necessary to know the optimal balance between the positive effect of air quality improvement due to reduced emissions and the negative impact of curbing economic activities through logistics. However, as far as we know, there is no evidence to avoid problems caused by this tradeoff, such as how the intensity of emission regulations relates to traffic volume or how people feel about the benefits of emission regulations. Whether LEZs are effective in improving air quality is still an important research question. Few credible analytical studies have shown that LEZs in Europe reduce NO_x emissions. Many previous studies on this issue conclude that stronger regulations are needed to reduce NO_x (Ellison, Greaves, and Hensher 2013; Santos, Gómez-Losada, and Pires 2019).

Air pollution from vehicle emissions is a significant social problem in the United States as well. According to the National Emissions Inventory, approximately 32% of NO_x and 29% of carbon monoxide (CO) emissions in the United States in 2018 were from vehicles traveling on highways. These air pollutants cause severe damage to health. Currie and Walker (2011) find that the introduction of the E-ZPass at highway tollgates reduced emissions from traffic jams and reduced low-weight births by more than 10% in nearby areas compared to other areas. Knittel, Miller, and Sanders (2016) determine the health effects of heavy traffic on infants and young children using data from California between 2002 and 2007.

[4] The Case of New York: http://a816-dohbesp.nyc.gov/IndicatorPublic/traffic/index.html (last accessed on Sep. 15, 2020).

This study exploits the characteristics of the world's largest LEZ, the Tokyo LEZ (hereafter, TLEZ), to examine whether the air quality of nearby locations with more heavy-duty diesel vehicle traffic improves more than those with less heavy-duty diesel vehicle traffic because of the LEZ setting, and the extent to which residents evaluate the economic value of the air quality improvement. Moreover, we examine the impact of emission regulations on infant mortality and low birth weight (LBW) as other outcomes. Panel data for approximately 20 years are used in the analysis of all outcomes. The world's largest LEZ is based on two emission regulations that took effect in the early 2000s in Tokyo and surrounding areas in Japan. This study uses detailed spatiotemporal data on road traffic, air quality, land prices, and infant health to measure the effects of the TLEZ. The structure of the dataset enables a strong identification strategy. This study focuses on SPM, NO_x, and NO_2 as air pollutants of analysis.

To identify the impact of the LEZ, we exploit the fact that the TLEZ covers a vast area. London's LEZ is a famous LEZ covering 1,530 km^2. The TLEZ has a coverage area of 13,562 km^2, about nine times larger. Because the TLEZ is so vast, there are two features useful for identification. First, the TLEZ also covers areas with low traffic volume of heavy-duty diesel vehicles, and the traffic volume is varied within a narrow range. Second, the magnitude relationship between traffic volume before the introduction of the TLEZ at any two different points is not likely to change after the introduction. Because the TLEZ covers the inner-city ring road, the detour cost is high. Owners of heavy-duty diesel vehicles would choose either to cease operations or to pay the cost of meeting the TLEZ standards. Hence, heavy-duty diesel vehicles would rarely change their traffic routes. As shown in Subsection II.A, there is no evidence that traffic changed after the introduction of the TLEZ. From these two features, we can exploit the traffic volume of heavy-duty diesel traffic before the introduction of the TLEZ as the intensity of the impact of the TLEZ.

To identify the causal impact of the TLEZ, we use traffic volume data surveyed on a road-by-road basis. The land price panel data were surveyed at over 7,500 locations, and the air quality panel data were surveyed at over 250 locations. According to simple calculations, air quality was surveyed to cover an average range of 54.2 km^2 (= 135,262/250, which is equivalent to a circle with a radius of 4.2 km). In practice, atmospheric stations are located more densely in the areas analyzed in this study. This rare spatially dense panel survey data allows us to contribute to the literature based on our strong identification strategies. The identification strategy of this study could be applied not only to the evaluation of traffic policy but also to the evaluation of spatially affected policy.

However, there are concerns that the relationship between traffic volume and air quality or land prices may have confounding factors that change over time due to differences in the spatial and socioeconomic characteristics of the region and the preferences of residents. To control for regional time-variant factors, we include in the analysis interaction terms between non-TLEZ-regulated vehicle traffic and year fixed effects, and interaction terms between over 300 municipal fixed effects and year fixed effects. This controlling allows us to avoid, for example, time-variant factors that are correlated with the structure of the local road infrastructure and municipality-specific policy effects.

This study makes two novel contributions in the context of the evaluation of vehicle emission regulations. First, this study investigates whether diesel emission regulations worked, and if yes, how well. Many traffic regulations around the world aim at reducing air pollution in urban areas from car exhaust, but these regulations often do not work (e.g., Auffhammer and Kellogg 2011; Chen et al. 2013; Davis 2008; Gallego, Montero, and Salas 2013; Zhang, Lin Lawell, and Umansakaya 2017). Although many cases of urban traffic regulation with improved air quality have been identified in relation to LEZs, there is little evidence that LEZs have improved residents' health (Mudway et al. 2019). The most reliable previous study of LEZs is Wolff (2014), which shows that German LEZs reduce PM10, and the epidemiological benefits are two to five times the cost. However, Wolff (2014) does not investigate NO_x emissions. Like many LEZs, the German LEZ might not have reduced NO_x because German LEZs have not improved infant health (Gehrsitz 2017). This study uses a rich and detailed dataset to investigate comprehensive evidence of the effects of LEZs.

Second, we calculate the economic benefits of improving urban air quality by identifying the impact of the TLEZ on land prices. Estimating the economic value of air quality has been recognized as an important research issue since the 1970s, but Chay and Greenstone (2005) are the first to obtain reliable evidence due to the difficulty of excluding the effects of unobserved variables. Several studies based on statistical causal inference have been published since Chay and Greenstone (2005). However, few studies have examined the value of air quality in urban areas. Clarifying the optimal regulatory levels in urban areas is an important issue because the economic benefits of improved air quality may be greater in densely populated areas. This study identifies the effect of air quality on urban land prices by using difference-in-differences methods based on the structure of the TLEZ.

Our estimation results are as follows. First, although the level of regulation of the TLEZ is similar to that of the European LEZ, the concentration of air pollutants subject to regulation has improved in Tokyo. SPM and NO_x concentrations improved by an average of 7.17% and 9.08%, respectively. The concentration of non-regulated air pollutants did not change. Second, land prices have risen by an average of 2.74%. Third, a survey of LBW, infant mortality, and stillbirth as health indicators for infants showed that almost all indicators improved by more than 10% on average. Fourth, cost–benefit analysis revealed that the benefits were about 14 times greater than the costs.

The rest of this paper is structured as follows. Section I describes the theoretical framework and background of the TLEZ, while Section II describes the data. The impacts of the introduction of the TLEZ on air quality are described in Section III, those on land prices are described in Section IV, and those on infant health are described in Section V. Section VI discusses the results. The conclusions are summarized in the final section.

I. Conceptual Framework and TLEZ

A. Theoretical Framework

This study adopts a hedonic approach to the cost–benefit analysis of the regulation of diesel vehicle emissions, focusing on residential land prices. There are few evaluations of the negative externality from mobile emission sources using the hedonic approach. This is because, for mobile sources, it is difficult to measure the spatial relationship between the point of origin and the point of exposure to externalities. We believe that by using the unique characteristics of the TLEZ and the information of neighborhood traffic volumes, we can assess the impacts of the TLEZ under a conceptual framework similar to that of Currie et al. (2015). We describe the partial equilibrium model of land prices under the TLEZ regarding the ideas of Currie et al. (2015) in Appendix A.

B. Tokyo Low Emission Zone

This subsection describes the history of the establishment of the TLEZ and the details of the system. At the end of the twentieth century, the Tokyo metropolitan area was among the regions with the most severe air environment in Japan. Although the level of the environmental SPM standard has remained unchanged since the 1970s, the environmental standard had an achievement rate of 78% outside of the Tokyo metropolitan area in 1996, but only 11% in the Tokyo metropolitan area (Tokyo Metropolitan Government 2000). Approximately 56% of NO_x and 52% of SPM concentration in Tokyo in 2000 were from diesel

TABLE 1. REGULATORY OVERVIEW

	Automobile NO_x/PM Law	Environmental protection ordinances of Tokyo and three neighboring prefectures
Administration	Japanese government	Local government
Objective	Reduction of NO_x and PM	Reduction of PM
Revision of laws/regulations	June 2001	September 2002**
Introduction to regulation	October 2002	October 2003
Target Area	Metropolitan area (including Tokyo and three prefectures)*	Tokyo and three prefectures (Excluding remote islands)
Target Vehicles	Vehicles that do not meet the 2005 emission standards	Vehicles that do not meet the 1999 emission standards
Regulations	Prohibition of registration in the region	No running in the area unless a DPF is fixed***
Grace period	8 to 12 years	7 years
Surveillance	SHAKEN	On-Site/on-road inspections
In the event of a violation	Unregistrable or fine	Prohibition order or fine

*In addition to the TLEZ, two other metropolitan areas are also regulated. **Since December 2000, local governments have been formulating ordinances at different times, and in September 2002, all local governments formulated ordinances. *** DPF is PM removal equipment.

emissions.[5]

In this study, the area of the Automobile NO_x/PM Law and the heavy-duty diesel emission regulations of Tokyo and the three neighboring prefectures are called the TLEZ. Table 1 provides an overview of the two regulations. The Automobile NO_x/PM Law was enacted by the Japanese government in June 2001 and implemented in October 2002 to reduce air pollutants originating from diesel vehicles in metropolitan areas. This law aims to set the expiration date for old and highly polluting vehicles and to encourage replacement with new vehicles with low

[5] http://www.nies.go.jp/pmdep/ctype/result/r 203/pdf/3/13.pdf (last accessed on March 20, 2020).

pollution levels. Before the introduction of the Automobile NO_x/PM Law, existing regulations set limits on air pollutant emissions for new vehicles only, according to the government's safety standards. Although the maximum restrictions under the safety standards have been tightened over the years, the regulations were only for new vehicles. Therefore, it was not possible to reduce PM emissions from highly polluting vehicles in use. The Automobile NO_x/PM Law prohibits the registration of diesel-powered vehicles that do not meet the 2005 exhaust emission standards in the three major metropolitan areas of Japan, including the Tokyo metropolitan area. Under this regulation, the expiration date of a car is set between 8 and 12 years.

In October 2003, Tokyo and the three neighboring prefectures introduced environmental protection ordinances to regulate exhaust emissions from heavy-duty diesel vehicles to supplement the Automobile NO_x/PM Law. There were concerns that the Automobile NO_x/PM Law was insufficient because vehicles registered outside the regulated area would pass through Tokyo and the three neighboring prefectures. The ordinances of Tokyo and the three neighboring prefectures have mandated that diesel vehicles that do not meet the 1999 national emission standards must be fitted with diesel particulate filters (DPFs) to regulate emissions from vehicles registered outside the TLEZ. The ordinances set a 7-year expiration date for diesel vehicles.

Based on this background, there are two standards for TLEZ emissions: the emission standards under the NO_x/PM Law to prohibit the registration of storage sites in the area, and heavy-duty diesel emission standards in Tokyo and the three neighboring prefectures to forbid traffic. The NO_x and PM Law is a registration regulation based on the emission standards in 2005, and the ordinances of one metropolis and three prefectures are operation regulations based on the emission standards in 1999. Thus, the emission standards are more stringent under the NO_x/PM Law than under the Environmental Ordinance. Table B.1 in Appendix B summarizes the emission standards of Japan, Europe, and the United States. The

NO_x and PM emission standards of Japan are similar to the Euro 4, which is the European LEZ regulation level analyzed in some previous studies, but there is little evidence that NO_x has decreased at the Euro 4 regulation level.

TLEZ has strict enforcement and punishment. The NO_x/PM Law and the environmental protection ordinances of Tokyo and the three neighboring prefectures enforce the regulations in different ways. Under the Automobile NO_x/PM Law, the use of heavy-duty diesel vehicles within the TLEZ is controlled by regularly checking that all vehicles meet safety standards using the vehicle inspection and registration system called SHAKEN. Trucks and buses that are subject to the NO_x/PM Law are inspected annually. Failure to submit to this inspection is a criminal offense, punishable by imprisonment and a fine. Moreover, owners are subject to administrative penalties, including suspension of their driver's license.

Meanwhile, under the ordinances of Tokyo and the three neighboring prefectures, before the regulations started, the people in charge of each local government inspected offices that owned trucks and buses. After the introduction of an ordinance, Tokyo and the three neighboring prefectures continued controlling regulations based on SHAKEN. Vehicles operating within the TLEZ but registered outside the TLEZ are audited on the streets and in parking lots. Those who violate the ordinance are punished by having their names published and a fine imposed of up to 500,000 yen (about 4,762 US dollars). Additionally, the names of the shippers are published. In other words, the operator has an incentive to follow the rules of the ordinance, not only to avoid administrative penalties but also to avoid damaging the company's reputation with customers.

TLEZ has three characteristics. First, it improves air quality at locations with high heavy-duty diesel traffic. Gasoline vehicles are unaffected. Second, air quality improves over time. The Vehicle NO_x/PM Act and the ordinances of Tokyo and the three neighboring prefectures had a gradual impact immediately after their introduction, because the grace period before they became regulated varies depending on when the vehicle was purchased. Based on these features, the scale of the improvement in air quality and the increase in land prices in areas where there was heavy diesel traffic before the introduction of the regulations are expected to increase year by year.

Third, as discussed in detail in Subsection II.A, the volume of heavy-duty diesel traffic on each road within the TLEZ changed very little before and after the restrictions, so that a large part of the amenity improvement can be deemed as an improvement in air quality.[6]

Apart from NOx and SPM, other air pollutants like SO2 and CO are also emitted from diesel vehicles. The TLEZ does not directly regulate these air pollutants. To confirm the robustness of this result, we examine whether the introduction of the TLEZ reduced SO2 and CO.

II. Data

We estimated the impact of the TLEZ on air quality, land prices, and infant health. In this study, the post-regulation period was assumed to be after 2001, when the Automobile NO_x and PM Law was enacted. The analysis used the information on heavy-duty diesel traffic on arterial roads, six air pollutants, published land prices, and infant health.

A. Heavy-duty Diesel Traffic

Because the TLEZ intends to reduce emissions from heavy-duty diesel vehicles passing through the area, more significant changes in air quality are expected around roads with higher traffic volumes. In this study, traffic volumes on arterial

[6] The reasons for this interpretation are described in Appendix C.

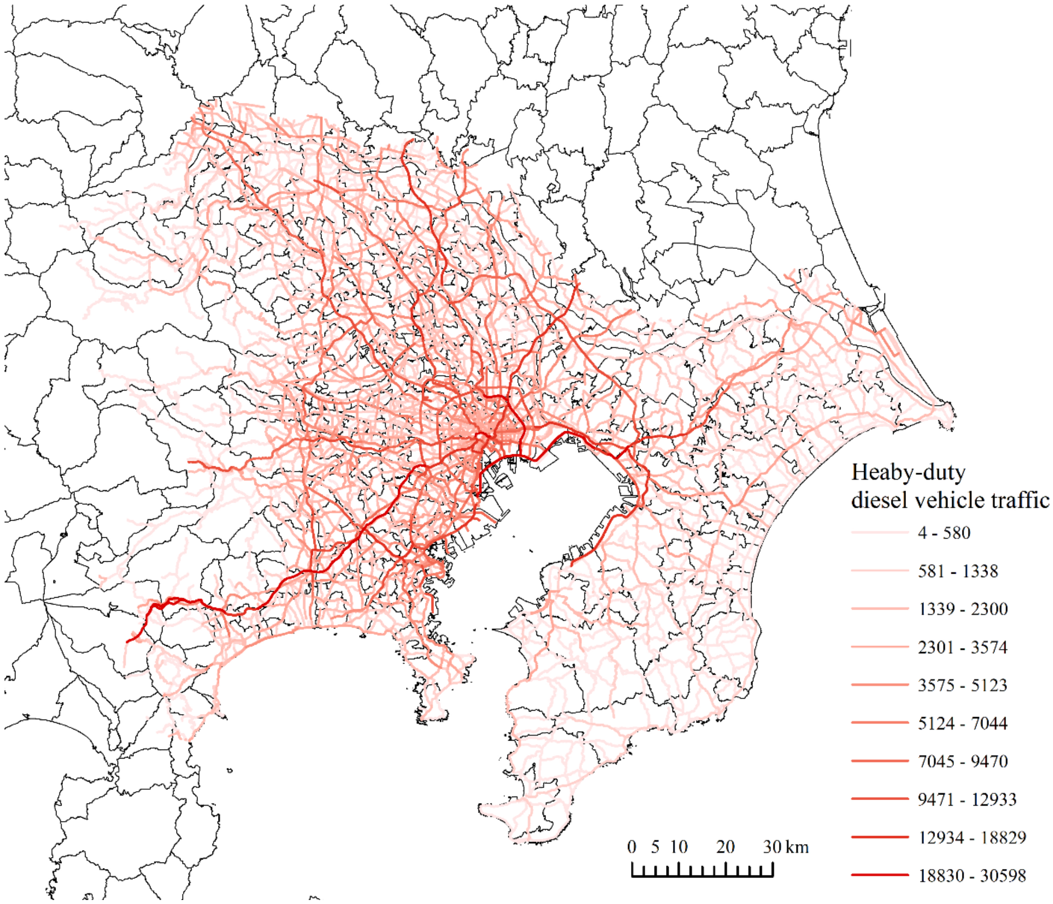


FIGURE 1. THE ROAD NETWORK AND HEAVY-DUTY DIESEL TRAFFIC ON A SINGLE DAY IN 1990

information on traffic volumes on each study section of the main roads in the Road Traffic Census provided by the Ministry of Land, Infrastructure, Transport, and Tourism. Information on traffic volumes in 1990 was used since the analysis is based on outcomes from 1990 to 2010. The Road Traffic Census is a database of traffic volumes on all highways, national roads, prefectural roads, and municipal roads in government-designated cities in Japan. In the traffic volume survey, vehicles that pass through each section are classified into four categories: passenger cars, small freight cars, large freight cars, and buses. In this study, we regarded the total traffic volume of large trucks and buses as the traffic volume of heavy-duty diesel vehicles. This assumption is because in Japan, heavy-duty diesel vehicles account for more than 90% of heavy-duty freight vehicles and buses. By contrast, large diesel vehicles account for only a small percentage of all other types of vehicles. The survey was conducted on a weekday from September to November. In other words, we assumed that the traffic volume of the day is a proxy for the annual traffic volume.

Figure 1 shows the road network and heavy-duty diesel traffic in 1990.[7] Two features characterize the road network. First, roads with high heavy-duty diesel traffic are laid out in a radial or circular pattern around the center of Tokyo. Roads with relatively high traffic volumes are highways and national roads. Roads with relatively low traffic volumes are laid to fill the gaps between those roads. Therefore, the traffic volume within a 2-km radius of a given point varies even in the central part of Tokyo. Second, the TLEZ covers roads laid out in a circular pattern around the center of Tokyo. In other words, the TLEZ does not have a bypass to circumvent the regulation.

Since there are no detours in the TLEZ, the distribution of traffic in the TLEZ may not have changed. As reported in Table D.1 in Appendix D, the correlation coefficient for heavy-duty diesel traffic in the TLEZ is 0.95 for the values in 1990, which is 10 years before the introduction of the TLEZ, and for the values in 2005, which is 5 years after the introduction of the TLEZ. The mean value is 3.9% larger after the introduction. These statistics suggest that the improvement in air quality due to the TLEZ is not related to a decrease in traffic volume.

[7] To merge information on road traffic volumes in the neighborhood to the observation sites of the outcomes, we obtained the line information of the road network from Open Street Map, a free road map, added the traffic volume information from the road traffic census to it, and then pieced together the road information with the outcome observation points. The Open Street Map can be downloaded from https://download.geofabrik.de/asia/japan.html (last accessed on July 13, 2020).

B. Air Quality

The air quality information observed by each municipality was used to identify the impact of the TLEZ on air quality.[8] The analysis used the annual average air pollutant concentrations at stations in Tokyo and the three prefectures from 1991 to 2009.[9] The National Institute for Environmental Studies has created a database of this data, which is available online.[10] This information includes the latitude, longitude, and address of the observation points; the monthly average of air pollution concentrations; the number of days of observation; the time of observation, and other information.

Atmospheric observations are conducted in densely populated plains.[11] There are five substances (SPM, NO_x, NO_2, CO, and SO_2) in diesel vehicle emissions that can be used for atmospheric observation data. Although the TLEZ is expected to reduce concentrations of SPM, NO_x, and NO_2, the concentrations of CO and SO_2 are likely to remain unchanged because they are not affected by the TLEZ. Therefore, to confirm the robustness of the result, we checked whether the concentration of unregulated substances did not change. Because not all stations observe the concentrations of the five elements, the number of observations used in the analysis differs for each air pollutant.

C. Land Price

Public land prices (called *kojichika*) are used to measure the increase in benefits to residents due to improvements in air quality. Public land prices are the appraisal

[8] Air quality is constantly surveyed by each municipality in accordance with the Basic Environmental Law and the Air Pollution Control Law.
[9] Information from atmospheric stations with fewer days of observation was treated with caution. For example, stations that started their observations in the middle of the year because of the tendency for SPM concentrations to be higher in winter were excluded from the analysis because they contain structural biases in the annual averages. We excluded them from the analysis when there were fewer than 274 days of observation.
[10] https://www.nies.go.jp/igreen/ (only in Japanese, last accessed on July 13, 2020).
[11] See Figure E.1 in Appendix E.

values assessed by real estate appraisers as of January 1 each year for locations selected by the Land Appraisal Committee of the Ministry of Land, Infrastructure, Transport, and Tourism under the Land Price Disclosures Act. Since the calculation of the appraisal value is based on the transaction cases of neighboring land in the previous year, the public land price is not the actual transaction price, but the amount that reflects the market value of the land. Public land price data are available online from the Ministry of Land, Infrastructure, Transport, and Tourism's National Land Information Download Service in shapefile format.[12] For the analysis, we employed the information on public land values used as residential land in Tokyo and the three prefectures from 1991 to 2010.

Public land prices have the following three characteristics. First, they are individual panel data. The public land price system is a follow-up survey of almost the same points every year.[13] Therefore, the analysis can control for time-invariant unobserved factors using individual fixed effects. Points where transactions are infrequent or where transactions take place due to exceptional circumstances are not included in the evaluation. Second, there is little sample selection bias. For example, when analyzed using the repeated sales method, sample selection causes bias in the estimates if there is a tendency for houses with poor air quality and low prices to be traded more often than those with poor air quality. Public land prices avoid this problem by surveying the land prices of the points deemed by experts to represent the area. Third, the measurement error is small. The purpose of the public land price system is to reduce the information asymmetry between sellers and buyers in land transactions by making land prices assessed by neutral experts available to the public. Thus, for example, the prices of unusual transactions that took place in the neighborhood are not reflected in the public land price calculation.

[12] https://nlftp.mlit.go.jp/ksj/ (only in Japanese, last accessed on July 13, 2020).
[13] Although the survey locations rarely change, they are not balanced panel data.

Figure E.1 in Appendix E shows the distribution of the observation points of public land prices. There are many observation points around the high traffic road. This concentration of observation points suggests that economic activity is relatively high in the vicinity of public land price points. Additionally, Figure 2 shows that the TLEZ also regulates areas where there is almost no survey point of public land price.

D. Infant health

Using the Vital Statistics, we examined whether infant mortality, LBW, and natural stillbirth rates were affected by the TLEZ. We continued to focus on neonatal deaths under 1 week of age, neonatal deaths under 4 weeks of age, and infant deaths under 1 year of age as infant deaths. Neonatal deaths under 4 weeks of age and under 1 week of age were included in infant deaths under 1 year of age; and neonatal deaths under 1 week of age were included in neonatal deaths under 4 weeks of age. Analyzing these categories enables us to discuss how air quality affects the health of newborns at any given time. The results of the Vital Statistics are available on the government's website for aggregate data from municipalities. The analysis in this study used 20 years of complete panel data for 300 municipalities.[14] However, since the information on infant health used in this study is aggregate data, it was estimated based on a weighted average of traffic volume in the neighborhood of the residents of the municipality.[15]

14 During the period under analysis, there were many mergers among municipalities in Japan. According to the analysis, fixed effects are created for each municipality after the merger.

15 Appendix F describes the calculation of the weighted average of the traffic volume.

TABLE 2. DESCRIPTIVE STATISTICS

	Pre				Post				
	No. of obs.	No. of obs. points	Mean	Std. dev.	No. of obs.	No. of obs. points	Mean	Std. dev.	Rate of change of the mean
Panel A: Air pollutants	1990–2000				2001–2010				
Suspended particulate matter (SPM)	3,125	337	48.4	10.2	3,344	358	30.7	7.3	-0.37
Nitrogen oxide (NO_X)	3,120	299	63.7	35.6	2,600	270	44.5	26.8	-0.30
Nitrogen dioxide (NO_2)	3,121	299	29.8	8.7	2,601	270	24.6	8.1	-0.18
Sulfur dioxide (SO_2)	2,185	216	6.5	2.1	1,633	176	3.5	2.0	-0.46
Carbon monoxide (CO)	1,477	168	1.1	0.6	813	93	0.6	0.2	-0.44
No. of heavy-duty diesel vehicles in 1990	4,721	486	26.3	22.8	4,539	478	26.2	23.2	0.00
No. of gasoline cars in 1990	4,721	486	69.3	75.1	4,539	478	68.8	77.0	-0.01
Panel B: Land price	1991–2001				2002–2010				
Land price	65,106	7,931	401758	613537	59,740	7,639	271152	313284	-0.33
No. of heavy-duty diesel vehicles in 1990	65,106	7,931	22.8	18.5	59,740	7,639	23.6	19.9	0.04
No. of gasoline cars in 1990	65,106	7,931	60.4	51.3	59,740	7,639	63.7	58.8	0.05
Panel C: Infant health	1991–2000				2001–2010				
Number of births	2,297	231	1271	1620	2,267	233	1299	1689	0.02
Birth weight < 2500 g	2,297	231	75.5	30.8	2,267	233	93.1	31.0	0.23
Infant deaths under 1 year of age	2,297	231	4.0	5.3	2,267	233	2.9	4.5	-0.28
Deaths of newborns within 4 weeks of birth	2,297	231	2.1	3.4	2,267	233	1.4	2.8	-0.32
No. of early neonatal deaths (within 7 days)	2,297	231	1.5	2.9	2,267	233	1.0	2.3	-0.34
No. of stillbirths	2,297	231	17.5	29.6	2,267	233	14.0	32.6	-0.20
Stillbirths after 22 weeks of gestation	2,297	231	5.0	20.3	2,267	233	4.4	22.7	-0.11
No. of heavy-duty diesel vehicles in 1990	2,301	231	16.2	16.6	2,270	233	16.4	16.6	0.01
No. of gasoline cars in 1990	2,301	231	43.4	47.1	2,270	233	43.9	47.3	0.01

Notes: All observations in Panel B are restricted to residential use. Panel C reports cross-municipalities mean and std. dev. As of January 2000, 1 dollar was about 105 yen. The units of measurement of SPM is micrograms per cubic meter of air (μg/m3). The units of measurement of NO_X, NO_2, SO_2, and CO are parts per million(ppm). The units of measurement of heavy-duty diesel vehicles and gasoline cars are in thousands. The units of measurement of land price is Yen per square meter of land. The units of measurement of birth weight < 2500 g, Infant deaths under 1 year of age, early neonatal deaths (within 7 days), stillbirths, and stillbirths after 22 weeks of gestation are in per thousand births.

E. Summary Statistics

Panel A of Table 2 reports the descriptive statistics for atmospheric stations for pre- and post-regulation. This analysis used information from about 480 atmospheric stations from 1990 to 2010. Air pollutants were studied at a larger number of atmospheric stations for SPM, NO_x, and NO_2, which are subject to the TLEZ regulations. The number of stations does not change much before and after the introduction of the TLEZ. Meanwhile, the number of atmospheric stations for SO_2 and CO was relatively low. In recent years, the number of stations has been decreasing. The number of heavy-duty diesel vehicles traveling within a 2-km radius of the atmospheric station averaged 26,000 per day, and the number of gasoline vehicles averaged 69,300 per day.

Comparison before and after the introduction of the TLEZ shows a decreasing trend in the concentrations of all air pollutants. SPM, NO_x, and NO_2 decreased by 37%, 30%, and 18%, respectively. SO_2 and CO, which are not regulated, decreased by 46% and 44%, respectively. In a simple pre-post analysis, the decrease in air pollution concentration cannot be interpreted as a TLEZ effect because the concentration of non-regulated substances is also decreasing.

Panel B of Table 2 reports the descriptive statistics for the observation points of public land prices used for residential purposes. The data used for the analysis were incomplete panel data from 1991 to 2010, with 124,846 observations and approximately 7,900 survey locations. The average public land price was about 402,000 yen/m^2 in the pre-TLEZ period and about 271,000 yen/m^2 in the post-TLEZ period. During the post-TLEZ period, Japan experienced a significant economic recession, and land prices fell significantly across the country. The number of heavy-duty diesel vehicles traveling within a 2-km radius of the observation points of public land price averaged 22,800–23,600 per day and that of gasoline vehicles averaged 60,400–63,700 per day.

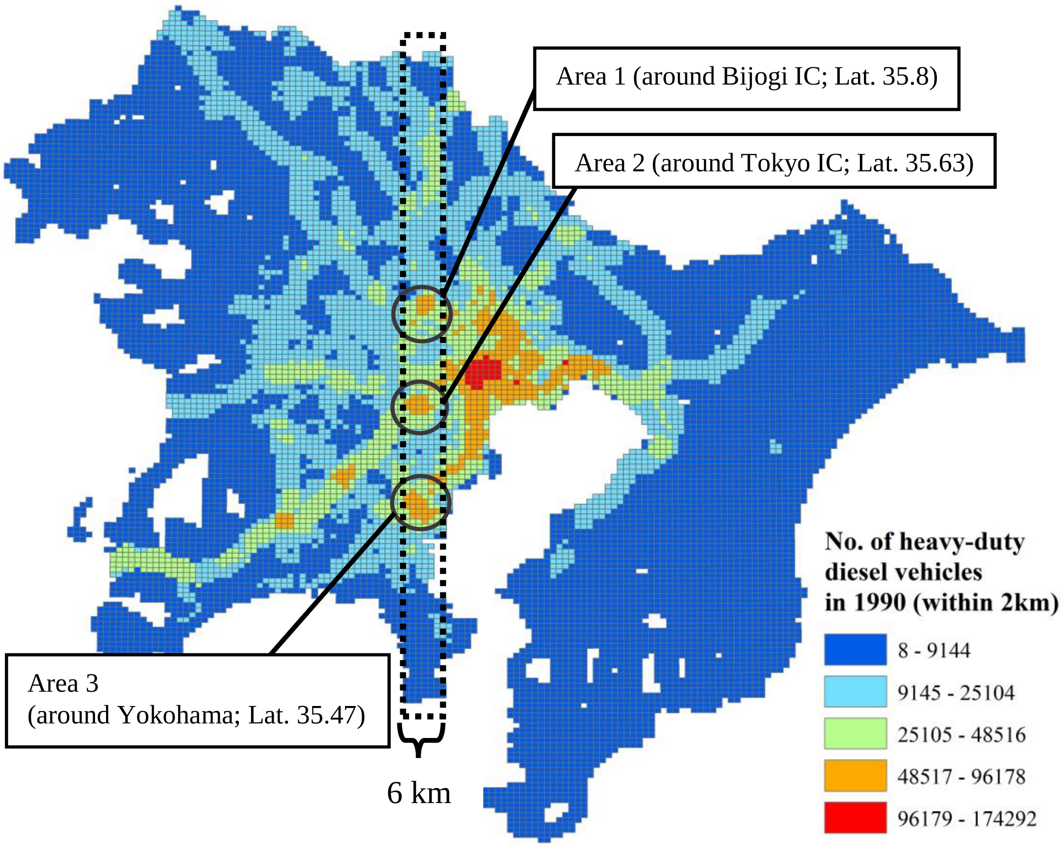
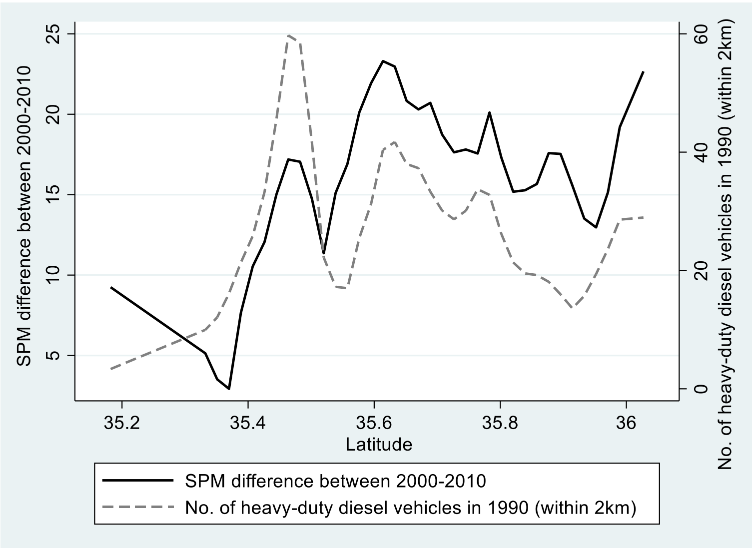


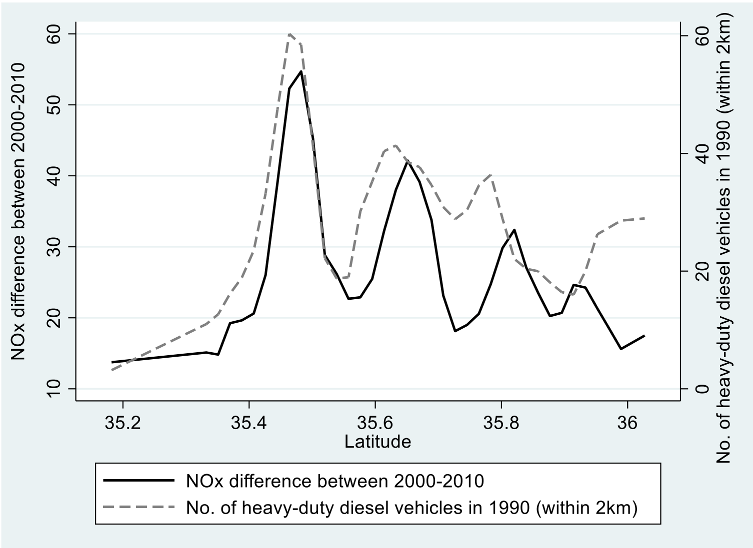
FIGURE 2. HEAVY-DUTY DIESEL TRAFFIC IN EACH 1-KM MESH

Notes: This figure presents the volume of heavy-duty diesel traffic within a 2-km radius of the center of each 1-km mesh on a single day in 1990 (see Appendix F for the 1-km mesh). The dotted line frame is approximately 6-km wide from east to west.

Panel C of Table 2 reports statistics on infant health and estimated traffic volumes in approximately 230 municipalities. All statistics are cross-municipal averages. The average number of births did not change significantly before and after the regulation. The number of LBW infants increased by 23% from 75 to 93 per 1,000. Regarding infant deaths, an improvement trend can be observed for all indicators. Specifically, the number of deaths of infants aged under 1 year decreased by 28%, the number of neonatal deaths of infants under 4 weeks decreased by 32%, the number of neonatal deaths of infants under 7 days decreased by 34%, and the number of spontaneous stillbirths decreased by 20%. The number of prenatal



Panel A: Changes in SPM concentrations (2000 to 2010)



Panel B : Changes in NO_x concentrations (2000 to 2010)

Figure 3. Changes in air pollution concentration and traffic volume of heavy-duty diesel vehicles in 1990

Notes: We use local polynomial smoothing to depict the difference in air pollution concentrations between 2000 and 2010 and the amount of heavy diesel traffic within a 2-km radius in 1990 at the values from air stations in the dotted-line frame of Figure 2.

stillbirths after 22 weeks of gestation decreased by 11%. Although there is a trend toward a more significant decrease in postpartum mortality, the rate of LBW is increasing. This shows the effect of advances in medical technology. The traffic volumes reported here are cross-municipal averages of the weighted averages of residents' neighborhood traffic volumes (see Appendix F).

Figure 2 shows the traffic volume within a 2-km radius of the center of the 1-km mesh. The traffic volume is higher around the interchanges of the major highways. For example, Area 1 (Bijogi IC) has heavy traffic, but immediately to its northwest is an area with little traffic. The statistics in Table 2 show that the coefficient of variation of diesel traffic for each panel is between 81.2% and 102.5%. Figure 2 shows that the traffic volume varies even in spatially close areas within the TLEZ.

Figure 3 shows the traffic volume in 1990 and the change in air pollution concentration from 2000 to 2010 at the air monitoring sites in the frame shown in Figure 2. In the frame of Figure 2, there are three particular traffic nodes, namely, Area 1 (Bijogi IC: 35.80° north latitude), Area 2 (Tokyo IC: 35.63° north latitude), and Area 3 (Yokohama city: 35.47° north latitude). This simple graph confirms the relationship between the volume of nearby traffic and changes in air pollution concentrations in 1990. Panel A shows changes in SPM and Panel B shows changes in NO_x. The horizontal axis indicates latitude, the left vertical axis indicates changes in air pollution concentration, and the right vertical axis indicates the amount of neighboring traffic in 1990.

These graphs indicate whether air quality improves more at sites with heavy diesel traffic. This shows the essence of the identification strategy in this study. Figure 3 is based on uncontrolled variables, but even this simple comparison suggests that the higher the traffic volume, the better the air pollution concentration. To more accurately measure the causality depicted in Figure 3, the analysis provides further controls.

III. Air Quality Improvement

Our identification strategy exploits the fact that the strength of the policy's impact varies between locations with high and low heavy-duty diesel traffic in the neighborhood. We assume that within a 2-km radius, diesel emissions affect air quality and, consequently, residential land values and infant health. This distance assumption is based on the findings of Currie and Walker (2011) and Currie et al. (2015).[16]

First, we examine the relationship between the amount of diesel traffic in the neighborhood and changes in regulated air pollutants. As discussed in Subsection I.B, three air pollutants are directly affected by the TLEZ: SPM, NO_x, and NO_2. Since CO and SO_2 are not regulated, they should have no direct impact. In other words, we expect to observe a decrease in SPM, NO_x, and NO_2 after the start of the TLEZ, and a different trend for CO and SO_2.

The impacts of the TLEZ are measured by the following linear model, using the merged data of air quality information and spatial location and traffic volume information of adjacent roads based on the latitude and longitude of atmospheric stations.

$$(1)\quad \text{Pollutants}_{jpt} = \alpha_j + \beta\left(D^{Post}{}_t \times \text{Diesel}_{0-2,jp1990}\right)$$
$$+\gamma\left(YearFE \times \text{Cars}_{0-2,jp1990}\right) + YearFE + PrefFE_j \times YearFE + \varepsilon_{jpt},$$

where $Pollutants_{jpt}$ is the air pollution concentration at atmospheric station j in prefecture p in period t. $\text{Diesel}_{0-2,jp1990}$ denotes the volume of heavy-duty diesel traffic

[16] The validity of this distance assumption and interpretation of the estimated results is discussed in Appendix G.

within a 2km radius of the atmospheric observatory j in 1990, and $D^{Post}{}_t$ denotes a dummy variable that takes the value of 1 after the introduction of the TLEZ and 0 otherwise. The NO_x/PM Law was enacted in June 2001, so that the impact of the TLEZ was assumed to begin in 2001. $\text{Cars}_{0-2,jp1990}$ is the total traffic volume of passenger cars (not subject to regulation) within a radius of 2 km of atmospheric observatory j in 1990; α_j is the individual fixed effect of atmospheric observatory j; $YearFE$ is the year fixed effect; $PrefFE_j$ is the fixed effect of m prefecture to which atmospheric observatory j belongs; and ε_{jpt} is the error term.

In equation (1), we are most interested in the coefficient β of the interaction term between $D^{Post}{}_t$ and $\text{Diesel}_{0-2,jp1990}$. Since the coefficient β is a DID estimator, the discrimination assumption in this estimation is that β is not affected by time-varying omitted variables that correlate with the effect of diesel traffic. Therefore, we draw event study graphs for each air pollutant before the estimation to ensure that there is no effect of such omitted variables, at least before the introduction of the TLEZ. These graphs are drawn by exchanging $D^{Post}{}_t$ in equation (1) for $YearFE$ and plotting the coefficients for each year. The graph is expected to be as follows. As described in Subsection I.B, since the TLEZ regulation becomes stronger year by year, the magnitudes of the SPM, NO_x, and NO_2 coefficients should become larger year by year.

Figures H.1 and H.2 in Appendix H show the event study graphs for each air pollutant. The DID estimator is plotted against the base case of 2000, just before the TLEZ policy was formulated. A 95% confidence interval for each estimator is also provided. In Figure H.1, the results of SPM in Panel A, NO_x in Panel B, and NO_2 in Panel C are reported as regulated air pollutants of the TLEZ. In Figure H.2, SO_2 in Panel A and CO in Panel B are reported as non-regulated air pollutants of the TLEZ.

Figure H.1 shows that the three air pollutants affected by the TLEZ, SPM, NO_x, and NO_2, do not change significantly before 2000. However, after 2000, there is a statistically significant trend of improvement in air quality. A pattern of betterment in air pollution concentrations of regulated substances can be observed in areas with higher traffic volumes, and there is a trend for TLEZ regulations to increase in the magnitudes of the DID estimates from year to year. These results suggest that the common-trend assumption can be satisfied. Meanwhile, Figure H.2 shows that both CO and SO_2, which are not regulated by the TLEZ, improved at a time that is unrelated to the impact of the TLEZ. SO_2 may reflect a decrease in the sulfur content of the fuel due to improvements in oil refining technology during this period. The atmospheric concentration of CO tended to improve after the revision of emission standards in 1997. In summary, this study considers that the DID estimate, β, indicates that the TLEZ's regulation of the amount of air pollution in emissions from heavy-duty diesel vehicles improved air quality in areas with higher traffic volumes.

Table 3 reports the results of estimations of the impact of the TLEZ on air pollution concentrations of SPM, NO_x, and NO_2 based on equation (1). The estimation results using the whole observations are reported in columns (1) to (3), and the estimation results limiting observations immediately before the introduction of the TLEZ and after 8 to 10 years from the introduction of the TLEZ are reported in columns (4) to (6). All estimates are controlled by atmospheric station fixed effects. Columns (1) and (4) are further controlled by a year fixed effect. Columns (2) and (5) add the interaction term between traffic volume of passenger cars (non-regulated) within the neighborhood and the year fixed effects as a control to the estimation in columns (1) and (4). This controls local time- variant factors, for example, those correlated with the structure of nearby roads and

TABLE 3. THE EFFECT OF TOKYO LEZ ON AIR POLLUTION

	1990–2010			1998–2000 & 2008–2010		
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: SPM						
1[Post LEZ] × No. of heavy-duty diesel vehicle (within 2 km)	-0.061	-0.122	-0.124	-0.073	-0.138	-0.132
	(0.020)	(0.036)	(0.034)	(0.022)	(0.036)	(0.037)
Year FE	YES	YES	NO	YES	YES	NO
Cars (within 2 km) × Year FE	NO	YES	YES	NO	YES	YES
Prefecture FE × Year FE	NO	NO	YES	NO	NO	YES
No. of observations	6,448	6,448	6,448	1,943	1,943	1,943
No. of groups	374	374	374	359	359	359
Panel B: NO_x						
1[Post LEZ] × No. of heavy-duty diesel vehicles (within 2 km)	-0.194	-0.135	-0.143	-0.202	-0.211	-0.220
	(0.040)	(0.067)	(0.064)	(0.045)	(0.078)	(0.076)
Year FE	YES	YES	NO	YES	YES	NO
Cars (within 2 km) × Year FE	NO	YES	YES	NO	YES	YES
Prefecture FE × Year FE	NO	NO	YES	NO	NO	YES
No. of observations	5,699	5,699	5,699	1,563	1,563	1,563
No. of groups	299	299	299	272	272	272
Panel C: NO_2						
1[Post LEZ] × No. of heavy-duty diesel vehicles (within 2 km)	-0.022	-0.028	-0.031	-0.026	-0.030	-0.034
	(0.011)	(0.015)	(0.014)	(0.011)	(0.017)	(0.016)
Year FE	YES	YES	NO	YES	YES	NO
Cars (within 2 km) × Year FE	NO	YES	YES	NO	YES	YES
Prefecture FE × Year FE	NO	NO	YES	NO	NO	YES
No. of observations	5,701	5,701	5,701	1,563	1,563	1,563
No. of groups	299	299	299	272	272	272

Notes: All regressions include individual fixed effects. Standard errors clustered by atmospheric stations are reported in parentheses.

economic activity. Columns (3) and (6) are controlled by replacing the year fixed effects of columns (2) and (4) with the interaction term of the year fixed effects and the prefecture fixed effects. Economic activity in Tokyo is very different from that in the three neighboring prefectures, and this may be correlated with changes in air quality. Estimates in columns (3) and (6) are derived to consider this possibility.

All the estimated results in Table 3 show that the TLEZ has improved the air pollution concentration of the regulated substances. Panel A in Table 3 reports the SPM estimation results. The results in column (1) show that for every 1,000 diesel vehicles in 1990 within a 2-km radius of an atmospheric station, SPM concentrations decreased by an average of 0.061 (μg/m^3). The results for column (2), which add non-regulated vehicle traffic in the vicinity as a control variable, show a decrease in SPM concentration of 0.122 (μg/m^3). Furthermore, the results of column (3), which consider the time-variant factors of each prefecture, are the same as those of column (2). Although the results of columns (4) to (6) should reflect that the atmospheric environment improvement effect of the TLEZ becomes stronger year by year, there were no significant differences from the results of columns (1) to (3) using the samples for the whole period. In Panel A of Figure H.1, the SPM coefficients from 1990 to 1995 were non-significant but positive. This may have overestimated the difference between the 10 years before and the 10 years after the initiation of the TLEZ using all specimens. Nevertheless, the results from columns (4) to (6) indicate that the TLEZ improved the concentration of SPM. Since the average value of SPM before 2000 was 48.4 and the average traffic volume in 1990 was 26.3, the average atmospheric concentration of SPM at the TLEZ can be said to have improved by about 7.17% (= 0.132 × 26.3/48.4) by 2010.

Panel B in Table 3 reports the estimated NO_x results. The results in column (1) show that for every 1,000 diesel vehicles in 1990 within a 2-km radius of an atmospheric station, NO_x concentrations decreased by an average of 0.194 parts per million (ppm). Because of controlling the amount of traffic in the neighborhood of non-regulated vehicles, column (2), the NO_x concentration decreased by 0.135 (ppm). There is no significant difference between the results of columns (2) and (3). The magnitude of the DID estimator of SPM in column (2) is more significant than that in column (1), but the magnitude of the DID estimator of NO_x in column (2) is smaller than that in column (1). These results suggest that the emissions sources of SPM and NOx other than large diesel vehicles could be different. The result in column (6) shows that the NO_x concentration decreased by 0.220 ppm, which means that the NO_x concentration improved by about 9.08% (= 0.220 × 26.3/63.7) over 10 years. Similarly, Panel C in Table 3 reports lower concentrations of NO_2 in the atmosphere. A comparison between 1998 and 2000, immediately before the introduction of the TLEZ, and 2008–2010, 10 years after the introduction, showed an improvement in NO_2 air pollution of about 3.00% (= 0.034 × 26.3/29.8).

From the results of the event study graph and estimation, we find that the concentration of air pollutants subject to regulation improved at locations with a high traffic volume of heavy-duty diesel vehicles within a 2-km radius before the introduction of the TLEZ. All estimates also control the volume of traffic in the vicinity of unregulated gasoline-powered passenger cars. Thus, it is unlikely that such factors as an economic activity that correlates with overall vehicle traffic are confounding factors. As shown in Table D.1 in Appendix D, there is little change in traffic conditions within the TLEZ, and thus, it is unlikely that the total amount of SPM generated from, for example, brakes have changed. Meanwhile, the effects of the TLEZ on air pollutants not subject to regulation are not confirmed in the event study graphs. As shown in Appendix G, heavy-duty diesel vehicle traffic within a 2-km radius well explains the SPM results and may underestimate the NO_x results. Therefore, in the analysis that follows, we assume that the volume of diesel traffic within a 2-km radius is a proxy variable for the strength of the impact of the TLEZ regulation, although this may be an underestimation.

IV. Land Price

The identification strategy for land prices is essentially the same as the estimation of the atmospheric environment. However, observation points for public land prices are spatially denser than those for atmospheric stations. Moreover, because they contain information on land attributes, more reliable control variables can be added. In other words, the estimation is performed using the following model:

$$(2)\quad \text{LandPrice}_{impt} = \alpha_i + \beta\left(D^{Post}{}_t \times \text{Diesel}_{0-2,imp1990}\right)$$
$$+\gamma_1\left(YearFE \times \text{Cars}_{0-2,imp1990}\right) + \gamma_2 X_{im} + MuniFE_m \times YearFE + \varepsilon_{impt},$$

Here, LandPrice_{impt} represents the public land price of observation point i in base municipality m of prefecture p in period t. X_{im} represents the attributes (presence or absence of public water supply, land area, floor-area ratio, building–land ratio, and linear distance to the nearest railway station) of the observation point of the public land price i. $MuniFE_m$ is the fixed effect of the municipality. Other variables are defined in the same way as the air pollution analysis in equation (1).

Changes in land prices in the TLEZ are based on the hedonic model and are distinguished from changes in air quality on a theoretical background. Changes in air quality capture the physical relationship of reduced pollutants from heavy-duty diesel vehicles, while changes in land prices measure the consequences of people's choice of where to live. For example, a residential choice can be influenced by policy changes that are different from air quality. Therefore, by adding the interaction term between the municipal fixed effect and the annual fixed effect as control variables, the trend based on the characteristics of each municipality is controlled more flexibly. In other words, this analysis measures the difference in changes in land prices at locations where the traffic volume of large diesel vehicles differs within the same municipality.

The coefficient of interest in this analysis is β, which represents the relationship between the volume of traffic and the change in land prices after the introduction of the TLEZ. Because this coefficient is a DID estimator, we draw an event study graph as well as an analysis of air quality to meet the common trend assumption. This graph is drawn by exchanging ${D^{Post}}_t$ equation (2) for $YearFE$ and plotting the coefficients for each year. Because the official land price is the value as of January 1, the influence of the TLEZ on land prices starts in 2002, the year following the formulation of the policy. Therefore, the event study graph is based on 2001. The official land price is reflected in the following year’s information based on the results of the annual transactions. However, since the TLEZ policy was formulated in October 2001, only the last three months of 2001 transactions are reflected in public land prices in 2002.Public land prices should fully reflect the impact of the policy after 2003.

Figure I.1 in Appendix I is an event study graph showing the coefficients for public land prices in each year. Public land prices tend to rise around roads with higher heavy-duty diesel traffic after the introduction of the TLEZ. The timing at which land prices begin to be affected by the TLEZ is in line with expectations. Before the introduction of the TLEZ, there is no evidence that public land prices continue to rise with higher heavy-duty diesel traffic. The magnitude of the coefficients has been increasing year by year, which is consistent with the TLEZ regulation being stricter year by year.

Table 4 reports the estimation results based on equation (2) for the impact of TLEZ enforcement on land prices. Columns (1) to (4) present estimates using observations from all periods, and columns (5) and (6) together present results using observations for a total of 5 years, from 1999 to 2001, the 3 years immediately before the start of the TLEZ, in the case of column (5) and 2009 and 2010, 10 years after the introduction of the TLEZ, for column (6). From columns (2) to (4), we have more control over regional time-variant factors. Column (2) is an estimate of column (1) plus a pattern related to the traffic volume of nearby cars as a control, and column (3) is an estimate of column (2) with time-variant

TABLE 4. THE EFFECT OF TOKYO LEZ ON LAND PRICE

	1991–2010				1999–2001 & 2009–2010	
	(1)	(2)	(3)	(4)	(5)	(6)
1[Post LEZ] × No. of diesel vehicles (within 2 km)	0.0016	0.0011	0.0012	0.0011	0.0012	-0.0001
	(0.0002)	(0.0002)	(0.0002)	(0.0003)	(0.0001)	(0.0002)
Year FE	YES	YES	NO	NO	NO	NO
Cars (within 2 km) × Year FE	NO	YES	YES	YES	NO	YES
Other Controls	NO	YES	YES	YES	YES	YES
Prefecture FE × Year FE	NO	NO	YES	NO	NO	NO
Municipality FE × Year FE	NO	NO	NO	YES	YES	YES
No. of observations	124,846	124,846	124,846	124,846	32,109	32,109
No. of groups	9,012	9,012	9,012	9,012	7,866	7,866

Notes: Other controls are public water supply, land area, floor-area ratio, building–land ratio, and linear distance to the nearest railway station. All regressions include individual fixed effects. Standard errors clustered by point of public land price are reported in parentheses.

factors for each prefecture as a control. Column (4) controls non-linear trends specific to each municipality by using the interaction term of the year fixed effect and municipalities fixed effect.

The estimates show that the higher the traffic volume of heavy-duty diesel vehicles in the neighborhood, the higher the land price after the start of the TLEZ. The results in column (1) of Table 4 show a 0.16% increase in land prices for every 1,000 large diesel vehicles in the neighborhood. The results for column (2) control time-variant factors by traffic volume of a passenger car, which is non-regulated, and the results for columns (3) and (4) control regional time-variant factors additionally; they show an almost equal 0.11–0.12% increase in land prices. These results suggest that the time-variant factors specific to the municipality are well controlled. According to the results in column (4), which are the most rigorous, land prices rose by an average of 2.74% (= 22.8 * 0.12). The column (5) results using a 3-year sample from 1999 to 2001 and a 2-year sample from 2009 to 2010 give a coefficient of 0.12%. Therefore, land prices per square meter of residential land in the TLEZ increased by an average of 11,000 yen (= 0.0012 * 22.8 * 401758). Column (6) has the same controls as column (4). Although the coefficient in column (6) is different from the results in other columns, the influence of the multiple collinearities with the traffic volume of the diesel vehicle is considered to strengthen because of the shortening of the panel in the time direction.

V. Infant Health

Identification strategies in the analysis of infant health are similar to the effects of the TLEZ on air quality.

(3) $\text{InfantHealth}_{mt} = \alpha_m + \beta\left(D^{Post}{}_t \times \overline{\text{Diesel}}_{0-2,m1990}\right) + YearFE + \varepsilon_{mt},$

InfantHealth_{mt} shows the health outcome of infants in municipality m in year t. $\overline{\text{Diesel}}_{0-2,m1990}$ shows the neighborhood traffic volume of heavy-duty diesel vehicles of residents in municipality m . As described in Appendix F, this traffic volume is the average value obtained by weighting the traffic volume within a 2-km radius of the center of the 1-km mesh in the municipality by the population in the mesh. α_m is the fixed effect of municipality m, $YearFE$ is the year fixed effect, and ε_{mt} is the error term. This estimate uses a generalized linear model to capture the average effect of the TLEZ on infant health.

We draw event study graphs for each outcome of infant health in the same way as air quality and land value analysis. Panels A to F in Figure J.1 in Appendix J show the coefficients (not a marginal effect) and their confidence intervals for outcomes of birth weight less than 2,500 g (LBW), death of an infant less than 1 year old, death of a newborn less than 4 weeks old, death of a newborn less than 1 week old, stillbirth, and perinatal death (from 22 weeks of pregnancy to delivery). As in the case of air quality, the impacts of the TLEZ are assumed to have started after 2001, with 2000 as the base year.

The LBW graph of Panel A shows that the higher the heavy-duty diesel traffic volume after the introduction of the TLEZ, the smaller the ratio of LBW year by year. The shape is very similar to that of SPM and NO_x in the event study graphs (Panels A and B in Figure J.1). None of the pre-TLEZ coefficients tended to be significant. Table 2 shows that although the ratio of LBW is higher on average after the start of the TLEZ, the probability of LBW decreases as the traffic volume increases, suggesting that the TLEZ has had a positive effect on the health of infants. In Panel B, although the significance of the coefficient after the initiation of the TLEZ is somewhat equivocal because it is less frequent than LBW, infant death under 1 year of age also tends to be similar to LBW. Although the coefficient after the initiation of the TLEZ is obscure, a pattern similar to that of infant deaths under 1 year of age is observed in all remaining panels.

In summary, the common trend assumption seems to be satisfied. In particular, LBW and infant deaths under 1 year of age showed a tendency to improve their indexes year by year in municipalities in which the traffic volume of heavy-duty diesel vehicles was high before the TLEZ. Therefore, it is likely that TLEZ has improved the health of infants.

Table 5 reports the marginal effects of the TLEZ on infant health based on the estimation of equation (3). Table 5 shows Panel A, which does not include the interaction between the average passenger car traffic volume and the year fixed effect as the control, and Panel B, which includes them in the analysis. Different from the analysis of pollution concentration and land price, the problem of multiple collinearities between the traffic volume of large diesel vehicles and that of passenger vehicles may arise, since the weighted average traffic volume in each local government is used. Two analyses are

TABLE 5. AVERAGE MARGINAL EFFECT OF TOKYO LEZ ON INFANT HEALTH (PER 1,000)

	Birth weight less than 2500 g	Infant deaths under 1 year of age	Deaths of newborns within 4 weeks of birth	No. of early neonatal deaths (within 7 days)	No. of stillbirths	Stillbirths after 22 weeks of gestation
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A						
1(Post LEZ) × No. of heavy-duty diesel vehicles (within 2 km)	-0.00063	-0.00004	-0.00002	-0.00001	-0.00012	-0.00002
	(0.00007)	(0.00001)	(0.00001)	(0.00000)	(0.00002)	(0.00001)
Panel B						
1(Post LEZ) × No. of heavy-duty diesel vehicles (within 2 km)	-0.00031	-0.00004	-0.00001	-0.00001	-0.00003	-0.00001
	(0.00018)	(0.00002)	(0.00002)	(0.00001)	(0.00007)	(0.00003)

Notes: This table reports the marginal effects of 1(Post LEZ) × No. of heavy-duty diesel vehicles (within 2 km) in each estimation. The number of observations in estimations (1) to (4) is 4564. The number of observations in estimations (5) and (6) is 4560. All regressions included individual fixed effects. Each coefficient in Panel B is from a regression that also includes controls for cars (within 2 km) × Year FE. Delta-method standard errors clustered by municipalities are reported in parentheses.

performed to consider this possibility.

According to the results in Panel A of Table 5, marginal effects other than the number of stillbirths after 22 weeks of perinatal dead pregnancy improved. It is also important to note that stillbirths might not be the effect of the TLEZ, because it was unclear whether the common trend assumptions were met. Table 2 shows that the average heavy-duty diesel vehicle traffic volume was 16,200, indicating that LBW decreased by 10.20 per 1,000 (= -0.00063 * 16.2 * 1,000) in this average traffic volume. This represents a 13.5% improvement in the rate of LBW. Similarly, the number of infant deaths under 1 year of age reduced by 0.63 per 1,000 (= -0.00004 * 16.2 * 1,000), which represents a 15.8% improvement on average. The number of neonatal deaths less than 4 weeks of age reduced by 0.24 per 1,000 (= -0.00002 * 16.2 * 1,000), which represents an 11.4% improvement on average. The number of early neonatal deaths within 7 days reduced by 0.16 per 1,000

(= -0.00001 * 16.2 * 1,000), which represents a 10.7% improvement on average. The number of stillbirths reduced by 1.92 per 1,000 (= -0.00012 * 16.2 * 1,000), which represents an 11% improvement on average. The number of stillbirths after 22 weeks of gestation reduced by 0.24 per 1,000 (= -0.00002 * 16.2 * 1,000), which represents a 4.8% improvement on average.

Panel B of Table 5 also shows a decreasing trend in LBW and mortality under the age of 1 year. The LBW has a coefficient scale of approximately half that of Panel A. LBW improved under-1-year mortality by 6.5% at the average traffic volume. The magnitude of the coefficients for the mortality rate hardly changed. The other coefficients did not change significantly. These results suggest that the health index for infants improved in the municipalities with higher traffic volume of heavy-duty diesel vehicles.

VI. Discussion

Our estimation results suggest that the TLEZ has improved the concentration of air pollutants subject to regulation, resulting in improved infant health and increasing land prices. We estimate the rough economic value of the TLEZ assessed by residents based on the rise in land prices. This estimate has several advantages over the epidemiological benefits of the TLEZ. Epidemiological benefits are estimated by accumulating the financial value of health improvements, but it might not be possible to list all health improvements, and it is not easy to measure improvements in labor productivity. No matter how significant the epidemiological benefits may be, it is not easy to implement policies if residents underestimate them. Meanwhile, if the evaluation is based on the hedonic approach adopted in this study, the economic value of the improvement in the associated atmospheric environment is estimated by measuring the total value felt by the residents for the effect of the TLEZ.

First, we estimate the cost of the TLEZ based on previous research. This cost estimation is based on Iwata and Arimura (2009), who conduct a pre-evaluation of the NO_x/PM Law, and Iwata (2011), who conducts a pre-evaluation of the ordinances of Tokyo and the three prefectures. The NO_x/PM Law mandates the replacement of automobiles that do not meet the 2005 emission standards, and the ordinances of one metropolis and three prefectures require the installation of DPFs if they do not meet the 1999 emission standards. Because of these characteristics, the cost of the NO_x/PM Law is around 521 billion yen, which is overwhelmingly higher than DPF installation. This cost is an estimate of the replacement cost only for vehicles registered in the area. Regulated vehicles that pass through the TLEZ should install DPFs following the ordinances of Tokyo and the three prefectures. According to Iwata (2011), DPFs cost about 7% as much as the NO_x/PM method when installed on all vehicles subject to the NO_x/PM Law. It is not clear how many diesel vehicles will enter the TLEZ from outside, and thus, it is assumed that 80% of the vehicles registered with the TLEZ enter from outside the TLEZ.[17] The cost is about 29 billion (= 521*0.07*0.8) yen. Therefore, the total cost of TLEZ is about 550 billion yen.

Next, the total value of the land price increase by the TLEZ is obtained. It should be noted that the official land price reflects the transaction price of a house in the TLEZ and does not survey the land price in an area in which no transaction takes place. Therefore, the total benefit cannot be calculated from the sum of the housing land area in the TLEZ. Then, the average land price of each municipality and the average traffic volume of

17 The Tokyo Metropolitan Government's Environmental Bureau has reported that 80% of the cars running in Tokyo are from outside Tokyo.

heavy-duty diesel vehicles are calculated based on the information on land price estimation in Section IV. The total benefit is estimated based on the assumption that the rate of land price increase per 1,000 vehicles of traffic volume is equal in the whole area; that is,

$$\text{Total Benefit} = 0.0012 \times \sum_M AvePL_m \times \text{AveDesels}_{0\sim2,\text{im}1990} \times TolRLA_m.$$

Here, $AvePL_m$ represents the average land price of municipality m; $AveDesels_{0\sim2,im1990}$ represents the average traffic volume of heavy-duty diesel vehicles of municipality m in 1990, based on the information of observation points of the public land price; and $TolRLA_m$ represents the total area of residential land in municipality m. 0.0012 is the DID estimator value in column (5) of Table 4. This formula gives a total economic value of about 7.72 trillion yen. The total cost of the TLEZ is 550 billion yen, and thus, the benefit–cost ratio is approximately 14. Therefore, the residents are likely to support the TLEZ policy.

To interpret the magnitude of this benefit–cost ratio, we compare it with the results of previous studies. A good comparison is Wolff (2014), who evaluates the German LEZ. Wolff (2014) reports an epidemiological benefit–cost ratio of 1.2–5.3, as underestimated results. Although it is not an evaluation of the LEZ, the EPA (2011), which evaluates the US Clean Air Act, provides useful information as an evaluation of air environment policy. According to the EPA (2011), the epidemiological benefit of the Clean Air Act from 1990 to 2010 was about 30.8 times its cost. Because Wolff (2014) uses fewer items than the EPA (2011) does to calculate the epidemiological benefits of the LEZ in Germany, it is not possible to compare the magnitude of the two epidemiological benefits. However, these studies allow us to interpret that the ratio of economic benefits to costs of the TLEZ is in the same order of magnitude as the epidemiological benefit to the cost of these atmospheric policies. In other words, residents may evaluate the economic benefits of air environment policies on a scale comparable to the epidemiological benefits.

VII. Conclusion

We examined the impacts of heavy-duty diesel emission regulations on air quality, land prices, and infant health in metropolitan areas. The estimation results showed that the greater the traffic volume of heavy-duty diesel vehicles before the introduction of the TLEZ, the more almost all the outcomes were affected even after controlling for the traffic volume of non-regulated gasoline vehicles. Although the TLEZ regulation is almost the same as the European LEZ regulation, this study confirmed that not only SPM and NO_2 but also NO_x tended to decrease. Land prices rose and the benefits were about 14 times the cost. Improvement in the health of infants was also confirmed. Although the conclusions of the three outcomes were derived from different estimation models, there were no inconsistent features. These results suggest that there are permanent health effects of exhaust gas regulation in cities and that residents recognize and evaluate this benefit.

The benefits of the TLEZ estimated in this study may have been underestimated. The target of the ordinances of Tokyo and three neighboring prefectures includes heavy-duty diesel vehicles that are registered outside the TLEZ and pass through the TLEZ. Hence, it is likely that air quality has improved outside the TLEZ as well as in the vicinity where those vehicles pass. Since this benefit is not included in the air quality improvement benefits derived in this study, the original benefits of the TLEZ will be greater. The results suggest that policies to regulate heavy-duty diesel emissions should be promoted in metropolitan areas.

REFERENCES

Anderson, Michael L. 2019. "As the Wind Blows: The Effects of Long-Term Exposure to Air Pollution on Mortality." *Journal of the European Economic Association,* DOI: 10.1093/jeea/jvz051.

Anenberg, Susan C., Joshua Miller, Ray Minjares, Li Du, Daven K. Henze, Foreest Lacey, Christopher S. Malley, Lisa Emberson, Vicente Franco, Zbigniew Klimont, and Chris Heyes. 2017. "Impacts and Mitigation of Excess Diesel-Related NO_x Emissions in 11 Major Vehicle Markets." *Nature*, 545: 467–471.

Arceo, Eva, Rema Hanna, and Paulina Oliva. 2015. "Does the Effect of Pollution on Infant Mortality Differ Between Developing and Developed Countries? Evidence from Mexico City." *Economic Journal*, 126(591): 257–280.

Auffhammer, Maximilian, and Ryan Kellogg. 2011. "Clearing the Air? The Effects of Gasoline Content Regulation on Air Quality." *American Economic Review,* 101(6): 2687–2772.

Chay, Kenneth Y., and Michael Greenstone. 2003. "The Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession." *Quarterly Journal of Economics,* 118(3): 1121–1167.

Chay, Kenneth Y., and Michael Greenstone. 2005. "Does Air Quality Matter? Evidence from the Housing Market." *Journal of Political Economy,* 113(2): 376–424.

Chen, Yuyu, Ginger Zhe Jin, Naresh Kumar, and Guang Shi. 2013. "The Promise of Beijing: Evaluating the Impact of the 2008 Olympic Games on Air Auality." *Journal of Environmental Economics and Management*, 66(3): 424–443.

Currie, Janet, Lucas Davis, Michael Greenstone, and Reed Walker. 2015. "Environmental Health Risks and Housing Values: Evidence from 1,600 Toxic Plant Openings and

Closings." *American Economic Review*, 105(2): 678–709.

Currie, Janet, Joshua Graff Zivin, Jamie Mullins, and Matthew Neidell. 2014. "What Do We Know About Short- and Long-Term Effects of Early-Life Exposure to Pollution?" *Annual Review of Resource Economics*, 6: 217–247.

Currie, Janet, Michael Greenstone, and Katherine Meckel. 2017. "Hydraulic Fracturing and Infant Health: New Evidence from Pennsylvania." *Science Advance*, 3: e1603021.

Currie, Janet, Eric A. Hanushek, E. Megan Kahn, Matthew Neidell, and Steven G, Rivikin. 2009. "Does Pollution Increase School Absences?" *Review of Economics and Statistics*, 91(4): 682–694.

Currie, Janet, and Matthew Neidell. 2005. "Air Pollution and Infant Health: What Can We Learn from California's Recent Experience?" *Quarterly Journal of Economics*, 120(3): 1003–1030.

Currie, Janet, Matthew Neidell, and Johannes F. Schmieder. 2009. "Air Pollution and Infant Health: Lessons from New Jersey." *Journal of Health Economics*, 28(3): 688–703.

Currie, Janet, and Reed Walker. 2011. "Traffic Congestion and Infant Health: Evidence from E-ZPass." *American Economic Journal: Applied Economics*, 3(1): 65–90.

Davis, Lucas W. 2008. "The Effect of Driving Restrictions on Air Quality in Mexico City." *Journal of Political Economy*, 116(1): 38–81.

De la Mata, Dolores, and Carlos Felipe Gaviria Garcés. 2019. "Exposure to Pollution and Infant Health: Evidence from Colombia." *CINCH Working Paper Series 1902*, Universitaet Duisburg-Essen, Competent in Competition and Health.

Ellison, Richard B., Stephen P. Greaves, and David A. Hensher. 2013. "Five Years of London's Low Emission Zone: Effects on Vehicle Fleet Composition and Air Quality."

Transport Research Part D, 23: 25–33.

EPA. 2011. “The Benefits and Costs of the Clean Air Act from 1990 to 2020.” U.S. Environmental Protection Agency Office of Air and Radiation. https://www.epa.gov/sites/production/files/2015-07/documents/fullreport_rev_a.pdf

Gallego, Francisco, Juan-Pablo Montero, and Christian Salas. 2013. “The Effect of Transport Policies on Car Use: Evidence from Latin American Cities.” *Journal of Public Economics*, 107: 47–62.

Gehrsitz, Markus. 2017. “The Effect of Low Emission Zones on Air Pollution and Infant Health.” *Journal of Environmental Economics and Management*, 83: 121–144.

Gentner, Drew R., Gabriel Isaacman, David R. Worton, Arthur W. H. Chan, Timothy R. Dallmann, Laura Davis, Shang Liu, Douglas A. Day, Lynn M. Russell, Kevin R. Wilson, Robin Weber, Abhinav Guha, Robert A. Harley, and Allen H. Goldstein. 2012. “Elucidating Secondary Organic Aerosol from Diesel and Gasoline Vehicles Through Detailed Characterization of Organic Carbon Emissions.” *PNAS*, 109(45): 18318–18323.

Graff Zivin, Joshua, and Matthew Neidell. 2018. “Air Pollution’s Hidden Impacts: Exposure Can Affect Labor Productivity and Human Capital.” *Science*, 359(6371): 39–40.

Greenstone, Michael, and Rema Hanna. 2014. “Environmental Regulations, Air and Water Pollution, and Infant Mortality in India.” *American Economic Review*, 104(10): 3038–3072.

Hanna, Rema, and Paulina Oliva. 2015. “The Effect of Pollution on Labor Supply: Evidence from a Natural Experiment in Mexico City.” *Journal of Public Economics*, 122: 68–79.

Isen, Adam, Maya Rossin-Slater, and Reed Walker. 2017. "Every Breath You Take—Every Dollar You'll Make: The Long-Term Consequences of the Clean Air Act of 1970." *Journal of Political Economy*, 125(3): 848–902.

Iwata, Kazuyuki. 2011. "Cost–Benefit Analysis of Enforcing Installation of Particulate Matter Elimination Devices on Diesel Trucks in Japan." *Environmental Economics and Policy Studies*, 13: 1–19.

Iwata, Kazuyuki, and Toshi H. Arimura. 2009. "Economic Analysis of Japanese Air Pollution Regulation: An Optimal Retirement Problem Under the Vehicle Type Regulation in the NO_x–Particulate Matter Law." *Transportation Research Part D*, 14(3): 157–167.

Jans, Jenny, Per Johansson, and J. Peter Nilsson. 2018. "Economic Status, Air Quality, and Child Health: Evidence from Inversion Episodes." *Journal of Health Economics*, 61: 220–232.

Knittel, Christopher R., Douglas L. Miller, and Nicholas J. Sanders. 2016. "Caution, Drivers! Children Present: Traffic, Pollution and Infant Health." *Review of Economics and Statistics*, 98(2): 350–366.

Marcus, Michelle. 2017. "On the Road to Recovery: Gasoline Content Regulations and Child Health." *Journal of Health Economics*, 54: 98–123.

Moretti, Enrico, and Mathhew Neidell. 2011. "Pollution, Health, and Avoidance Behavior: Evidence from the Ports of Los Angeles." *Journal of Human Resources*, 46(1): 154–175.

Mudway, Ian S., Isobel Dundas, Helen E. Wood, Nadine Marlin, Jeenath B. Jamaludin, Stephen A. Bremner, Louise Cross, Andrew Grieve, Alex Nanzer, Ben M. Barratt, Sean Beevers, David Dajnak, Gary W. Fuller, Anna Font, Grainne Colligan, Aziz Sheikh, Robert Walton, Jonathan Grigg, Frank J. Kelly, Tak H. Lee, and Chris J. Griffiths. 2019. "Impact of London's Low Emission Zone on Air Quality and Children's Respiratory Health: A Sequential Annual Cross-Sectional Study." *Lancet Public Health* 4: e28–40.

Neidell, Matthew. 2011. "Information, Avoidance Behavior, and Health: The Effect of Ozone on Asthma Hospitalizations." *Journal of Human Resources*, 44(2): 450–478.

Parry, Ian W. H., Margaret Walls, and Winston Harrington. 2007. "Automobile Externalities and Policies." *Journal of Economic Literature*, 45(2): 373–399.

Santos, Francisca M., Álvaro Gómez-Losada, and José C. M. Pires. 2019. "Impact of the Implementation of Lisbon Low Emission Zone on Air Quality." *Journal of Hazardous Materials*, 365: 632–641.

Schlenker, Wolfram, and Reed Walker. 2016. "Airports, Air Pollution, and Contemporaneous Health." *Review of Economic Studies*, 83: 768–809.

Tokyo Metropolitan Government. 2000. *Environment White Paper* 2000.

Wolff, Hendrik. 2014. "Keep Your Clunker in the Suburb: Low-Emission Zones and Adoption of Green Vehicles." *Economic Journal*, 124(August): F481–F512.

Zhang, Wei, C.-Y. Cynthia Lin Lawell, and Victoria I. Umansakaya. 2017. "The Effects of License Plate-Based Driving Restrictions on Air Quality: Theory and Empirical Evidence." *Journal of Environmental Economics and Management*, 82: 181–220.

APPENDIX

Appendix A: Theoretical Framework

The local economy in the LEZ is constructed by agents who choose to reside in two regions $r \in \{H, L\}$. Some live in areas with high heavy-duty diesel traffic $(r = H)$, while others live in areas with low heavy-duty diesel traffic $(r = L)$. However, we assume that they work in the same labor market regardless of the area in which they reside. Moreover, we assume that residents of both locations work in the same labor market and, therefore, earn the same wage w. Residents pay location-specific amenities and costs of living in each area. Each resident i has a specific preference η_{ir} for both locations and η_{ir} is heterogeneous regarding amenities. We assume that η_{ir} is independently and identically distributed across individuals and has a continuous multivariate distribution with a zero mean value. It is assumed that heavy-duty diesel traffic stimulates neighborhood economic activity through logistics.

Individuals maximize their utility through residential choice.

$$U_{ir} = max\{vH + \eta_i H, vL + \eta_i L\}$$

Here, vr represents the average utility of region r. Individuals live in areas with higher utility. If there is heterogeneity in individual preferences, for example, the preferences of individuals residing in region H satisfy the relationship $vH - vL > \eta_i L - \eta_i H$. The distribution function $\varepsilon_i \equiv \eta_i L - \eta_i H$ is defined by $R(\cdot)$. Let $SH \equiv \Pr(\eta_i < vH - vL)$ be a measure of the individuals in region *H*.

The social welfare of workers in regions H and L is calculated as follows:

$$V = \mathrm{E}[vH + \eta_i H, vL + \eta_i L]$$

Consider the impact of the LEZ in the region. The establishment of the LEZ has three effects. One is to increase the cost of passage in the zone for a diesel vehicle performing commercial activities. Hence, the traffic volume in each area is reduced. Since this cost of passage is uniform within the LEZ and the TLEZ is large, this cost cannot be decreased by options like detours. Since our model assumes that traffic affects regional productivity, the first effect of the LEZ is a marginal deterioration of productivity in the local economy. This productivity deterioration lowers the wages of residents of H and L. Second, the average amount of air pollutants emitted from a diesel vehicle is reduced. Thus, their health improves. Third, the decrease in traffic volume alleviates traffic congestion, reduces traffic accidents, improves noise, and reduces PM generated by the braking of automobiles. In other words, amenities can be improved based on reduced traffic.

The effect of the introduction of the LEZ on workers' welfare can be obtained as follows:

(A.1) $$\frac{dV}{dLEZ} = SH \times \left[\frac{\partial w}{\partial LEZ} + \frac{\partial AH}{\partial LEZ}\right] + SL \times \left[\frac{\partial w}{\partial LEZ} + \frac{\partial AL}{\partial LEZ}\right]$$

$$= S \times \frac{\partial w}{\partial LEZ} + SH \times \frac{\partial AH}{\partial LEZ} + SL \times \frac{\partial AL}{\partial LEZ}$$

Here, $dLEZ$ means a marginal effect due to the implementation of LEZ and $dV/dvr = Sr$. Equation (A.1) summarizes the impact of the LEZ in three terms. Term 1 is the total wage effect of implementing the LEZ. We assume that all agents are in the same labor market and are affected equally. Terms 2 and 3 show the changes in amenities due to the implementation of the LEZ in each region.

The implementation of the LEZ increases marginal welfare in areas with more traffic ($SH \times \partial AH/\partial LEZ > SL \times \partial AL/\partial LEZ$). Some residents of low-traffic areas consider moving to high-traffic areas for better utility. Because of this migration, residential prices in each region change. The effect of the LEZ implementation on economic welfare may be approximated by the change in land prices in each region. This study measures the impact of the LEZ on economic welfare improvement by using difference-in-differences (DID) estimation to measure the relationship between, the difference between $SH \times \partial AH/\partial LEZ$ and $SL \times \partial AL/\partial LEZ$, and traffic volume. For example, we measure the difference in welfare improvement due to an increase of 1,000 vehicles in traffic volume. Furthermore, by assuming that the improvement of air quality per diesel vehicle is uniform within the LEZ and the air pollutant reduction improves welfare, it is possible to discuss the average welfare improvement per diesel vehicle.

Appendix B: Emission Standards for Heavy-Duty Diesel

TABLE B.1. EMISSION STANDARDS FOR HEAVY-DUTY DIESEL

	Year the regulation began	NO_x	SPM
Japan	1994	6.80	0.96
	1999	4.50	0.25
	2005	2.70	0.036
EU			
Euro III	2000	5.00	0.10
Euro IV	2005	3.50	0.020
US EPA			
Tier 2	2004	5.36	0.13

Notes: All units of pollutants are g/kWh. g/kWh = g/bhp.h × 1.341

Appendix C: The Interpretation of TLEZ

In general, because traffic volumes may decrease once traffic restrictions are in place, the change in amenities in region H can be expressed as follows:

(C.1) $\partial AH/\partial LEZ = Z(\Delta TH) + TH \times \Delta P - \Delta TH \times (P - \Delta P),$

where TH is the traffic volume in H, ΔTH is the change in traffic volume in H, and ΔP is the average improvement in air pollution per heavy-duty diesel vehicle by LEZ. $Z(\cdot)$ represents the non-air quality amenities (traffic congestion, traffic noise, likelihood of traffic accidents, etc.) due to traffic volume. The first term in equation (C.1) represents the change in non-air quality amenities due to changes in traffic volume. The second term represents the total change in air pollutants emitted by all vehicles passing through the neighborhood before the implementation of the LEZ. The third term represents the reduction in air pollutants due to a decrease in traffic volume arising from the implementation of the LEZ, minus the change overlapping the second term. However, if there is no reduction in traffic ($\Delta TH = 0$), then equation (2) can be rewritten as follows:

$$\partial AH/\partial LEZ = TH \times \Delta P$$

In other words, it can be interpreted that improvements in air quality drove the increase in land prices due to the implementation of the TLEZ.

Appendix D: Changes in Neighborhood Traffic Volume

Table A reports the statistics of neighborhood traffic based on the road traffic census for different waves at the locations surveyed for official land prices in 2000. The road traffic census was conducted in 1990, 1994, 1997, 1999, and 2005. The survey results of each census were merged with road information, and traffic volume on the road within 2 km from the public land price survey point in 2000 was calculated using ArcGIS. Although the average traffic volume in the vicinity of heavy-duty diesel vehicles fluctuates every year, the correlation coefficients between the 1990 survey and other surveys are 0.95–0.97, which is a very high value. Because heavy-duty diesel vehicles are often driven over long distances, the absence of extensive bypass constructions during this period may contribute to the high correlation coefficient. This table also reports the correlation coefficient between the traffic volume of heavy-duty diesel vehicles and that of passenger cars, based on the 1990 survey, which is 0.87. Therefore, we believe that we can control the structure of nearby roads and related factors using passenger car traffic.

TABLE D.1. TRAFFIC STATISTICS AND TRENDS

	No. of obs.	Mean	Std. dev.	Correlation with no. of diesel vehicles in 1990	Correlation with no. of cars in 1990
No. of heavy-duty diesel vehicles in 1990 (within 2 km)	6,659	22.9	(18.7)	-	0.87
No. of heavy-duty diesel vehicles in 1994 (within 2 km)	6,659	24.4	(19.9)	0.97	
No. of heavy-duty diesel vehicles in 1997 (within 2 km)	6,659	25.9	(20.0)	0.96	
No. of heavy-duty diesel vehicles in 1999 (within 2 km)	6,659	25.3	(20.1)	0.97	
No. of heavy-duty diesel vehicles in 2005 (within 2 km)	6,659	23.8	(19.2)	0.95	

Notes: This table reports the basic statistics of the traffic volume in each traffic census at the survey point of the public land price as of 2000 and their correlation. The units of measurement of heavy-duty diesel vehicles and gasoline cars are in thousands.

Appendix E: Observation Points of Air Quality and Public Land Price in TLEZ

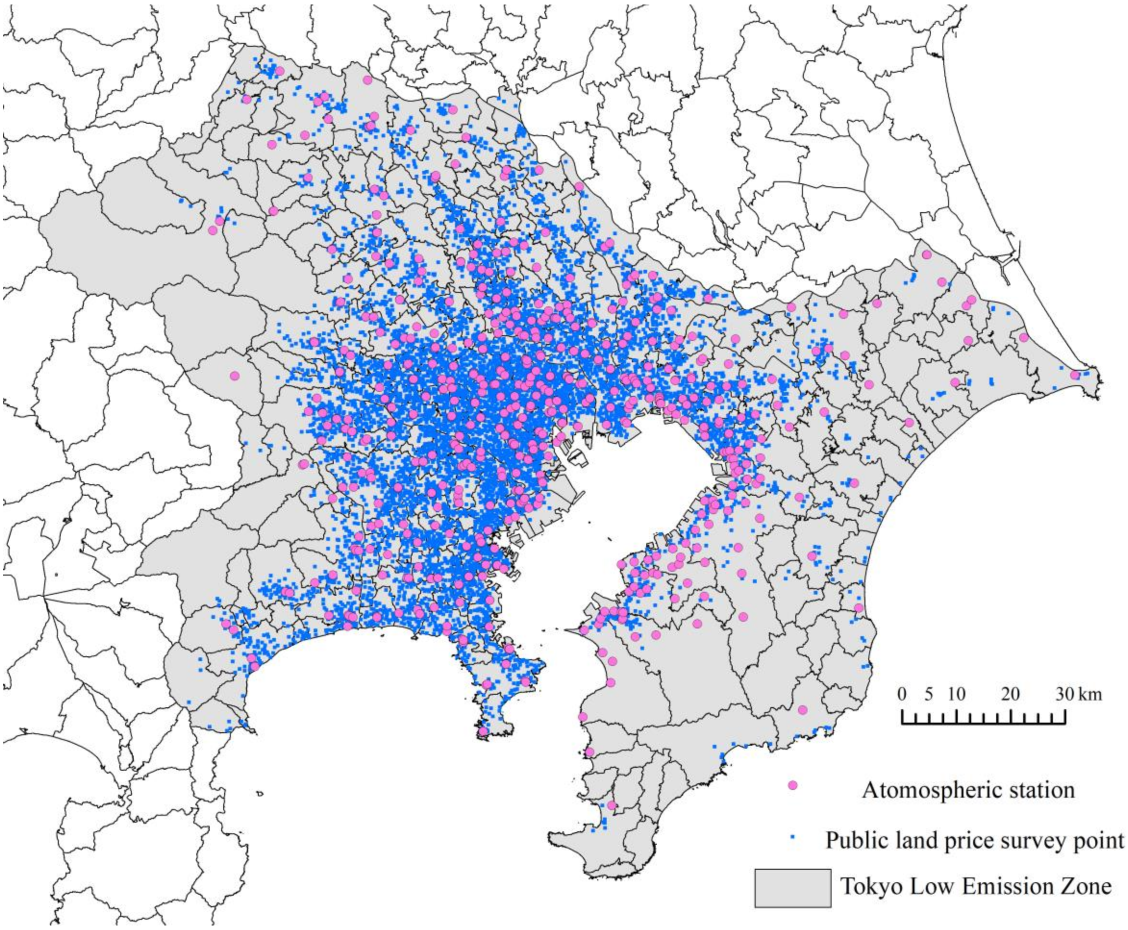


FIGURE E.1. OBSERVATION POINTS OF AIR QUALITY AND PUBLIC LAND PRICE IN TLEZ

Appendix F: Calculation of weighted average of traffic volume

We use 1-km mesh data to obtain the weighted average of the traffic volume of each municipality. A 1-km mesh is the area defined for the report of the Japanese census. In Japan, an area called the "reference area mesh" divides the entire country into a mesh of approximately the same size based on latitude and longitude for reporting statistics. A 1-km mesh is a reference area mesh, and the demographics in this area are reported.

The weighted average of each municipality is obtained by first measuring the traffic volume within 2 km from the center of 1-km mesh and then calculating the value of each municipality with a population of the 1-km mesh as a weight.

Appendix G: Validity of distance assumption

This study assumes that the traffic volume of heavy-duty diesel vehicles within 2 km from the atmospheric observation station affects the atmospheric environment. Unlike the previous point emission source, this study assesses the effects of mobile emission sources, and it is not easy to measure the effective distance from a source. Therefore, we explain the assumption that heavy-duty diesel traffic within 2 km of an atmospheric observatory has an impact on air quality and the interpretation of the estimated results by comparing the estimates for the definition of a neighborhood with radii of 1 km, 3 km, 4 km, and 5 km.

Consider the following procedure for a radius for measuring traffic that better explains the change in air quality at a point. Assume that there is an optimal radius for measuring neighborhood traffic that best describes the change in air quality at a point. When the radius is other than this optimal radius, the traffic volume used to explain the change in air quality at a point contains a measurement error. If this measurement error is random, then the average treatment effect is underestimated. Under the assumption that the measurement error is random, we consider a better radius by comparing the average effect of varying the definition of the neighborhood.

Table B reports the results of the estimates for changing the distance at which heavy-duty diesel traffic is measured from 2 km in the estimates in Table 4. Columns (1)–(5) report the estimation results when the radius is changed. Column (2) has the same value as Column (3) in Table 4. Table B also reports the mean and standard deviation of each variable and the average effect based on the estimation results.

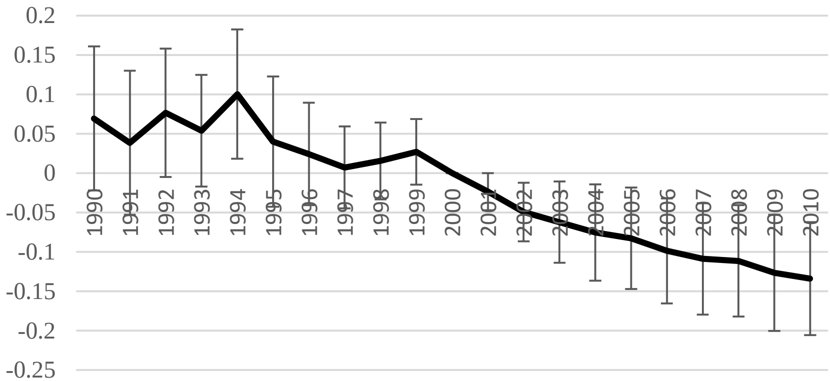
Panel A reports the estimation results of the SPM changes. The largest average effect was found for a radius of 2 km. Panel B reports the estimated results for the change in NOx. The largest average effect for NOx is indicated for a radius of 4 km. This means that the NOx estimates reported in Table 4 may be underestimated. Based on these results, we use traffic volumes within a 2-km radius when assessing the effects of TLEZ on land prices and infant health.

TABLE G.1. THE EFFECT OF TOKYO LEZ ON AIR POLLUTION (ROBUSTNESS CHECKS)

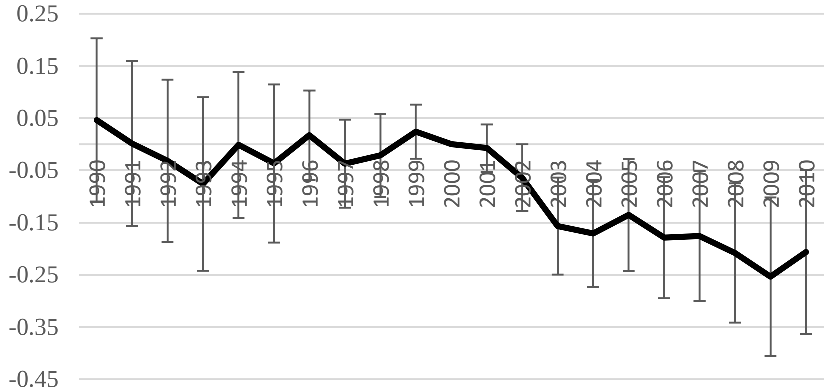
Radius	1 km	2 km	3 km	4 km	5 km
	(1)	(2)	(3)	(4)	(5)
Panel A: SPM					
1(Post LEZ) × No. of heavy-duty diesel vehicles	-0.1249	-0.1244	-0.0654	-0.0490	-0.0396
	(0.0342)	(0.0338)	(0.0178)	(0.0132)	(0.0101)
Observations	6,340	6,448	6,448	6,448	6,448
Mean of no. of heavy-duty diesel vehicles	14.4	25.4	39.6	53.4	68.6
Std. dev. of no. of heavy-duty diesel vehicles	14.0	22.3	34.4	44.0	53.6
Average effects	-1.79	-3.16	-2.59	-2.62	-2.72
Panel B: NO_x					
1(Post LEZ) × No. of heavy-duty diesel vehicles	-0.1984	-0.1432	-0.1064	-0.0927	-0.0635
	(0.0624)	(0.0640)	(0.0372)	(0.0261)	(0.0201)
Observations	5,594	5,699	5,699	5,699	5,699
Mean of no. of heavy-duty diesel vehicles	14.9	25.8	40.2	54.0	69.3
Std. dev. of no. of heavy-duty diesel vehicles	13.9	23.1	35.2	44.7	53.9
Average effects	-2.95	-3.69	-4.28	-5.00	-4.40

Notes: All regressions include individual fixed effects, year fixed effects, 1(Post LEZ) × No. of gasoline cars (within 2 km), and Prefecture FE × Year FE. Standard errors clustered by atmospheric stations are reported in parentheses.

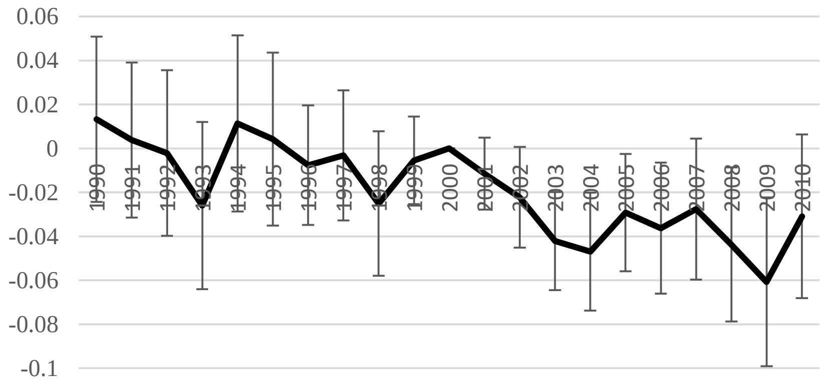
Appendix H: Event Study Graphs for Each Air Pollutant



PANEL A: SPM



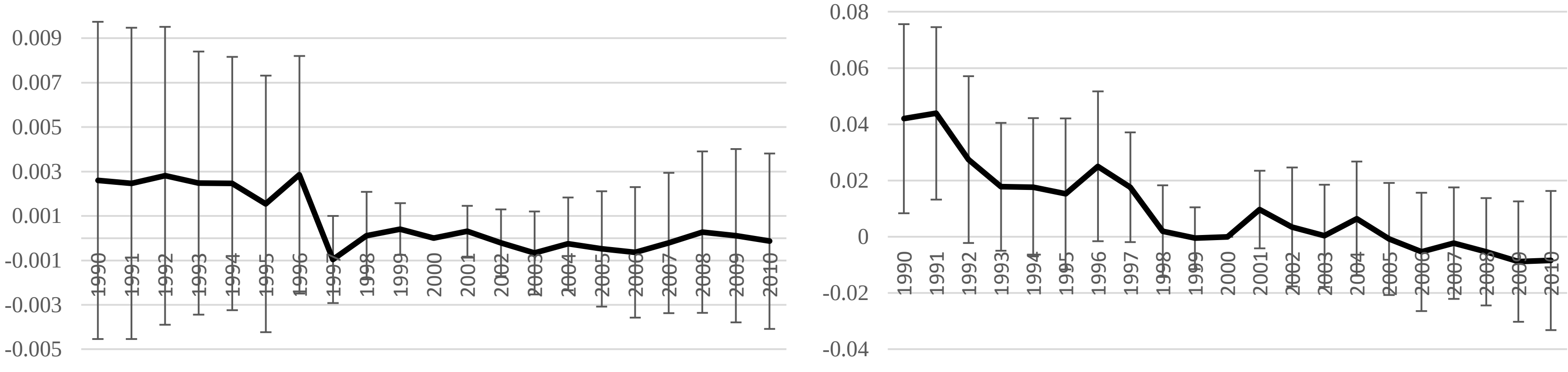
PANEL B: NO_X



PANEL C: NO_2

FIGURE H.1. EVENT STUDY GRAPH OF REGULATED AIR POLLUTANTS

Notes: These figures present DID estimators of the impacts of the TLEZ on each air pollutant. The solid line shows the DID estimator based on 2000, and the error bar shows the 95% confidence interval.



PANEL A: SO_2 PANEL B: CO

FIGURE H.2. EVENT STUDY GRAPH OF NON-REGULATED AIR POLLUTANTS

Notes: The graphs present DID estimators of the impacts of the TLEZ on each air pollutant. The solid line shows the DID estimator based on 2000, and the error bar shows the 95% confidence interval.

Appendix I: Event Study Graphs for Public Land Price

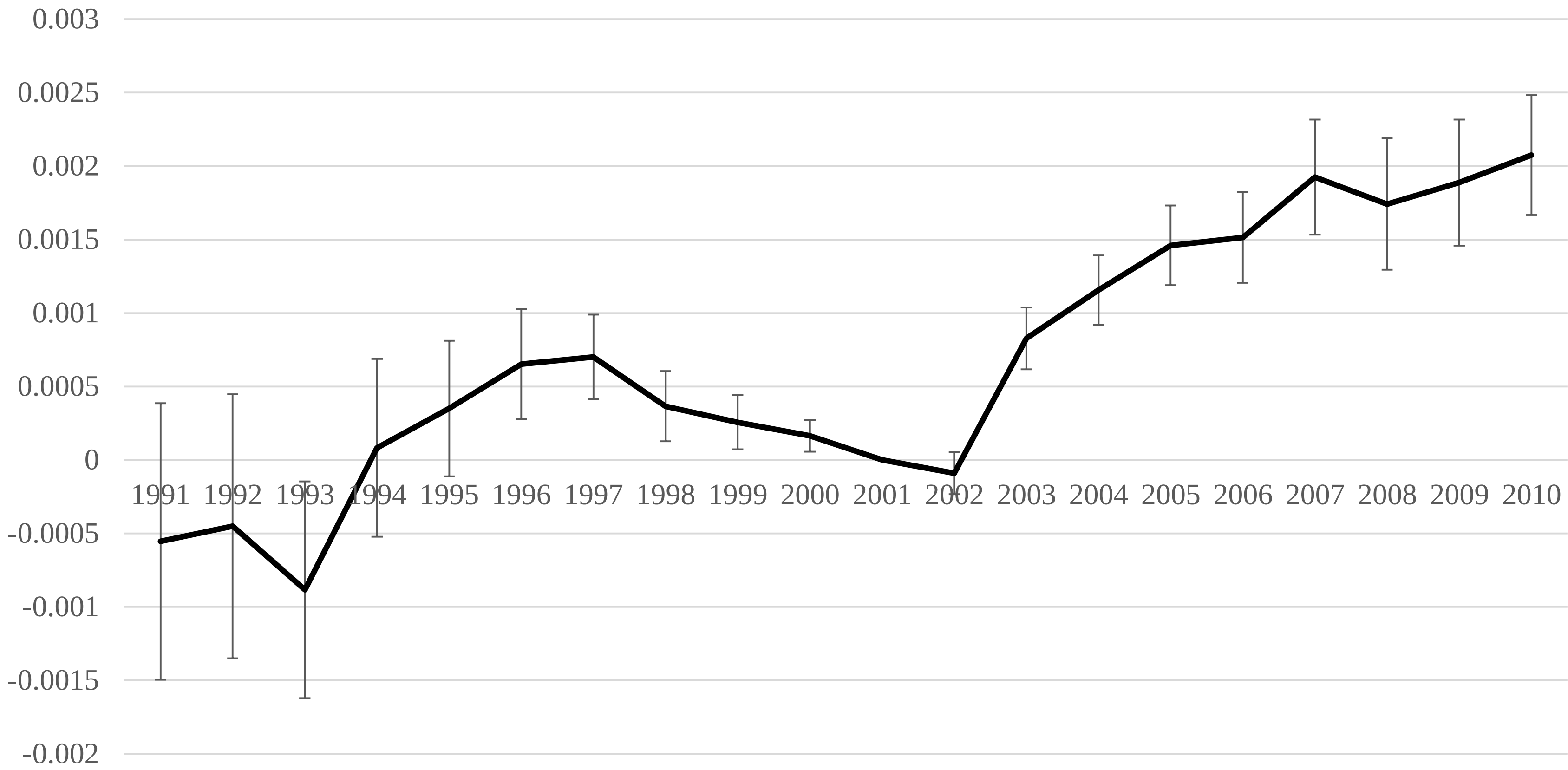
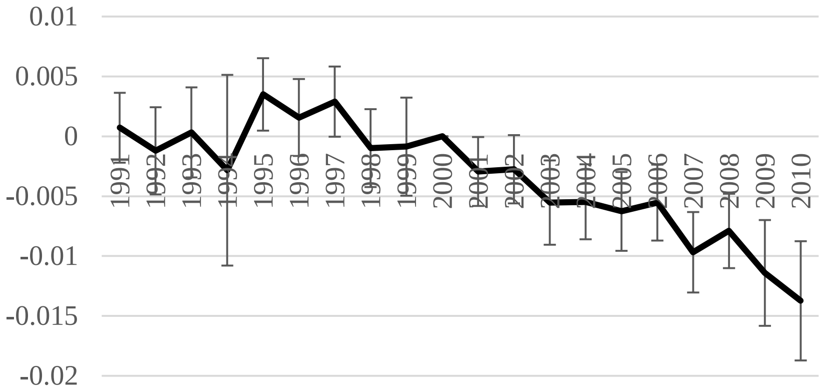


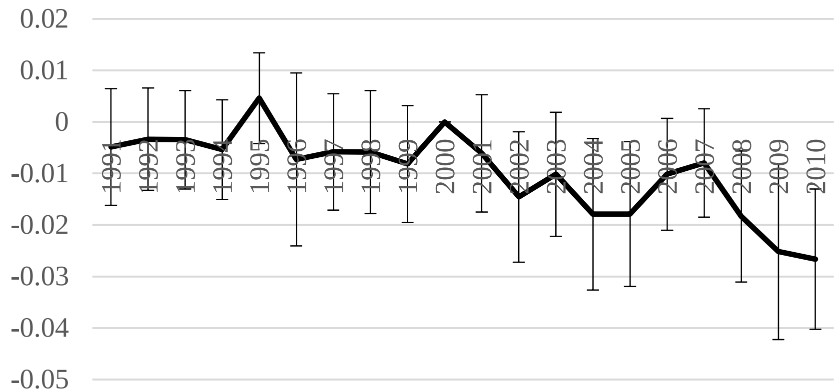
FIGURE I.1. EVENT STUDY GRAPH OF PUBLIC LAND PRICE

Notes: These figures present DID estimators of the impacts of the TLEZ on public land prices. The solid line shows the DID estimator based on 2001, and the error bar shows the 95% confidence interval.

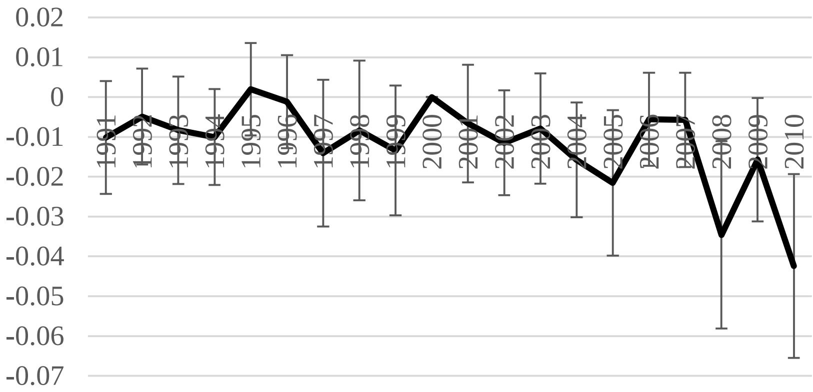
Appendix J: Event Study Graphs for Infant Health



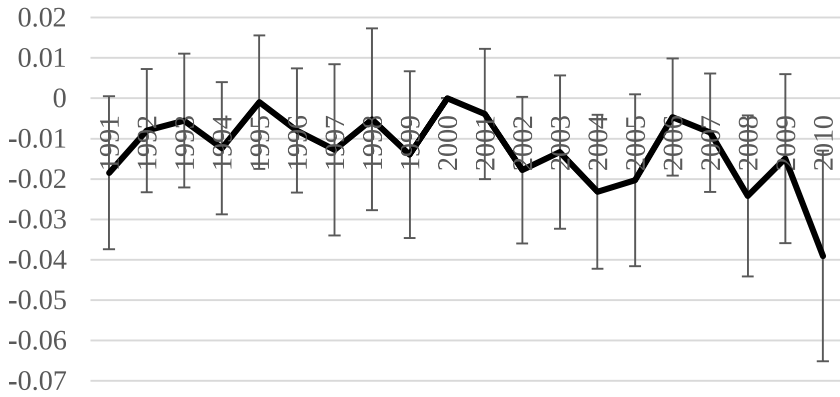
PANEL A: BIRTH WEIGHT LESS THAN 2500 G



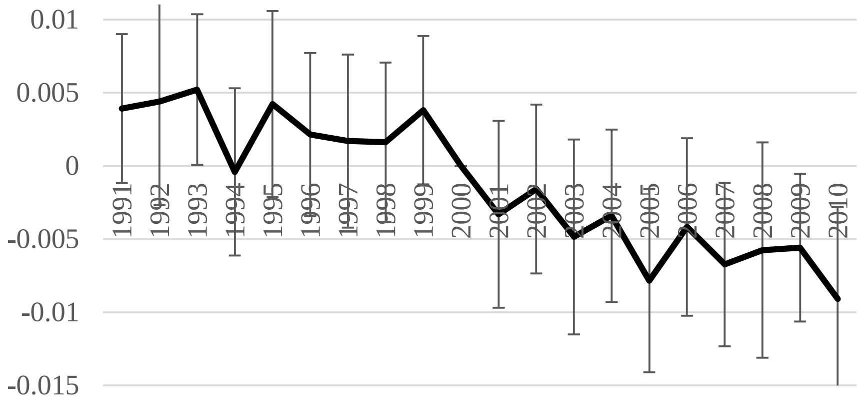
PANEL B: INFANT DEATHS UNDER 1 YEAR OF AGE



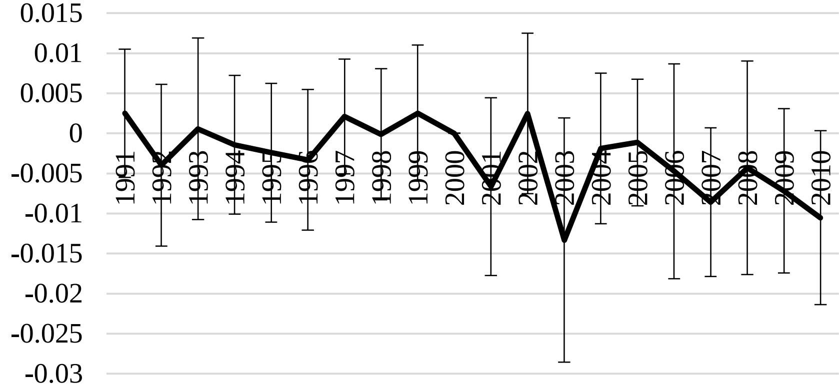
PANEL C: DEATHS OF NEWBORNS WITHIN 4 WEEKS OF BIRTH



PANEL D: NO. OF EARLY NEONATAL DEATHS (WITHIN 7 DAYS)



PANEL E: NO. OF STILLBIRTHS



PANEL F: STILLBIRTHS AFTER 22 WEEKS OF GESTATION

FIGURE J.1. EVENT STUDY GRAPHS OF INFANT HEALTH

Notes: These figures present DID estimators of the impacts of the TLEZ on infant health. The solid line shows the DID estimator based on 2000, and the error bar shows the 95% confidence interval. The analyses of Panels E and F exclude the sample with Y = 1. The addition of these samples does not significantly affect the interpretation of the results.