Crawford School of Public Policy

Centre for Climate & Energy Policy

Have vehicle registration restrictions improved urban air quality in Japan?

CCEP Working Paper 1904
November 2019

Shuhei Nishitateno
School of Policy Studies, Kwansei Gakuin University

Paul J. Burke
Crawford School of Public Policy, The Australian National University

Abstract
About 2.6 million non-compliant vehicles were removed from designated metropolitan areas in Japan after the introduction of vehicle registration restrictions under the 1992 Automobile NOx Control Law. Based on a difference-in-differences framework and using a monitor-level panel dataset for the period January 1981–December 2015, we find that the intervention led to a 3–6% reduction in the monthly mean ambient concentration of nitrogen dioxide (NO2) in the treated areas. Back-of-the-envelope calculations identify benefits equal to about US$104 million as a result of reduced mortality from asthma.

Keywords:
vehicle restrictions, health, road transport

JEL Classification:
Q53, Q58

Suggested Citation:
Nishitateno, S. and Burke, PJ. (2019), Have vehicle registration restrictions improved urban air quality in Japan?, CCEP Working Paper 1904, Nov 2019. Crawford School of Public Policy, The Australian National University.

Address for Correspondence:
Shuhei Nishitateno
School of Policy Studies
Kwansei Gakuin University
2-1 Gakuen, Sanda,
Hyogo, Japan 669-1337
Email: shuhei0828@kwansei.ac.jp

Paul J Burke
Crawford School of Public Policy
The Australian National University
ANU College of Asia and the Pacific
J. G. Crawford Building
132 Lennox Crossing
Acton ACT 2601 Australia
Tel: +61 (0) 2 6125 6566
Email: paul.j.burke@anu.edu.au

I. Introduction

In June 1992, Japan introduced an Automobile NOx Control Law (ANCL) to improve urban air quality. The ultimate aim of the law was for all monitors in designated areas to meet the national air quality standard for nitrogen dioxide (NO_2): below 60 parts per billion (ppb) in terms of the 98th percentile of the daily mean throughout the year. A key measure to achieve this goal was to ban vehicles that violated the emission standards under the ANCL from being registered in designated areas, resulting in the removal of 2.6 million polluting vehicles from metropolitan areas between June 1992 and December 2015.

The ANCL has been controversial for two reasons. First, it imposed costs on the owners of non-compliant vehicles, especially truck companies for which replacements can be expensive. Owners of non-compliant vehicles were required to replace vehicles earlier than they intended. Second, there is no consensus on how much, or even if, the ANCL has contributed to improvements in air quality. For example, Iwata and Arimura (2009) found that the ANCL has helped reduce NOx emissions from motor vehicles markedly, whereas the Ministry of Internal Affairs and Communications (2004) concluded that its pollution-reducing effects have been minimal. Such a discrepancy primarily emanates from a lack of convincing evidence based on a valid counterfactual.

This study exploits the quasi-experimental conditions of the ANCL, allowing for a difference-in-differences (DD) approach. The idea is simple: we compare the average temporal changes in pollution levels before and after the intervention in municipalities subject to the ANCL with those that were not. The analysis uses a monthly panel dataset at the pollution monitor level for January 1981–December 2015.

The treatment group consists of 109 municipalities designated in 1992, whereas the control group comprises five urban municipalities that were not subject to the ANCL. Like the key municipalities in the treatment group, the selected control municipalities were categorized as major cities under Japan's Local Autonomy Law. We find no differential pre-trends for NO_2 concentration in the treatment and control groups. The choice of the control group is also motivated by the fact that the five selected municipalities are geographically distant from the treated areas, reducing concerns that spatial leakages exist from the treatment to control groups.

The estimation challenge is to disentangle the effects of the intervention under the ANCL from the effects of unobserved factors. This concern arises because a sharp policy effect cannot be detected given that the vehicle registration restriction was introduced in a staggered way between 2004 and 2015. To the best of our knowledge, the Diesel Vehicle Driving

Regulation (DVDR) enacted by the prefectures in designated areas poses the most significant threat. As reported herein, we find evidence that the ANCL intervention had noticeable pollution-reducing effects, even after the DVDR is controlled for. Despite this, our estimates could still be biased upward given that it is impossible to fully control for all omitted variables. Our estimates should be seen as an upper bound of the benefits of the intervention.

We find that the vehicle registration restriction under the ANCL on average led to a 3–6% reduction in the monthly mean ambient concentration of NO_2 between June 1992 and December 2015. The evidence also suggests that the pollution-reducing effects kicked in seven years after the ANCL was enacted in 1992, peaking around 2004 when the first compliance requirements started. The effects persisted afterward. Back-of-the-envelope calculations monetize the benefits in treated areas of reduced mortality from asthma as a result of the ANCL intervention as about US$ 104 million (in year-1997 dollars).

An important contribution of the current study is that it provides the first evidence of the environmental benefits of an intervention involving geographical registration restrictions. The empirical evidence provided by studies that have evaluated regulations on exhaust gas emissions from motor vehicles in urban areas has been limited to license plate-based driving restrictions (Davis, 2008; Viard and Fu, 2015; Zhang et al., 2017), gasoline content regulations (Auffhammer and Kellogg, 2011), low-emission zones (Wolff, 2014; Gehrsitz, 2017), and road pricing (Gibson and Carnovale, 2015; Fu and Gu, 2017).

The rest of this paper is structured as follows. Section II describes the data and provides an overview of the vehicle registration restriction. This section also discusses the validity of the choice of the treatment and control groups. Section III presents the estimation models. Section IV reports the estimation results. Section V concludes.

II. Background

A. <u>Data</u>

The main data source is the Environmental GIS compiled by the National Institute for Environmental Studies (NIES). These data provide comprehensive information on the ambient atmospheric concentrations of targeted pollutants, including NO_2, at the pollution monitor level. The ambient concentration of NO_2 is recorded every hour. The monthly level is the highest frequency data available. As an alternative, we also use the days per month on which daily averages exceeded the national standard for NO_2 (60 ppb). The sample is limited to monitors that operated for at least 70% of the month and that do not have missing readings between January 1981 and December 2015.

Meteorological data come from the Japan Meteorological Agency (JMA). We use the meteorological station nearest to each pollution monitor. The municipality designation status is from the Ministry of the Environment. Annual data on demographic and socioeconomic factors are downloaded from the System of Social and Demographic Statistics compiled by the Ministry of Internal Affairs and Communications (MIAC). The definitions and data sources are listed in Appendix 1.

B. NO_2

NO_2 is soluble in water, reddish-brown in color, and a strong oxidant. On a global scale, NO_2 emissions from natural sources (e.g., lightning, forest fires, and bacterial and volcanic activity) far outweigh anthropogenic emissions. However, natural emissions are distributed over the entire surface of the Earth, with background atmospheric concentrations being very small. A major source of anthropogenic emissions of NO_2 in the atmosphere is the combustion of fossil fuels. In urban areas, automobile exhaust gas emissions are the major source (OECD, 2014).[1]

Exposure to high concentrations of NO_2 can endanger human health and living environments. Recent studies of asthmatic children and adults have revealed associations between NO_2 and symptoms of asthma, reduced response to bronchodilators, and reductions in lung function (Guarnieri and Balmes, 2014). Epidemiological studies have revealed an association between exposure to high-concentrated NO_2 and mortality. Faustini et al. (2014) conduct a meta-analysis of 23 papers published between 2004 and 2011 and conclude that the long-term effects of NO_2 on mortality are as great as those of $PM_{2.5}$. NO_2 also plays an important role in the formation of acid rain and photochemical smog.

C. The intervention

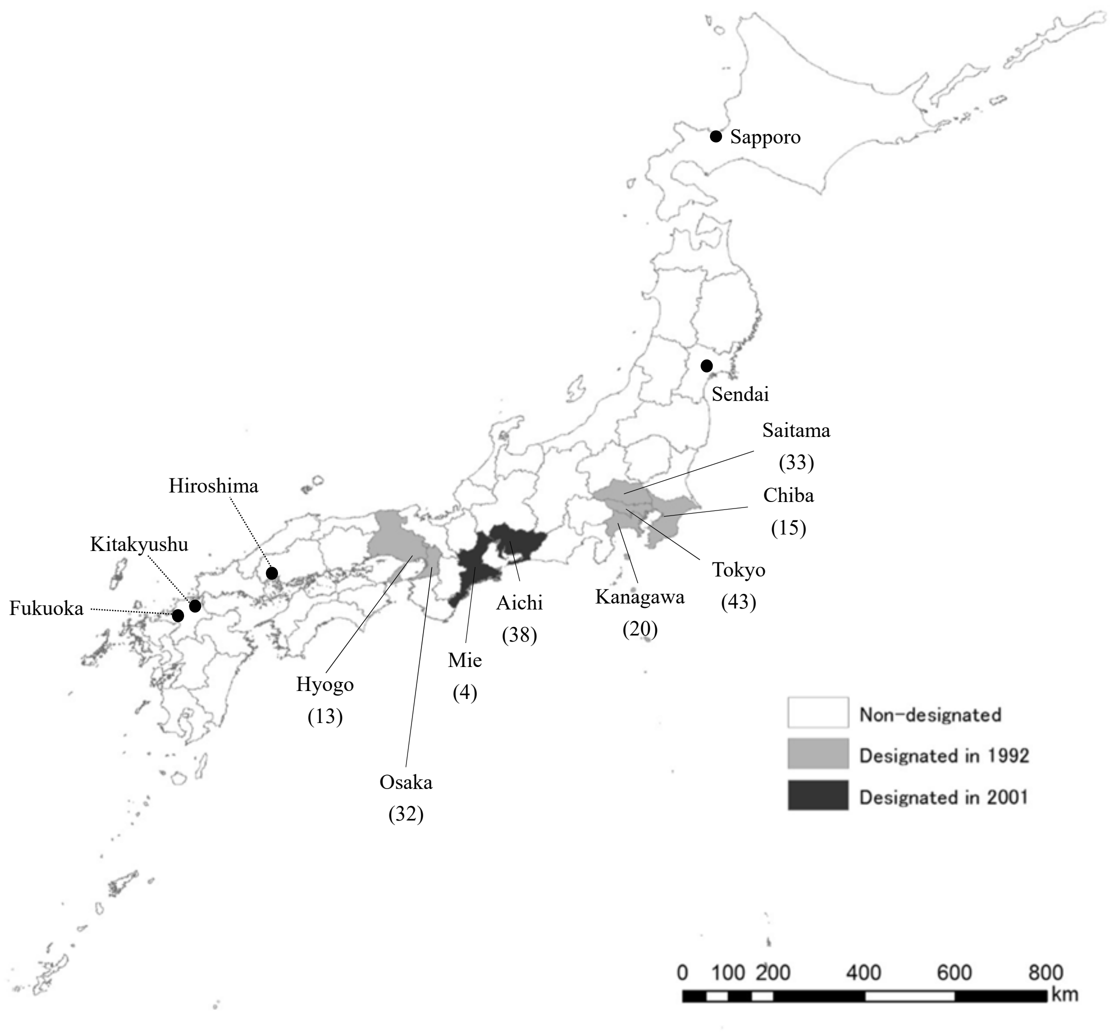
Because of discontent over the deteriorating urban air quality and deregulation of the national NO_2 standard, in 1978 the residents sued the national government, expressway companies, and automakers for the health damage brought on by vehicular air pollution. These lawsuits led to official recognition that vehicular air pollution, including NO_2, was responsible for health damage. In some cases, the government and expressway companies were ordered to implement measures to reduce emissions from road transport. In response, the Japanese government enacted the ANCL in June 1992.

The ANCL stipulated that all monitors in the designated areas shown in Figure 1 must meet the national standard for NO_2. As of 2015, 198 municipalities in Tokyo, Saitama, Chiba, Kanagawa, Osaka, Hyogo, Aichi, and Mie prefectures had been designated. These are just

[1] As of 2002, 52% of NOx emissions in Japan originated from cars (Ministry of Environment, 2002).

some of the municipalities in these prefectures. The designation criteria are (i) vehicle travel density, (ii) vehicle ownership rate, and (iii) ambient concentration of NOx. If all these criteria were more than three times the national average as of 1992, a municipality would be designated after hearings involving the prefectural governor and officials. Designations were enacted in 1992 and 2001 only. Once imposed, no designation has been lifted to keep polluting vehicles away from designated areas.

FIGURE 1
Designated areas under the ANCL



Notes: The numbers in parentheses are the number of designated municipalities. Designated municipalities in Tokyo, Kanagawa, Saitama, Chiba, Osaka, and Hyogo are defined as the treatment group. Note that 47 municipalities are excluded from the treatment group, owing to data limitation. The dots indicate the five municipalities used as the control group.

The central feature of the ANCL is a local ban on the registration of vehicles that do not meet the emission performance standard within certain grace periods. The intervention has been applied to trucks, buses, special-use vehicles, and diesel passenger cars, amounting to 2.6 million vehicles (Iwata and Arimura, 2009). Among the regulated vehicles, trucks dominate (56%), followed by diesel passenger cars (30%), special-use vehicles (11%), and buses (2%).

The vehicle registration restriction was designed to ensure that the most polluting vehicles would be expelled from designated areas. The ANCL stipulated that the NOx emission performance standard should be met for targeted vehicles. The emission standards for trucks, buses, and special-use vehicles are 0.48 g/km for gross vehicle weights of less than 1.7 tons, 0.63 g/km for 1.7–2.5 tons, and 5.9 g/kWh for more than 2.5 tons, respectively. The emission standard for diesel passenger vehicles is 0.48 g/km regardless of weight. These emission standards have remained constant over time. Targeted vehicles are labeled non-compliant if their emission control standards in the manufacturing process exceed the ANCL emission standards.[2]

The registration restriction was introduced in a staggered way during 2004–2015, determined by the first year of vehicle registration (Appendix 2). No compliance was required before 2004. Compliance years were arbitrarily set such that older vehicles received shorter grace periods. For example, non-compliant standard trucks first registered in 1988 or before were not allowed to register in designated areas as of 2004, whereas the compliance target year for those registered in 2002 was 2012. This staggered implementation of the registration restriction was carried out in the same way for all designated areas, regardless of designation timings.

D. Choice of treatment and control groups

As explained in Section III, our empirical strategy involves the DD method, indicating that the credibility of estimates lies in the validity of the treatment and control groups. We focus on designated municipalities in Tokyo, Kanagawa, Chiba, Saitama, Osaka, and Hyogo prefectures (i.e., the 1992 designation groups) as the treatment group, whereas we exclude municipalities designated in June 2001 from the sample. The reason for this is that the inclusion of the 2001 designation group changes the composition of the treatment and control groups for the sample period.

[2] Given that emission control standards are easily identified from basic vehicle information, it is unlikely that the owners of non-compliant vehicles could cheat this examination.

The choice of the control group was based on two criteria: comparability and geographical location. First, we sought non-designated municipalities that are as urbanized as the treatment group using the list of major cities under Japan's Local Autonomy Law. As of 2015, 20 municipalities were classified as major cities under this law, including nine designated municipalities under the ANCL and 11 non-designated municipalities: Sapporo, Sendai, Nigata, Hiroshima, Okayama, Hamamatsu, Shizuoka, Kyoto, Kitakyusyu, Fukuoka, and Kumamoto. Major cities must meet several standards such as having more than 500,000 residents, less than 10% of employment in the primary industry, and adequate urban infrastructure.

We excluded Okayama, Hamamatsu, Shizuoka, and Kyoto from the control group, as they are geographically close to the designated municipalities in Tokyo, Kanagawa, Chiba, Saitama, Osaka, and Hyogo prefectures. This was important for minimizing the potential for geographical spillovers, because new compliant vehicles could be driven outside designated areas. Although it is not reported here, we carefully examined the extent and scope of the spatial leakages of the intervention and found that neighboring municipalities (such as the four municipalities) benefitted from the intervention *vis-à-vis* more distant municipalities. Therefore, we assume that spatial leakages are negligible in the remaining municipalities.[3]

This assumption is consistent with the freight survey conducted by the Tokyo Metropolitan Area Transport Planning Council (2005) based on large-scale freight data between origin and destination at the facility level for manufacturing, wholesale, retail, services, and transport including road, marine, air, and storage. The survey covered Tokyo, Kanagawa, Saitama, and Chiba prefectures, which are comparable to the largest designated areas under the ANCL (Figure 1). An important finding is that most freight demand—predominantly trucks—emanates from intra-metropolitan areas rather than inter-regional areas. This is mainly because the economic activities in those areas are highly concentrated. Another relevant finding is that about one-third of inter-regional freight is distributed by marine and rail transport, suggesting that the use of diesel trucks for long-haul trips is relatively limited in Japan.

[3] The domestic transfer of non-compliant vehicles from the treatment to the control groups through a second-hand market is another source of pollution leakage. However, data from the Ministry of Economy, Trade and Industry (2008) suggest that 70% of vehicles replaced under the ANCL were scrapped and 28% were exported overseas, indicating that such pollution leakages are negligible.

As mentioned above, the sample is limited to those monitors with full readings between January 1981 and December 2015, causing another 47 designated municipalities and two non-designated municipalities (Nigata and Kumamoto) to drop from the treatment and control groups, respectively. Therefore, the selected treatment-group municipalities in this study are 109 designated municipalities with 190 monitors. There are five control-group (i.e., non-designated) municipalities, namely Sapporo, Sendai, Hiroshima, Kitakyusyu, and Fukuoka, with 35 monitors located in these municipalities.

Table 1 shows the simple averages of air pollution, weather, and some demographic and socioeconomic factors during the sample period for the treatment and control groups. We use annual data on the demographic and socioeconomic factors at the municipality level for 1985, 1990, 1995, 2000, 2005, 2010, and 2015. Overall, the treatment and control groups appear to be comparable. One noticeable difference is snowfall. This is because the control group includes Sapporo and Sendai, which are snowy areas. The other difference is population size, emanating from the fact that the treatment group covers relatively small municipalities as well. The exclusion of these small municipalities from the sample leads the average population sizes to be comparable between the treatment and control groups. In the robustness checks, we examine whether the coverage of the treatment group affects the estimates (see Section IV).

TABLE 1
Sample averages for 1981–2015

	Entire sample	Treatment group	Control group
Air pollution			
Ambient concentration of NO_2, ppb			
Mean	25	25	21
Hourly maximum	110	111	88
Daily maximum	48	48	40
Days exceeding the national standard	5	6	2
Weather variables			
Temperature, degree Celsius	16	16	14
Precipitation, millimeters	123	123	121
Sunlight duration, hours	165	165	158
Snowfall, centimeters	1	1	10
Wind, meters per second	3	3	3
Cloud cover, 0–10	7	7	7
Demographic and socioeconomic factors			
Population, thousand	396	352	1,261
Population aged above 65 years, %	15	15	15
Income per capita, thousand yen	3,942	3,969	3,408
Unemployment rate, %	5	5	5

Notes: The treatment group is 109 designated municipalities with 190 monitors. The control group is five non-designated municipalities (Sapporo, Sendai, Hiroshima, Kitakyusyu, and Fukuoka) with 35 monitors. The averages of the air pollution and weather variables are based on monthly data for January 1981–December 2015. The averages of the demographic and socioeconomic factors are based on annual data for 1985, 1990, 1995, 2000, 2005, 2010, and 2015.

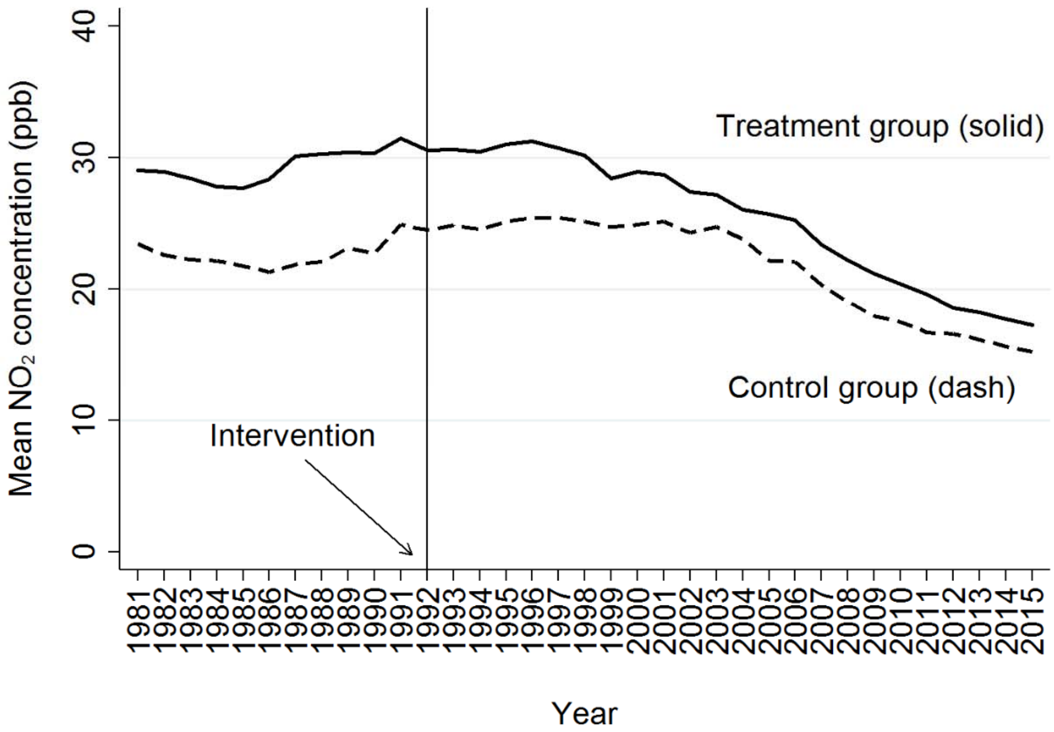
E. Time trends of NO_2 concentration

Figure 2 shows the unadjusted time trends of the yearly ambient concentration of NO_2 in the treatment and control groups. Here, we show NO_2 trends using yearly data, rather than monthly data, for visual simplicity. The monthly trends are available in Appendix 3. Panel A shows that the mean NO_2 trends for the pre-intervention period seem to be common, with 29 ppb (standard deviation = 1.2) for the treatment group and 22 ppb (standard deviation = 0.9) for the control group. Statistical tests fail to reject the null hypothesis that the slopes of the time trends are the same for the two groups, controlling for the year dummies.[4]

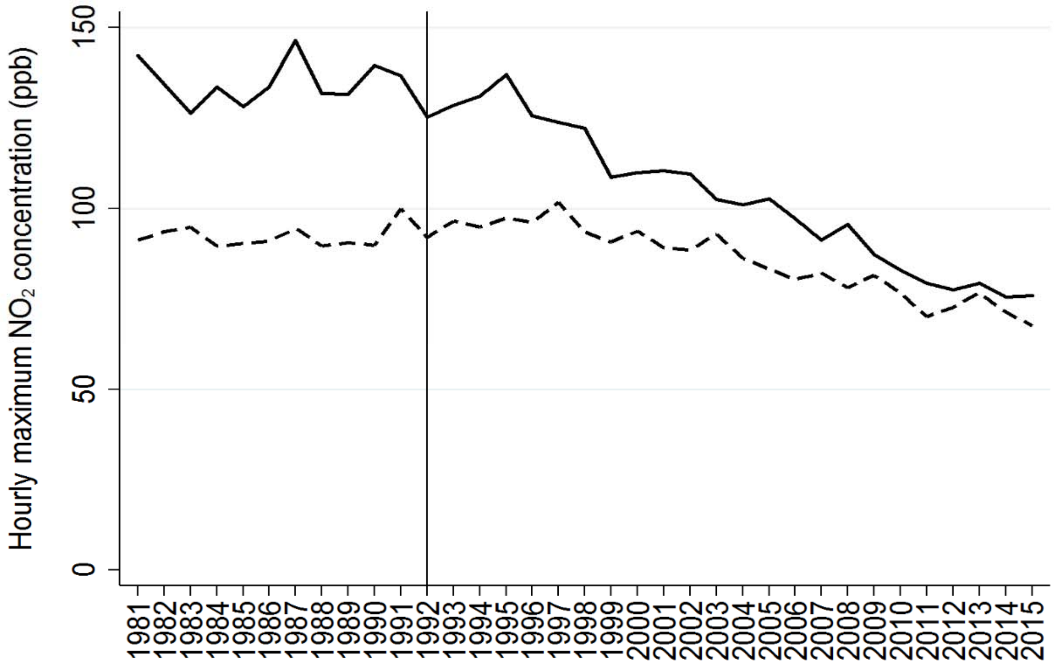
[4] The trend slope difference for 1981–1992 is 0.012 with a p-value of 0.322.

FIGURE 2
Time trends of the yearly ambient concentration of NO_2

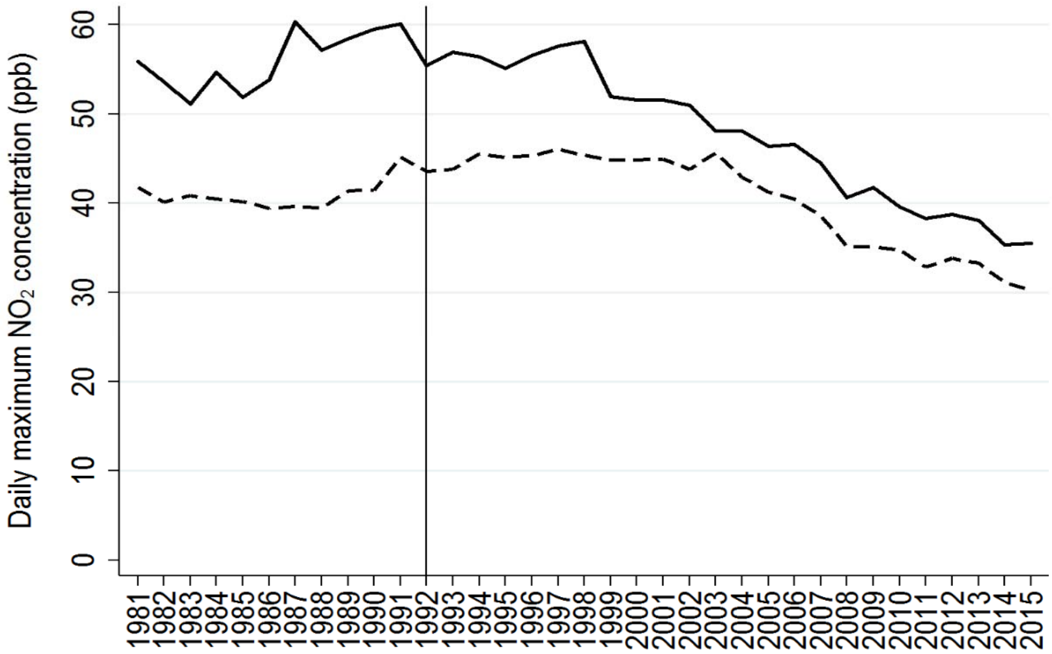
Panel A. Mean



Panel B. Hourly maximum



Panel C. Daily maximum



Notes: The treatment group covers 190 monitors in 109 designated municipalities in Tokyo, Kanagawa, Chiba, Saitama, Osaka, and Hyogo prefectures. The control group covers 35 monitors in five non-designated municipalities (Sapporo, Sendai, Hiroshima, Kitakyusyu, and Fukuoka).

In contrast, the results show diverging NO_2 trends for the post-intervention period. The mean NO_2 concentration in the treatment group declined at a faster rate than in the control group between 1992 and 2015: the mean NO_2 dropped by about 13 ppb for the treatment group and 9 ppb for the control group. Different post-trends are also suggested by the statistical tests that reject the common slope hypothesis for both groups, controlling for the year dummies.[5]

Panels B and C demonstrate that common pre-trends and different post-trends are observed between the treatment and control groups for the hourly maximum and daily maximum NO_2 concentrations, respectively. We find no evidence of different pre-trends: the trend slope difference is 0.035 with a p-value of 0.256 for the hourly maximum and 0.021 with a p-value of 0.185 for the daily maximum NO_2 concentrations. In contrast, their post-trends are statistically different: the trend slope difference is –0.061 with a p-value of zero for the hourly maximum and –0.023 with a

[5] The trend slope difference for 1992–2015 is –0.012 with a p-value of 0.073.

p-value of 0.008 for the daily maximum NO_2 concentrations.

III. Models

Our identification strategy involves a DD procedure. We estimate the average treatment effect (β) using the following specification:

$$\ln N_{m,t} = \alpha + \beta Treatment_{m,t} + \delta \boldsymbol{X}_{m,t} + \sum_{m=1}^{225} \theta_m \, Monitor_m + \sum_{t=1}^{420} \gamma_t \, Time_t + \varepsilon_{m,t} \qquad (1)$$

where *m* stands for the pollution monitor and *t* is month. The dependent variables are the log NO_2 ambient concentrations (in terms of the monthly mean, hourly maximum, and daily maximum) and days exceeding the national standard for NO_2. $Treatment_{m,t}$ is the interaction of the dummy variable indicating the period after the ANCL was enacted ($Post_{June1992}$) with the dummy variable indicating whether the pollution monitor is located in the designated areas under the ANCL ($Treated_m$). We do not use the post-compliance period (January 2004–December 2015) as the treatment period because January 2004 is not a clear cutoff: some non-compliant vehicles were replaced before the compliance obligation began, induced by government support such as tax breaks and low interest loans (Ministry of Environment, 2002).

X is a vector of weather conditions that may well be underlying determinants of pollution levels, as well as monitor-specific time trends. Given that no monthly data on the demographic and socioeconomic factors are available, controlling for monitor-specific time trends is crucial to ensure the parallel trends assumption holds: that in the absence of the ANCL, NO_2 concentration would follow the same trends as those observed in the control group. θ represents the monitor fixed effects that account for the time-invariant factors relevant to pollution level (e.g., location). γ is the month-of-the-year fixed effects to control for any national-level monthly changes during the sample period, such as tightened vehicle emission standards. ε is an error term.

The discrete specification of equation (1) provides no indication of the dynamics of the intervention effects (i.e., how quickly NO_2 concentrations declined after the law was enacted and whether this impact increased, stabilized, or declined over time). Hence, to examine the dynamics of the treatment effects, we estimate the following specification:

$$\ln N_{m,t} = \alpha + \sum_{year=1992}^{2015} \beta_{year}\left(Treated_m \times Post_{year}\right) + \delta \boldsymbol{X}_{m,t} + \sum_{m=1}^{225} \theta_m\, Monitor_m + \sum_{t=1}^{420} \gamma_t\, Time_t + \varepsilon_{m,t} \quad (2)$$

where $Post_{year}$ is the year dummy indicating the post-intervention period. The other elements are identical to in equation (1). β_{year} indicates the extent to which the post-intervention NO_2 concentrations in treated areas, relative to the pre-intervention period (1981–1991), differ from those of the control group. A higher negative coefficient implies greater pollution-reducing effects of the intervention in a given year.

The use of a monitor-level panel dataset raises two concerns. First, model errors for monitors in the same municipality might be correlated because of common shocks such as local government policies. Second, model errors in different time periods might be serially correlated. The failure to adjust for within-cluster correlations may thus lead to misleadingly low standard errors.

The simplest approach is a clustering adjustment. Conventional wisdom in DD analysis is to cluster standard errors at the level at which the treatment is applied (Bertrand et al., 2004). We thus report robust standard errors clustered at the municipality level throughout. The number of clusters is 114, sufficiently large for the standard cluster adjustment to be reliable (Angrist and Pischke, 2009).

IV. Results

A. <u>Baseline results</u>

Table 2 reports the results for equation (1) for panel datasets covering 225 monitors for January 1981–December 2015, amounting to 90,430 observations. Column 1 shows that the point estimate for the treatment variable is –0.128 at the 1% significance level and that the 95% confidence interval ranges from –0.190 to –0.066. This result suggests that designation under the ANCL reduced the monthly mean ambient concentration of NO_2 by 7–19% on average over June 1992–December 2015 for monitors in treated areas. We also find that the average treatment effects on the hourly and daily maximum NO_2 concentrations are reductions of 16% and 14%, respectively. Column 2 reports the results with the monitor-specific time trends. The point estimates for the treatment variable reduce to –0.059, –0.038, and –0.069 for the monthly mean, hourly maximum, and daily maximum, respectively.

TABLE 2
Estimated effects of designation under the ANCL on air pollution

Dependent variables	Ln monthly mean ambient concentration of NO_2		Days exceeding the national standard for NO_2 per month	
	(1)	(2)	(3)	(4)
Treatment	–0.128***	–0.059***	–0.539***	–0.092
	(0.031)	(0.015)	(0.143)	(0.139)
R^2	0.73	0.77	0.16	0.33
Month-of-the-year fixed effects	Yes	Yes	Yes	Yes
Monitor fixed effects	Yes	Yes	Yes	Yes
Weather variables	Yes	Yes	Yes	Yes
Monitor-specific time trends	No	Yes	No	Yes
Monitors	225	225	225	225
Observations	90,430	90,430	90,430	90,430
Coefficients of the treatment variable when the pollution variables are measured by:				
Hourly maximum	–0.161***	–0.038***	-	-
Daily maximum	–0.144***	–0.069***	-	-

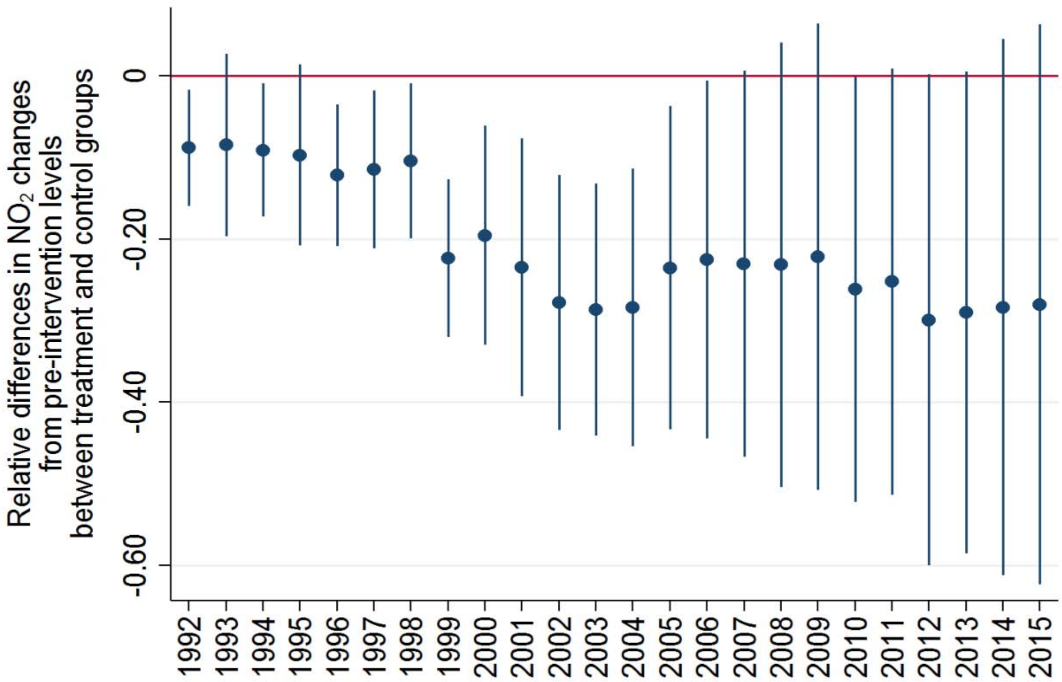
Notes: This table presents the estimation results for equation (1), using monitor-level panel data for January 1981–December 2015. The weather variables include temperature, precipitation, sunlight duration, snowfall, wind, and cloud cover. Standard errors are robust to heteroscedasticity and clustered at the municipality level.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

Column 3 presents an estimation using the days exceeding the national standard for NO_2. The point estimate is –0.539 (different from zero at the 1% significance level). The 95% confidence interval ranges from –0.822 to –0.256. This result suggests that the intervention decreased the number of days for which the daily mean ambient NO_2 concentration exceeded 60 ppb by 0.3–0.8 on average. However, controlling for the monitor-specific time trends causes the treatment effect to become not significantly different from zero (Column 4).

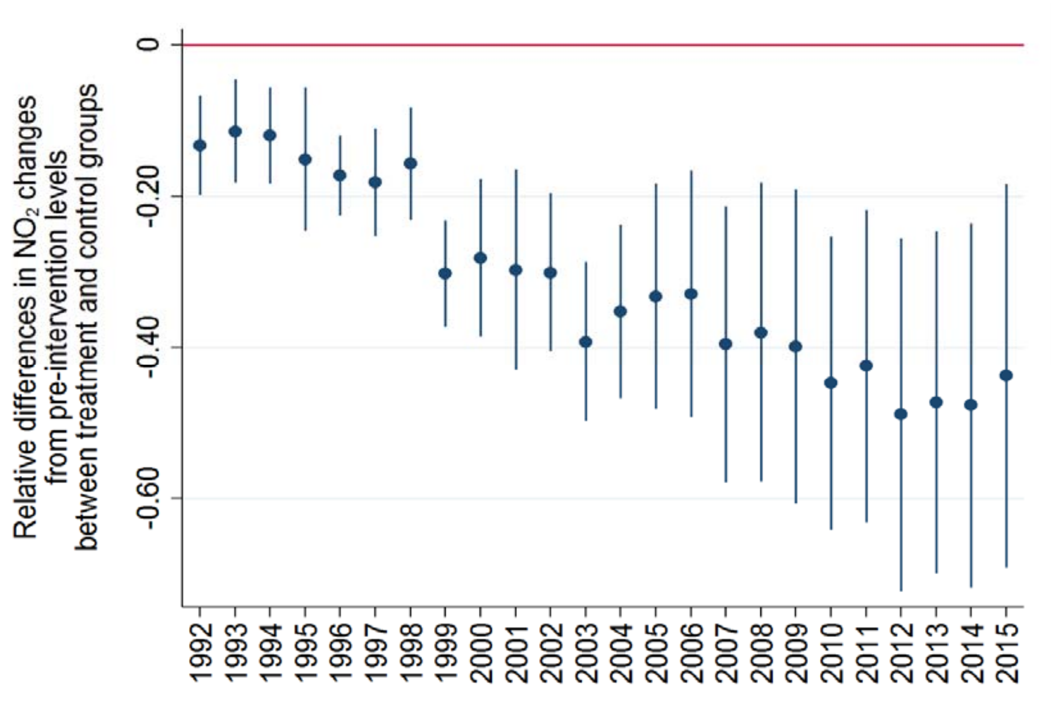
Figure 3 reports the estimates of equation (2), controlling for the monitor-specific time trends. Overall, the results demonstrate that regardless of the different NO_2 measurements, the intervention effects peaked in 2004 when the first compliance requirements started and the effect persisted afterward. For example, Panel A suggests that the effects kicked in after seven years and accelerated over the next six years, peaking in 2004. The point estimate indicates that mean NO_2 for 2004 relative to what was to prevail during the pre-intervention period was 28% lower than its counterpart for the control group. The average coefficient of the treatment lags between 2005 and 2015 is –0.256. We find similar dynamics for the hourly and daily maximum measures (Panels B and C).

The results in Figure 3 make sense, as owners of non-compliant vehicles had little incentive to replace their polluting cars during the early period of the legislation. However, they became more responsive to the regulation as the compliance requirements approached. As explained above, the government also incentivized owners to replace non-compliant vehicles before their compliance duties. The persisting policy effects after the first compliance period reflect the nature of the vehicle registration restriction: non-compliant vehicles were gradually phased out during 2004–2015, as their retirement year was set by the government based on the initial registration year and type.

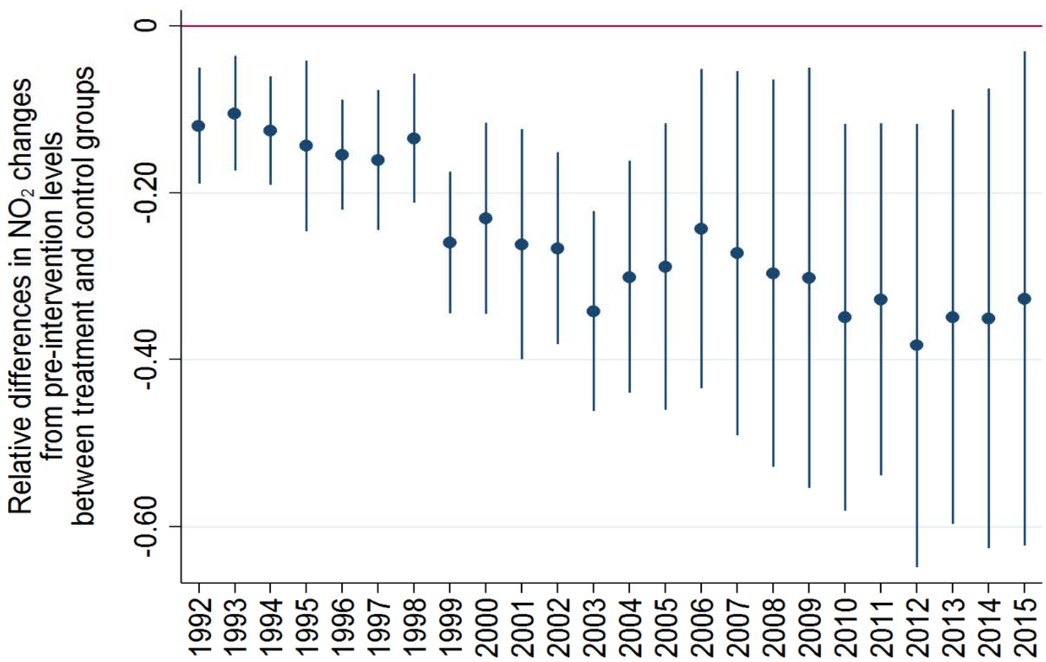
FIGURE 3
Estimates of the lag effects
Panel A. Mean



Panel B. Hourly maximum



Panel C. Daily maximum



Notes: This figure presents the estimation results for equation (2), using monitor-level panel data for January 1981–December 2015. The points show the point estimate of β_{year} and the vertical bands represent the 95% confidence intervals. Standard errors are robust to heteroscedasticity and clustered at the municipality level.

B. Robustness

The baseline estimates suggest that the average treatment effect of the registration restriction under the ANCL on the monthly NO_2 mean is –6% (Column 2, Table 2). Table 3 reports the robustness of this baseline result. An important issue is that many other factors besides the intervention under the ANCL may have affected pollution levels in treated areas, leading the treatment effects to be biased upward. To the best of our knowledge, the DVDR enacted by prefectures in designated areas poses the most significant threat. The DVDR prohibits diesel trucks and buses registered in non-designated areas from entering designated areas unless they meet these new emission standards. The DVDR was enforced in October 2003 for Tokyo, Saitama, Chiba, and Kanagawa; in October 2004 for Hyogo; and in January 2009 for Osaka.

To examine the influence of the DVDR, we include in equation (1) a dummy variable taking the value of one if a monitor is located in municipalities subject to the DVDR and zero otherwise. Column 1 of Table 3 shows the result. An important finding is that the ANCL intervention produces pollution-reducing effects even after the influence of the DVDR is controlled for. The lower part of the table suggests that the same conclusions are reached for the hourly and daily maximum measures.

The estimates might be picking up industry-related reductions in NO_2 emissions induced by government interventions in treated areas. As far as we are aware, the most important intervention was the NOx emission controls introduced in 1981 to designated plants in some industrial areas in Tokyo, Osaka, and Kanagawa. These are still in effect. However, this intervention was in place throughout the sample period. We are not aware of any other major interventions that aimed to reduce NO_2 emissions from stationary sources in treated areas.

On the contrary, the treatment effects might be biased downward owing to unintended responses to the ANCL. For example, the owners of non-compliant vehicles may have transferred the registration of their vehicle outside designated areas and kept using them in designated areas. In addition, some non-compliant vehicles might have continued to be driven in designated areas after their compliance period. However, as far as we are aware, these factors are not a major concern. Japan’s Automobile Garage Act stipulates that vehicles must be garaged within a 2-km radius of the home of the vehicle registration, making the transfer of the vehicle registration outside designated areas expensive. The Road Transport Vehicle Act already imposed regular inspections of every motor vehicle, with any non-compliant vehicle automatically failing its inspection.

TABLE 3
Robustness checks

Dependent variables: Ln mean ambient concentration of NO_2	DVDR effects (1)	Control group: polluting monitors (2)	Treatment group: major cities (3)	Heterogeneous treatment effects (4)
Treatment	–0.030**	–0.032**	–0.061**	–0.037**
	(0.013)	(0.012)	(0.022)	(0.015)
DVDR	0.057***			
	(0.021)			
Treatment × Roadside				–0.078***
				(0.017)
R^2	0.77	0.77	0.76	0.77
Month-of-the-year fixed effects	Yes	Yes	Yes	Yes
Monitor fixed effects	Yes	Yes	Yes	Yes
Weather variables	Yes	Yes	Yes	Yes
Monitor-specific time trends	Yes	Yes	Yes	Yes
Monitors	225	209	87	225
Observations	90,430	83,919	35,318	90430
Coefficients of the treatment variable when the pollution variables are measured by:				
Hourly maximum	–0.022*	–0.022	–0.046**	-
Daily maximum	–0.048***	–0.052***	–0.071***	-

Notes: All the columns present the results for the full sample period (January 1981–December 2015). Column 1 includes DVDR, which is a time-variant dummy indicating that a monitor is located in a municipality subject to the DVDR. Column 2 constructs a control group equivalent to the treatment group in terms of the mean NO_2 concentration as of June 1991. Column 3 restricts the treatment group to major cities under Japan's Local Autonomy Law. Column 4 includes an interaction of the treatment variable with "Roadside," which is a time-invariant dummy indicating that a monitor is located roadside. The weather variables include temperature, precipitation, wind, sunlight duration, snowfall, and cloud cover. Standard errors are robust to heteroscedasticity and clustered at the municipality level.
***, **, and * indicate statistical significance at 1%, 5%, and 10%, respectively.

The other issue is comparability between the treatment and control groups. Monthly volatility in pollution is much greater for the treatment group than the control group (Appendix 3). This finding suggests that systematic differences between the two groups may be driven by the selection criteria for inclusion in the treatment group (e.g., NO_2 level). To address this, we construct a control group that is close to the treatment group in terms of the monthly mean NO_2 concentration as of June 1991. Column 2 of Table 3 shows that the point estimates of the treatment variable are –0.032, –0.022, and –0.052 for the monthly mean, hourly maximum, and daily maximum, respectively. While all of the estimates are below the baseline estimates in absolute value, the main conclusion does not change.

We originally chose five non-designated municipalities listed as major cities under Japan's Local Autonomy Law. The treatment group includes both these major cities and non-major cities, perhaps reducing the comparability of the treatment and control groups. To address this, we restricted the treatment group to major cities only and re-estimate equation (1). Column 3 of Table 3 shows that the point estimates of the treatment variable are almost the same as the baseline estimates.

Lastly, pollution reduction should be larger when measured at roadside monitors, as the ANCL aims to reduce vehicular emissions. To examine this, we interacted the treatment variable with "Roadside," a dummy variable taking the value of one if a monitor is located roadside and zero otherwise. In accordance with our expectation, the point estimates suggest that the average treatment effect for roadside monitors is 8% greater than that for monitors in the remaining areas (Column 4). This provides supportive evidence that improvements in air quality were attributable to the ANCL intervention.

C. Back-of-the-envelope calculations

Exposure to lower NO_2 concentrations could reduce mortality by improving respiratory symptoms such as asthma. Samoli et al. (2006) show that a 10 $\mu g/m^3$ decrease in the daily NO_2 concentration is associated with a 0.34% decrease in respiratory mortality. The baseline estimate indicates that the ANCL intervention decreased the monthly mean NO_2 concentration in treated areas by 2.26 ppb, equivalent to 4.25 $\mu g/m^3$.[6] This suggests that the effect of the ANCL intervention on reductions in respiratory mortality was about 0.14%. The annual vital statistics of the Ministry of Health, Labor and Welfare indicate that total mortality by asthma in treated areas was 12,656 over 1992–2015, implying that the ANCL intervention perhaps saved about 18 lives from reduced asthma deaths. Using the value of a statistical life estimate of US$ 5.8 million (1997$) from the EPA (2000), we thus conclude that the health benefits of the ANCL in terms of reduced mortality from asthma amounted to about US$104 million (in year-1997 dollars). This estimate is approximate.

[6] We use the World Health Organization's conversion factor of 1 ppb = 1.88 $\mu g/m^3$.

Our back-of-the-envelope calculations have some important caveats. Owing to data limitations, we do not consider the separate effects of the ANCL on other instances of respiratory and cardiovascular mortality. Our estimates also do not take into account the effects of the ANCL on other pollutants such as particulate matter. Lastly, our estimates do not consider the benefits of the ANCL intervention in municipalities adjacent to treated areas.

V. Conclusion

Japan introduced vehicle registration restrictions under the 1992 ANCL to improve urban air quality. Utilizing the quasi-experimental conditions under this law, the current study estimated the causal effects of the intervention on ambient NO_2 concentrations. We found evidence that the intervention contributing to air quality improvements in metropolitan regions.

Whether the geographically-focused registration restriction of the ANCL was a first-best policy measure is debatable. In terms of cost effectiveness, market-based measures might be more efficient than regulatory approaches. Emissions reductions could be induced by tightening the automobile weight tax on older diesel vehicles, for example. It is also worth considering other approaches such as low emission zones (Wolff, 2014) and road pricing (Gibson and Carnovale, 2015), which have been proven to be effective in other countries. To formally evaluate the validity of the ANCL intervention, full cost-benefit analyses would need to be undertaken. This is an interesting avenue for future research.

References

Angrist, Joshua D., and Jorn-Steffen Pischke. *Mostly Harmless Econometrics*. Princeton and Oxford: Princeton University Press, 2009.

Auffhammer, Maximilian, and Ryan Kellogg. "Clearing the air? The effects of gasoline content regulation on air quality." *American Economic Review*, 101, 2011, 2687–2722.

Bertrand, Marianne, Esther Duflo, and Sendhil Mullainathan. "How much should we trust differences-in-differences estimates?" *Quarterly Journal of Economics*, 119, 2004, 249–275.

Davis, Lucas W. "The effect of driving restrictions on air quality in Mexico City." *Journal of Political Economy*, 116 (1), 2008, 38–81.

EPA. *Guidelines for preparing economic analyses*. US Environmental Protection Agency, Washington, DC, United States, 2000.

Faustini, Annunziata, Regula Rapp, and Francesco Forastiere. "Nitrogen dioxide and mortality: Review and meta-analysis of long-term studies." *European Respiratory Journal*, 44, 2014, 744–753.

Fu, Shihe, and Yizhen Gu. "Highway toll and air pollution: Evidence from Chinese cities." *Journal of Environmental Economics and Management*, 83, 2017, 32–49.

Gehrsitz, Markus. "The effect of low emission zones on air pollution and infant health." *Journal of Environmental Economics and Management*, 83, 2017, 121–144.

Gibson, Matthew, and Maria Carnovale. "The effects of road pricing on driver behaviour and air pollution." *Journal of Urban Economics*, 89, 2015, 62–73.

Guarnieri, Michael, and John R. Balmes. "Outdoor air pollution and asthma." *Lancet*, 383, 2014, 1581–1592.

Iwata, Kazuyuki, and Toshi H. Arimura. "Economic analysis of Japanese air pollution regulation: An optimal retirement problem under the vehicle type regulation in the NOx-particulate matter law." *Transportation Research Part D*, 14, 2009, 157–167.

Ministry of Environment. *Overview of Automobile NOx Control Law*. Tokyo, Japan, 2002. (in Japanese).

Ministry of Economy, Trade and Industry. *Survey on Deregistered Vehicles*. Tokyo, Japan, 2008. (in Japanese).

Ministry of Internal Affairs and Communications. *Policy evaluation on air quality protection in metropolitan areas*. Tokyo, Japan, 2004. (in Japanese).

OECD. *The cost of air pollution: Health impacts of road transport*. OECD Publishing, 2014.

Samoli, E., E. Aga, G. Touloumi, K. Nisiotis, B. Forsberg, A. Lefranc, J. Pekkanen, B. Wojtyniak, C. Schindler, E. Niciu, R. Brunstein, M. Dodič Fikfak, J. Schwartz, and K. Katsouyanni. “Short-term effects of nitrogen dioxide on mortality: An analysis within the APHEA project.” *European Respiratory Journal*, 27, 2006, 1129–1137.

Tokyo Metropolitan Area Transport Planning Council. *4th survey on distributions in Tokyo metropolitan areas*. Tokyo, Japan, 2005. (in Japanese).

Viard, V. Brian, and Shihe Fu. “The effect of Beijing’s driving restrictions on pollution and economic activity.” *Journal of Public Economics*, 125, 2015, 98–115.

Wolff, Hendrik. “Keep your clunker in the suburb: Low-emission zones and adoption of green vehicles.” *Economic Journal*, 124, 2014, 481–512.

Zhang, Wei, C.-Y. Cynthia Lin Lawell, and Victoria I. Umanskaya. “The effects of license plate-based driving restrictions on air quality: Theory and empirical evidence.” *Journal of Environmental Economics and Management*, 82, 2017, 181–220.

Appendix 1. Variable Descriptions

Ambient concentration of NO_2: Monitor-level NO_2 concentration measured by the monthly mean, daily maximum, and hourly maximum. Unit: ppb. NIES.

Days exceeding national standard: Days exceeding 60 ppb in terms of the daily average per month. NIES.

Treatment: Time-varying dummy variable equal to one if a monitor is located in a municipality subject to the ANCL and zero otherwise. Ministry of the Environment.

Temperature: Monthly mean temperature measured every 10 minutes at a meteorological station nearest to the pollution monitor (same as below), degree Celsius. JMA.

Precipitation: Total precipitation per month, millimeters. JMA.

Wind: Monthly mean wind velocity measured every 10 minutes, meters per second. JMA.

Sunlight: Total daylight duration per month, hours. JMA.

Snowfall: Total snowfall per month, centimeters. JMA.

Cloud: Degree of cloud cover per month, 0–10. JMA.

Population: Total municipal population. MIAC.

Population aged above 65 years: People aged above 65 years divided by total municipal population, percent. MIAC.

Income per capita: Total municipal taxable income divided by taxpayers, thousand yen. MIAC.

Unemployment rate: Unemployed workers divided by total municipal labor force, percent. MIAC.

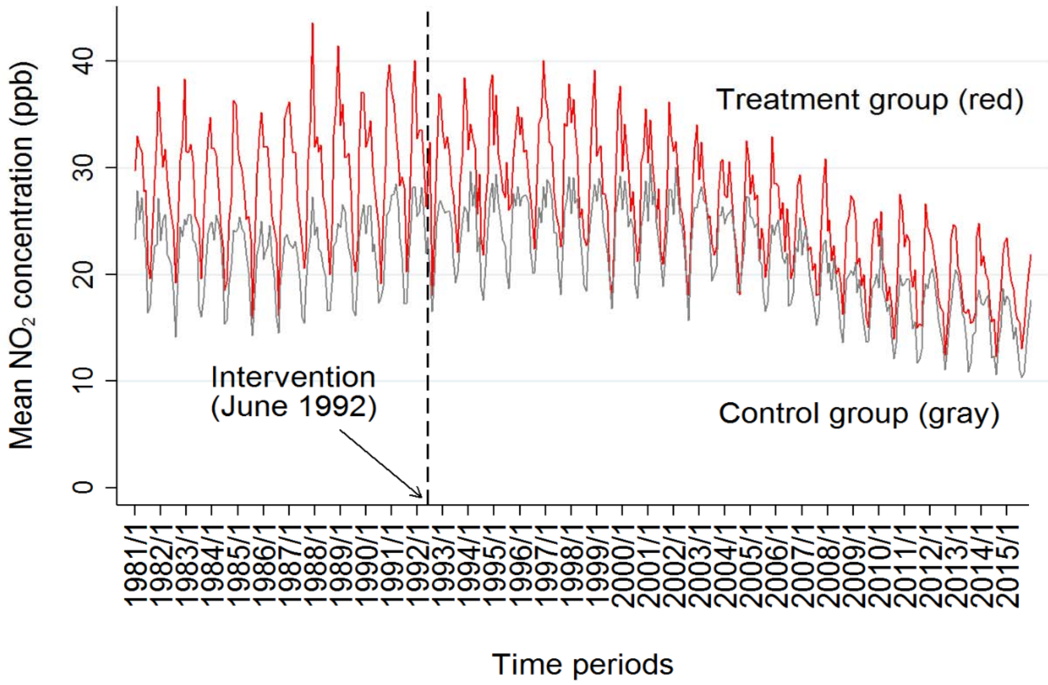
Appendix 2. ANCL Compliance by the First Year of Registration

Initial registration year	Trucks		Buses		Special-use vehicles		Diesel passenger cars	
	Standard	Small	Standard	Small	Standard	Small	Standard	Small
1988 or before	2004	2004	2005	2004	2004	2004	2005	2005
1989	2004	2004	2005	2005	2005	2005	2005	2005
1990	2005	2004	2005	2005	2005	2005	2005	2005
1991	2005	2005	2006	2005	2005	2005	2005	2005
1992	2005	2005	2006	2005	2005	2005	2005	2005
1993	2005	2005	2006	2006	2006	2006	2005	2005
1994	2006	2005	2007	2006	2006	2006	2005	2005
1995	2006	2006	2008	2006	2006	2006	2005	2005
1996	2006	2006	2009	2007	2007	2007	2006	2006
1997	2007	2006	2010	2008	2008	2008	2007	2007
1998	2008	2007	2011	2009	2009	2009	2008	2008
1999	2009	2008	2012	2010	2010	2010	2009	2009
2000	2010	2009	2013	2011	2011	2011	2010	2010
2001	2011	2010	2014	2012	2012	2012	2011	2011
2002	2012	2011	2015	2013	2013	2013	2012	2012

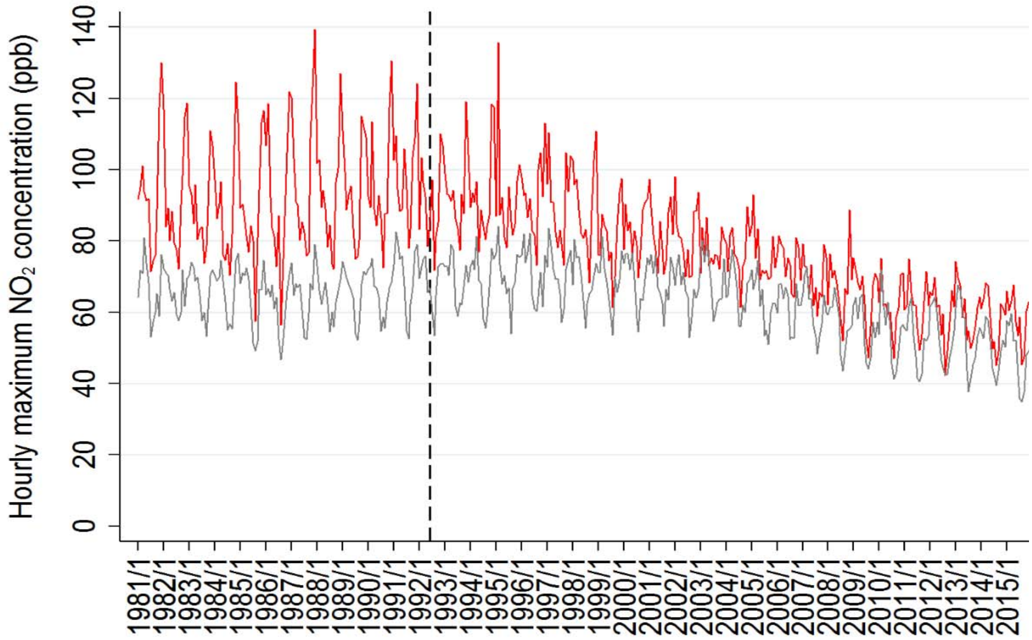
Source: Iwata and Arimura (2009).

Appendix 3. Time Trends of the Monthly Ambient Concentration of NO_2

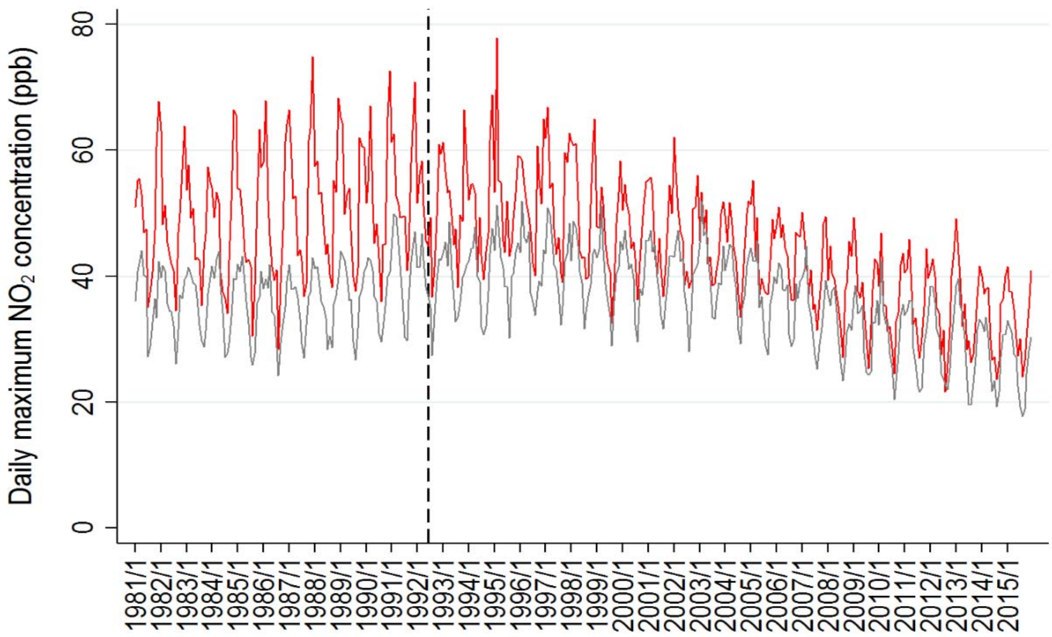
Panel A. Mean



Panel B. Hourly maximum



Panel C. Daily maximum



Notes: The treatment group covers 190 monitors in 109 designated municipalities in Tokyo, Kanagawa, Chiba, Saitama, Osaka, and Hyogo prefectures. The control group covers 35 monitors in five non-designated municipalities (Sapporo, Sendai, Hiroshima, Kitakyusyu, and Fukuoka).