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Short Report

Particulate air pollution, birth outcomes, and infant mortality: Evidence from Japan's automobile emission control law of 1992

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ABSTRACT

This study investigates the impacts of the Automobile NO_x Law of 1992 on ambient air pollutants and fetal and infant health outcomes in Japan. Using panel data taken from more than 1500 monitoring stations between 1987 and 1997, we find that NO_x and SO_2 levels reduced by 5% and 11%, respectively in regulated areas following the 1992 regulation. In addition, using a municipal-level panel data set from Japan's Vital Statistics Survey and a difference-in-differences approach, we find that the regulation explains most of the improvements in the fetal death rate after the regulation came into effect. This study provides evidence on the positive impacts of this large-scale automobile regulation policy on fetal health.

1. Introduction

A growing body of the literature in the field of health economics and medical studies has found that ambient air pollution has serious health consequences. Air pollution affects not only adult well-being, but also fetal, infant, and child health (Dockery et al., 1993; Schwartz, 2004; Currie & Neidell, 2005; Bateson & Schwartz, 2007; Currie, Neidell, & Schmieder, 2009; Coneus & Spiess, 2012; Janke, 2014). Moreover, recent studies have found that high levels of air pollution can also be directly linked to suicidal behavior and inversely related to happiness and life expectancy (Li, Folmer, & Xue, 2014; Ng, Stickley, Konishi, & Watanabe, 2016; Hill et al., 2019). The weight of this evidence has led to the consensus that air pollution control regulations are required to maintain well-being, especially in developing countries (Greenstone & Hanna, 2014).

In this study, we contribute to the literature by analyzing the impacts of Japan's Automobile NO_x Law of 1992 on birth outcomes and infant mortality. The extensive previous literature has studied the health impacts of regulations on pollutant emissions from power plants (Luechinger, 2014; Tanaka, 2015), nationwide air pollution control policy (Sanders & Stoecker, 2015; Lee, Yoo, & Nam, 2018), and the introduction of an emissions market for nitrogen oxides (Deschénes, Greenstone, & Shapiro, 2017). The negative effects of air pollutants emitted from automobiles on infant health have also been highlighted (Currie et al., 2009; Coneus & Spiess, 2012). However, the impacts of automobile emission regulations on fetal and infant health have been understudied. While the related study by Beatty and Shimshack (2011) focused on a localized emission reduction program on school buses in the state of Washington, we evaluate a generalized emission reduction program on automobiles across Japan. As health outcomes, we investigate and measure the impacts on several fetal and infant health outcomes in more detail than in their study.

As regulated areas, the 1992 regulation selected 196 municipalities exceeding the emission control standard in Saitama, Chiba, Tokyo, Kanagawa, Osaka, and Hyogo prefectures. In these areas, a stringent regulation was enforced; trucks, buses, and even special motor vehicles such as ambulances were regulated through motor vehicle inspections. We use this quasi-experimental setting induced by the regulation to compare the changes both in air pollutant concentrations and in birth and infant health outcomes between regulated and non-regulated areas before and after the treatment, using the differences-in-differences (DID) methodology.

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To conduct the analysis, we first use panel data taken from more than 1500 monitoring stations between 1987 and 1997. As air quality outcomes, we consider a wide variety of pollutants, namely nitrogen dioxide (NO_X), sulfur dioxide (SO_2), photochemical oxidants (O_x), and suspended particulate matter (SPM). Although related studies have compared air quality in regulated and non-regulated areas, we assume that the treatment effects vary between the core regulated areas and surrounding areas (Greenstone, 2004; Auffhammer & Kellogg, 2011). Using these monitoring data with location information, we thus investigate the neighboring effects of the regulation by controlling for the meteorological features around monitoring stations. We then draw on municipal-level data on fetal and infant health outcomes from the *Vital Statistics of Japan (VSJ)*, which contains *all* birth and death records for the six target prefectures in 1989, 1991, 1993, and 2000. The fetal death rate (FDR), low-birth weight rate (LBWR), infant mortality rate (IMR), and neonatal mortality rate (NMR) are used to comprehensively analyze the potential effects of the regulation.

We find that the regulation significantly improved air quality in regulated areas. Our estimates suggest that NO_x and SO_2 levels decreased by 5% and 11%, respectively, in regulated areas following the 1992 regulation. Accordingly, we find that the enactment of the regulation law reduced the risk of fetal deaths. Our estimate suggests that the regulation reduced the FDR by 3.5%, which fully explains the improvements in these rates in regulated areas before and after the regulation. We also find stronger ameliorating effects in 2000, suggesting a positive and lasting effect on fetal health.

The remainder of this paper is structured as follows. Section 2 provides a brief overview of the historical background of the regulation policies. Section 3 describes the data used. Section 4 presents our empirical strategy and the results. Section 5 concludes.

2. Background

The occurrence of diseases due to environmental pollution emerged as a serious problem in Japan during the country's period of rapid economic growth in 1954–1973 (Harada, 1995). This led to the enactment of the Basic Act for Environmental Pollution Control in 1967. This law established environmental quality standards on air pollutants. To ensure compliance with these standards, the Air Pollution Control Act, which aimed to limit emissions of air pollutants from factories, business establishments, and automobiles, was then enacted in 1968. However, NO_2 concentration failed to meet this standard—even by 1985; Indeed, it subsequently exhibited a worsening trend because of the increase in the use of diesel automobiles (Air Quality Bureau of the Environment Agency and Automobile NOx Law Research Group, 1994).

Thus, to reduce NO_x emissions, especially NO_2, from automobiles, the Automobile NO_x Law was enacted in 1992. This law selected 196 municipalities in Saitama, Chiba, Tokyo, Kanagawa, Osaka, and Hyogo prefectures as regulated areas based on two considerations: traffic flow in these areas was heavy and it would be difficult for them to comply with the environmental standards for NO_2 using only existing regulations. In these areas, trucks, buses, and special motor vehicles (e.g., ambulances) began to be regulated through motor vehicle inspections to satisfy the emission control standards (Table 1). The standards controlled NO_x emissions from diesel automobiles at 28–65% of the level in the previous standards. As a result of the regulation, the use of diesel automobiles that emit considerable amounts of toxic exhaust gas was controlled (Appendix A).

Fig. 1 displays the annual average concentrations of NO_x and SO_2 from 1987 to 1997. In addition to NO_x, SO_2 is an important pollutant in diesel exhaust emissions. Fig. 1a shows that the level of NO_x in regulated areas decreased after the regulation was introduced. The mean NO_x concentrations of the regulated areas before and after the enactment of the regulation were 67.60 and 63.77 parts per billion (ppb), respectively. At the same time, the level of SO_2 also decreased between 1991 and 1993, as shown in Fig. 1b. The decrease in SO_2 levels in the regulated areas was larger than that in non-regulated areas. This is the first time such a finding has been documented in the literature (Arimura & Iwata, 2008; Wakamatsu, Morikawa, & Ito, 2013). This fact highlights the need to reassess the effectiveness of the Automobile NO_x Law.

3. Data

3.1. Air pollutant concentrations

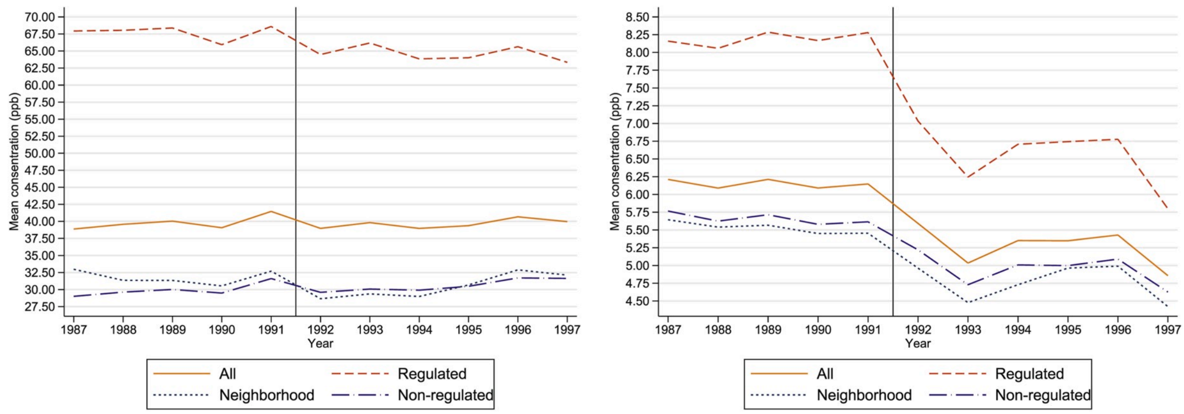
For our empirical analyses, we use a panel dataset on the annual average air pollutant concentrations of NO_X, SO_2, O_x, and SPM at the monitoring station level between 1987 and 1997. Data were taken from the *Environmental Database* provided by the National Institute for Environmental Studies (units in ppb or $\mu g/m^3$ for SPM). In this study, O_x and SPM are also viewed as regulation-related pollutants because they can increase as a result of diesel exhaust emissions. Fig. 2 illustrates the location of regulated areas and the stations that monitored SO_2 concentration. There were more than 1500 stations nationally around 1992. Regulated areas had as many as 342 stations, or 20.6% of the total number.

Although the mechanisms through which each air pollutant affects health outcomes are still not well understood, some plausible mechanisms and pathways exist. NO_x can oxidize tissue components and eliminate the anti-oxidizing protective systems of an organism. Increasing lipidic peroxidation in the maternal or fetal compartment has been associated with premature birth (Lacasaña, Esplugues, & Ballester, 2005). The sulfur inhaled with SO_2, which is highly soluble in water, enters the blood rapidly after the onset of exposure (Rogers et al., 2000). Ozone, which is a secondary pollutant, damages tissue, reduces lung function, and sensitizes the lungs to other irritants (Currie & Neidell, 2005). SPM can take various forms, depending on the source. Nevertheless, recent studies indicate that inflammation mediated by oxidative

Table 1
Emission control standards for automobiles.

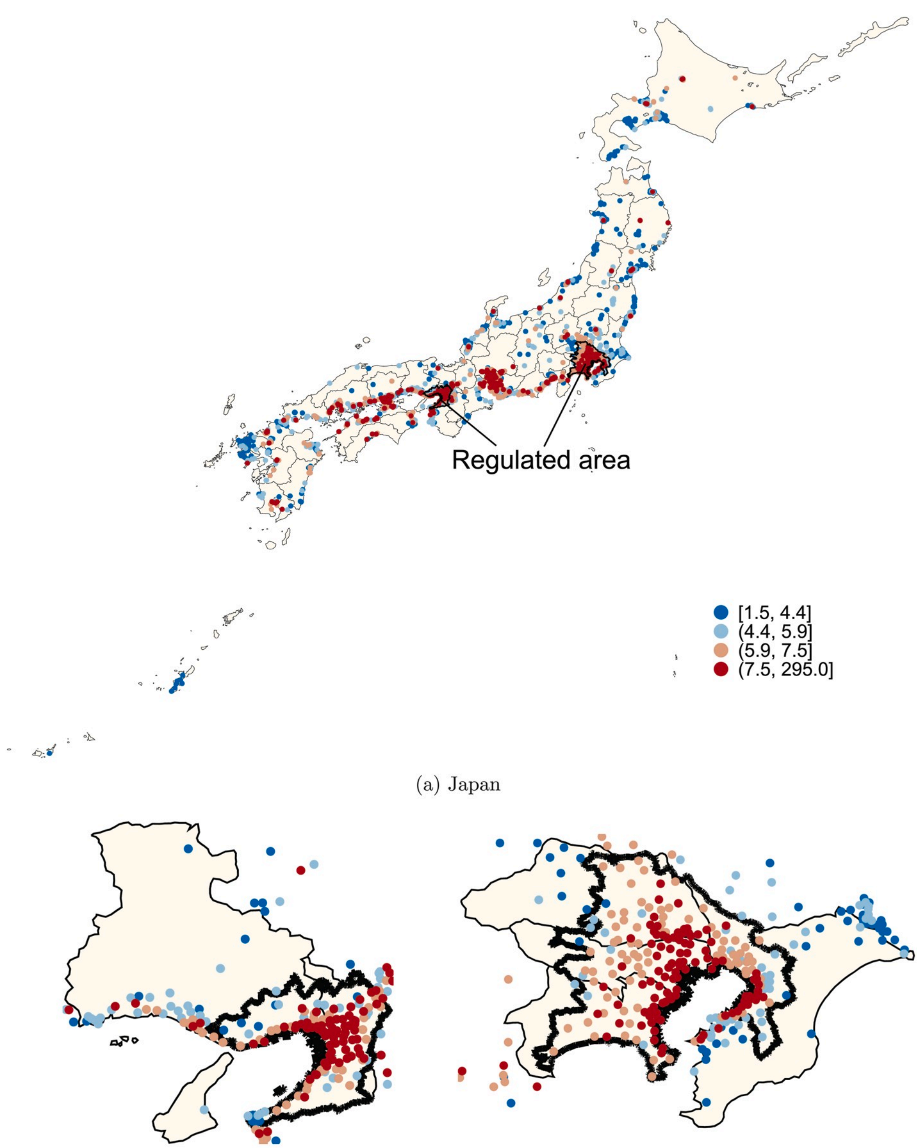
	Diesel				Gasoline			
Weight class	Test mode	Measure	Max	Mean	Test mode	Measure	Max	Mean
≤1.7	10·15	g/km	0.48	0.25	10·15	g/km	0.48	0.25
	D6	ppm	100	70	–	–	–	–
$1.7 < x \leq 2.5$	10·15	g/km	0.98	0.70	10·15	g/km	0.98	0.70
	D6	ppm	210	150	–	–	–	–
$2.5 < x \leq 5.0$	D13	g/kWh	6.90	5.10	13	g/kWh	6.90	5.10
	D6	ppm	350	260	6	ppm	600	450
> 5.0	D13	g/kWh	9.40	7.20	13	g/kWh	9.40	7.20
	D6	ppm	520	400	6	ppm	900	690

Notes: The unit of weight is metric tons. The initial character D in the second column indicates the mode for diesel automobiles. Measure, Max, and Mean indicate amounts of nitrogen oxide. This emission control standard was partly updated in 1999. Sources: (Air Quality Bureau of the Environment Agency and Automobile NOx Law Research Group, 1994), p. 85.



(a) NO_x (b) SO_2

Fig. 1. Annual average concentrations of NO_x and SO_2, 1987–1997.
Notes: The solid, dashed, dotted, and chain lines indicate average concentrations of NO_x and SO_2 in all areas, regulated areas, neighboring areas, and non-regulated areas, respectively. The neighboring areas are not included in the regulated areas, but are part of the six included prefectures. The vertical line indicates the timing of the enactment of the Automobile NO_x Law. Sources: National Institute for Environmental Studies, Environmental Database (Appendix B.1).



(a) Japan

(b) Hyogo and Osaka (c) Chiba, Kanagawa, Saitama, and Tokyo

Fig. 2. Spatial distribution of SO_2 concentration and regulated areasNotes
The SO_2 concentrations (ppb) represent the mean value during 1987–1991. The data on longitudes and latitudes are available for only those stations still in use in 2001, and this figure covers 91.4% (1,519/1,662) of the stations used in the regression analyses for SO_2 concentration (NO_x shows a similar distribution). Sources: National Institute for Environmental Studies, Environmental Database (Appendix B.1).

stress creates a mechanism through which diesel particulate matter may cause toxicity (Ristovski et al., 2012). Because we focus on SPM emitted from diesel automobiles, this mechanism offers a valid explanation.

3.2. Birth outcomes and infant mortality

For the fetal and infant health outcomes, we constructed a municipal-level panel data set from 390 municipalities for the years 1989, 1991, 1993, and 2000 using data from the *VSJ*. The data on 1989 and 1991 are used as the pre-treatment period, and the data on 1993 and 2000 are used as the post-treatment period. As described in Section 2, 196 municipalities were regulated by the law. Therefore, in our analysis in Section 4.2, we regard these 196 municipalities as our treatment group; the remaining 194 municipalities in the non-regulated area are used as the control group. Although one may expect that the set of municipalities surrounding the 196 municipalities would be a the potential treatment group, we confirm that the law did not improve the air pollutant concentration in the non-regulated municipalities (Section 4.1). Therefore, we do not regard these surrounding municipalities as the treatment group in our analysis.

As Sanders and Stoecker (2015) discussed, birth- and death-related outcome variables such as the FDR and IMR calculated from survey samples are more likely to suffer sample selection issues. However, our comprehensive registration-based birth and death records enable us to overcome such potential selection issues in the regression analyses. As noted earlier, we adopt the FDR, LBWR, IMR, and NMR in our statistical analyses. The FDR is the number of fetal deaths per 1000 births, the LBWR is defined as the number of births with a weight less than 2500 g per 100 births, the IMR is the number of infant deaths (within a year of birth) per 1000 live births, and the NMR is the number of neonatal deaths (within four weeks of birth) per 1000 live births. Regarding the LBWR, the weight recorded in the VSJ is measured at birth, and thus, both term and preterm births are included. One can infer that more than half of the children weighing less than 2500 g are term births (Takemoto, Ota, Yoneoka, Mori, & Takeda, 2016).

The related literature suggests that specific fetal exposure windows to air pollution have greater or lesser relevance for adverse pregnancy outcomes and child survival (e.g., Hu et al., 2018). Because the VSJ does not contain any information on the date or month of births, we could not identify the potential critical windows of the exposure to the regulation. Therefore, we try to capture the overall effects of the regulation on the health outcomes of the treatment group.

3.3. Control variables

We use meteorological data as the control variables in the air pollutant regressions because weather shocks can affect both air quality and birth outcomes (Deschênes, Greenstone, & Guryan, 2009; Silva et al., 2017); strong wind and rain may carry air pollutants away and short periods of sunshine may mitigate ozone production. If meteorological conditions changed at the same time and in the same place as the enforcement of the Automobile NO_x Law, we would fail to capture the regulation's effects. To deal with this potential issue, we use variables controlling for the number of days with rainfall of over 1 mm, the number of days with a maximum wind speed of over 10 m/s, and the percentage of sunshine hours in a year. Each air pollution monitoring station uses meteorological data from the nearest weather monitoring station.

In the health regressions, we use data on public health and regional standards of living. We consider the coverage of hospitals because accessibility to medical institutions may be negatively correlated with health outcomes. The share of low-income households, namely the number of households receiving welfare benefits per 100 households, is also considered. The Japanese economy was already developed in the 1990s, and thus the density of low-income households is a more suitable control variable than average household income for capturing adverse birth and infant health outcomes (Cabinet Office, 2016).

Appendix B reports the details and summary statistics of the dependent and control variables.

4. Empirical analysis

4.1. Air pollutant concentrations

We begin our empirical analysis by examining the effects of the 1992 regulation on air pollutant concentrations. To do so, we employ a fixed effects model in the spirit of the DID approach in the following form:

$$\text{Pollutant}_{it} = \alpha + \beta Regulation_i \times Post_t + \gamma Neighborhood_i \times Post_t + \mathbf{x}'_{it}\boldsymbol{\delta} + \nu_i + \mu_t + \varepsilon_{it} \quad (1)$$

where i indexes monitoring stations and t indexes years. The dependent variable $Pollutant_{it}$ represents average NO_x, SO_2, O_x, or SPM concentrations (ppb or $\mu g/m^3$). $Regulation_i$ represents an indicator variable for regulated areas and $Post_t$ is an indicator variable for the post-regulation period. Therefore, our parameter of interest is β, and its estimate $\widehat{\beta}$ can be interpreted as a potential effect of the regulation. To capture the external effects, we also include the interaction term $Neighborhood_i \times Post_t$, where $Neighborhood_i$ is an indicator variable coded one if i is not included in the regulated areas but is in the six included prefectures. If the estimate $\widehat{\gamma}$ is statistically significantly negative, therefore, the regulation might have had positive neighboring effects. $\mathbf{x}_{it}$ is a vector of the meteorological control variables introduced in Section 3.3. ν_i and μ_t represent the monitoring station and year fixed effects, respectively. ε_{it} is a random error term.

Table 2 presents the results. Columns (1)–(4) show that the estimated effects of the regulation are significantly negative across all specifications. Moreover, our results remain largely unchanged if we include the neighborhood interaction in Eq. (1), as shown in Columns (5)–(8). In contrast, the estimated coefficients of *Neighborhood* × *Post* are close to zero and statistically insignificant. This finding suggests that the regulation did not have a strong effect on pollutants in the neighborhood of the regulated areas.

The estimates reported in Columns (5) and (6) indicate that the law decreased the levels of NO_x and SO_2 in regulated areas by roughly 5% (3.458/67.86) and 11% (0.893/8.20), respectively. Clearly, the 1992 regulation significantly reduced both NO_x and SO_2 pollution, as discussed in Section 2. Columns (7) and (8) confirm that the regulation also reduced the O_x and SPM concentrations. The decreases in O_x and SPM attributed to the regulation are calculated as roughly 5% (1.1/22.74) and 3% (1.45/49.86), respectively.

4.2. Birth outcomes and infant mortality

As described in Section 3, we use a municipal-level panel data set on birth outcomes and infant mortality, taken from 390 municipalities for 1989, 1991, 1993, and 2000. Here, 196 of 390 municipalities in the regulated area are defined as the treatment group. Our finding in Section 4.1 confirms two important features of the regulation: (1) it played an important role in reducing air pollutant concentrations; and (2) it does not significantly improve the effects in neighboring areas. Considering these features, we do not include the surrounding municipalities of the regulated area in the treatment group in our analysis. We then investigate the potential improving effects of the regulation on a wide variety of fetal and infant health outcomes using the regression DID models in the following form:

$$\begin{aligned}Health_{jt} &= \pi + \kappa Regulation_j + \eta_1 I(\text{Year}=1991)_t + \eta_2 I(\text{Year}=1993)_t + \eta_3 I(\text{Year}=2000)_t \\ &+\theta_1 Regulation_j \times I(\text{Year} = 1991)_t + \theta_2 Regulation_j \times I(\text{Year} = 1993)_t \\ &+\theta_3 Regulation_j \times I(\text{Year} = 2000)_t + \mathbf{z'}_{jt}\varphi + \lambda_{g_j} + u_{jt}\end{aligned} \quad (2)$$

where j denotes municipalities and t indexes years. The d2ependent variable $Health_{jt}$ is the FDR, LBWR, IMR, or NMR. *Regulation* is a dummy variable for the regulated area, and $I(\cdot)$ is an indicator variable for a specific year. Because the potential treatment effects of the law may not necessarily be constant after the regulation, we include interaction terms between the *Regulation* and the indicator variables for each year since 1992 ($Regulation \times I(\text{Year} = 1993)$ and $Regulation \times I(\text{Year} = 2000)$) to capture the heterogeneity in the effects. Our parameters of interest are thus θ_2 and θ_3, the estimates of which, $\widehat{\theta}_2$ and $\widehat{\theta}_3$, respectively, can be interpreted as potential treatment effects of the regulation on health outcomes. We expect the condition $\widehat{\theta}_2 > \widehat{\theta}_3$ to hold if the law had persistent ameliorating effects on health outcomes. As a falsification test, we also include the interaction term between *Regulation* and the indicator variables for the year *before* the regulation (i.e., 1991). We expect that the estimated coefficient $\widehat{\theta}_1$ must be statistically insignificant because the regulation should not improve the health outcomes prior to when it was implemented. $\mathbf{z}_{jt}$ is a vector of the control variables introduced in Section 3.3, λ_{g_j} is a city-county fixed effect, which captures the unobservable time-constant factors varying over cities and counties, and v_{jt} is a random error term.

Table 3 presents the results. Column (1) indicates that the estimated treatment effects on the FDR are negative and statistically significant. The estimate of the effect on the FDR in 1993 is − 3.49, implying that the regulation reduced the FDR by approximately 3.5%. Thus, it accounts for roughly 10% (3.5/36.8) of the mean value of the rate in the regulated areas before it was enacted. An important finding is that this ameliorating effect of the law on the FDR increased after 2000: the regulation reduced the FDR by approximately 7.1%, accounting for roughly 20% (7.1/36.8) of the mean value of the rate in the regulated areas in the pre-intervention period. This result suggests that the regulation might have had persistent improving effects on the risk of fetal deaths in the regulated area. That the Air Pollution Control Act had a positive effect on fetal deaths is consistent with the findings of previous studies (Sanders & Stoecker, 2015). Finally, the estimated coefficient on $Regulation \times I(\text{Year} = 1991)$ for our falsification test is close to zero and statistically insignificant, which supports the validity of our specification.

In columns (2)–(4), the estimated effects on the LBWR, IMR, and NMR are statistically insignificant. One plausible explanation for these unexpected results is the counteraction: if the regulation improved postnatal outcomes, the reduction in the FDR would increase the proportion of unhealthy babies to total births via the mortality selection mechanism. In addition, the poor model fit in Columns (3) and (4), reflected in the *R*-squared values, is consistent with the fact that standards of infant care were sufficiently high in Japan in the 1990s.

Finally, our results remain unchanged if we cluster the standard errors at the city-county level, rather than at the municipal level, to take into account potential correlations between cities and counties (Appendix C.1). Previous studies suggest that improvements in air quality have positive effects on the risk of child mortality (Bailey et al., 2018). To investigate whether the regulation improved child death rates, we ran DID regressions using prefecture-level data on the 1990, 1995, and 2000 death rates. Although we investigated the potential effects on child death rates for age 0, age 1–5, and ages 6–10, we found no ameliorating effects on child death rates in all age bins. This may be because the data are aggregated at the prefecture-level, or because the attenuation bias might be higher, owing to measurement errors in the treatment variables. See Appendix C.1 for further details on these analyses.

5. Conclusion

The present study assessed the Automobile NO_x Law in Japan using quantitative methods. The estimated reductions in NO_x (3.46 ppb) and SO_2 (0.89 ppb) attributable to the regulation account for 87% and 52%, respectively, of the total decreases in the regulated areas (3.97 ppb for NO_x and 1.71 ppb for SO_2). The estimated 3.5% reduction in FDR attributable to the regulation fully accounts for the observed 2.4% decrease in FDR. Furthermore, the ameliorating effects of the regulation were still robust in 2000, suggesting the persistence of the improving effects on fetal health.

We contribute to the related literature in the following two ways. First, as discussed in the Introduction, this study provides empirical evidence on the positive impacts of this large-scale automobile regulation policy. While Beatty and Shimshack (2011) investigated a localized

Table 2
Effects of the Automobile NO_x Law on air pollutants.

	(1) NO_x	(2) SO_2	(3) O_x	(4) SPM	(5) NO_x	(6) SO_2	(7) O_x	(8) SPM
	[67.86]	[8.20]	[22.74]	[49.86]	[67.86]	[8.20]	[22.74]	[49.86]
Regulation	− 3.388***	− 0.893***	− 1.098***	− 1.480***	− 3.458***	− 0.893***	− 1.100***	− 1.450***
× *Post*	(0.525)	(0.101)	(0.224)	(0.358)	(0.527)	(0.102)	(0.230)	(0.362)
Neighborhood					− 0.653	0.001	− 0.018	0.263
× *Post*					(0.627)	(0.130)	(0.444)	(0.517)
Meteorological Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Station FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Observations	14,085	13,743	9286	12,193	14,085	13,743	9286	12,193
Clusters	1312	1274	860	1186	1312	1274	860	1186
Adj.*R*-squared	0.9733	0.8227	0.6918	0.8510	0.9733	0.8227	0.6918	0.8510

Notes: Each dependent variable represents annual average concentration (ppb or $\mu g/m^3$). The mean values of the dependent variables in regulated areas in the pre-intervention period are reported in brackets. The meteorological control variables include the number of days with rainfall of over 1 mm, the number of days with a maximum wind speed of over 10 m/s, and the percentage of sunshine hours in a year. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors clustered at the monitoring station level are in parentheses.

Table 3
Effects of the Automobile NO_x Law on fetal and infant health outcomes.

	(Air Quality Bureau of the Environment Agency and Automobile NOx Law Research Group, 19941) FDR	(2) LBWR	(3) IMR	(4) NMR
	[36.79]	[6.40]	[4.46]	[2.45]
Regulation	2.593	−0.088	−0.017	−0.003
	(2.799)	(0.315)	(0.916)	(0.685)
I (Year = 1991)	−1.179	0.168	−0.246	−0.310
	(1.497)	(0.171)	(0.524)	(0.361)
I(Year = 1993)	−1.655	0.624***	−0.255	−0.249
	(1.521)	(0.191)	(0.538)	(0.382)
I(Year = 2000)	−4.397**	2.290***	−1.055**	−0.360
	(2.029)	(0.227)	(0.450)	(0.386)
Regulation × *I* (Year = 1991)	−1.501	0.202	−0.026	−0.078
	(1.570)	(0.183)	(0.545)	(0.377)
Regulation × *I* (Year = 1993)	−4.218**	0.105	0.188	0.019
	(1.637)	(0.201)	(0.567)	(0.401)
Regulation × *I* (Year = 2000)	−7.094***	0.060	0.115	−0.397
	(2.130)	(0.238)	(0.502)	(0.404)
Control variables	Yes	Yes	Yes	Yes
City-county FE	Yes	Yes	Yes	Yes
Observations	1559	1559	1559	1559
Municipalities	390	390	390	390
Adj. *R*-squared	0.5595	0.5759	0.0276	0.0392

Notes: FDR, LBWR, IMR, and NMR represent the fetal death rate, low-birth weight rate, infant mortality rate, and neonatal mortality rate, respectively. The regression shown in Column (1) is weighted by the number of births, whereas the regressions shown in Columns (2)–(4) are weighted by the number of live births. The mean values of the outcome variables in regulated areas in the pre-intervention period are reported in brackets. The control variables include the coverage of hospitals and proportion of households receiving welfare benefits. ***, **, and * represent statistical significance at the 1%, 5%, and 10% levels, respectively. Standard errors clustered at the municipal level are in parentheses.

emission reduction program on school buses, we evaluate a more generalized emission reduction program on automobiles. Moreover, we investigate the impacts of the regulation on several fetal and infant health outcomes not considered in their study.

Second, we provide a case study of Japan. Existing evidence on the relationship between air pollution and infant and child health is predominantly from Western developed countries, such as England, Germany, Sweden, and the United States (Chay & Greenstone, 2003; Currie et al., 2009; Coneus & Spiess, 2012; Janke, 2014; Simeonova, Currie, Nilsson, & Walker, 2019). The vast majority of studies investigating the role of air quality regulations have also focused on these western developed countries (Greenstone, 2004; Luechinger, 2014). In addition to the extensive studies of the case of China (Tanaka, 2015; Henneman et al., 2017), recent works have started to examine the case of South Korea (Altindag et al., 2017; Lee et al., 2018). However, the effectiveness of Japan's regulation policy remains understudied. Despite its rapid post-war economic growth, Japan overcame its air pollution problems to a great degree by the 1980s (Wakamatsu et al., 2013) by implementing the strictest regulations in the world (Air Quality Bureau of the Environment Agency and Automobile NO_x Law Research Group 1994). In this respect, Japan is considered to be the ideal example of an Asian country for studying effective regulation policies. Our findings support the evidence that a stringent (i.e., wide-scale inspection-based) automobile regulation can reduce the risk of fetal deaths in highly polluted areas.

However, this study is not without limitations. Since our municipal-level aggregated data did not contain information on birth dates, it is difficult to fully explain the mechanism between air pollution and fetal health outcomes. Moreover, we could not utilize the independent variables to control for potential confounding factors such as the percentage of older pregnant women, availability of neonatal intensive care units, and precise measurements on the standard of living in each municipality. Despite these limitations, this study suggests that large-scale automobile regulation policy may be a significant factor associated with the improvement of fetal health.

CRediT authorship contribution statement

Tatsuki Inoue: Software, Formal analysis, Data curation, Writing - original draft, Visualization, Project administration. **Nana Nunokawa:** Investigation, Resources, Data curation. **Daisuke Kurisu:** Writing - review & editing, Funding acquisition. **Kota Ogasawara:** Conceptualization, Methodology, Validation, Supervision.

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Appendix A. Supplementary data

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