sustainability

MDPI

Article

The Effect of Diesel Vehicle Regulation on Air Quality in Seoul: Evidence from Seoul's Low Emission Zone

Dongkyu Park [1,*] and Nori Tarui [2,*]

[1] The Research Institute of Basic Sciences, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul 08826, Republic of Korea
[2] Department of Economics, University of Hawai'i at Mānoa, Saunders Hall 542, 2424 Maile Way, Honolulu, HI 96822, USA
* Correspondence: p0924l@gmail.com (D.P.); nori@hawaii.edu (N.T.)

Abstract: This study investigates the effect of the low emission zone (LEZ), designed to restrict old diesel vehicles, on air quality in Seoul, Republic of Korea, using the regression discontinuity in time (RDiT) approach. While previous studies have examined LEZ impacts using traditional econometric models such as time series and panel data approaches, our research uniquely integrates high-frequency daily weather data to better control for confounding environmental variables and captures time-of-day effects on pollutant concentrations. Our findings reveal that the LEZ policy effectively reduced NO_2 and SO_2 concentrations by 4.7% and 11.6%, respectively. Notably, during daytime hours, when traffic is heaviest, NO_2, SO_2, and PM_{10} concentrations decreased by 7.1%, 14.8%, and 13.6%, respectively. These results suggest that the observed improvements can be attributed not only to reduced diesel vehicle registrations but also to significant declines in overall traffic volume.

Keywords: low emission zone (LEZ); policy; air pollutants; PM_{10}; NO_2; regression discontinuity in time (RDiT)

check for updates

Citation: Park, D.; Tarui, N. The Effect of Diesel Vehicle Regulation on Air Quality in Seoul: Evidence from Seoul's Low Emission Zone. *Sustainability* **2024**, *16*, 9573. https://doi.org/10.3390/su16219573

Academic Editors: Ling Huang, Jiani Tan, Kun Zhang and Qing Mu

Received: 18 September 2024
Revised: 27 October 2024
Accepted: 31 October 2024
Published: 3 November 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

Seoul, the capital of Republic of Korea (hereafter Korea), has experienced rapid development since the 1980s, with a primary focus on the economy and less emphasis on environmental issues [1]. Coal and diesel fuel were the primary sources of heating and transportation, leading to air pollution that could harm people's health [2]. Today, Seoul's air quality is significantly better than in the 1980s, thanks to advanced technology that has reduced emissions from car tailpipes, factory smokestacks, and individual households [3]. Despite these improvements, air pollution continues to be a persistent problem, affecting not only Seoul but the entire country of Korea [4].

In an effort to reduce pollutants, the Seoul Metropolitan Government enacted the Special Act on the Improvement of Air Quality in Seoul Metropolitan Area in 2003, and the Korean Ministry of Environment (KME) established the Basic Plan on the Improvement of Air Quality in Seoul Metropolitan Area (BPIAM) every 10 years since 2005 [5]. However, since 2012, particulate matter (PM) concentration levels have not significantly improved while the number of high-PM-level days has increased [6]. To address this issue, the Special Plan on The Improvement of Air Quality in Seoul was established in 2016. This plan includes various programs, such as reducing the number of old diesel vehicles [5], supporting electric vehicle infrastructure, controlling dust scattering on construction sites and roads, and managing the demands of transportation [7].

The low emission zone (LEZ) is a policy aimed at restricting the driving of vehicles that do not meet specific conditions within the zone. This policy is intended to improve air quality by reducing pollutants emitted from vehicles. London's LEZ, implemented in 2008, is the largest in the world, and various studies have assessed its effectiveness. By using vehicle registrations and enforcement data, Ellison et al. [8] found that the LEZ not

only reduced PM concentration by 2.46% to 3.07% but also decreased pre-Euro III rigid and light commercial vehicles by 20% and 10%, respectively. Zhai and Wolff [9] found that PM_{10} was reduced by 14.8% in the short term and 5.5% in the long term. Meanwhile, Qadir et al. [10] studied the LEZ in Munich, Germany, and found that it reduced pollutants from traffic sources by 60%. Wolff [11] identified that it reduced PM emissions by 9% in Germany. Da Silva et al. [12] also found that Lisbon's LEZ reduced PM and nitrogen dioxide (NO_2) concentration by 16% and 6%, respectively.

Seoul's LEZ started on 1 January 2017. It focuses on restricting the driving of old diesel vehicles with emission grades of 5 or higher in the zone to reduce pollutants such as particulate matter (PM) and nitrogen oxides (NOx). The literature cited above indicates that LEZ policies in EU have led to reduced air pollution, but it is not clear if the same applies to Seoul because its air quality may be significantly affected by economic activities and the air quality in China due to meteorological seasonality (According to the "Joint Research Project for Long–range Transboundary Air Pollutants in Northeast Asia", it was found that China's $PM_{2.5}$ contributes 32.1% to air pollution in major Korean cities).

The purpose of this study is to identify the effect of Seoul's LEZ on air quality and to uncover the underlying mechanism by building on several relevant studies in the literature. Davis [13] analyzed the effect of the alternate no-driving policy in Mexico City with ordinary least squares (OLS) and regression discontinuity in time (RDiT) but found no evidence of improving air quality. Percoco [14] showed the limited effect of congestion traffic fees in London LEZ with RDiT, while Li et al. [15] demonstrated the effect of fuel standard changes in China with both Difference-in-Difference (DD) and RDiT methods. On the other hand, Wolff [11] showed the effect of LEZ in Germany with DD.

Although most of the previous studies about LEZ policy used DD, finding a suitable control group comparable to Seoul for DD analysis is almost impossible in Korea due to its unique features such as high population density, intensive transportation system, and big size of administrative district. Therefore, RDiT was employed to reflect these characteristics of Seoul. The potential issue with using RDiT is the possibility of discontinuous effects on the outcome variable caused by unobservable time-varying confounders besides a treatment variable. To address this potential time-varying treatment effect, we employ augmented local linear RD estimation [16]. This approach enables the control of variable factors such as seasonality and economic conditions within a narrow bandwidth around the policy intervention [15].

In this article, we compile average daily-frequency pollution and weather data based on hourly air pollution data on five pollutants (PM_{10}, CO, NO_2, SO_2 and O_3) from 40 observation stations in Seoul city, as well as the temperature, rainfall, and wind pattern information from 27 observation stations in the city. We utilize the Inverse Distance Weighting (IDW) interpolation method to reduce the measurement bias and interpolate the weather data at each air pollution station by using the observations from the three nearest air pollution observation stations.

In what follows, Section 2 provides background information on pollutants from diesel vehicles and LEZ policy. Section 3 describes the data used and Section 4 introduces the empirical strategy. The results are presented in Section 5, and the significance and limitations of the study are discussed in Section 6.

2. Background

2.1. Diesel Vehicle and Pollutants

Diesel engine systems are used in various sectors such as transportation, power plants, and construction sites. Although the improvement in diesel engine technology has reduced the pollutants from diesel vehicles, the risk of the pollutants from diesel emissions remains a concern worldwide. Emissions from diesel vehicle include exhaust smoke, PM, NOx, unburned hydrocarbon (HC), CO, and SO_2 [17]. Yang et al. [18] also showed that diesel vehicles produce higher emissions of $PM_{2.5}$ and NOx than gasoline vehicles.

Research related to the risk of pollutants on human health has been conducted in various fields. According to the International Agency for Research on Cancer (IARC), there is a positive relationship between pollutants from diesel exhaust and cancer [19]. Furthermore, diesel exhaust irritates the eyes and nose, leading to symptoms such as headaches, nausea, and respiratory illnesses including lung cancer [2]. Additionally, nitrogen oxides (NOx) in diesel exhaust can react with other chemicals in the air, forming both particulate matter (PM) and ozone (O_3), which increase the risk of respiratory and cardiovascular diseases such as heart attacks and asthma [20].

2.2. Low Emission Zone Policy

To mitigate diesel pollutants, many European countries have implemented the low emission zone (LEZ). These LEZs restrict high-emission diesel vehicles that fail to meet certain pollutant emission standards within designated areas. The LEZ policy varies across different countries. Holman et al. [21] and Ku et al. [22] succinctly summarized the LEZ schemes by country (See Tables 1 and 2). Most LEZs operate 24/7, but some are only in effect on weekdays or during 12 daytime hours on weekdays. The types of vehicles regulated also differ across countries.

Table 1. Summary of European low emission zones (source: adopted from [21]).

Country	Number of LEZs	Applicable Vehicles	National Framework /Legislation
Austria	3	Heavy goods vehicles (HGVs)	Yes
Czech Republic	1	HGVs	No
Denmark	6	HDVs	Yes
Finland	1	buses and refuse trucks	No
France	1	HGVs	No
Germany	∼70	All vehicles except motorcycles	Yes
Greece	1	All vehicles in inner LEZ, vehicles > 2.2 t outer LEZ.	No
Italy	∼92 *	Various	No
Netherlands	13	HGVs	Yes
Portugal	1	Cars and HGVs	No
Sweden	8	All vehicles > 3.5 t	Yes
UK	3	HDVs and in London	No
EU	∼200	-	No

* The Lombardi Regional LEZ has been counted as one. The table only includes those in existence in 2014. LEZs are planned for Belgium and Czech Republic.

Table 2. Low emission zone policy comparison between London, Milan, Paris, and Rome (source: adopted from [22]).

	London	Milan	Paris	Rome
Area	most of London	71% of Milan	All Paris	Total area is about 5 km^2
Type	LEZ (and CC)	LEZ (and CC)	LEZ	LEZ (and CC)
Rules	Pay to enter Or meet standard	CC and parking charge + access restriction	Pay to enter (vignettes for all)	CC and parking charge + access restriction
Banned Vehicles	Euro 6 diesel and Euro 4 petrol	- Euro 4 diesel - No access for freight vehicles (8–10 a.m.) And bulky vehicles (Monday-Friday, 7:30 a.m. to 7:39 p.m.)	Diesel except Euro 5 and 6 (will be banned in 2020)	Each zone has its own rules

Despite these differences in the policy design, LEZs have demonstrated beneficial effects on air quality in several European countries. For instance, Ellison et al. [8] observed that London's LEZ reduced PM concentration by 2.46% to 3.07% and notably reduced the registration share of pre-Euro III rigid and light commercial vehicles by 20% and 10%, respectively. Zhai and Wolff [9] noted that PM_{10} was reduced by 14.8% in the short term and 5.5% in the long term due to London's LEZ. In Munich, Germany, Qadir et al. [10] found the LEZ reduced traffic-related pollutants by 60%. Wolff [11] reported a 9% reduction in PM emissions in Germany, while Da Silva et al. [12] discovered that Lisbon's LEZ lowered PM and nitrogen dioxide (NO_2) concentrations by 16% and 6%, respectively.

Since 2015, the Republic of Korea has largely aligned with European emission standards, prohibiting the sale of passenger diesel vehicles exceeding 0.08 g/km for NOx and 0.0045 g/km for PM, as well as heavy-duty diesel vehicles exceeding 0.46 g/kWh for NOx and 0.01 g/kWh for PM, following the Euro 6 standard. Nevertheless, many diesel vehicles in Seoul were manufactured before 2015, contributing significantly to emissions and air pollution. To address this, Seoul introduced an LEZ in January 2017 focusing on "old diesel" vehicles. Vehicles classified as "old diesel" include those of the 5th emission grade (over 0.560 g/km for NOx and HC or over 0.050 g/km for PM) or higher, manufactured before 2006, without a DPF, or failing vehicle inspection (There are various types of diesel vehicles in Korea (depending on the vehicle's engine capacity), but they are typically categorized into two types: light duty diesel (for passenger) and heavy-duty diesel (for commercial)). Violators are charged a penalty of approximately $200. Seoul city also offers incentives, including subsidies up to $3000 for vehicle replacement or DPF installation, covering up to 90% of the cost.

Figure 1 illustrates the expansion of LEZ enforcement cameras in Seoul. Prior to 2017, only 12 cameras were installed. Post-2017, the number escalated to 34 in 2017, 43 in 2018, 67 in 2019, and 100 in 2020. This increase indicates a strengthening of the LEZ policy relative to other traffic regulations implemented in Seoul before 2017.

However, this study acknowledges that Seoul's LEZ policy may have had a negligible or slightly positive impact on air quality. This is attributed to the significant influence of air pollutants from China on Korea's air quality, especially during the winter and spring. Detailed analysis of weather seasonality is provided in Section 3.

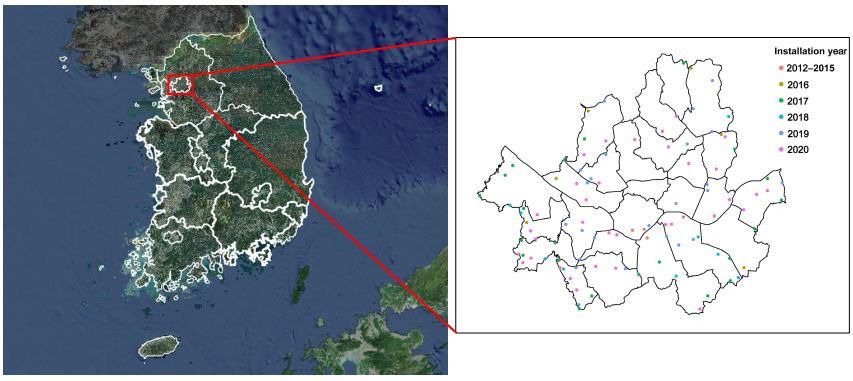


Figure 1. The locations of enforcement cameras in Seoul. Each circle represents a LEZ enforcement camera, with colors corresponding to the year of installation as indicated in the legend. The national map on the left is sourced from the Seoul Metropolitan Government.

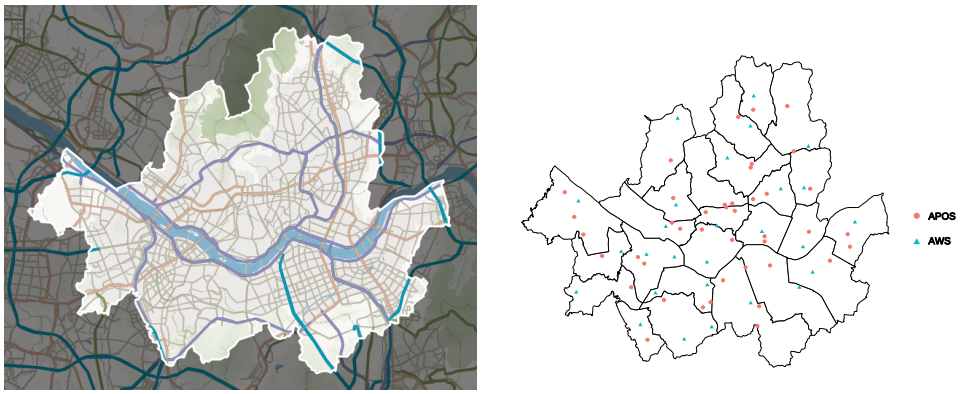
3. Data

The weather data used in this study were sourced from the Korean Meteorological Administration (https://data.kma.go.kr (accessed on 17 February 2021)). They encompass temperature, precipitation, and wind pattern (wind speed, wind direction) collected from the 510 Automatic Weather Stations (AWSs) in the country.

The air pollution data were obtained from the Korea Environment Corporation (https://airkorea.or.kr (accessed on 5 February 2021)). They cover 162 prefectures and

comprise data from approximately 600 Air Pollution Observation Stations (APOSs). The pollutants measured include SO_2 (ppm), NO_2 (ppm), O_3 (ppm), CO (ppm), PM_{10} ($\mu g/m^3$) and $PM_{2.5}$ ($\mu g/m^3$). However, due to the instability of $PM_{2.5}$ observations, this study primarily focuses on PM_{10} to gauge the level of particulate matter (It is worth noting that although the Korean government began observing $PM_{2.5}$ since 2015, numerous observations were omitted due to equipment errors over the observation period).

The dataset consists of weather observations from 27 AWSs and air pollution observations from 40 APOSs in Seoul (see Figure 2). These data were collected over a two-year period between 2015 and 2018, encompassing the time before and after the implementation of the LEZ policy on 1 January 2017.



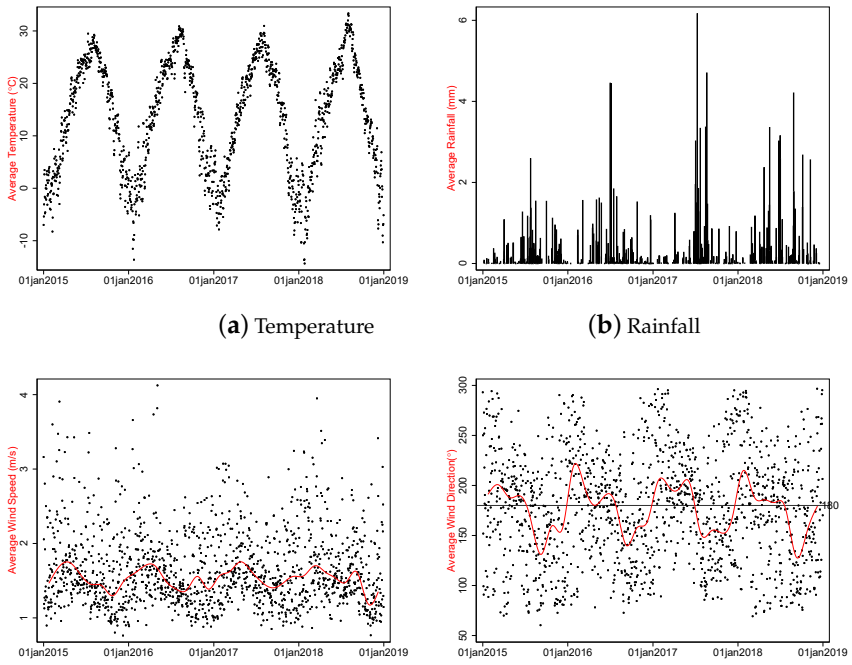
(**a**) (**b**)

Figure 2. The map of (**a**) Seoul and (**b**) the locations of AWSs and APOSs. (**a**) is sourced from the Seoul Metropolitan Government.

Some additional steps are necessary to compose the daily frequency panel structure. Due to differences in the number and locations of observation stations between the weather and air pollution datasets, it is not possible to directly measure accurate weather observations at specific Air Pollution Observation Stations (APOSs). We employ the Inverse Distance Weighting (IDW) interpolation method to mitigate this issue. IDW is chosen because it is intuitive, efficient [23], and commonly used in spatial analysis, despite potential errors in mountainous areas (Note that, due to the limited number of Automatic Weather Stations (AWSs) at high-elevation areas (three AWSs), data from these stations are excluded before interpolation). We interpolate the weather observations using an hourly frequency dataset, taking measurements from the three nearest AWSs at each APOS. Subsequently, we aggregate the data into a daily frequency to reduce noise and calculate an average for each day across the entire Seoul area.

Table 3 provides the summary statistics. As explained in Section 2, the weather conditions in Korea vary significantly depending on the season. Temperature and precipitation exhibit large variations, with high temperatures and significant rainfall in the summer, and low temperatures and little rainfall in the winter. The dominant wind direction is northwestern in the winter and northeastern in other seasons. Figure 3 illustrates the seasonality of weather variables. The mean wind speed is weaker in the winter and spring, typically below 2 m/s. Wind direction is reported in cardinal directions, with 0 or 360 degrees indicating north wind, and 180 degrees representing south wind.

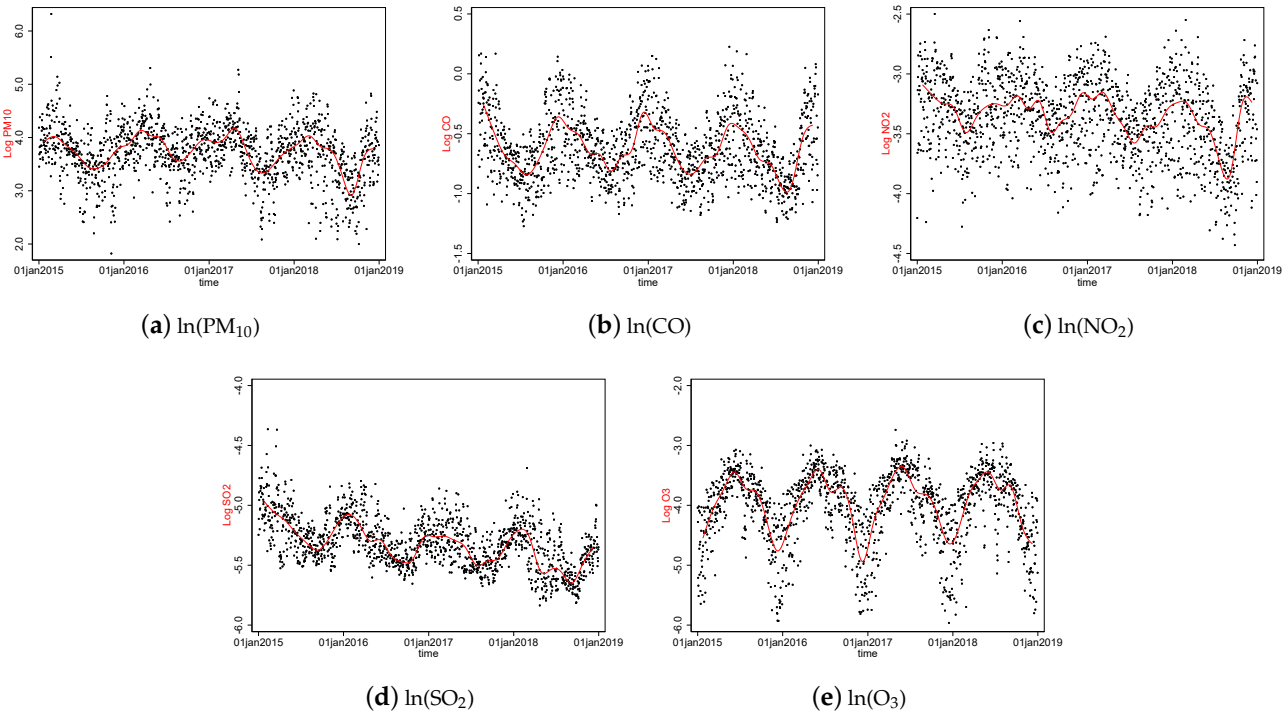
Seasonality significantly influences the variation in the air pollutant levels. Typically, air pollutant concentrations are higher in the winter and spring seasons, except for ozone (see Figure 4) (Ozone is affected by high temperature and strong sunlight, resulting in an opposite pattern).



(**a**) Temperature (**b**) Rainfall

(**c**) Wind Speed (**d**) Wind Direction

Figure 3. The pattern of weather conditions over time. The red lines in (**c**,**d**) represent a cubic spline fitted to the data using cross medians as knots, showing the trends. In (**d**), the black horizontal line at 180° indicates the southward wind direction, with a label marking this reference point.



(**a**) ln(PM_{10}) (**b**) ln(CO) (**c**) ln(NO_2)

(**d**) ln(SO_2) (**e**) ln(O_3)

Figure 4. The seasonal pattern (spline) of the air pollutants. The red line in each panel represents a cubic spline fitted to the data using cross medians as knots, showing the trends.

Table 3. Summary of statistics before and after LEZ implementation.

Variables	Obs.	Mean	SD	Min	Max
Before LEZ (1 January 2015∼31 December 2016)					
Weather Variables					
Temperature (°C)	731	13.86	10.24	−13.62	30.89
Wind Direction (°)	731	173.59	53.52	60.33	294.25
Wind Speed (m/s)	731	1.65	0.52	0.76	4.12
Rainfall (mm)	731	0.10	0.36	0.00	4.46
Air Pollution Variables					
PM_{10} (μg/m^3)	731	48.98	30.29	6.19	555.69
$PM_{2.5}$ (μg/m^3)	731	24.63	11.58	3.44	70.63
CO (ppm)	731	0.57	0.17	0.28	1.18
NO_2 (ppm)	731	0.04	0.01	0.01	0.08
SO_2 (ppm)	731	0.01	0.00	0.00	0.01
O_3 (ppm)	731	0.02	0.01	0.00	0.05
After LEZ (1 January 2017∼31 December 2018)					
Weather Variables					
Temperature (°C)	730	13.13	10.92	−14.34	33.35
Wind Direction (°)	730	179.90	53.72	69.27	296.68
Wind Speed (m/s)	730	1.66	0.51	0.77	3.95
Rainfall (mm)	730	0.14	0.52	0.00	6.17
Air Pollution Variables					
PM_{10} (μg/m^3)	730	44.52	23.77	7.38	194.80
$PM_{2.5}$ (μg/m^3)	730	24.16	14.81	3.31	99.43
CO (ppm)	730	0.54	0.17	0.29	1.25
NO_2 (ppm)	730	0.03	0.01	0.01	0.08
SO_2 (ppm)	730	0.01	0.00	0.00	0.01
O_3 (ppm)	730	0.02	0.01	0.00	0.06

Source: Korean Meteorological Administration and Korea Environment Corporation (location: 42 Hwangyeong-ro, Seo-gu, Incheon, Republic of Korea).

In addition, when comparing air pollutant levels before and after the implementation of the LEZ policy, a slight decrease in concentrations of PM_{10}, $PM_{2.5}$, CO and NO_2 is observed (see Table 3). However, this initial observation does not conclusively attribute the reduction to the LEZ policy alone, as weather factors and traffic patterns could also have contributed to the changes. Therefore, we apply the RDiT approach to rigorously assess the causal impact of the LEZ policy on air quality, focusing on the precise time of policy implementation to better identify its effects.

4. Econometric Strategy

This study employs regression discontinuity in time (RDiT) as an empirical analysis tool, instead of the commonly used Difference-in-Difference (DD) approach, to measure the effectiveness of an air quality policy. In a related context, Davis [13] used RDiT to estimate the impact of Mexico City's *Hoy No Cirrcula*, a Weekly Car Free Day system, on air quality. Davis [13] cited two reasons for choosing the RDiT: (i) its capability to address endogeneity from unobserved factors through Ordinary Least Squares (OLS); and (ii) the applicability of RDiT in scenarios without a reasonable counterfactual. For instance, comparing Mexico City to any other city could potentially address time-varying omitted variables. However, due to Mexico City's unique attributes, such as its geography, transportation system, and high population, finding a credible counterfactual is challenging. Similarly, in the context of Seoul, Korea, the absence of valid comparison groups due to its distinct characteristics makes RDiT a reasonable choice for this study.

In traditional RD analysis, the treatment is considered as good as random within a narrow bandwidth [16]. This method compares group observations adjacent to a threshold, assuming they exhibit similar characteristics within the narrow bandwidth. In the case of RDiT, where time serves as the running variable, additional complexities arise. This

is because unobservable variables correlated with time can have discontinuous impacts on the outcome. Consequently, RDiT often requires the inclusion of a comprehensive set of control variables to address these discontinuities [16]. Therefore, this paper employs the "Augmented Local Linear Approach" introduced by Hausman and Rapson [16], which enables the control of variable factors such as seasonality and economic conditions within a narrow bandwidth around the intervention [15]. The approach involves a two-step procedure. The first step involves regressing the natural logarithm of dependent variables on the control variables to obtain residuals ($\overset{resd}{Y}$). This approach allows a specific equation to be used for this step, given as follows:

$$ln(p_t) = \alpha_0 + X_t + \omega_d + \epsilon_t, \tag{1}$$

where $ln(p_t)$ represents the natural logarithm of the average pollution concentration at time t, while X_t and ω_d refer to control variables and fixed effects, respectively (According to Auffhammer and Kellogg [24], whom we follow for selecting control variables and fixed effects, X_t includes cubic polynomials of the maximum/minimum of temperatures, wind speed, and mean rainfall. These are complemented by lagged variables and various interaction terms, such as interactions between the maximum and minimum temperature, the mean rainfall, and the maximum wind speed (including its lagged term). Interactions between the maximum and the minimum wind speeds are also included. To capture weather effects, interactions of these variables with season dummies are incorporated. Additionally, a dummy variable is introduced to reflect the closure of two thermal power plants in Seoul in March 2017. The wind direction variable is transformed into a dummy variable, where northwestern wind is coded as 1, and all others as 0. In addition, ω_d includes a series of dummy variables for holidays, weekends, days of the week, weeks of the month, and months of the year).

The second step is to apply RD to derive the estimators ($\hat{\beta}_{RD}$), following the method outlined by [15]. This step is essential for quantifying the estimated effects of the variables under study. The specific equation used for this step is as follows:

$$\begin{aligned} \hat{\beta}_{RD} &= \lim_{d \to d_0^+} E[\overset{resd}{Y} \mid D = d] - \lim_{d \to d_0^-} E[\overset{resd}{Y} \mid D = d] \\ &= \hat{\beta}_+ - \hat{\beta}_-, \end{aligned} \tag{2}$$

where D indicates dates (time) and d_0 the threshold, i.e., the initiation date of the LEZ. The estimate $\hat{\beta}_{RD}$ is calculated by the following minimization problem as mentioned in several studies [15,25–27]:

$$\hat{\beta}, \hat{\theta}, \hat{\gamma} = \min_{\beta, \theta, \gamma} \sum_{d=1}^{n} [\overset{resd}{y_d} - \beta - \theta(d - d_c) - \gamma Z_d]^2 K(\frac{d - d_c}{h}) \tag{3}$$

where $K(\cdot)$ denotes the kernel function (specified as a uniform kernel in our study) and h represents the bandwidth.

As noted by Hausman and Rapson [16], it is essential to demonstrate the serial correlation of dependent variables because air pollutants require time to dissipate. Hausman and Rapson [16] also emphasized the significance of including lagged variables in the second step to reduce bias, acknowledging that air pollutants exhibit delayed responses to various factors. Given that each coefficient for first-order autoregressive (AR(1)) air pollutants is both positive and statistically significant, we incorporate Z_d (i.e. a lagged variable) in the second step (see Table 4).

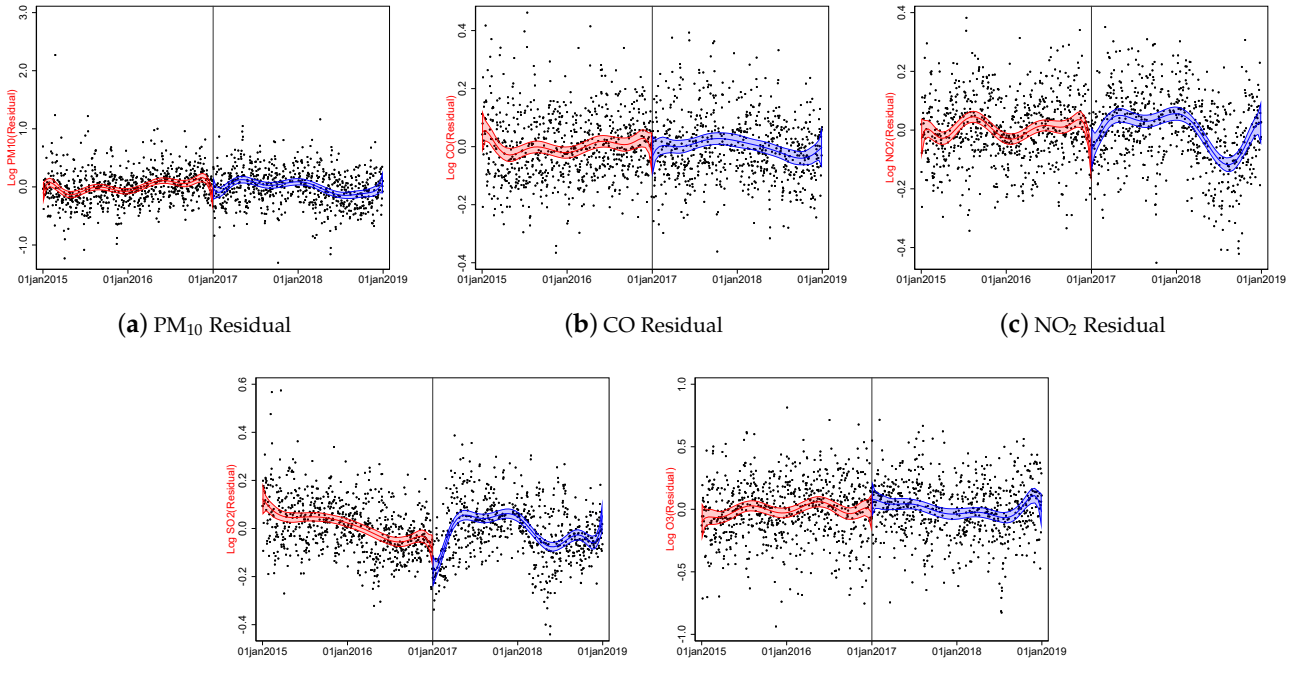
Table 4. AR(1) parameters.

Log Lagged Pollutants	Dependent Variable: Log Pollutants		
	Baseline Estimates	Placebo	
		1 Year Before	1 Year After
PM_{10}	0.437 ***	0.407 ***	0.513 ***
	(0.036)	(0.035)	(0.047)
CO	0.380 ***	0.305 ***	0.393 ***
	(0.039)	(0.035)	(0.020)
NO_2	0.321***	0.237 ***	0.328 ***
	(0.043)	(0.024)	(0.031)
SO_2	0.436 ***	0.344 ***	0.555 ***
	(0.044)	(0.022)	(0.027)
O_3	0.279 ***	0.286 ***	0.322 ***
	(0.033)	(.047)	(0.062)

Note: *** indicates 1% significant level. The week cluster standard error is in parentheses.

5. Results

Figure 5 displays an eighth-degree global polynomial trend for each pollutant, marked by a vertical line at the policy's initiation date. Hausman and Rapson [16] cautions against expanding the time window in such analysis. This is because including data further from the policy initiation threshold can increase the likelihood of bias, as these data might fundamentally differ from those closer to the threshold. Such expansion also complicates the precise specification of time-varying treatment effects, given the evolving nature of external factors over time. Additionally, Hausman and Rapson [16] warn of the risk of overfitting when using a global polynomial approach, especially in the presence of potential confounders, which can distort the true relationship. To mitigate these concerns, our study adopts a local polynomial approach.



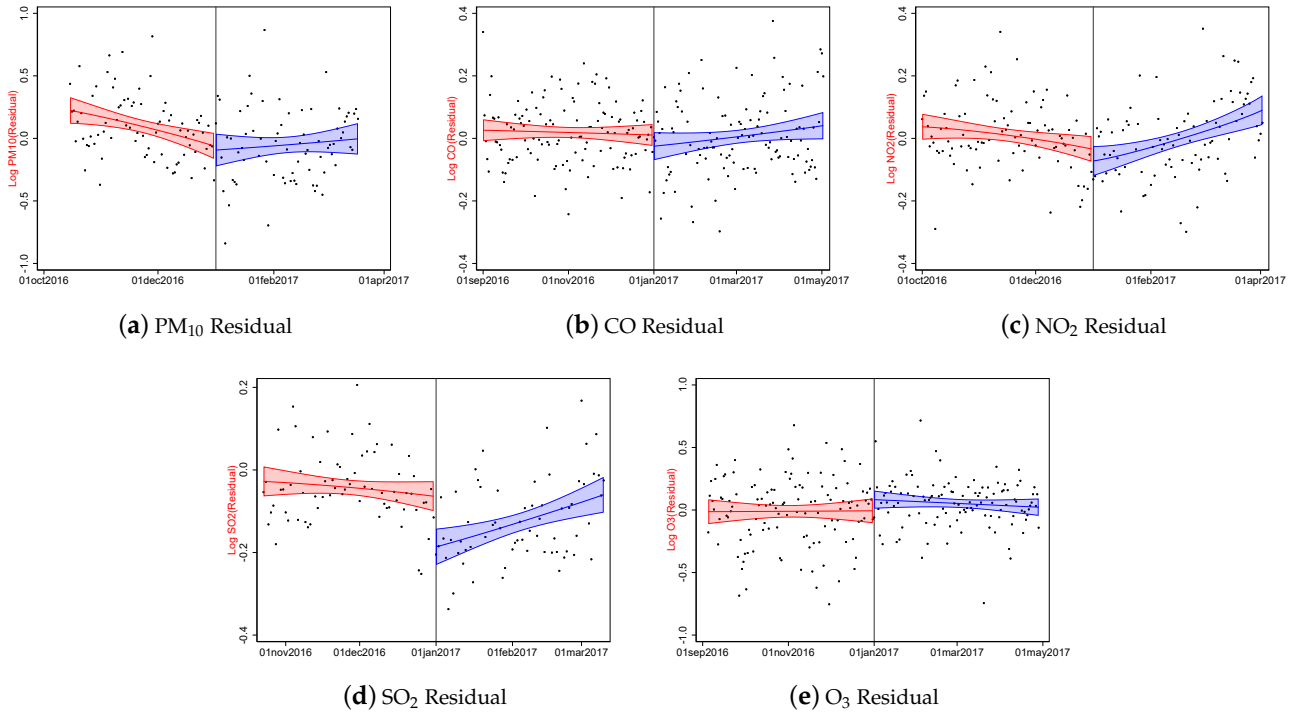
(**a**) PM_{10} Residual (**b**) CO Residual (**c**) NO_2 Residual

(**d**) SO_2 Residual (**e**) O_3 Residual

Figure 5. The global polynomial trend of the air pollutants. The red and blue lines represent the eighth-degree local polynomial trend before and after the intervention, respectively, with shaded areas indicating 95% confidence intervals. The black dots represent the residual values, and the vertical line (black) indicates the intervention date.

Selecting the optimal bandwidth is a critical aspect of employing a local polynomial trend in our analysis. Following the approach recommended by Calonico et al. [27] and Gelman and Imbens [28], we use a low-order polynomial time trend in our model. These sources suggest that lower-order polynomials are preferable because higher-order polynomials can lead to noisy estimates and poor confidence interval coverage. This issue arises because high-order polynomials may overfit the data, capturing random fluctuations rather than reflecting the actual underlying trend. Therefore, we have chosen to apply a first-order polynomial time trend in our model. This simpler approach not only avoids the pitfalls of overfitting but also ensures that our model remains interpretable and robust, making it more suitable for accurately capturing the core dynamics of our study's focus.

Figure 6 demonstrates a visible effect of LEZ on air quality with the first-order local polynomial trend. As discussed in Section 2, the primary target pollutants of the LEZ policy are PM and NO_2, which are predominantly generated by diesel vehicles. Accordingly, this study anticipated a decrease in PM_{10} and NO_2 concentrations. However, the results show some deviations from these expectations (see Table 5). The LEZ policy only reduces NO_2 and SO_2 by 4.7% and 11.6% at 10% and 1% significance levels, respectively (see column 1 in Table 5) (Even though the primary pollutants from diesel vehicles are PM_{10} and NO_2, diesel vehicles also emit SO_2 as mentioned in Section 2) (Since we take the natural logarithm of the dependent variables, $e^{\beta} - 1$ should be used to interpret the estimators). To further validate these findings, we conduct robustness checks to ensure the reliability of our results.



(**a**) PM_{10} Residual (**b**) CO Residual (**c**) NO_2 Residual

(**d**) SO_2 Residual (**e**) O_3 Residual

Figure 6. The local polynomial trend of the air pollutants with optimal bandwidth. The red and blue lines represent the first-order local polynomial trend before and after the intervention, respectively, with shaded areas indicating 95% confidence intervals. The black dots represent the residual values, and the vertical line (black) indicates the intervention date.

Table 5. RD results.

Dependent Variables (Residual)	Baseline Estimates		Placebo Test		Donut RD Dropping		
	RD Estimator	Optimal Bandwidth	1Y Before	1Y After	1 Day	7 Days	14 Days
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
PM_{10}	−0.035	77	0.119	−0.101	−0.059	−0.041	0.026
	(0.092)		(0.097)	(0.070)	(0.096)	(0.139)	(0.135)
CO	−0.037	122	−0.044	0.003	−0.038	−0.044	−0.034
	(0.028)		(0.027)	(0.020)	(0.028)	(0.035)	(0.039)
NO_2	−0.049 *	92	0.027	0.008	−0.051 *	−0.093 ***	−0.124 ***
	(0.027)		(0.028)	(0.037)	(0.028)	(0.019)	(0.017)
SO_2	−0.124 ***	69	−0.005	−0.036	−0.125 ***	−0.153 ***	−0.163 ***
	(0.025)		(0.020)	(0.038)	(0.024)	(0.039)	(0.060)
O_3	0.071	118	0.032	−0.055	0.065	0.082	0.063
	(0.071)		(0.074)	(0.067)	(0.075)	(0.088)	(0.079)

Note: *, *** indicate 10%, 1% significant level, respectively. The week cluster standard error is in parentheses.

5.1. Placebo Test

To ensure that the observed effects are specifically attributable to the LEZ policy, and not influenced by other critical policy changes during the same period, we conduct a placebo test. We consider one year before and after the actual policy dates as fake treatments. This approach helps in determining whether similar effects could be observed due to factors other than the LEZ policy. If the baseline RD result does not pass the placebo test, it would be challenging to conclude that the pollutants are directly affected by the policy. For both placebo tests, all coefficients are statistically insignificant, indicating the absence of other policy changes during the entire period (see columns 3 and 4 in Table 5).

5.2. Donut RD Specification

According to Barreca et al. [29], RD estimates need to demonstrate stability at the threshold. To assess the stability of the RD estimates, out study employs the 'Donut RD' approach, which entails re-estimating the results while systematically omitting data points at one-day, seven-day, and fourteen-day intervals around the threshold. This approach helps to check for any short-term selection, anticipation, or avoidance effects that might bias the results as noted by Hausman and Rapson [16]. In our analysis, the coefficients for NO_2 and SO_2 in the Donut RD specification consistently remain negative and statistically significant. This consistency indicates that the baseline RD estimates are not influenced by short-term fluctuations around the threshold (see columns 5, 6, and 7 in Table 5).

5.3. Policy Overlapping

In our analysis, we consider the possibility that overlapping policies with objectives similar to the LEZ could potentially distort our results. Overlapping policies might introduce confounding variables, making it challenging to isolate the effects of the LEZ policy. To mitigate this concern, we perform a simple review of the timeline of air quality control policies and other traffic regulations (see Tables A2 and A3). This review reveals that most of the traffic regulation policies in Seoul were implemented after 2019. Importantly, during our analysis period, we find no evidence of any other policy that directly influenced air quality like the LEZ. This finding strengthens our confidence that the observed changes in air quality can be attributed specifically to the LEZ policy, without significant interference from other concurrent policy initiatives.

5.4. Time Heterogeneity

In our study, we opt for daily data analysis to capture the longer-term trends in air pollution despite the inherent hourly volatility of air pollutants. To understand the LEZ policy's impact throughout the day, we differentiate between daytime and nighttime

intervals, as well as morning and evening rush hours, given the expected variation in traffic patterns. We find that the LEZ policy reduces PM_{10} concentration by 13.6% during the daytime, which is in contrast to the baseline result. For NO_2 and SO_2, reductions of 7.1% and 14.8% are observed, respectively, exceeding the baseline effect. However, during the nighttime, only SO_2 remains statistically significant, with a smaller effect of 8.7%. During rush hours, a different pattern emerges. While PM_{10} and NO_2 decrease by 0.8%, 10.5%, respectively, NO_2 and SO_2 experience more substantial reductions of 8.5% and 19.3%, respectively (see Table 6). This time-specific heterogeneity in the policy's effectiveness underscores the importance of considering traffic volumes in the design and evaluation of urban air quality policies.

Table 6. RD results by time of day.

Dependent Variables (Residual)	Daytime (9 a.m.∼6 p.m.)	Nighttime (8 p.m.∼7 a.m.)	Rush Hour (Morning) (7 a.m.∼9 a.m.)	Rush Hour (Evening) (6 p.m.∼8 p.m.)
PM_{10}	−0.146 **	0.058	−0.009 *	−0.129
	(0.071)	(0.114)	(0.123)	(0.119)
CO	−0.047	−0.035	−0.082	−0.017
	(0.057)	(0.037)	(0.053)	(0.077)
NO_2	−0.074 ***	−0.008	−0.111 ***	−0.089 **
	(0.028)	(0.033)	(0.030)	(0.039)
SO_2	−0.161 ***	−0.091 ***	−0.035	−0.215 ***
	(0.037)	(0.013)	(0.037)	(0.045)
O_3	0.057	0.016	0.155	0.013
	(0.097)	(0.094)	(0.115)	(0.066)

Note: *, **, *** indicate 10%, 5%, 1% significant level, respectively. The week cluster standard error is in parentheses.

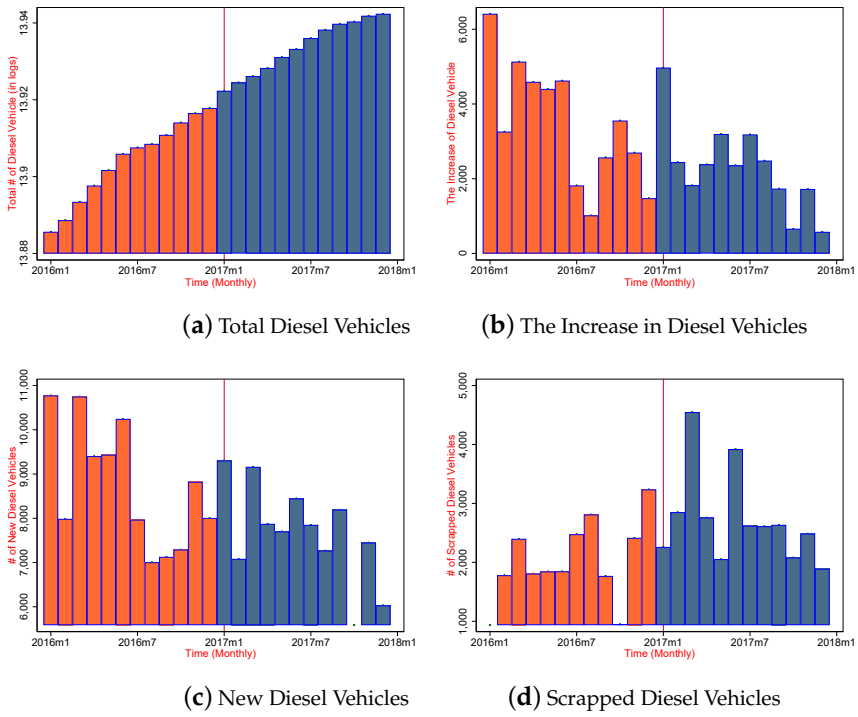
5.5. Indirect Evidence Supporting the Result

Since the introduction of ultra-low sulfur diesel in 2005, Korea has achieved an average SO_2 level of nearly zero, with our dataset indicating an average concentration of 0.005 ppm (see Table 3). Although this value is well below the national SO_2 concentration standard at 0.05 ppm (see Table A1), the observed 11.6% reduction in SO_2 levels in the baseline result might seem relatively small. Nevertheless, it is worth noting that SO_2 levels may continue to decrease due to the ongoing reduction of pollutants from diesel vehicles, considering that there are already no coal power plants or heavy industrial areas around Seoul city. In contrast, the NO_2 concentrations in Seoul are influenced by a variety of factors including the number of diesel vehicles, the installation of DPFs, and traffic flow patterns. Identifying which factor is primarily affected by the LEZ policy is a complex task due to these diverse influencing factors. Our paper addresses this challenge by analyzing the changes in these various factors following the LEZ policy implementation, employing methodologies such as statistical analysis and comparative studies to understand the LEZ's impacts on NO_2 concentrations.

5.5.1. The Number of Diesel Vehicles

Decisions to purchase or replace a vehicle usually involve some lead time. Hence, changes in diesel vehicle registration or consumption patterns immediately after the LEZ policy implementation may not be visible. Nevertheless, this study can offer valuable insights from statistics related to diesel vehicles. In Figure 7, panels (a) through (c) depict the total number of diesel vehicles, new diesel vehicles, and scrapped diesel vehicles for one year before and after the policy's implementation, respectively. The total number of diesel vehicles continues to rise over time, with the increase being significantly greater than the month just before the policy (as shown in panels (a) and (b) of Figure 7). The increase is primarily due to the gap between new and scrapped diesel vehicles. While pinpointing exact patterns from these statistics is challenging, there appears to be a decreasing trend in

new diesel vehicles and an increasing trend in scrapped diesel vehicles over time after the implementation of the LEZ policy. As discussed in Section 2, Seoul City provides subsidies to diesel vehicle owners who replace their vehicles with new ones. These subsidies can also be availed by vehicle owners who purchase new or used diesel vehicles as long as they are not old vehicles. Therefore, even though the number of registered diesel vehicles is increasing, air pollutant emissions from diesel vehicles may decrease because newer vehicles tend to produce fewer pollutants, as they have fewer vehicle years. On the other hand, Figure 8 displays the number of diesel vehicles equipped with DPF. While it may be expected that more owners of older diesel vehicles would install DPF, the graph does not show any significant changes following the policy.



(**a**) Total Diesel Vehicles (**b**) The Increase in Diesel Vehicles

(**c**) New Diesel Vehicles (**d**) Scrapped Diesel Vehicles

Figure 7. The number of total, new, and scrapped diesel vehicles in Seoul. The red and blue bars represent the periods before and after the policy intervention, respectively, with the red vertical line indicating the policy start date. The figure is based on the data from Statistics Korea.

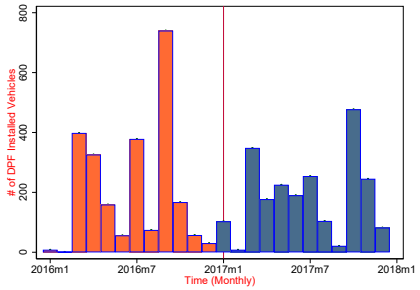


Figure 8. The number of DPF installed diesel vehicles. The red and blue bars represent the periods before and after the policy intervention, respectively, with the red vertical line indicating the policy start date. The figure is based on the data from the Seoul metropolitan government.

5.5.2. The Traffic Changes

The Seoul Metropolitan Government annually publishes traffic analysis reports, which include average hourly traffic data from various traffic measurement cameras. These cameras are categorized into five areas: central (A), border (B), main road (C), bridge (D),

and inter-city highway (F) (see Figure 9). However, since the statistics are only collected from cameras that operate 24/7, they may not fully represent the total traffic in Seoul. Table 7 provides a comparison of traffic changes over a four-year period, with each year's traffic volume compared to the previous year. Notably, there was a significant reduction in traffic in 2017, particularly in central and border areas. This suggests that the LEZ policy may have contributed to a decrease in the number of diesel vehicles on the road in Seoul.

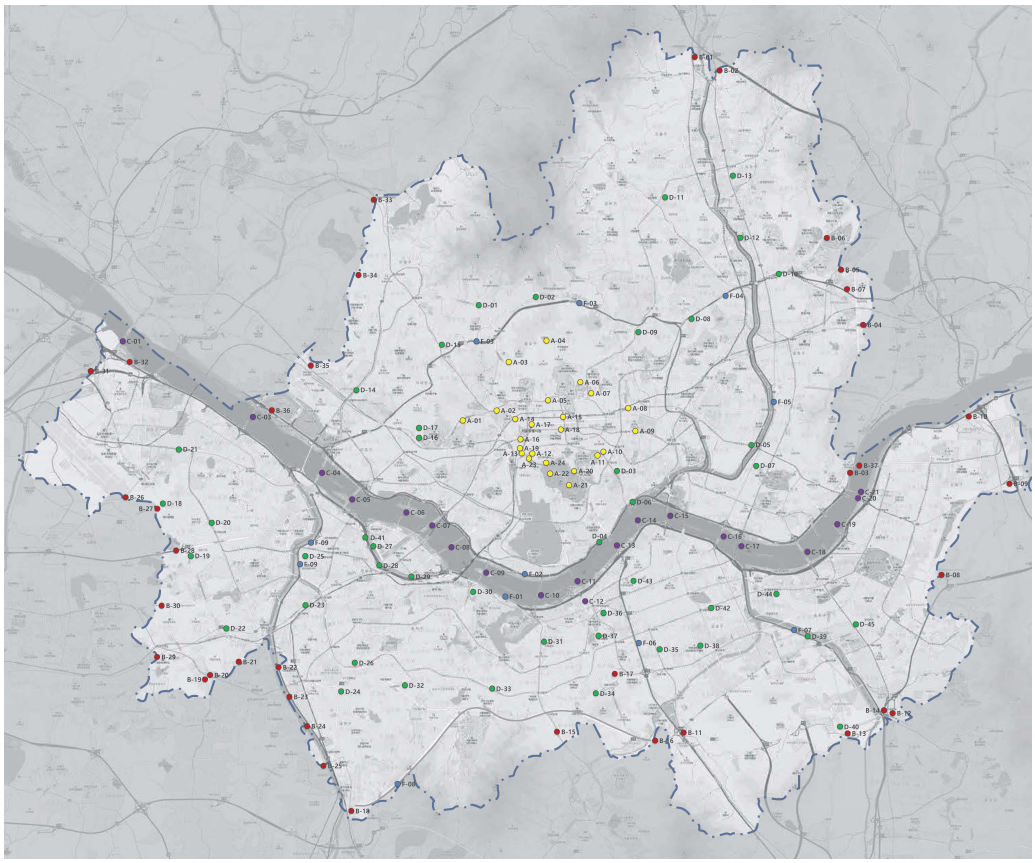


Figure 9. The location of traffic cameras in (A: yellow) central area, (B: red) border, (C: green) main road, (D: purple) bridge, and (F: blue) inter-city highway. Adapted from [30].

Table 7. Traffic variation.

Year	2015	2016	2017	2018
Total	2.6%	−0.5%	−2.6%	−3.0%
Central Area	−0.3%	−2.9%	−7.7%	−4.1%
Border (Boundary)	12.6%	1.0%	−6.2%	0.1%
Main Road	−0.1%	−0.3%	0.2%	−2.6%
Bridge	−1.9%	−1.1%	0.4%	−5.6%
Inter−City Highway	-	−0.1%	−3.1%	−2.3%

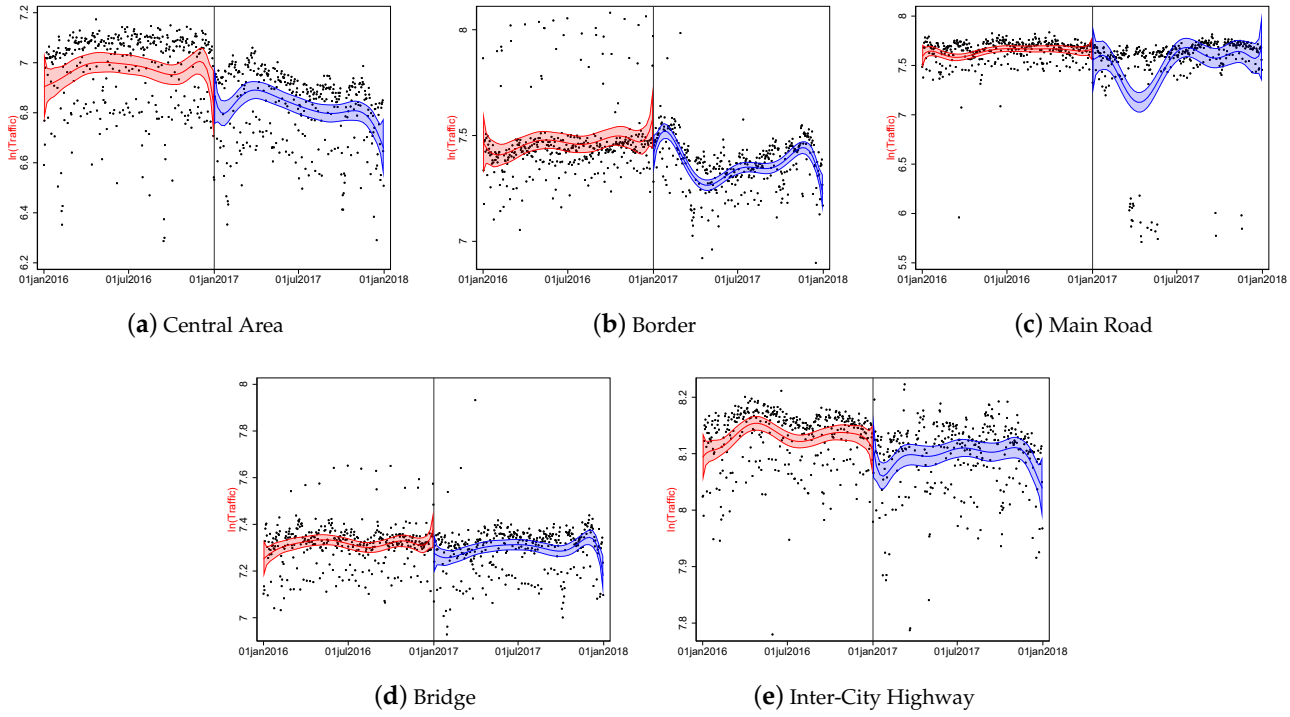
Source: Seoul Metropolitan Government.

To support the traffic reduction in 2017, we employ a simple regression model using the raw traffic data utilized in the traffic analysis reports. The data are available at an hourly frequency from 2016 to 2017 for each traffic measurement camera. For the regression analysis, we aggregate these data to daily average traffic figures across the five areas and use the model as the following equation:

$$ln(traffic_{it}) = \beta_0 + \beta_1 Policy_t + \beta_2 Holiday_t + \lambda_t + \eta_i + \varepsilon_{idt} \quad (4)$$

where $ln(traffic_{it})$ is the natural logarithm of the average traffic in area i at time t. $Policy_t$ is a dummy variable for the intervention, and the model includes a holiday dummy, $Holyday_t$, as well as other time-specific dummies (month, week of the month, and day of the week), denoted as λ_t, to account for time-varying traffic patterns. Additionally, an area fixed effect, η_i, is included to control for time-invariant heterogeneity.

The results indicate that traffic in the central area, the main road, and the inter-city highway experienced reductions of 6.9%, 12.8%, and 7.9%, respectively (see Table 8 and Figure 10). However, the coefficient for total traffic exhibits a negative sign but is statistically insignificant. Therefore, we can conclude that the changes in traffic patterns contribute to the reduction in NO_2 levels observed in the baseline result (As of 4 October 2018, Seoul had a total of 279,709 registered fifth-grade vehicles. Remarkably, these fifth-grade diesel vehicles constituted 96% (268,922) of the total, underscoring their dominance in the city's vehicle fleet. Assuming that these diesel vehicles are not in operation, the reduction in traffic could substantially contribute to the reduction in NO_2 concentration).



(**a**) Central Area (**b**) Border (**c**) Main Road

(**d**) Bridge (**e**) Inter-City Highway

Figure 10. The global polynomial trend of the traffic changes from Each Area. The red and blue lines represent the eighth-degree local polynomial trend before and after the intervention, respectively, with shaded areas indicating 95% confidence intervals. The black dots represent the residual values, and the vertical line (black) indicates the intervention date.

Table 8. Result of the traffic change.

D. Variable ln Traffic (Mean)	Total	Central Area	Border	Main Road	Bridge	Inter-City Highway
	(1)	(2)	(3)	(4)	(5)	(6)
Policy (LEZ)	−0.055	−0.072 ***	−0.041	−0.137 **	0.059 **	−0.083 ***
	(0.033)	(0.005)	(0.032)	(0.039)	(0.015)	(0.004)
Holiday	−0.179 *	−0.413 ***	0.031	−0.187 ***	−0.217 ***	−0.111 ***
	(0.072)	(0.028)	(0.042)	(0.013)	(0.010)	(0.010)

Table 8. *Cont.*

D. Variable ln Traffic (Mean)	Total (1)	Central Area (2)	Border (3)	Main Road (4)	Bridge (5)	Inter-City Highway (6)
Fixed Effect						
Area	o	-	-	-	-	-
Time (Month, Week, Day)	o	o	o	o	o	o
Cluster						
Area	o	-	-	-	-	-
Week	-	o	o	o	o	o
Observation	3614	730	727	727	728	702
R^2	0.864	0.715	0.266	0.223	0.586	0.477

Note: *, **, *** indicate 10%, 5%, 1% significant level, respectively. The week cluster standard error is in parentheses.

5.6. Benefit of Seoul's LEZ Policy

Up to this point, we have not discussed $PM_{2.5}$ due to data limitations. However, many studies have highlighted the formation of secondary $PM_{2.5}$, which results from chemical and physical reactions between pollutants such as SO_2, NOx, VOCs, and NH_3 [31–33].

In a study by Moon et al. [34], the $PM_{2.5}$ contribution rate of emission from each pollutant (NOx, SOx, NH_3, VOCs, $PM_{2.5}$) and each source (factory smokestacks, tailpipes on roads, others) was estimated for 17 local prefectures in Korea. They found that the $PM_{2.5}$ contribution rate of NOx emission from roads was −0.4%. The negative contribution rate implies that reducing NOx emission leads to an increase in $PM_{2.5}$ emission. This phenomenon, known as 'NOx disbenefit', occurs in large cities where the emission of NOx per unit area is high [35]. Under the condition of being 'NOx-rich' in big cities, the reduction of NOx concentration causes chemical reactions, such as generating O_3 [33,34]. Therefore, the secondary $PM_{2.5}$ resulting from the reduction of NO_2 concentration relative to the baseline result should be considered.

Air pollutants directly affect human health. Several studies measure the social cost of air pollution, but there are not many studies conducted in Korea. Among them, Shin [36] analyzed the effect of NO_2 on the number of acute respiratory diseases across the country, and showed that when the average NO_2 concentration increased by 10%, medical costs of about USD 441,666 occurred (For simplicity, we consider that USD 1 is equal to KRW 1200 (Korean won) to convert Korean currency to the US dollar). The Korea Environmental Institute (KEI) evaluated the health impact of PM in Seoul and estimated the cost of damage through the concentration-response function based on the Value of a Statistical Life (VSL) [37]. According to Ahn et al. [37], the cost of damage to respiratory diseases caused by the $PM_{2.5}$ concentration of 25.89 $\mu g/m^3$ was USD 59.44 million, and the cost of damage from death was USD 1015.82 million in 2015.

Benefits

To calculate the health benefit from the reduction of NO_2 concentration, we employ the cost from Shin [36]. Since Shin [36] used the 1998 Korea National Health and Nutrition Examination Survey (KNHANES) and was conducted across the whole nation, we need to adjust the cost to the present value using the Consumer Price Index (CPI) and population in Seoul and total Korea in 1998 (CPI 2020 = 100. The total population of Korea in 1998 was 46,991,171 and the number of people in Seoul in 1998 was 10,321,496). Then, the benefits attributed by the NO_2 reduction can be calculated as follows:

[\$441,666 (Respiratory) × 0.036 (NO_2 Avg.) × 0.047 (Reduction in NO_2) × 1.758 (1998 CPI) × 0.219 (Ratio Seoul pop./total pop. in 1998)]/0.0027 (10% of 0.027(ppm)) = \$106,559.83.

The cost of the secondary $PM_{2.5}$ resulting from the reduction in NO_2 concentration can be calculated similarly:

[$59.44M (Respiratory) × 0.036 (NO_2 Avg.) × 0.047 (Reduction in NO_2) × 0.004 ($PM_{2.5}$ contribution rate) × 1.135 (2015 CPI)]/25.89 $\mu g/m^3$ = $17.63

[$1015.82M (Mortality) × 0.036 (NO_2 Avg.) × 0.047 (Reduction in NO_2) × 0.004 ($PM_{2.5}$ contribution rate) × 1.135 (2015 CPI)]/25.89 $\mu g/m^3$ = $301.39

Therefore, the total health effect of the LEZ policy in Seoul is USD 106,240.81 (see Table 9).

Table 9. Health effect associated with the result of the traffic change.

Health Impact	Social Cost of Air Pollutants in Reference Korea (USD)	Social Cost (USD)	Health Benefit (USD)
Respiratory illness	Shin YC (2002) [36]	1% increase in NO_2 (Avg. 0.027): USD 44,166.6 in 1998	106,559.83
Respiratory illness	KEI (2017) [37]	25.89 $\mu g/m^3$ of $PM_{2.5}$: USD 59.44 million in 2015	17.63
Mortality	KEI (2017) [37]	25.89 $\mu g/m^3$ of $PM_{2.5}$: USD 1015.82 million in 2015	301.39
Benefit (106,559.83) − Cost (17.63 + 301.39)			106,240.81

6. Conclusions

This study evaluates the impact of Seoul's LEZ policy on air quality. Our findings demonstrate a significant reduction in NO_2 concentrations by 4.7% and SO_2 by 11.6% following the policy's implementation. While the baseline results for PM_{10} show no notable change, more pronounced effects are observed during specific periods, such as daytime (13.6% reduction) and the morning rush hour (0.8%). This indicates that the policy's effectiveness is closely tied to traffic patterns. These results suggest that the LEZ policy influences the behavior of diesel vehicle owners, impacting their decisions around vehicle purchasing, scrapping, and usage patterns.

Actually, the LEZ policy in Korea has expanded beyond Seoul, now encompassing the surrounding areas, Incheon and Gyeonggi Province, forming a metropolitan-wide LEZ. This expansion is not limited to the capital region, as the policy is being implemented in other major cities across Korea. Furthermore, since December 2019, Seoul has also introduced an Ultra-Low Emission Zone (ULEZ) in its central areas, which restricts not only old diesel vehicles but all vehicles that exceed emission grade five. By 2025, this restriction will extend to grade four vehicles, further strengthening the policy.

Despite lingering skepticism regarding the policy's effectiveness, our findings provide strong evidence supporting its success in reducing key pollutants like NO_2 and SO_2. Given the clear environmental benefits demonstrated in this study, policymakers should consider not only further strengthening LEZ and ULEZ regulations but also expanding their application to additional areas. Strengthening restrictions on higher-emission vehicles and expanding the zones where these policies apply could lead to even greater reductions in pollution. Additionally, continuing to promote the growing adoption of electric vehicles (EVs) and further leveraging Seoul's already well-developed public transportation infrastructure could accelerate the transition away from diesel vehicles and enhance the overall effectiveness of air quality improvement measures.

The success of the LEZ policy in reducing pollutant levels in Seoul suggests that other cities could benefit from similar measures. However, to maximize the effectiveness of LEZ policies, cities should consider adjusting regulations based on local traffic patterns and pollutant sources. For example, enforcing stricter vehicle emission standards during peak traffic hours, as observed in this study, could yield more significant improvements in air quality. Moreover, addressing potential loopholes, such as the continued use of older, high-emission vehicles outside designated LEZ areas, should be a priority in future policy revisions.

Nevertheless, this study has some limitations. It did not fully account for spatial heterogeneity within Seoul, nor did it capture pollution originating from areas outside the city. Furthermore, the lack of detailed traffic data distinguishing vehicles by fuel type limited our ability to fully explore the mechanisms through which the LEZ policy reduced emissions. Future research should aim to address these gaps by incorporating more granular data and conducting spatial analyses to gain deeper insights into the policy's broader impacts.

Author Contributions: Conceptualization, D.P.; Methodology, D.P.; Validation, N.T.; Formal analysis, D.P.; Writing—original draft, D.P.; Writing—review and editing, D.P. and N.T.; Supervision, N.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

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

Appendix A

Table A1 shows the air quality standards of Korea, the USA, and the EU. The Korean air quality standard is similar to that of the USA, although the vehicle emission standard follows that of the EU. Most average levels of pollutants appear to meet the standard, even though the averaging time for measurement is not identical.

Table A1. Air-quality standard.

Pollutant	Unit	Korea		USA		EU	
		Level	Averaging Period	Level	Averaging Period	Level	Averaging Period
PM_{10}	$\mu g/m^3$	50	1 year	50	1 year	40	1 year
CO	ppm	9	8 h	9	8 h	0.01	8 h
NO_2	ppm	0.03	1 year	0.053	1 year	0.04	1 year
SO_2	ppm	0.05	1 year	0.03	1 year	0.125	24 h
O_3	ppm	0.06	8 h	0.07	8 h	0.12	8 h

Table A2. Timeline of other air-quality-control policies.

Timeline	Policy	Details
Jan 2006	Total amount of Pollutants Control from Stacks	Cap and Trade
Jan 2006	Low NOx burner Installation	Industrial sector
Jan 2017	Changing relative price of fuel by type	Increasing price of diesel
Jun 2017	Regulation of Coal Power Plant	No operation during winter and spring seasons
Jan 2020	Intensive Standard of Air Pollutant from Stacks (30% increase)	

Table A3. Timeline of traffic regulation policies.

Timeline	Policy	Applied Regions
Before 2017	Low Emission Zone	All (not strict)
Jan 2017		Seoul
Jan 2019		Incheon, 17 cities of Gyung-gi province
Jan 2020		11 cities of Gyung-gi province
Feb 2019	Emergency Reduction Operation	Seoul
Feb 2019		Gyung-gi province
Apr 2019		Incheon
Feb 2020	Seasonal Air Quality Control	All
Dec 2019	Green Transportation Zone	15 towns in Seoul

References

1. Shin, D.H. Economic Growth and Environmental Problems in South Korea: The Role of the Government 1. In *Asia's Environmental Crisis*; Routledge: London, UK 2019; pp. 235–256. [CrossRef]
2. Ali, R. Effect of Diesel Emissions on Human Health: A. *Int. J. Appl. Eng. Res.* **2011**, *6*, 1333–1342. Available online: https://www.researchgate.net/profile/Rashid-Ali-59/publication/236897080_Effect_of_Diesel_Emissions_on_Human_Health_A_Review/links/0046351a104cf9dd7b000000/Effect-of-Diesel-Emissions-on-Human-Health-A-Review.pdf (accessed on 17 September 2024).
3. Kim, Y.P.; Lee, G. Trend of air quality in Seoul: Policy and science. *Aerosol Air Qual. Res.* **2018**, *18*, 2141–2156. [CrossRef]
4. Kim, D.; Kim, J.; Jeong, J.; Choi, M. Estimation of health benefits from air quality improvement using the MODIS AOD dataset in Seoul, Korea. *Environ. Res.* **2019**, *173*, 452–461. [CrossRef] [PubMed]
5. Ho, C.H.; Heo, J.W.; Chang, M.; Choi, W.; Kim, J.; Kim, S.W.; Oh, H.R. Regulatory measures significantly reduced air-pollutant concentrations in Seoul, Korea. *Atmos. Pollut. Res.* **2021**, *12*, 101098. [CrossRef]
6. Oh, H.R.; Ho, C.H.; Koo, Y.S.; Baek, K.G.; Yun, H.Y.; Hur, S.K.; Choi, D.R.; Jhun, J.G.; Shim, J.S. Impact of Chinese air pollutants on a record-breaking PMs episode in the Republic of Korea for 11–15 January 2019. *Atmos. Environ.* **2020**, *223*, 117262. [CrossRef]
7. Kim, Y.G.; Lim, H.; Lee, J. Decarbonizing road transport in Korea: Role of electric vehicle transition policies. *Transp. Res. Part Transp. Environ.* **2024**, *128*, 104084. [CrossRef]
8. Ellison, R.B.; Greaves, S.P.; Hensher, D.A. Five years of London's low emission zone: Effects on vehicle fleet composition and air quality. *Transp. Res. Part D Transp. Environ.* **2013**, *23*, 25–33. [CrossRef]
9. Zhai, M.; Wolff, H. Air pollution and urban road transport: Evidence from the world's largest low-emission zone in London. *Environ. Econ. Policy Stud.* **2021**, *23*, 721–748. [CrossRef]
10. Qadir, R.; Abbaszade, G.; Schnelle-Kreis, J.; Chow, J.; Zimmermann, R. Concentrations and source contributions of particulate organic matter before and after implementation of a low emission zone in Munich, Germany. *Environ. Pollut.* **2013**, *175*, 158–167. [CrossRef]
11. Wolff, H. Keep your clunker in the suburb: Low-emission zones and adoption of green vehicles. *Econ. J.* **2014**, *124*, F481–F512. [CrossRef]
12. Da Silva, F.N.; Custódio, R.A.L.; Martins, H. Low Emission Zone: Lisbon's Experience. *J. Traffic Logist. Eng.* **2014**, *2*. Available online: https://www.researchgate.net/profile/Renata-Lajas/publication/265583813_Low_Emission_Zone_Lisbon's_Experience/links/5412d62f0cf2788c4b3582de/Low-Emission-Zone-Lisbons-Experience.pdf (accessed on 18 May 2023). [CrossRef]
13. Davis, L.W. The effect of driving restrictions on air quality in Mexico City. *J. Political Econ.* **2008**, *116*, 38–81. [CrossRef]
14. Percoco, M. Environmental effects of the London Congestion Charge: A regression discontinuity approach. In *Working Paper*; 2015. Available online: https://transp-or.epfl.ch/heart/2015/abstracts/hEART_2015_submission_114.pdf (accessed on 18 May 2023).
15. Li, P.; Lu, Y.; Wang, J. The effects of fuel standards on air pollution: Evidence from China. *J. Dev. Econ.* **2020**, *146*, 102488. [CrossRef]
16. Hausman, C.; Rapson, D.S. Regression discontinuity in time: Considerations for empirical applications. *Annu. Rev. Resour. Econ.* **2018**, *10*, 533–552. [CrossRef]
17. Tan, P.Q.; Zhao, J.Y.; Hu, Z.Y.; Lou, D.M.; Du, A.M.; Du, D.M. Effects of fuel properties on exhaust emissions from diesel engines. *J. Fuel Chem. Technol.* **2013**, *41*, 347–355. [CrossRef]
18. Yang, H.H.; Dhital, N.B.; Wang, L.C.; Hsieh, Y.S.; Lee, K.T.; Hsu, Y.T.; Huang, S.C. Chemical characterization of fine particulate matter in gasoline and diesel vehicle exhaust. *Aerosol Air Qual. Res.* **2019**, *19*, 1349–1449. [CrossRef]
19. IARC. Diesel and Gasoline Engine Exhausts and Some Nitroarenes. *IARC Monogr. Eval. Carcinog. Risks Humans* **2014**, *105*, 9. Available online: https://www.ncbi.nlm.nih.gov/books/NBK294269/ (accessed on 18 May 2023).
20. Tasneem, A. Particulate Matter Pollution and Its Impact on Human Health. Ph.D. Thesis, Brac University, Dhaka, Bangladesh 2020. Available online: http://hdl.handle.net/10361/14890 (accessed on 18 May 2023).

21. Holman, C.; Harrison, R.; Querol, X. Review of the efficacy of low emission zones to improve urban air quality in European cities. *Atmos. Environ.* **2015**, *111*, 161–169. [CrossRef]
22. Ku, D.; Bencekri, M.; Kim, J.; Leec, S.; Leed, S. Review of European low emission zone policy. *Chem. Eng* **2020**, *78*, 241–246. [CrossRef]
23. Azpurua, M.A.; Dos Ramos, K. A comparison of spatial interpolation methods for estimation of average electromagnetic field magnitude. *Prog. Electromagn. Res. M* **2010**, *14*, 135–145. [CrossRef]
24. Auffhammer, M.; Kellogg, R. Clearing the air? The effects of gasoline content regulation on air quality. *Am. Econ. Rev.* **2011**, *101*, 2687–2722. [CrossRef]
25. Calonico, S.; Cattaneo, M.D.; Titiunik, R. Robust data-driven inference in the regression-discontinuity design. *Stata J.* **2014**, *14*, 909–946. [CrossRef]
26. Calonico, S.; Cattaneo, M.D.; Titiunik, R. Rdrobust: An R package for robust nonparametric inference in regression-discontinuity designs. *R J.* **2015**, *7*, 38. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=e84f1362dfbf93063bf69f2a4dfc50c4e1950e89 (accessed on 18 May 2023). [CrossRef]
27. Calonico, S.; Cattaneo, M.D.; Farrell, M.H. Optimal bandwidth choice for robust bias-corrected inference in regression discontinuity designs. *Econom. J.* **2020**, *23*, 192–210. [CrossRef]
28. Gelman, A.; Imbens, G. Why high-order polynomials should not be used in regression discontinuity designs. *J. Bus. Econ. Stat.* **2019**, *37*, 447–456. [CrossRef]
29. Barreca, A.I.; Guldi, M.; Lindo, J.M.; Waddell, G.R. Saving babies? Revisiting the effect of very low birth weight classification. *Q. J. Econ.* **2011**, *126*, 2117–2123. [CrossRef]
30. Seoul TOPIS. Seoul Metropolitan Government Transportation Information. Available online: https://topis.seoul.go.kr/refRoom/openRefRoom_2.do (accessed on 20 October 2024).
31. Hodan, W.M.; Barnard, W.R. *Evaluating the Contribution of PM2.5 Precursor Gases and Re-Entrained Road Emissions to Mobile Source PM2.5 Particulate Matter Emissions*; MACTEC Federal Programs: Research Triangle Park, NC, USA, 2004. Available online: https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=29f2923b16b1e496233b6de6fe2b1bb13261ba39 (accessed on 18 May 2023).
32. Guerra, S.A.; Olsen, S.R.; Anderson, J.J. Evaluation of the SO2 and NOx offset ratio method to account for secondary PM2.5 formation. *J. Air Waste Manag. Assoc.* **2014**, *64*, 265–271. [CrossRef]
33. Kim, S.; Kim, J.; Jung, S.; Sung, K.; Kim, J.; Kim, I. Experimental Study on the NO_2/NO_X Ratio from Exhaust of Diesel Vehicles by Chassis Dynamometer. *Trans. Korean Hydrog. New Energy Soc.* **2017**, *28*, 220–224. [CrossRef]
34. Moon, N.; Seo, J.; Kim, S. Estimation of Contribution and Emission-to-$PM_{2.5}$ Conversion Rate by Each Local Government for Policy Support. *J. Korean Soc. Atmos. Environ.* **2021**, *37*, 891–906. [CrossRef]
35. Lee, S.; Ghim, Y.S.; Kim, Y.P.; Kim, J.Y. Estimation of the seasonal variation of particulate nitrate and sensitivity to the emission changes in the greater Seoul area. *Atmos. Environ.* **2006**, *40*, 3724–3736. [CrossRef]
36. Shin, Y. Estimating the Cost of Air Pollution on Morbidity: Focusing on Hospital Visit for Acute Respiratory Diseases. Ph.D. Thesis, 2002. Available online: https://koreascience.kr/article/JAKO200217551615292.page (accessed on 18 May 2023).
37. Ahn, S.; Bae, H.; Kwak, S.; Lim, Y.; Kim, M.; Oh, S. Assessment of Human Health Effects of Air-Pollution Using Cohort DB and Estimation of Associated Economic Costs in Korea (3). The Korea Environment Institute. 2017. Available online: https://www.nkis.re.kr/subject_view1.do?otpId=KEI00049833&otpSeq=0&popup=P (accessed on 18 May 2023).

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.