Replication Work of Greenstone & Hanna (2014) and Preliminary Exploration of the Effect of 2008 Economic Crisis on the Performance of India's Environmental Regulations

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Abstract. Inspections of environmental regulation effects in developing countries are important. Greenstone & Hanna (2014) took a deep insight into the performance of India's air and water regulations, including the Supreme Court Action Plans (SCAP), the Catalytic Converter Policies (CAT), and the National River Conservation Plan (NRCP). The authors applied a difference-in-difference (DID) design using a two-stage econometric approach based on their organized city-level panel data for the years 1986-2007. Results have shown the association between the catalytic converter policies and substantial improvement in air quality, while no measurable benefits have been found for water regulations. In addition, the authors determined a modest relationship between the decline in infant mortality rate and successful air regulations, though the relationships were not statistically significant. The parallel-trend assumption for DID was tested by Quandt Likelihood Ratio (QLR). We managed to use the R language to replicate their main findings and apply a preliminary DID approach to study the effects of the 2008 Economic Crisis on the effects of air policies. Only CAT was still likely to sustain their influence albeit disturbed by the crisis. Further research may take spatial insights and systematic homogeneity among cities in response to policies or events into consideration.

This replication project is made available on GitHub by Zhijie Zhou: https://github.com/zjalexzhou/replication-Greenstone-and-Hanna-2014

Introduction

Environmental protection, including reducing greenhouse gas emissions, is one of the most beneficial practices for developing countries. According to the survey, India's economy is growing at 6.4 per year, putting enormous pressure on the environment. For India, environmental protection and economic development are not in balance. This article assesses India's environmental protection and environmental law based on air pollution, water pollution, environmental regulations, and infant mortality. India provides a compelling setting to explore the efficacy of environmental regulations for several reasons:

- India has large number of population.
- It has been experiencing rapid economic growth of about 6.4 % annually over the last two decades (much pressure on the environment).
- India is widely regarded as having suboptimal regulatory institutions; we can test the advantages and disadvantages of Indian environmental policies.
- India has a rich history of environmental regulations that dates back to the 1970s, so we would have a larger data range to see the environmental effects.

We care about policy effects in India also because we could learn from India's lessons for China's environmental regulations. Both China and India have received extensive attention from the central government regarding the status of air pollution. Both countries prefer the control of vehicle emissions. However, the Chinese government has defined regulations to reduce the number of cars on the road. In contrast to the Indian government, the Chinese government has focused more on the root causes of pollutants while the Indian government has pursued regulatory and ameliorative measures (Feng, 2020; Library of Congress, 2018; Ganguly, 2020). In comparison with the water management policies of China and India, they both focus on restoration of river ecosystems and reduction of pollutant discharges. However, China's water pollution control policies are more effective because the Chinese government has strict regulations and penalties that make it more costly to violate the law, whereas India does not (Schrag, 2020; Samad et al., 2015; Krishan et al., 2019).

In Greenstone and Hanna (2014), the analysis of PM, SO2, and NO2 concentrations shows that the Indian government's installation of catalytic converters on vehicles has effectively reversed the trend of increasing pollution concentrations. It can be concluded that catalytic converter policy is closely related to the reduction of air pollution. From the data, the rapid growth rate of environmental pollution concentration before the implementation of catalytic converter policy by the Indian government. On the contrary, the growth rate of environmental pollution concentration was significantly reduced after implementing the catalyst policy. Comparing the data of BOD, FColi, and DO, the National River Conservation Program (NRCP) effectively treats and improves water pollution. Although the NRCP mainly focuses on improving domestic pollution, the data show that FColi has not been significantly improved, which might be due to the lack of federal or state funding for municipalities, which has resulted in only 82 of the 152 approved wastewater treatment plants being built. Infant mortality is measured as a method of evaluating air and water pollution policies. However, this article does not take into account the influence of the infant's parents and some extraneous factors.

We attempt to use R to replicate the main findings with the DID method, i.e., whether the implemented air/water policies had effects on the corresponding environmental qualities or infant mortality rates based on the investigation of shifting means or trends of several pollutant concentrations, including:

- First-step (event study): measure the average annual pollution concentration in the years before and after a policy's implementation.
- Second-step (trend break): whether the policies are associated with pollution reductions with mean shift in pollution concentrations after a policy's implementation and a policy's impact evolving over time.
- Quandt likelihood ratio (QLR) Test as robustness check.

Based on the replication findings, we also would like to apply the authors' methodologies on air quality, water quality, and infant mortality data of India after 2007 to test if the conclusions still hold true in more recent settings. We have collected air pollution and infant mortality data from 2009 to 2019 for further insights (reliable sources of water pollution data have not been found yet). Based on our preliminary findings, only CAT policy was still likely to sustain their influence albeit disturbed by the crisis. More insights into the environmental conditions, spatial clustering and systematic homogeneity among cities in response to policies or events may be helpful to answer similar questions.

Methods

The released codes for replication were in STATA. We reproduced the main findings of the study using R.

Data Wrangling

Greenstone and Hanna (2014) managed to organize the first-ever panel data for India at city-level, including 140 cities with air pollution data, 424 cities (along 162 rivers) with water pollution data, and infant mortality (IM) rate data collected from *Vital Statistics of India* (prior to 1996) or from database searching efforts (post 1996). The study period for the authors was from 1986 to 2007.

Each observation is a summarized record for air/water pollution or IM data for a particular city at a particular year, with the status of the corresponding policy adoption coded as 1 (adopted) or 0 (non-adopted). The raw data sets were cleaned to remove missing values and for adopting cities, a city would be included in the sample if it has at least one observation 3 or more years before the policy's adoption and at least 1 observation 4 or more years afterward (including the year of adoption). The year of policy adoption is coded as year 0 ($\tau = 0$). And event-year dummies were created for each year with valid observations. All τs were set equal to zero for non-adopting cities (those cities that never had environmental regulations within the scope of this study adopted).

However, some data cleaning steps were not disclosed or there existed gaps between STATA and R's treatment on missing values. We observed a slightly difference in the number of observations left for regression between the authors' work and ours.

Difference-in-Difference (DID) Design

The authors used a Difference-in-difference experimental design with the pollution and infant mortality data as observational study data, comparing the differential effect of a treatment on a 'treatment group' (those cities adopted any pollution control policy) versus a 'control group' (those cities never adopted such policies). The method calculated the effect of a treatment on an outcome by comparing the average change over time in the outcome variable for the treatment group to the average change over time for the control group. Table 1 attached is a simple demonstration for the process and logic of DID design adapted from the work of our classmate Min Hu:

Table 1: The Difference-in-Difference Quasi-experimental Process

	Before Policy Adoption	After Policy Adoption	Difference in Estimates
Treatment Group	$\beta_0 + \beta_1$	$\beta_0 + \beta_1 + \beta_2 + \beta_3$	$\beta_2 + \beta_3$
Control Group	β_0	$\beta_0 + \beta_2$	β_2
Difference in Estimates	β_1	$\beta_1 + \beta_3$	β_3 (DID)

First-stage Regression: Event Study

Event study is the first step of the two-stage regression approach used by the authors. Equation (1) is an event-study style function to figure out the association between a particular policy's effects and the variations in one of the seven "outcomes," including SPM (Pariculate Matter), SO2 (Sulfur Dioxide), NO2 (Nitrogen Dioxide), BOD (Biochemical Oxygen Demand), ln(FColi) (Logarithm of Fecal Coliform), DO (Dissolved Oxygen), and Infant Mortality (IM) Rate. Note that the regression was weighted by urban population (pollution concentration as outcome) or the number of birth (IM as outcome) for each city, each year.

$$Y_{ct} = \alpha + \sum_{\tau} \sigma_\tau \mathbf{D}_{\tau,ct} + \mu_t + \gamma_c + \beta \mathbf{X}_{ct} + \epsilon_{ct} \tag{1}$$

- Y_{ct}: One of the seven outcomes per city per year from the city-level panel data.
- $\mathbf{D}_{\tau,ct}$: indicator {1,0} of whether an observation is τ years before or after policy adoption.
- σ_τ: Regression estimate for $\mathbf{D}_{\tau,ct}$.
- $\mu_t + \gamma_c$: Fixed effects of city, year.
- $\beta \mathbf{X}_{ct}$: Demographic and socio-economic variables, including literacy and per capital consumption.
- α and ϵ_{ct}: Constant and error terms.

Here is an example showing how to implement the first stage regression in R (for more details, please refer to `Perform_Regression_1` and `Present_Event_Study_Results` embedded in *main-functions.r* on Github):

```r
reg_event_study <- lm(outcome ~ tauSCm7+tauSCm6+tauSCm5+tauSCm4+tauSCm3+tauSCm2+tauSCm1+
                       tauSC0+tauSC1+tauSC2+tauSC3+ tauSCL+tauSCR+
                       tauCATm7+tauCATm6+tauCATm5+tauCATm4+tauCATm3+tauCATm2+tauCATm1+
                       tauCAT0+tauCAT1+tauCAT2+tauCAT3+tauCAT4+tauCAT5+
                         tauCAT6+tauCAT7+tauCAT8+tauCAT9+tauCATL+tauCATR+
                       lit_urban + mean + as.factor(year) + as.factor(city),
                     data = input_tau_panel, weights = pop_urban)
```

Second-stage Regression: Mean Shift

An examination of mean shift and possible trend break is the second step of the two-stage regression approach used by the authors. Equation (2A), (2B), and (2C) formally tests whether the policies are associated with pollution or infant mortality rate reductions with three alternative specification from the "time" perspective. Note that at this stage we have the "mean" effects of policies for all cities estimated by the first-stage regression. π_1 tests for a mean shift in the outcome after the policy's implementation; π_2 is introduced to control for a linear time trend in event time τ to adjust for differential pre-existing trends in adopting cities; π_3 indicates a policy's impact evolving over time.

$$\hat{\sigma}_\tau = \pi_0 + \pi_1 1(Policy)_\tau + \epsilon_\tau \tag{2A}$$

$$\hat{\sigma}_\tau = \pi_0 + \pi_1 1(Policy)_\tau + \pi_2 \tau + \epsilon_\tau \tag{2B}$$

$$\hat{\sigma}_\tau = \pi_0 + \pi_1 1(Policy)_\tau + \pi_2 \tau + \pi_3 (1(Policy)_\tau \ \times \ \tau) + \epsilon_\tau \tag{2C}$$

Note that the authors also included the impact of a policy five years after its implementation as $\pi_1 + 5\pi_3$.

- $\hat{\sigma}_\tau$: Event-study regression estimate for each event year (for each kind of outcome).
- $1(Policy)_\tau$: Indicator, whether the policy is in force.
- $1(Policy)_\tau \ \times \ \tau$: Interaction between the policy-in-effect indicator and the event-year variable.
- π_0 and ϵ_τ: Constant and error terms.

Here is an example (of SCAP policy) showing how to implement the second stage regression in R (for more details, please refer to `Perform_Regression_2` and `Present_2_Stage_Results` embedded in *main-functions.r* on Github):

```r
# 2A
reg_outcome_2a_SCAP <- lm(taubSC ~ scap,
                          data = sigmas_outcome,
                          weights = 1/tauseSC)
# 2B
reg_outcome_2b_SCAP <- lm(taubSC ~ tauSC+scap,
                          data = sigmas_outcome,
                          weights = 1/tauseSC)
# 2C
reg_outcome_2c_SCAP <- lm(taubSC ~ tauSC+scap+scap_trend,
                          data = sigmas_outcome,
                          weights = 1/tauseSC)
# Five-year effect
lincom_5yr_effect_SCAP <- lincom(reg_outcome_2c_SCAP, c("scap + 5*scap_trend"))
```

- Note that the `lincom` function from `biostat3` package in R is the best possible parallel to the `lincom` function in STATA, but the R version would not give out a p-value for its linear combination estimates.

Quandt Likelihood Ratio (QLR) Test for DID Assumption

Recall the basic assumption of DID approach that: If the treated subjects had not actually been treated, then their over-time change would have been the same as that of the control group, aka, the **parallel-trend** assumption. As a necessary complement to the regression results, Greenstone and Hanna (2014) adapted a Quandt likelihood ratio (QLR) test (Quandt, 1960) from the time-series econometric literature to the difference-in-differences (DID) style setting to probe the validity of the findings.

Why do we concern if there is any structural break between the control and treatment group before treatment? The assumption of DID is the parallel trend before treatment, in this case, before an air or water policy is adopted. That means the only break should be the quasi treatment we input by the DID method. If there is no structural breaks before the treatment, we proved the assumption of DID and therefore the validity of the results.

QLR test statistic is the largest $F(\tau)$ statistic computed over a range of eligible break dates ($\tau_0 <= \tau <= \tau_1$):

$$QLR = max[F(\tau_0), F(\tau_0 + 1), ..., F(\tau_1)] \tag{3}$$

Here is an example (of SCAP policy) showing how to implement the second stage regression in R (for more details, please refer to `Test_QLR` embedded in *main-functions.r* on Github):

```r
# Final organized dataset for QLR test
sigmas_QLR <- rbind(sigmas_air, sigmas_water) %>%
  mutate(breakpt_temp = 0, breaktd_temp = 0)
# Obtain the index range for the middle 50% taus
# for air/water policy effect estimates (taum7 to tau9/tau10)
pot_breakpt <- c(-3:6)
# for CAT policy effect estimates on Infant Mortality (taum10 to tau5)
if(input_outcome == "IMCAT"){pot_breakpt <- c(-6:3)}
test_data = sigmas_QLR %>% filter(outcome == input_outcome)
Fstats = numeric(length(pot_breakpt))
for(i in 1:length(pot_breakpt)){
  test_data$breakpt_temp = test_data$tau >= pot_breakpt[i]
  test_data$breaktd_temp = ifelse(test_data$breakpt_temp == 1,
                                  test_data$tau+(1-pot_breakpt[i]), 0)
  reduced <- lm(taub ~ tau, data=test_data, weights = 1/tause)
  full <- lm(taub ~ breakpt_temp+tau+breaktd_temp,
             data=test_data, weights = 1/tause)
  Fstats[i] = anova(reduced, full)$F[2]
}
# QLR is the largest F-stats for all event years (as potential breakpoint) tested
# tau_break is the event-year of QLR
QLR = round(max(Fstats), 1)
tau_break = which.max(Fstats) - (1 - (min(pot_breakpt)))
```

DID for Effects of the 2008 Economic Crisis

Greenstone and Hanna (2014) did not mention why they only include the years from 1987 to 2007, even though the study was done in 2011 (no reasons mentioned).We want to see whether the trends of air pollutants are significantly different before and after the economic crisis of 2008, and whether the air policies are continuously effective in decreasing air pollutants. We used a simplified DID approach to analyze the air quality before and after the crisis. We collected air data on SO2, NO2, and SPM from 1990 to 2015 from Kaggle (Vishal and Bhargava, 2017). Then we divided the cities into four categories, including those cities only implemented SCAP, those only implemented CAT, those implemented both, and those have adopted neither. We used the year of 2008 as a potential break-point for the DID analysis with city- and year-fixed effects. Codes for this extension (`extension-functions.r`) are also available on Github.

Results

Policy Effects

Average annual pollution concentration (standardized changes) in the years before and after a policy's implementation. Note: "standardized" estimates are plotted against tau (event year). All estimated are standardized based on the value of the estimates for **1 year before policy adoption** ($\tau = -1$). The figures plot the estimated σ_{τ}s against the τs from the estimation of equation (1).

All of our plots (event study results) perfect align with the authors' outputs, whereas some discrepancies exist in the mean shift and trend break estimates resulted from the tricky data-cleaning process - the number of our input observations valid for regression uses differs from the authors'. (see Appendix 2 for more information).

The most important findings of the two-stage regression process are the predicted five-year effects of policies on each pollutant or infant mortality rate.

Tips for table reading (the * label for estimates):

- ***Significant at the 1 percent level ($p < 0.01$).
- **Significant at the 5 percent level ($p < 0.05$).
- *Significant at the 10 percent level ($p < 0.10$).
- The number enclosed in parenthesis ( ) is the corresponding standard error for the estimate in front of it.

Air: SPM (Pariculate Matter)

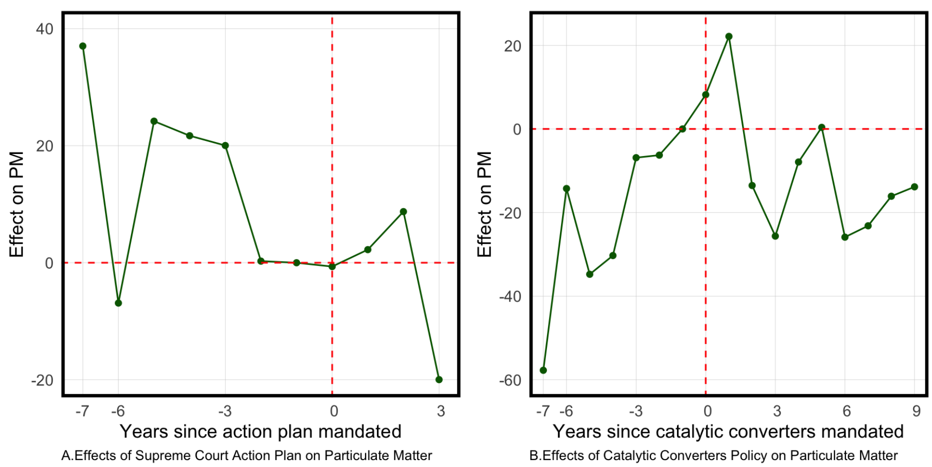

Figure 1: SCAP and CAT Policy Effects on Particulate Matter Concentration

- As shown in Figure.1 and Table.2, SCAP policy had a mixed effect on PM concentrations albeit not statistically significant; CAT trend estimates indicated that five years after the policy was in force, PM, would declined by 48.6 $\mu g/m^3$ and was statistically significant.

Table 2: Trend Break Estimates of the Effect of Air Pollution Policy on Particulate Matter (Summary of 2C and Five-year Effects ONLY)

	Supreme Court Action Plans	Catalytic Converters
π_2: time trend	-3.7*(2.8)*	7.8****(2.5)*
π_1: $1(Policy)$	7.5*(19.4)*	5.6*(12.8)*
π_3: $1(Policy)_\tau \times \tau$	-1.3*(6.8)*	-10.8****(2.9)*
5-year Effect $= \pi_1 + 5\pi_3$	1.1	-48.6**

Air: SO2 (Sulfur Dioxide)

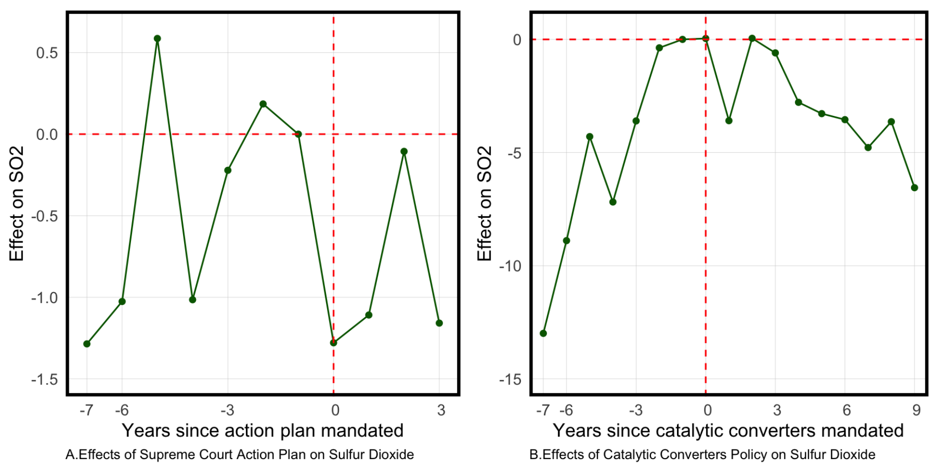

Figure 2: SCAP and CAT Policy Effects on Sulfur Dioxide Concentration

- As shown in Figure.2 and Table.3, SCAP policy also had a mixed effect on SO2 concentrations albeit not statistically significant; CAT trend estimates indicated that five years after the policy was in force, SO2 concentration, would declined by 13.4 $\mu g/m^3$ but this was not statistically significant.

Table 3: Trend Break Estimates of the Effect of Air Pollution Policy on Sulfur Dioxide (Summary of 2C and Five-year Effects ONLY)

	Supreme Court Action Plans	Catalytic Converters
π_2: time trend	0.2*(0.1)*	2****(0.3)*
π_1: $1(Policy)$	-1.5*(0.8)*	-0.5*(1.5)*
π_3: $1(Policy)_\tau \times \tau$	0*(0.3)*	-2.6****(0.3)*
5-year Effect $= \pi_1 + 5\pi_3$	-1.7	-13.4***

Air: NO2 (Nitrogen Dioxide)

- As shown in Figure.3 and Table.4, SCAP policy held a generally decreasing effect on NO2 concentrations albeit not statistically significant; CAT trend estimates indicated that five years after the policy was in force, NO2 concentration, would declined by 4.4 $\mu g/m^3$ but was not statistically significant.

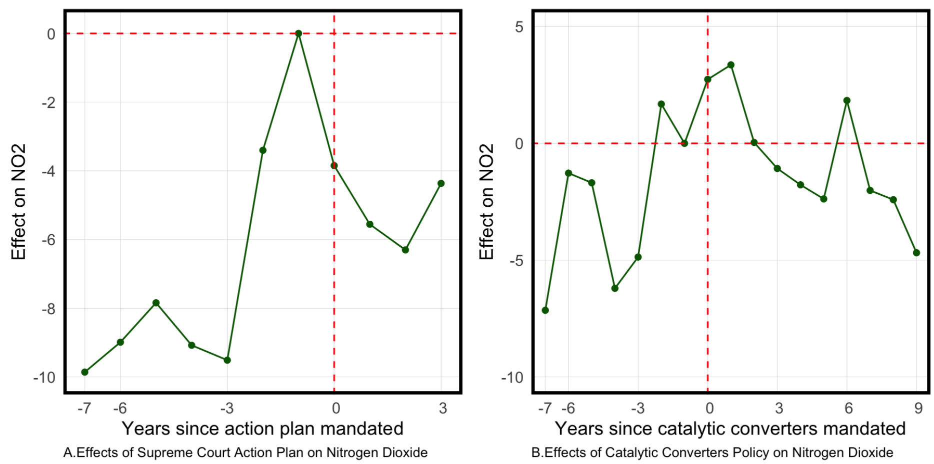

Figure 3: SCAP and CAT Policy Effects on Nitrogen Dioxide Concentration

Table 4: Trend Break Estimates of the Effect of Air Pollution Policy on Nitrogen Oxide (Summary of 2C and Five-year Effects ONLY)

	Supreme Court Action Plans	Catalytic Converters
π_2: time trend	1.4** *(0.4)*	0.9* *(0.4)*
π_1: $1(Policy)$	-1.8*(3)*	3.2*(2.2)*
π_3: $1(Policy)_\tau \times \tau$	-1.7*(1)*	-1.5*** *(0.5)*
5-year Effect $= \pi_1 + 5\pi_3$	-10.2*	-4.4

Water: BOD (Biochemical Oxygen Demand)

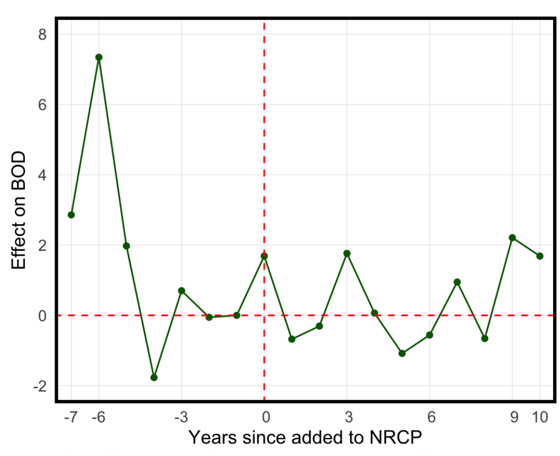

Figure 4: NRCP Policy Effects on Bio chemical Oxygen Demand

- Figure.4 and Table.5 indicated that the evidence in favor of a policy impact on BOD is weak. Indeed, the richest statistical models suggest that BOD concentrations are higher after the NRCP's implementation, as trend estimates indicated that five years after the policy was in force, BOD concentration, would increased by 5.85 mg/L.

Table 5: Trend Break Estimates of the Effect of the National River Conservation Plan on Biochemical Oxygen Demand (Summary of 2C and Five-year Effects ONLY)

	National River Conservation Plan
π_2: time trend	-0.88** *(0.35)*
π_1: $1(Policy)$	1*(1.66)*
π_3: $1(Policy)_\tau \times \tau$	0.97** *(0.38)*
5-year Effect $= \pi_1 + 5\pi_3$	5.85*

Water: ln(FColi) (Logarithm of Fecal Coliform)

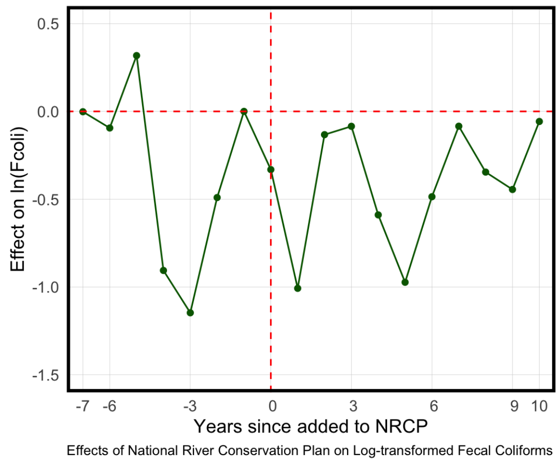

Figure 5: NRCP Policy Effects on Logarithm of Fecal Coliform Concentration

- As shown in Figure.5 and Table.6, while the NRCP targets domestic pollution, the data fail to reveal a statistically significant change in FColi concentrations, which is the best measure of domestic sourced water pollution. Trend estimates indicated that five years after the policy was in force, the logged value of Fcoli concentration, would increased by 0.54. The number could be translated into $e^{0.54} = 1.716$, which means the policy would be associated with a 71.6% increase in Fcoli concentration.

Table 6: Trend Break Estimates of the Effect of the National River Conservation Plan on Logarithm of Fecal Coliform Concentration (Summary of 2C and Five-year Effects ONLY)

	National River Conservation Plan
π_2: time trend	-0.1 *(0.09)*
π_1: $1(Policy)$	-0.01 *(0.4)*
π_3: $1(Policy)_\tau \times \tau$	0.1 *(0.09)*
5-year Effect $= \pi_1 + 5\pi_3$	0.54

Water: DO (Dissolved Oxygen)

- Figure.6 and Table.7 suggested that NRCP was associated with a decrease in DO concentrations by 0.62 mg/L and was statistically significant.

Table 7: Trend Break Estimates of the Effect of the National River Conservation Plan on Dissolved Oxygen (Summary of 2C and Five-year Effects ONLY)

	National River Conservation Plan
π_2: time trend	0.1^{***} *(0.03)*
π_1: $1(Policy)$	0.03 *(0.12)*
π_3: $1(Policy)_\tau \times \tau$	-0.13^{***} *(0.03)*
5-year Effect $= \pi_1 + 5\pi_3$	-0.62^{***}

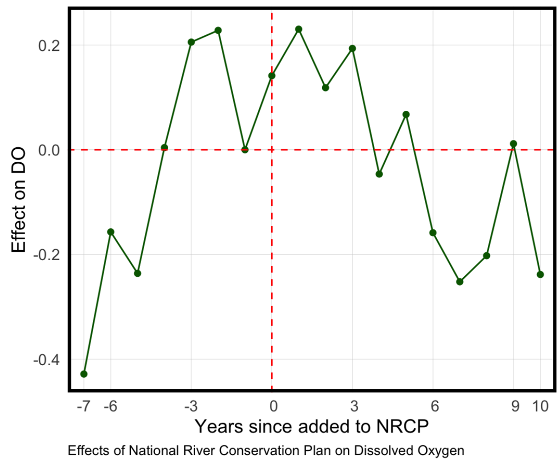

Figure 6: NRCP Policy Effects on Dissolved Oxygen Concentration

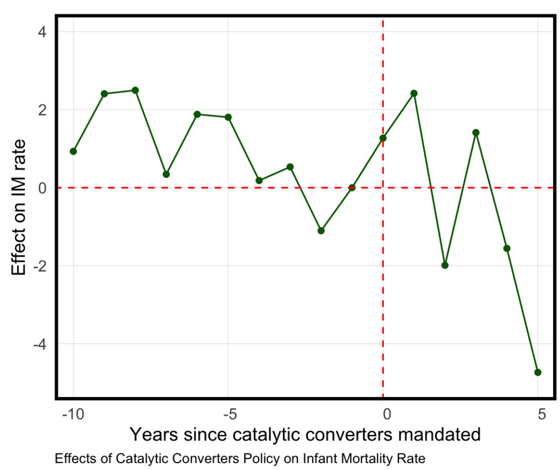

Figure 7: CAT Policy Effects on Infant Mortality Rate

Air: Infant Mortality (IM) Rate

- Table.8 suggests that the catalytic converter policy is associated with a reduction in the infant mortality rate of 0.63 per 1,000 live births. However, this estimate is imprecise and is not statistically significant.

Table 8: Trend Break Estimates of the Effect of the Catalytic Converters Policy on Infant Mortality Rate (Summary of 2C and Five-year Effects ONLY)

	Catalytic Converters
π_2: time trend	-0.26 *(0.15)*
π_1: $1(Policy)$	3.59 *(1.49)*
π_3: $1(Policy)_\tau \times \tau$	-0.84 *(0.35)*
5-year Effect $= \pi_1 + 5\pi_3$	-0.63

QLR: Did the Parallel-Trends Assumption Hold True?

Recall that the authors used the QLR test to assess whether the structural break occurs around the year of policy adoption. Since only CAT policies have significant effects on air quality improvement, the structural test was performed with respect to the adoption of CAT. The ideal trend break and the only one trend break, should be observed around or most confidently after the year of policy adoption, i.e., year 0.

Table 9: QLR Test Results for Six Pollutants

Outcome	Potential Break Year	QLR Statistic
SPM	2	15.8
SO2	-1	30.1
NO2	-2	9.1
BOD	-3	4.9
ln(Fcoli)	-2	3.5
DO	-3	18.7

Note that as the authors suggested, asymptotic critical values are invalid due to the small sample sizes. Instead, they conducted a Monte Carlo analysis to generate the appropriate small sample critical values (we were not able to replicate this process). The critical value corresponding to a 99 percent confidence level is 13.98. Since Therefore, only the trend breaks for SPM, SO2, and DO were considered significant with $QLR > F_{critical}$.

The authors found evidence of a structural break in adopting cities around the year of adoption of the catalytic converter policy (from SPM, SO2, and NO2 trend breaks) and no breaks in the time-series that correspond to cities' adoption of the National River Conservation Plan (from BOD, ln(Fcoli) and DO trend breaks largely before the adoption).

Extension: Effects of the 2008 Economic Crisis

With the difference among cities and periods controlled, the DID regression estimates unveiled (partly) of the amount of effect that the 2008 Economic Crisis had on those cities grouped with respect to their status of air regulation policies in force.

Table 10: DID Estimates of the Effects of the 2008 Economic Crisis

	SCAP Only	CAT Only	Both	Neither
SPM	-71.98***	-19.67	46.78**	10.03
SO2	-2.96*	0.81	-1.23	0.80
NO2	2.35	0.50	7.98***	-4.23**

As shown in Table.10, the crisis might be associated with the decrease of SPM and SO2 in cities only adopting SCAP policies; while for cities adopting both SCAP and CAT policies, we observed an increasing tendency in SPM and NO2; for cities without air regulations, the crisis tended to be correlated with the decrease in NO2. However, no statistically significant effects were found on cities that only adopted CAT policies.

Discussion

Main Findings of Greenstone & Hanna (2014)

Note: some discrepancies in our replication did not affect the total functioning of the analysis - conclusion.

- Air regulations (mostly the Catalytic Converter Policies) were in part responsible for observed improvements in air quality from 1986 to 2007. The most successful air regulation resulted in a modest but statistically insignificant decline in infant mortality.
- On the contrary, the results indicate that the NRCP - the cornerstone of India's water policies - failed to lead to improvements in any of the three available measures of water pollution.

Limitations of Greenstone & Hanna (2014)

- **Bias in data collection:** Infant mortality After 1996, the city-level data were no longer compiled centrally. Many births and deaths are not registered in India and the available evidence suggests that this problem is greater for deaths, so the infant mortality rate is likely downward-biased.
- **Problems shown in results:** Event Study of Air Pollution Policies fail to reveal symmetry around a mean pollution concentration that would indicate that any of the three measured pollutants follow a mean reverting process. The regression estimate of Infant Mortality with respect to the catalytic converter policy is associated with a reduction in the infant mortality rate of 0.64 per 1,000 live births is imprecise and is not statistically significant. (Replicated)
- **Unresolved question:** The fundamental questions of the magnitudes of the marginal benefits and costs of regulation-induced emissions reductions and whether the benefits exceed the costs. Currently, there is very limited information on the costs and benefits of environmental regulations in developing countries and this is a rich area for future research.

Challenges & Unsolved Problems in Replication

- "Standardize" + "Normalize": Each observations (per city per year) needed to be standardized as event-year Raw regression results needed to be normalized by the estimate for one year before the policy enactment in a particular city.
- Need to bridge the gap between STATA and R: Some functions/operations differ in usage & design.

(1) X >=. in STATA means X is NA
(2) Y <. in STATA means Y is not NA
(3) 0 / 1 VS NA / 1
(4) the function `lincom` in R would not give out P-values for the estimates as STATA does.

- Data cleaning & "grouping" steps are neither obvious in the code provided nor in the text.

- No reliable data sources found post-2007 (India government website under maintenance)
- Inconsistency among sources of statistics for pollution data
- All event and policies have a “time-lag” or some extent of “duration”: Economic crisis; from policy enactment to full performance, etc.

Possible Effects of the 2008 Economic Crisis

As shown in our extension study results, cities with only CAT policy implemented didn’t have significant differences before and after the crisis. So, we assume that the economic crisis didn’t significantly affect the effectiveness of the CAT policy. And the author’s conclusion still holds true in terms of the effectiveness of CAT. However, this is just very simplified and preliminary results. Due to lack of data, such as population and literacy in each city, we couldn’t replicate the authors’ method in our study. The more ideal approach was to use a redesigned DID as implemented in Prof. He Guojun’s study published on Nature-Sustainability (2020). This DID method can evaluate the effects of multiple events and policy. The results should also be tested with QLR. But due to time limits, we couldn’t perform those analyses. More detailed research is needed about the effects of the 2008 economic crisis.

Future Research Directions

- **Spatial autocorrelation of air/water pollution & infant mortality of cities:** whether there are clusters of pollutant concentration, or whether cities under similar geographical contexts would have similar response to policies enforced.
- **Check whether the effects of the 2008 economic crisis are systematically homogeneous among cities in India reinforcing the validity of the DID assumption:** parallel trends between the control and treatment groups before the “treatment” / “event” takes place.
- **Update the full city panel data to include years beyond 2007:** We were only able to gather the city-year variables and the pollutants.

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Appendix

1 - Note on Each Group Member's Role and Main Contribution

- Yixin Fang: Study of DID design and investigation of the effects of the 2008 Economic Crisis on environmental regulation outcomes.
- Yiming Li: Data collection and research into the Quandt Likelihood Ratio Test and DID design.
- Xinkai Wang: Literature review and qualitative comparison of the environmental regulation design in India & China.
- Weichen Xu: Examination of limitations in the original study and possible future research questions with both quantitative and qualitative reasoning, especially related to event and trend studies.
- Zhijie Zhou: Back-end support of replication process and the organization of manuscript.

2 - Synthesis of Results Produced by Greenstone and Hanna (2014) for Reference

Original Figure 5. Event Study of Air Pollution Policies

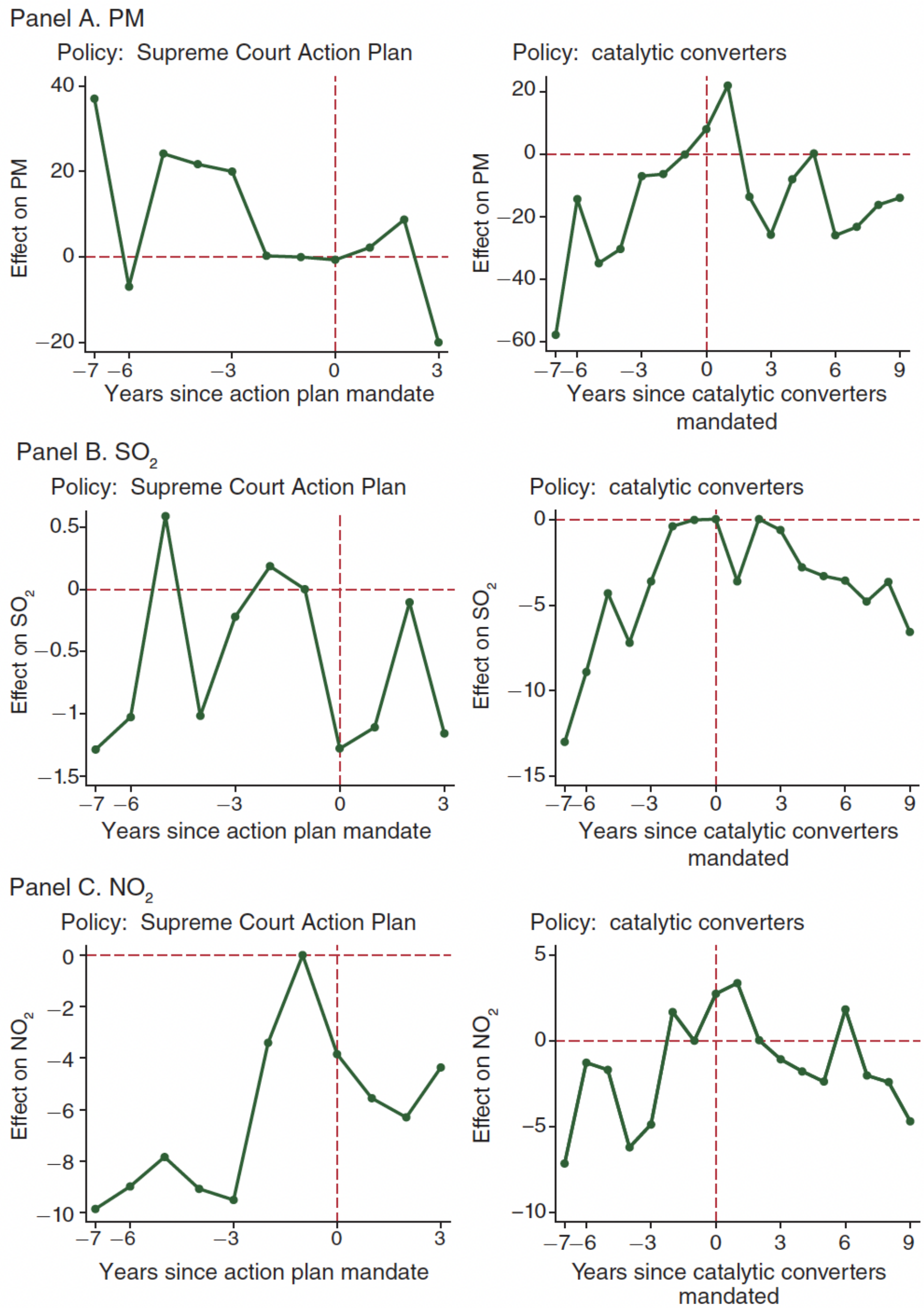


Figure 5. Event Study of Air Pollution Policies

- Notes: The figures provide a graphic analysis of the effect of the SCAPs and mandated catalytic converter policies on air pollution.

Original Table 3. Trend Break Estimates of the Effect of Policy on Air Pollution

Table 3—Trend Break Estimates of the Effect of Policy on Air Pollution

	Supreme Court Action Plans				Catalytic converters			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A. PM								
π_2: time trend		−3.8	−3.6	−2.9		−0.3	7.8***	7.8**
		(2.4)	(2.8)	(4.3)		(1.8)	(2.5)	(3.3)
π_1: 1(*Policy*)	−16.2	4.9	7.5	0.3	11.9	14.7	5.6	7.6
	(9.4)	(15.8)	(20.6)	(21.5)	(8.8)	(17.4)	(12.8)	(12.3)
π_3: 1(*Policy*) × time trend			−1.5	0.1			−10.8***	−11.2**
			(7.1)	(6.0)			(2.9)	(4.6)
5-year effect $= \pi_1 + 5\pi_3$			−0.2	0.9			−48.6**	−48.4*
p-value			0.99	0.98			0.04	0.06
Observations	11	11	11	1,165	17	17	17	1,165
Panel B. SO_2								
π_2: time trend		0.2	0.2	0.1		0.1	2.0***	1.9***
		(0.1)	(0.1)	(0.6)		(0.3)	(0.3)	(0.7)
π_1: 1(*Policy*)	−0.5	−1.5*	−1.4	−1.3	2.5	1.5	−0.5	−0.8
	(0.4)	(0.7)	(0.9)	(2.1)	(1.7)	(3.3)	(1.5)	(2.6)
π_3: 1(*Policy*) × time trend			−0.1	0.1			−2.6***	−2.4**
			(0.3)	(1.0)			(0.3)	(1.0)
5-year effect $= \pi_1 + 5\pi_3$			−1.7	−0.8			−13.5***	−12.7**
p-value			0.21	0.87			0.00	0.02
Observations	11	11	11	1,158	17	17	17	1,158
Panel C. NO_2								
π_2: time trend		1.2**	1.4**	1.6*		−0.3	0.9*	0.7
		(0.4)	(0.4)	(0.9)		(0.3)	(0.4)	(0.8)
π_1: 1(*Policy*)	1.9	−4.4	−1.7	−2.6	2.2	4.5	3.2	3.7
	(2.0)	(2.7)	(3.1)	(4.4)	(1.4)	(2.8)	(2.2)	(4.0)
π_3: 1(*Policy*) × time trend			−1.6	−1.7			−1.5***	−1.4
			(1.1)	(2.1)			(0.5)	(1.2)
5-year effect $= \pi_1 + 5\pi_3$			−9.8*	−11.3			−4.4	−3.3
p-value			0.06	0.22			0.25	0.62
Observations	11	11	11	1,177	17	17	17	1,177
Equation (2A)	Yes	No	No	No	Yes	No	No	No
Equation (2B)	No	Yes	No	No	No	Yes	No	No
Equation (2C)	No	No	Yes	No	No	No	Yes	No
One-stage version of (2C)	No	No	No	Yes	No	No	No	Yes

- Notes: This table reports results from the estimation of the second-step equations (2A), (2B), and (2C) for PM, SO2, and NO2, in panels A, B, and C respectively. Columns 4 and 8 complement the second-step results from the estimation of equation (2C) by reporting results from the analogous one-step approach for the SCAPs and the catalytic converter policy respectively. Rows denoted "5-year effect" report $\pi_1 + 5\pi_3$, which is an estimate of the effect of the relevant policy 5 years after implementation from equation (2C) and the analogous one-step approach. The p-value of a hypothesis test for the significance of this linear combination is reported immediately below the fiveyear estimates.

Original Figure 6. Event Study of Water Pollution Policy

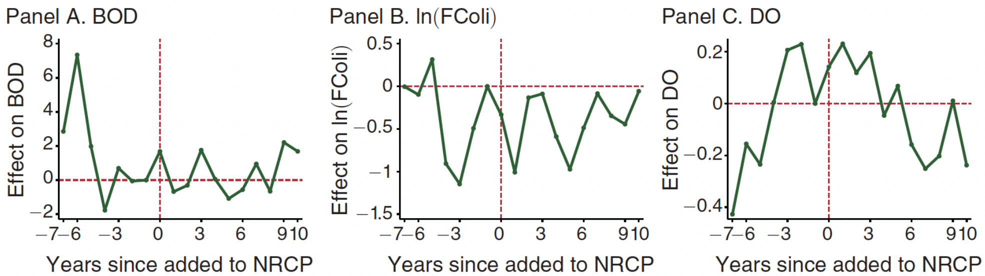


Figure 6. Event Study of Water Pollution Policy

- Notes: The figures provide a graphical analysis of the effect of the NRCP policy on water pollution.

Original Table 4. Trend Break Estimates of the Effect of NRCP on Water Pollution

TABLE 4—TREND BREAK ESTIMATES OF THE EFFECT OF THE NRCP ON WATER POLLUTION

Time trend	(1)	(2)	(3)	(4)
Panel A. BOD				
π_2: time trend		−0.12	−0.88**	−0.92
		(0.18)	(0.34)	(0.86)
π_1: 1(*policy*)	−1.11	−0.06	1.07	0.87
	(0.99)	(1.88)	(1.67)	(2.07)
π_3: 1(*policy*) × time trend			0.96**	1.03
			(0.38)	(0.79)
5-year effect $= \pi_1 + 5\pi_3$			5.85*	6.03
p-value			0.06	0.28
Observations	18	18	18	5,576
Panel B. ln(Fcoli)				
π_2: time trend		0.01	−0.08	−0.06
		(0.04)	(0.08)	(0.11)
π_1: 1(policy)	−0.08	−0.14	−0.01	−0.07
	(0.20)	(0.39)	(0.40)	(0.46)
π_3: 1(policy) × time trend			0.11	0.10
			(0.09)	(0.17)
5-year effect $= \pi_1 + 5\pi_3$			0.53	0.42
p-value			0.45	0.66
Observations	18	18	18	4,640
Panel C. DO				
π_2: time trend		−0.02	0.09***	0.07
		(0.02)	(0.02)	(0.08)
π_1: 1(*policy*)	0.04	0.19	0.03	0.08
	(0.10)	(0.18)	(0.12)	(0.29)
π_3: 1(*policy*) × time trend			−0.13***	−0.12
			(0.03)	(0.09)
5-year effect $= \pi_1 + 5\pi_3$			−0.63***	−0.51
p-value			0.01	0.40
Observations	18	18	18	5,553
Equation (2A)	Yes	No	No	No
Equation (2B)	No	Yes	No	No
Equation (2C)	No	Yes	Yes	No
One-stage version of (2C)	No	No	No	Yes

- Notes: This table reports results from the estimation of the second-step equations (2A), (2B), and (2C) for the impact of the NRCP on BOD, ln(Fcoli), and DO in panels A, B, and C respectively. Column 4 complements the second-step results from the estimation of equation (2C) by reporting results from the analogous one-step approach. The row denoted "5-year effect" reports $\pi_1 + 5\pi_3$, which is an estimate of the effect of the policy five years after implementation from equation (2C) and the analogous one-step approach.

Original Figure 7. F-Statistics from QLR Test for Catalytic Converter Policies

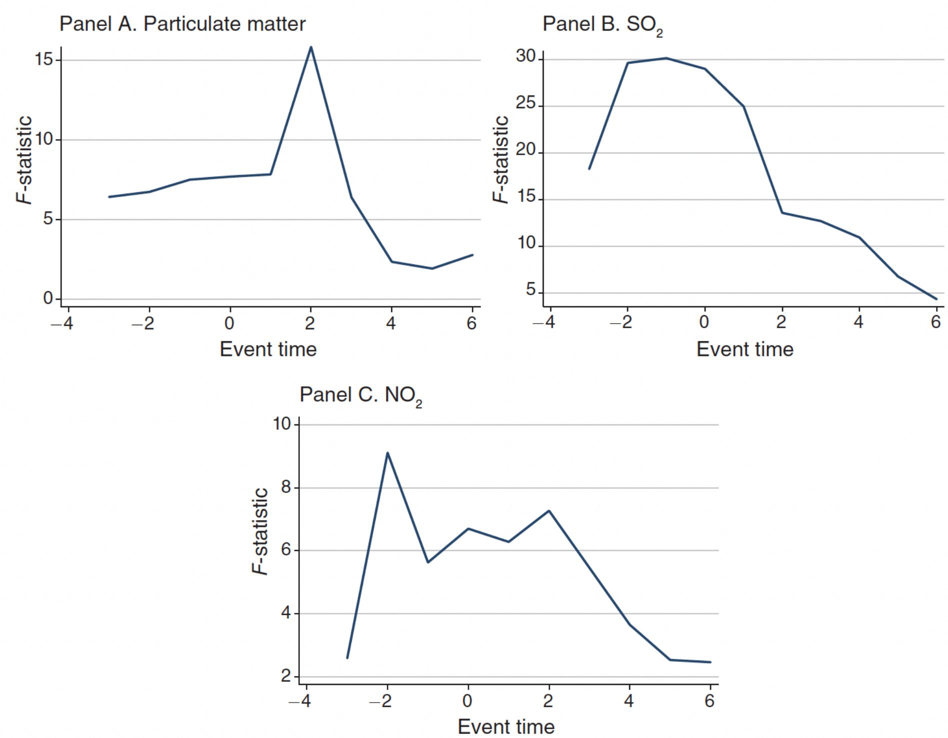


FIGURE 7. *F*-STATISTICS FROM QLR TEST FOR CATALYTIC CONVERTER POLICIES

- Note: Recall that QLR statistic is the maximum of F-statistics for all event-times.

Original Table 5. Structural Break Analysis

TABLE 5—STRUCTURAL BREAK ANALYSIS

	Year of maximum *F* (1)	QLR test statistic (2)
Panel A. Catalytic converter policy		
PM	2	15.8
SO_2	−1	30.1
NO_2	−2	9.1
Panel B. National River Conservation Plan		
BOD	−3	4.9
ln(Fcoli)	−2	3.5
DO	−3	18.7

Notes: This table provides the QLR test statistic, as well as the corresponding year of the break in the data, for equation (2C). Asymptotic critical values are invalid due to the small sample sizes. Instead, we conducted a Monte Carlo analysis to generate the appropriate small sample critical values. The critical value corresponding to a 99 percent confidence level is 13.98.

- Notes: This table provides the QLR test statistic, as well as the corresponding year of the break in the data, for equation (2C). Asymptotic critical values are invalid due to the small sample sizes. Instead, we conducted a Monte Carlo analysis to generate the appropriate small sample critical values. The critical value corresponding to a 99 percent confidence level is **13.98**.

Original Figure 8. Event Study of Catalytic Converters on Infant Mortality

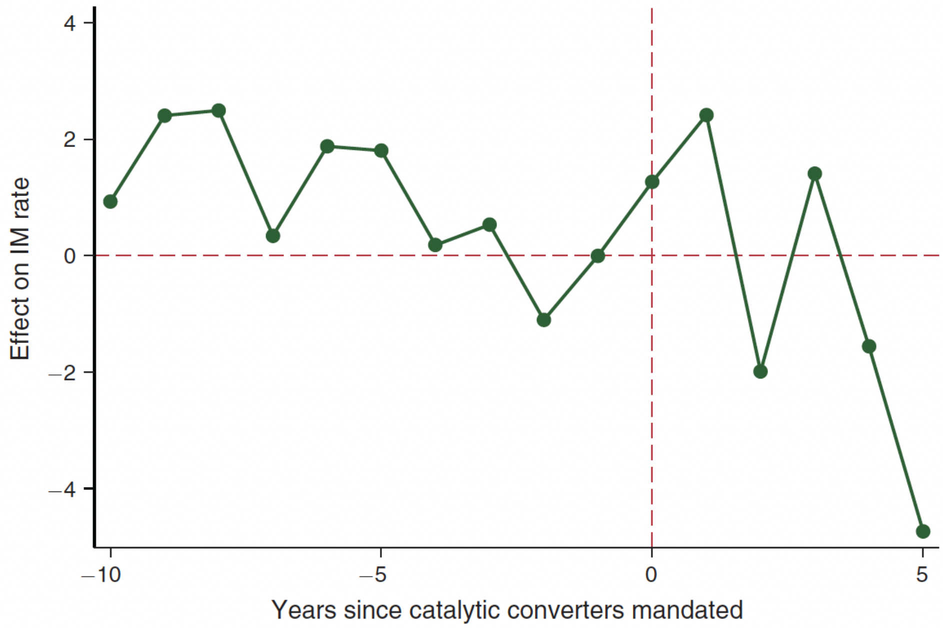


FIGURE 8. EVENT STUDY OF CATALYTIC CONVERTERS AND INFANT MORTALITY

- Notes: The figure provides a graphical analysis of the effect of the catalytic converter policy on the infant mortality rate.

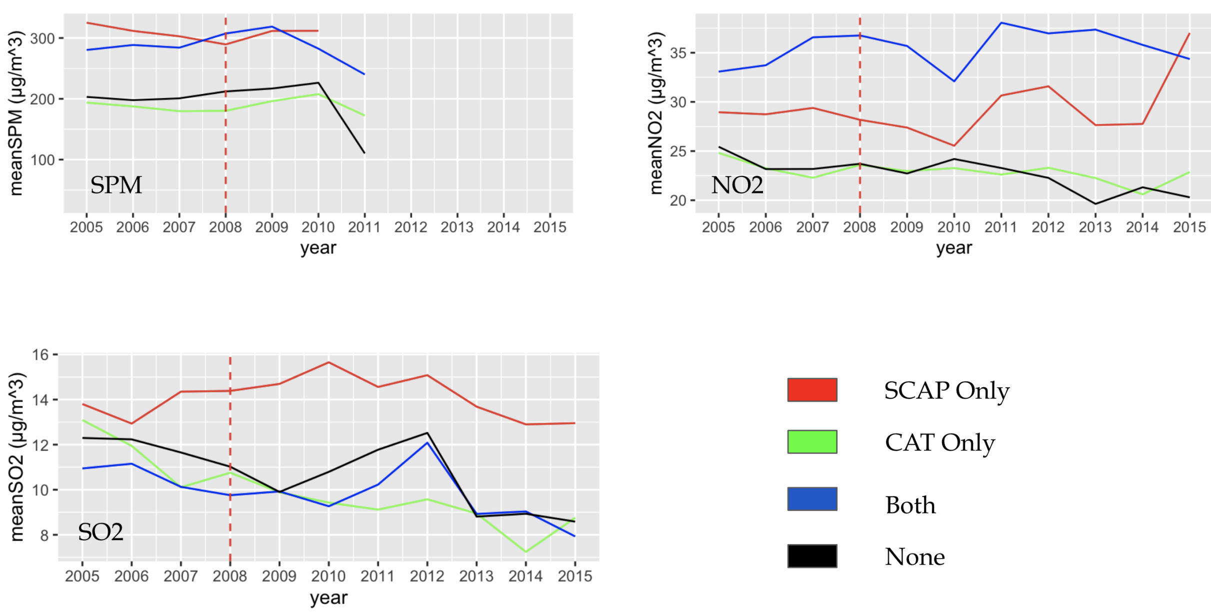
Original Table 6. Trend Break Estimates of the Effect of the Catalytic Converter Policy on Infant Mortality

Table 6—Trend Break Estimates of the Effect of the Catalytic Converter Policy on Infant Mortality

	(1)	(2)	(3)
π_2: time trend		−0.4**	−0.3
		(0.2)	(0.2)
π_1: 1(*policy*)	−1.5	1.8	3.6
	(1.0)	(1.5)	(1.5)
π_3: 1(*policy*) × time trend			−0.84**
			(0.4)
5-year effect $= \pi_1 + 5\pi_3$			−0.6
p-value			0.7
Observations	16	16	16
Equation (2A)	Yes	No	No
Equation (2B)	No	Yes	No
Equation (2C)	No	No	Yes

- Notes: This table reports estimates of the impact of the catalytic converter policy on infant mortality rates from the fitting of equations (2A), (2B), and (2C). The row denoted “5-year effect” reports $\pi_1 + 5\pi_3$, which is an estimate of the effect of the relevant policy five years after implementation from equation (2C).

3 - Plots of Trends of Air Pollutants After 2007



- Notes: data source not official (from Kaggle user collection).

4 - A Qualitative Comparison of Environmental Regulations: India vs. China (Full-text)

Air pollution policy

China

- China released its Air Pollution Action Plan in September 2013 (Feng, 2020), which set PM2.5 level targets for the city clusters of Beijing-Tianjin-Hebei and the Pearl and Yangtze Deltas: banned new coal-fired plants and closed highly polluting ones, limiting the number of cars on the road and introducing all-electric buses.
- The Great Green Wall: planted more than 35 billion trees across 12 provinces
- In 2018, China launched the Three-Year Action Plan to Win the Blue Sky Defense War (China, 2018): Target the main air pollutants in the country's provinces: SO2 and NO2. emissions in China's major cities would be reduced by 10% and NO2 emissions by 15%.

India

- In January 2019, the Indian government launched the National Clean Air Program (NCAP) and established real-time monitoring stations to measure pollutants in various cities (Ganguly, 2020):

1. the number of stations was increased from 703 to 1500.
2. at least 1000 sensors were set up to implement monitoring.
3. Expanded satellite monitoring of air pollutants.
4. expanded monitoring of PM2.5.
5. Adopted compressed natural gas (CNG) as an alternative fuel to gasoline and diesel to reduce emissions.

Both China and India have received extensive attention from the central government regarding the status of air pollution. Both countries prefer the control of vehicle emissions. However, the Chinese government has defined regulations to reduce the number of cars on the road. In contrast to the Indian government, the Chinese government has focused more on the root causes of pollutants while the Indian government has pursued regulatory and ameliorative measures.

Water Pollution Policy

China

- In April 2015, the Chinese government released the Water Pollution Prevention and Control Action Plan (Schrag, 2020) and announced three "red lines":

1. maximum total water use, water use efficiency, and pollution control.
2. enforce stricter standards.
3. Increase water monitoring efforts.
4. Strengthen the enforcement of environmental laws to punish polluters.

- In January 2020, the Chinese government enacts the Yangtze River Protection Law which declares the 10-year fishing ban policy (Schrag, 2020). In ten years, all fishing behaviors in the Yangtze River will be strongly prohibited and illegal:

1. improve water quality to reduce water pollution.
2. help organisms to reproduce
3. reduce numbers of fishing boats
4. balance the ecosystem

India

- In 2010, the Government of India issued the National Green Tribunal Act and established a special tribunal to deal with cases related to environmental issues (Samad et al., 2015):

1. to protect the right of citizens to a healthy environment
2. administrative remedies for victims of environmental damage
3. Punitive measures against polluters

- In 2015, the Government of India launched the Ganga River Basin Management Plan (Krishan et al., 2019). Its main objective is to reduce pollution and toxic waste discharge and to improve the water quality of Ganga River through governmental control:

1. to restore the ecological balance of the Ganga
2. To provide a favorable environment for the growth of flora, fauna and micro-organisms
3. reduce pollution in the river

In comparison with the water management policies of China and India, they both focus on restoration of river ecosystems and reduction of pollutant discharges. However, China's water pollution control policies are more effective because the Chinese government has strict regulations and penalties that make it more costly to violate the law, whereas India does not.