The Effects of Fuel Standards on Air Pollution: Evidence from China

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Abstract

This paper examines the causal relationship between China's fuel standards, which specify lower sulfur content, and air pollution. Combining measures of prefectures' regulations with hourly station-level pollution data from 2013 to 2015, we show that the enforcement of high-quality gasoline standards has significantly improved air quality, especially in terms of fine particles and ozone. The benefits of the regulations have outweighed the costs. These findings demonstrate the efficacy of precise standards in reducing air pollution in a developing country setting.

Key words: Fuel standards; Sulfur content; Vehicle Emissions; Pollution

JEL Codes: L51; Q53; Q58

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1 Introduction

92% of the world's population lives in places where the average air quality is beyond the World Health Organization's suggested limit for pollutants. Those in Asia, Africa and the Middle East are disproportionately exposed to high concentrations of air pollution (WHO, 2015). With rapid urbanization, low quality fuel and numerous old and poorly maintained vehicles have come to contribute over 90% of the air pollution in the developing world, imposing alarming health costs on the public (United Nations, 2005). The sheer size of the population and particularly the growing urban mass in less-developed countries make the welfare consequences of targeted environmental regulations–for example, to improve fuel quality–of high importance. Yet, systematic empirical evidence on the extent to which such policies can effectively address automobile pollution remains scant.

In an important contribution, Auffhammer and Kellogg (2011) examine the effects of gasoline content regulations on ambient pollutant concentrations in the United States. But evidence from developed economies cannot readily be transferred to the developing world, given the different contexts and institutions. This paper attempts to bridge this gap by documenting novel empirical evidence in the largest developing country, China (Zheng and Kahn, 2013).

More precisely, we study the relationship between China's fuel standards and levels of air pollution. There are four reasons for this focus. First, China has become the world's largest automobile market. There has been an unprecedented increase in the country's vehicle ownership. Intensive oil consumption is associated with a large number of externalities (Parry, Walls, and Harrington, 2007), as shown in Figure 1. China's cities rank among the most polluted in the world (World Bank, 2007; Greenstone and Hanna, 2014; Chen et al., 2013; Cropper, 2010). This makes regulating fuel content of great policy relevance. Second, uniform fuel standards have gradually been introduced in Chinese cities, which provides a new opportunity to understand their environmental implicationss. The different standards together with accurate data allow overcoming methodological obstacles that have impeded progress in the field.

[Insert Figure 1 vehicle ownerships and emissions here]

Third, a vehicle and its fuel are an integrated system. Improved fuel quality will make the emission control systems of both existing and new vehicles more effective and is a key step toward more stringent vehicle emissions standards (EPA, 2014). Chinese automobile manufacturers have long been concerned that without cleaner fuels the effectiveness of their vehicle emission controls will be undermined (Zheng and Kahn, 2013). Fourth, Chinese automobile fuel standards primarily follow the practices of Europe, Japan and the United States. The very similar regulations enable us to compare policy effectiveness between developing and developed countries.

The study's analyses exploit a compelling quasi-experiment: the changes in fuel standards for fuel sales in Chinese cities. According to official statistics from China's Ministry of Environmental Protection (MEP), exhaust from motor vehicles contributes a quarter to a third of particulate matter (PM) air pollution and at least a quarter of urban nitrogen oxide (NO_x) pollution throughout the country (MEP, 2013). Against this background, since 2013 China has gradually tightened its gasoline standards from III to IV, and then from IV to V, followed by diesel standards upgrading in certain cities. The introduction of low-sulfur fuel standards aims to reduce emissions from the motor vehicle fleet substantially, and they have been strictly enforced by the retailers.

The study's analyses involve merging data on prefecture-level regulations with station-level hourly pollution data. The data cover 1,436 air quality monitoring stations in 337 prefectures for the three years 2013 to 2015. In addition to the air quality index (AQI), a composite measure of pollution, data on suspended particulates less than 10 μm in diameter (PM_{10}) and less than 2.5 μm ($PM_{2.5}$) and on ozone (O_3) concentrations are analyzed. Those pollutants are particularly related to fuel content, and are among the most harmful to human health. To our knowledge, this is the first time that high-quality data on fine particulates and ozone have been used in research on Chinese environmental issues (Pope and Dockery, 2013).

We focus on precisely estimating the effect on air pollution of the gasoline standard IV regulations, the first standard implemented during the period studied. Two estimation strategies are applied. First, both temporal and geographic variations in the implementation of the new gasoline standard are exploited to identify its effects. The empirical analysis compares daily changes in the local concentrations of air pollutants between cities implementing the new standard earlier (the treatment group) and later (the control group). The validity of the difference-in-differences (DD) methods applied and the causal interpretation of the results rely on the assumption that cities that adopted the new standard later are proper counterfactuals for what would have happened to earlier adopters in the absence of the reform. A large number of other variables are added to address the selected nature of the enforcement dates, including monitoring station fixed effects, day fixed effects, station-specific seasonality, and weather conditions. It is also necessary to remove the confounding influence of other on-going policies aimed at curbing air pollution by directly controlling for them. Beyond that, a robustness test verifies that the treatment and control cities are comparable in terms of their pre-regulation trends of outcomes.

A second set of analyses follows the work of Davis (2008) and of Auffhammer and Kellogg (2011). A Regression Discontinuity (RD) framework is used to identify the effect of gasoline standards on air pollution. After the new regulations came into force, all the gas stations in the treatment cities were assumed to have immediately switched to supplying only gasolines meeting the new standards. That creates a sharp discontinuity in tailpipe emissions. In effect, the sharp change makes other things smooth at the implementation day of new regulations, so the day just before the new regulations serves a good counterfactual to the day the new regulations came into force.

The analyses yield several main results. First, the enforcement of more stringent fuel standards significantly improved air quality. The progression from gasoline standard III to standard IV led to a 2.3% fall in the concentration of $PM_{2.5}$, an average reduction of 1.39 $\mu g/m^3$. Such improvement points to the importance of fuel standards in mitigating vehicles' environmental adversities.

Second, there are some intra-day fluctuations, but these are well explained by the atmospheric chemistry of the pollutants. Topography is found to be another important factor. The new standards are more effective in cities with flatter topography, because the urban structure facilitates the dispersion of pollutants by the wind.

Third, a suggestive benefit-cost analysis reveals that the regulations' benefits outweigh their costs. Applying the World Bank's baseline value for a life (US$0.1613 million), a 1.39 $\mu g/m^3$ reduction in $PM_{2.5}$ concentration implies US$4.39 billion to US$4.75 billion in health benefits from reduced mortality. The upgrading from gasoline standard III to IV involves a cost increase (measured at consumer prices) of about US$3.99 billion.

Fourth, the adoption of gasoline standard IV has led to faster implementation of tighter vehicle emission standards, and it has also promoted the phasing out of older vehicles. These results suggest that high fuel standards help drive a more rapid transition to clean technologies.

This paper contributes to several strands of literature assessing the impact of environmental regulations. It is related to a growing body of work that emphasizes the technological aspects of environmental policies (Copeland and Taylor, 2004). Scholars have previously demonstrated negative relationships between regulatory measures that tightened vehicle emission standards and air pollution outcomes (Kahn, 1996; Kahn and Schwartz, 2008; Greenstone and Hanna, 2014).[1] While the impact of vehicle emission standards on air

[1] Kahn (1996) as well as Kahn and Schwartz (2008) found that both government regulation and auto manufacturer innovation in the United States have significantly reduced the regional air pollution caused by driving. The enviromental impact of regulation should increase with time as the share of pre-regulation vehicles on the roads declines. Greenstone and Hanna (2014) have shown that India's air pollution regulations requiring catalytic converters for new vehicles improved air quality and thus reduced death rates.

pollution takes effect only gradually through turnover in the vehicle fleet, the results of this study show that the new fuel standards in China immediately affected all vehicles on the road and influenced air quality dynamics in the near as well as the long term. This study has also enriched these work by showing how a fuel reform enabled more advanced emission standards in China.

Closest in spirit to this work is that published by Auffhammer and Kellogg (2011). They showed that the effectiveness of American gasoline content standards depends on flexibility in choosing a compliance mechanism. Flexible federal gasoline standards did not improve air quality, but accurately targeted, inflexible regulations in California significantly improved air quality. These results from China echo theirs and highlight the role of precise standards in reducing air pollution. Moreover, this study extends their work by including for the first time $PM_{2.5}$ levels as a main outcome.

Another strand of research has focused on regulatory policies designed to reduce the scale of pollution. In particular, several studies have examined regulations targeting gasoline consumption and emissions (Parry, Walls and Harrington, 2007; Jacobsen, 2013; Anas, Timilsina and Zheng, 2009).[2] Others have looked at the relationship between driving restrictions and air quality, including Davis (2008), Wolff (2014), as well as Viard and Fu (2015).[3] In contrast to costly administrative restrictions on the on-road vehicle fleet number, the findings of this study suggest that improving fuel standards could be a more efficient policy tool, since compliance can be more strictly enforced. Our findings imply that environmental regulations should put greater emphasis on cleaner technologies, of which cleaner fuel is a prominent example.

The rest of the paper proceeds as follows. Section 2 lays out the fuel standard reform background, followed by a description of the empirical strategy and data in section 3. Section 4 presents the empirical results. The last section concludes.

[2]Parry, Walls, and Harrington (2007) have shown that among a set of policy instruments in the U.S., gasoline taxes reduced a greater number of important externalities than did fuel economy standards. Further advances have been made by Jacobsen (2013), who has specifically studied the mechanisms and welfare implications of fuel economy standards. Anas,Timilsina and Zheng (2009) compared the effectiveness of a congestion toll and a fuel tax in reducing traffic congestion as well as gasoline consumption and emissions in Beijing.

[3]They have shown that the policy outcome varies depending on the context, from no effects in Mexico, to significant effects in Germany and Beijing. Such differences crucially depend on the behavioral responses of the drivers influenced (compliance versus compensating responses).

2 Fuel Standards in China

It has been well documented that gasoline's sulfur concentration is among the most relevant determinants of vehicle emissions.[4] Higher sulfur gasoline generates more nitrous oxide, carbon monoxide (CO), and hydrocarbons (HCs) (EPA, 1998, 1999) through what is known as sulfur inhibition. Chemical reactions involving HCs and NOx produce secondary air pollutants such as particulate matter (PM) and ozone, which are the main components of smog and haze.

A large number of epidemiological studies link pollutant exposure to human health. $PM_{2.5}$ in particular pose a great risk to humans because the particles can penetrate deep into the lungs and remain there for long periods of time. They diffuse readily into indoor environments, and are transported over long distances (Pope and Dockery, 2006). They are associated with increased incidence of lung cancer and with respiratory and heart disease mortality, and are known to aggravate asthma seriously (Pope and Dockery, 2013; Greenstone, 2004; Parry, Walls and Harrington, 2007). Ozone is another important air pollutant which damages both human health and agricultural crops.

It is noteworthy that the air pollutant concentrations observed at different locations depend on more than the quantity of various emissions. Extensive studies have shown that the weather—wind speed, temperature and rainfall—play an important role in determining local pollutant levels. Indeed, most air pollutants, including ozone and fine particulates, exhibit pronounced seasonal patterns because of weather (Bharadwaj et al., 2016). It is therefore important to control for weather and seasonality in any attempt to identify the impact of fuel standards on local pollutant concentrations. Topographical features such as mountains and hills may also influence air quality by changing airflow patterns and consequently the dispersion of pollutants in the atmosphere (United Nations, 2005). Fuel content regulations are likely to exhibit different effects in areas with different topography.

China has primarily followed the precedent of the European Union for fuel standards since the late 1990s. After a decade of practice in addressing worsening air pollution, especially in urban areas, China has decided to strengthen the hazardous materials control standards for vehicle gasoline and diesel. In May 2011 the China IV gasoline standard had been issued specifying the maximum sulfur content 50 (parts per million (ppm) sulfur in the fuel), phased in by the end of 2013. In early 2013, the State Council further issued a directive calling for the nationwide introduction of ultra-low-sulfur fuels (10 parts per million, or ppm) by the

[4] Sulfur content is also one of the most important characteristics affecting diesel vehicles' NO_x and PM emissions (International Council on Clean Transportation, 2010). During combustion, sulfur in the diesel fuel converts into direct particulate matter emissions and sulphur dioxide emissions which can lead to secondary particle formation.

end of 2017 (State Council, 2013). That directive was translated into formal regulations over the course of 2013 (ICCT, 2013, 2014). Ultimately, three new standards were issued: China IV diesel (50ppm) in February 2013 to be phased in by December 31, 2014; China V diesel (10ppm) in June 2013 to be phased in by December 31, 2017; and China V gasoline (10ppm) in December 2013 to be phased in by December 31, 2017.[5] Together, those standards constituted a road map for improving China's nationwide fuel standards, as shown in Table 1.

[Insert Table 1 Fuel Standards Roadmap here]

Following the central government's directive, China's provinces have been revising their regulations to implement the new fuel standards. Some provinces have moved faster than others in releasing local implementation rules. For twenty-nine provinces, each decided its own effective date for the standards and then applied them simultaneously to all of its cities. Jiangsu and Guangdong provinces chose to extend the new standards to their cities gradually. A list of cities were selected to adopt the new standards first, followed by the rest in the second stage. Although cities and regions in China may implement fuel quality standards according to their own timelines, fuel price changes are tightly regulated by the National Development and Reform Commission (NDRC), the nation's top economic planner. To compensate for the required refinery upgrades and increased production costs of cleaner fuels, the NDRC announced a new pricing policy. The wholesale prices of China IV gasoline and diesel were increased by ¥290 and ¥370/ton, respectively. The prices of China V gasoline and diesel were raised by a further ¥170 and ¥160/ton. Upon the implementation of the new standards, retail stations raised their gasoline and diesel prices accordingly.

Figure 2 shows the gradual upgrading of the China III gasoline and diesel fuel quality standards to IV and then to V in Chinese cities. By the end of 2013, 25.5% of prefectures had implemented the gasoline IV standard, and 1.5% of prefectures had adopted diesel IV. Those ratios had increased to 100% and 22%, respectively, by the end of 2014. By 2015 all of China's prefectures were supplying only gasoline IV and diesel IV. As for the ultra-low-sulfur fuels, the gasoline V and diesel V standards are still in the process of implementation. By 2013, 3% of prefectures had started to supply gasoline V, while only 0.3% of prefectures had adopted diesel V. Those ratios had increased to 12.5% and 3.9% in the following year. By the end of the sample period in 2015, 14.5% of prefectures had adopted gasoline V and

[5] In addition to sulfur reductions, the progression from China III to China V gasoline standards involves a reduction in maximum permitted manganese levels and reductions in minimum octane requirements. The progression from China III to V diesel standards involves changes in the required cetane content.

14.2% of prefectures had adopted diesel V.

[Insert Figure 2 Evolution of Fuel Content Regulations in China here]

3 Estimation Strategy

3.1 Data

Analysing pollution levels in response to changes in fuel standards involved assembling data set containing matched indicators of fuel standards implementation, fuel prices, air pollution, and weather conditions.

The fuel standards and fuel prices information was assembled from circulars issued by the Provincial Development and Reform Commissions on Implementing Gasoline (or Diesel) Standard IV (or V) in the various provinces. The price data were compiled from NDRC circulars.[6] The fuel market is not fully integrated in China due to geography, distance, and different levels of regional development. There are regional price policy variations. Twenty-four provinces apply a province-specific price in the cities they administer. Another six provinces apply city-specific prices. However, nationally, fuel price changes are tightly regulated by the NDRC. During the period studied, the top planner adjusted fuel prices 52 times in response to changes in international crude prices. In the circulars they issued they specified incremental price changes and effective dates for all provinces.

Air pollution data are published hourly and daily by the MEP. The data for 2013 to 2015 cover 1,436 monitoring stations in 337 prefectures. Following the implementation of new ambient air quality standards (MEP, 2012), data on fine particulates and O_3 became publicly available in for the first time in 2013. An AQI was developed based on the hourly and daily observations of sulfur dioxide, nitrogen dioxide, carbon monoxide, PM_{10}, $PM_{2.5}$, and ozone. This was a notable shift from the previous index (the API) which considered only SO_2, NO_2, and PM_{10}. All 337 prefectures were required to disclose their once-classified air quality data beginning in 2015. The AQI scale ranges from 0 to 500. It is further divided into six ranges: 0–50, 51–100, 101–150, 151–200, 201–300 and 301–500. In public reports these are termed good, moderate, unhealthy for sensitive groups, unhealthy, very unhealthy, and hazardous, respectively.

Those Chinese data were supplemented by weather data from the U.S. National Climatic Data Center. Those data contains daily readings from 365 weather stations in China during the 2013 to 2015 period. The meteorological variables were aggregated to the prefecture

[6] Source: http://www.sdpc.gov.cn/zcfb/zcfbtz (in Chinese).

level by averaging the daily readings of all the weather stations within a prefecture. The indicators used were temperature, precipitation and wind speed. Weather stations for which there were fewer than 100 records were winsorized.

Other data on exhaust emission regulations were obtained from the official documents published by prefecture-level transportation and public security bureaus. Those documents clearly state the exact dates when the prefectural governments began enforcing the exhaust emission standard IV for gasoline vehicles and required the scrapping of yellow label vehicles, which are defined as gasoline vehicles not meeting the Chinese gasoline standard I and diesel vehicles not meeting the Chinese diesel standard III.

Detailed variable definitions and descriptive statistics are presented in Table 2.

[Insert Table 2 Summary Statistics here]

3.2 Estimation Framework

To quantify the effects of the fuel content regulations on air pollution, we use two estimation techniques: a DD specification, and an RD framework.

3.2.1 DD Framework

Time and regional variations in the regulations are exploited to conduct a DD estimation. Specifically, air pollution outcomes in the cities with new fuel content regulations are compared with those in cities without them (the first difference) before and after the implementation of the regulations (the second difference).

We choose to focus on the shift from Chinese gasoline standard III to standard IV for the analysis for several reasons. First, because fuel standard III had been implemented in China by 2009, so there had been two years without any fuel content regulation changes before the upgrading to gasoline standard IV. That provides a relatively long window to check the comparability between treatment and control groups in the pre-treatment period. Second, the sequence of later fuel standard reforms (including the upgrading from IV to V and two sequential diesel standard upgrades from III to IV and then to V) was highly correlated with that of the gasoline standard IV reform. As a result, even if the treatment and control groups were comparable before the gasoline standard IV reform, that change would make the two groups different given the potential policy impact. That would violate the parallel trend assumption for the later reforms, making it more difficult to quantify any air pollution effects.

To contain any possible contamination of the gasoline standard IV reform's effect from the later fuel content reforms, those later reforms are included as explicit controls in the DD estimation. Specifically, the DD specification is:

$$y_{scd} = \beta \cdot Gasoline4_{cd} + \boldsymbol{\rho}\mathbf{LPolicy}_{cd} + \boldsymbol{\lambda}_s + \boldsymbol{\lambda}_d + \boldsymbol{\gamma}\mathbf{X}_{scd} + \varepsilon_{scd}, \tag{1}$$

where s, c, and d denote monitoring station, city, and day, respectively. y_{scd} denote the logarithm of daily average pollutant concentrations, including AQI, $PM_{2.5}$, PM_{10}, and O_3. $Gasoline4_{cd}$ is a dummy variable indicating whether city c has upgraded to gasoline standard IV by day d. $\boldsymbol{\lambda}_s$ is the set of station fixed effects, controlling for all time-invariant variations across monitoring stations within a city, including topographic features; $\boldsymbol{\lambda}_d$ is the set of day fixed effects controlling for the daily shocks common to all cities (e.g., monetary policy and exchange rate changes); and ε_{scd} is the error term. The standard errors are clustered at the station level to control for possible heteroskedasticity and serial correlation.

$\mathbf{LPolicy}_{cd} = \{Gasoline5_{cd}, Diesel4_{cd}, Diesel5_{cd}\}$, where $Gasoline5_{cd}$ is a dummy variable indicating whether city c has upgraded to gasoline standard V by day d; similarly, $Diesel4_{cd}$ is a dummy variable indicating whether city c's diesel standard has progressed from III to IV; and $Diesel5_{cd}$ is a dummy variable indicating whether city c has upgraded its diesel standard from IV to V.

The identification exploits daily variations among cities, so any potential bias could only have arisen from omitted variables on the day level. One primary threat is seasonality. Specifically, if the implementation of new gasoline and diesel content regulations corresponded with specific weather conditions, the estimates could be mistakenly attributed to policy effects. While the day fixed effect has effectively controlled for all national average seasonality, station-specific seasonality is addressed by including three sets of controls in $\mathbf{X}_{scd}$: $\boldsymbol{\lambda}_s \times \mathbf{Day\ of\ Week}_d$, where $\mathbf{Day\ of\ Week}_d = \{Monday, Tuesday, ..., Sunday\}$; $\boldsymbol{\lambda}_s \times \mathbf{Week\ of\ Month}_d$, where $\mathbf{Week\ of\ Month}_d = \{Week1, ..., Week5\}$; and $\boldsymbol{\lambda}_s \times \mathbf{Month\ of\ Year}_d$, where $\mathbf{Month\ of\ Year}_d = \{January, ..., December\}$. As weather conditions are well known to significantly influence pollution levels, concerns about station-specific weather conditions are further dealt with by adding a series of weather variables in $\mathbf{X}_{scd}$: $Temperature_{cd}$, $Rainfall_{cd}$, and $Wind\ Speed_{cd}$. Finally, as fuel prices changed a number of times during the period studied, a $Fuel\ Price_{cd}$ is included in X_{scd} to isolate the effects of the regulatory changes.

Another threat to the identification is that if there were other on-going reforms around the time of the gasoline standard IV reform the estimates might also reflect those confounding factors. To address this concern, the government documents setting out environmental protection policies around the time of the gasoline standard IV reform are examined carefully.

A prominent policy change was the change in vehicle emission regulations with two measures targeting new and old vehicles separately. Exhaust emission standard IV is imposed for new gasoline vehicles. For old vehicles, China adopts one of the world's most ambitious voluntary scrapping programs aimed at gasoline vehicles not meeting Chinese gasoline standard I and diesel vehicles not meeting Chinese diesel standard III (termed "yellow label vehicles"). Two additional controls were included to remove the confounding effect of those changes. $Gasoline\ Car4_{cd}$ indicates whether city c had adopted exhaust emission standard IV for gasoline vehicles by day d, and $Yellow\ Car_{cd}$ indicates whether city c had started to phase out yellow label vehicles.

To further verify the DD identifying assumptions, we examine whether the parallel trend assumption holds in this setting. Specifically, we examine whether or not cities which had adopted the $Gasoline4_{cd}$ policy and those which had not showed similar time trends before the adoption. The estimation specification is:

$$y_{scd} = \sum_{j=-60}^{-1} \boldsymbol{\delta}_j \cdot (Gasoline4_{cd_{c0}+j}) + \boldsymbol{\beta} \cdot \mathbf{Policy}_{cd} + \boldsymbol{\lambda}_s + \boldsymbol{\lambda}_d + \boldsymbol{\gamma}\mathbf{X}_{scd} + \varepsilon_{scd}, \qquad (2)$$

where d_{c0} denotes the date when city c started to supply gasoline IV; $(Gasoline4_{cd_{c0}+j})$ is a series of dummies indicating whether $d - d_{c0} = j$, with $j = -60, ..., -3, -2, -1$. The omitted time category is $j \prec -60$. In other words, $\boldsymbol{\delta}_j$ captures the difference in air pollution levels between cities with and those without the gasoline IV requirement up to 60 days prior to the start of the regulations‘ implementation. All the other controls are as previously defined.

3.2.2 RD Framework

To adress the concern that the DD estimates might still suffer from some incomparability between the treatment and control cities, we apply the RD technique of Davis (2008) and of Auffhammer and Kellogg (2011). Regression discontinuity analysis focuses on a narrow window around the policy change in which unobservables are allowed to act nonlinearly so long as they move smoothly at the time of the reform. The RD technique is applicable here because (1) gasoline standard IV was imposed on all vehicles simultaneously, generating a discontinuous change in their emissions; and (2) the formation of pollutants responds quickly to changes in emissions.

Hahn, Todd and Van der Klaauw (2001) have shown that β can be identified as

$$\beta = \lim_{d \downarrow d_{c0}} E\left[y_{scd} | d_c = d\right] - \lim_{d \uparrow d_{c0}} E\left[y_{scd} | d_c = d\right] = \hat{\beta}_{RD}. \qquad (3)$$

We estimate $\hat{\beta}_{RD}$ using a nonparametric approach, specifically, local linear regression, as suggested by Hahn, Todd and Van der Klaauw (2001). $\hat{\beta}_{RD}$ is estimated from

$$\min_{\alpha,\beta,\delta,\tau} \sum_{s=1}^{N} K\left(\frac{d_c - d_{c0}}{h}\right) \left[y_{scd} - \delta - \tau\left(d_c - d_{c0}\right) - \beta E_c - \alpha E_c \left(d_c - d_{c0}\right)\right]^2, \tag{4}$$

where E_c takes a value of 1 if $d_c \geq d_{c0}$ and 0 otherwise; h is the bandwidth; and $K(.)$ is a rectangle kernel function.

Essentially, RD compares for each station the outcomes just before the gasoline content IV reform with those just after the reform. Since the reform was carried out in different locations at different times, station fixed effects must also be controlled for (which then restricts comparisons within the same station, before and after the reform), along with station-specific seasonality (i.e., $\boldsymbol{\lambda}_s \times$ **Day of Week**$_d$, $\boldsymbol{\lambda}_s \times$ **Day of Week**$_d$, $\boldsymbol{\lambda}_s \times$ **Month of Year**$_d$), station-specific weather conditions and fuel prices that potentially changed abruptly with the reform. The estimation involved two steps. First the outcome y_{scd} is regressed against these controls to obtain a residual $\widetilde{y_{scd}}$. That value is used in the second step, the nonparametric estimation (4) to obtain the parameter of interest $\hat{\beta}_{RD}$.

We calculate the optimal bandwidth h using the method developed by Imbens and Kalyanaraman (2012). To check whether the results are sensitive to the optimal bandwidth selected, alternative bandwidths are tested (see, e.g., Carneiro, Pedro, Loken, and Salvanes, 2015 for the details). Following the suggestion of Lee and Lemieux (2010), robust standard errors are calculated, which capture random sampling errors and provide conservative statistical inference.[7]

4 Findings

4.1 DD Estimates

Table 3 reports the results from the DD estimation of equation (1), showing the effect of fuel standard regulations on the logarithm of daily average AQI and the concentrations of $PM_{2.5}$, PM_{10}, and O_3. The coefficients for $Gasoline4_{cd}$ are precisely estimated. Column 1 indicates that the gasoline IV standard improved the AQI by about 3.2% on average.

Columns 2 to 4 confirm the contribution of cleaner gasoline fuels in reducing particulates and ozone, the major components of smog and haze in Chinese cities. As column 2 shows, the progression from gasoline standard III to IV caused a reduction in $PM_{2.5}$ concentration

[7] Using the standard errors clustered at the station level produces similar statistical significance (results available on request).

by 2.3%. Given that the average mean of $PM_{2.5}$ concentration in the pre-treatment period was 59.64 $\mu g/m^3$, the estimate implies that implementing standard IV caused an average 1.39 $\mu g/m^3 = 0.023 \times 59.64$ reduction in $PM_{2.5}$ concentration. Similarly, column 3 suggests that the higher quality gasoline reduced PM_{10} concentrations by 5.1%, equivalent to a total reduction of 5.19 $\mu g/m^3$ on average from the mean pre-treatment PM_{10} concentration of 101.69 $\mu g/m^3$.

In column 4, the findings on ozone are consonant with those of Auffhammer and Kellogg (2011) to the effect that only precisely-targeted, inflexible regulations requiring the removal of particularly harmful compounds can significantly improve air quality.[8]

[Insert Table 3 Daily Average Pollutant Concentration here]

Parallel Pre-Trends. Despite the exhaustive set of controls included in the analyses, there may still be some concern about the comparability between the treatment and control groups central to DD estimation. One validity check commonly used in DD analysis is to examine whether the treatment and control groups have parallel pre-treatment trends. That test is conducted using a 60 day lead-up period before the implementation of the gasoline IV regulations.

Figure 3 plots the estimated coefficients of the pre-treatment dummies from equation (2) as well as the 95% level confidence intervals. There was no hike or dip in the air pollution outcomes before the new fuel standard–gasoline IV–took effect. None of the indicators shows any statistical power, suggesting that the treatment and control cities followed similar time trends for at least 60 days before the adoption of the higher quality fuels. This inspires confidence that the control group cities provide a good counterfactual for the treatment group in the period studied.

[Insert Figure 3 Tests for Parallel Trends here]

4.2 RD Estimates

Figures 4a through 4d plot the relationship between normalized time variable (the assignment variable; $\tilde{d}_c = d_c - d_{c0}$) and four pollutant measures. The circles represent mean values for each bin with a size of 1 day; the lines indicate the fitted values from local linear regression with the optimal bandwidth calculated using the method of Imbens and Kalyanaraman (2012). The grey areas are the 95% confidence intervals, and the vertical line is the cutoff

[8] The estimation results are very similar using the logarithm of the daily maximum pollutant concentration as the dependent variable.

point for the assignment variable.

[Insert Figures 4 RD Estimates here]

All four figures show a clear drop in pollutants at the cutoff point, consistent with the DD estimates. That is, the implementation of the gasoline IV standards caused a fall in the pollution levels.

Regression results are reported in Table 4. The estimates of β, the parameter of interest, are all negative and statistically significant in the four regressions, further confirming the patterns of Figures 4a–4d and the DD estimates in Table 3. The DD and RD estimations use different control groups and different identifying assumptions, but the consistent results between two estimation frameworks lend support to the conclusion that the new gasoline content regulations achieved their primary goal of reducing city air pollution.

[Insert Table 4 RD Estimates here]

Alternative bandwidth. The nonparametric estimation requires the calculation of optimal bandwidth. The method developed by Imbens and Kalyanaraman (2012) is used. To check whether the findings might be sensitive to the optimal bandwidth selected, alternative bandwidth from $h^* - 10$ to $h^* + 10$ with intervals of 2 are tested. Estimates using those alternative bandwidths are plotted in figures 5a through 5d. The estimates remain stable, suggesting that the results are not driven by a particular bandwidth.

[Insert Figure 5 Sensitivity Test on Choice of Bandwidth here]

4.3 Heterogeneous Effects

In this subsection, we examine the potential heterogeneous effects of fuel content regulations on air quality. The DD estimations are used to discuss temporal and topographical differences in the results. The RD estimates display similar patterns (see Figure A1 and Table A1 in the appendix).

Results by hours. Intra-day differential effects can be highlighted by dividing each day into eight time periods, specifically, 12–2 am, 3–5 am, ..., 9–11 pm. Figure 6 reports estimated coefficients for each time period separately. The coefficients are quite stable; that is, the pollution reduction effects of the fuel content regulations persist throughout the day. There are, however, some interesting intra-day fluctuations. For ozone, the effect of fuel standards on its concentration seems to follow an inverse U-shaped curve. Pollution mitigation starts to decline after daybreak and is at its weakest in the mid-afternoon. The effect picks up again after late in the afternoon. This pattern is corroborated by the fact sunlight and temperature, the essential elements in forming ground-level ozone, usually peak during mid-afternoon. The regulations are most effective in reducing particulates in the afternoon and least effective in the evening. This is probably associated with daily variations in the depth of the boundary layer and with anthropogenic emissions (Zhang and Cao, 2015).

[Insert Figure 6 Effects of Fuel Standards on Air Quality through the Day here]

Results by topography. We consider the role of an important topographical feature, *slope*, in influencing the effects of the new fuel standards on air pollution. Surrounding hills and urban structures can obstruct air movement and trap pollutants emitted by vehicles in the street where they accumulate. To quantify this effect, information on the slope of the area within a one kilometre radius of each monitor station is collected.[9] The area's average slope is the value assigned to the station. The 1,436 monitoring stations are then ranked according to their slope values. The top 30% of the stations are classified as high slope locations, with the bottom 30% classed as low slope. The effects of the fuel standard regulations on air quality are then investigated for the two groups separately.

As is shown in columns 1 to 8 of Table 5, the low slope stations in general show larger effects of the adoption of higher-quality fuels, compared with the group with greater slopes. Topography (slope in this case) apparently complements the fuel standard regulations. Flat urban structures are less obstructive, and geographical barriers limit the dispersion of pollutants by reducing wind turbulence. So the flatter the terrain, the more effective better fuel standards are in improving air quality.

[Insert Table 5 Effects of Fuel Standards on Air Quality by Topography here]

4.4 Cost-Benefit Analyses

We use the estimates to conduct "back of the envelope" benefit-cost analyses for the fuel quality upgrading. The primary benefits are assumed to be health improvements associated with air pollutant reductions, especially reductions in particulate matter (Wolff, 2014). There is evidence from the European Union that PM is the most lethal air pollutant, with an impact much greater than that of the second most deadly air pollutant, ozone (Watkiss et al., 2005). The analysis therefore focuses on inferring the health benefits related to reducing

[9] The slope data are extracted from the Shuttle Radar Topographic Mission 90m Digital Elevation Model data.

$PM_{2.5}$ pollution.[10]

To do so, we resort to a number of recent studies that have examined the mortality impacts of China's environmental policies.[11] Chen et al. (2013) provide useful benchmark estimates of the effect of total suspended particles (TSP) exposure on mortality risk. Their analysis suggests that long-term exposure to an additional 100μg/m3 of TSP is associated with a 14% increase in the overall mortality rate and a reduction in life expectancy at birth of about 3 years. No Chinese study has yet directly explored the relationship between $PM_{2.5}$ exposure and mortality, but Cao et al. (2011) propose using a 32.5% ratio to convert TSP to $PM_{2.5}$ based on current and historical Chinese data. As an alternative, a 30% ratio is also tested, as suggested by Pope and Dockery (2013). That suggestion is based on the average concentrations in the most polluted U.S. cities in the late 1970s. Chen et al. (2013)'s estimates imply that a 30 to 32.5 $\mu g/m^3$ reduction in $PM_{2.5}$ is associated with a decrease of 0.000893 (i.e., $0.14 \times (638.3 \div 100000)$) in the mortality rate (Chen et al., 2013).

Applying the estimates from column 2 of Table 2 (an average 1.39 $\mu g/m^3$ reduction in $PM_{2.5}$ concentration), the implementation of gasoline standard IV is associated with a 0.000038 to 0.000041 reduction (i.e., 1.39/32.5*0.000893 to 1.39/30*0.000893) in the mortality rate. With 711.82million living in China's cities in 2012, that translates into a predicted 27,186 to 29,452 lives saved. That prolongation can be monetize by applying the "value of a statistical life" (VSL), defined as the sum the average person would pay to reduce their risk of dying by small amounts that, together, add up to one statistical life (World Bank, 2007). Multiplying the VSL by the number of predicted lives saved (27,186 to 29,452) through $PM_{2.5}$ reduction and using the World Bank's baseline value for a statistical life—US$0.1613million based on a contingent valuation approach—a 1.39 $\mu g/m^3$ reduction in $PM_{2.5}$ concentration implies US$4.39billion to US$4.75billion in health benefits from reduced mortality. However, the World Bank's value of life tends to be conservative. As incomes have increased, the willingness to pay for risk reduction is likely to have risen (Costa and Khan, 2004). The Chinese economy has been growing rapidly during the past few decades, so it might be preferable to use an alternative VSL suggested by Qin (Qin et al., 2013)—US$0.6194million based on a hedonic wage approach. The health benefits related to adopting the gasoline IV standard are then US$16.84billion to US$18.24billion.

The costs of the regulations are those related to fuel upgrading. Considering the cost

[10] Many studies have examined the health effects of PM10 exposure in China, but much less attention has been paid to $PM_{2.5}$, largely due to data availability (see He et al., 2016; Viard and Fu, 2015). In fact, $PM_{2.5}$ is known to be a better predictor of PM-driven acute and chronic health effects than the levels of coarser particles (Schwartz et al., 1996; Cifuentes et al., 2000; Pope and Dockery, 2006; Matus et al., 2012).

[11] Due to data limitations, morbidity was ignored. Adding that into the calculations would of course increase the benefits figure.

pass-through to the consumers, the pricing information published by the NDRC can be used. The wholesale price of China IV gasoline were set to be increased by ¥290/ton. In 2012, gasoline consumption was 86.84million tons. Lack of data compelled the simplifying assumption that the price changes applied to all gasoline consumption, without considering the gradual expansion of the use of higher quality fuels across China. A progression from fuel standard III to IV would then have induced cost increases of approximately ¥25.18billion (or US$3.99billion at an exchange rate of 6.3125).

Overall, this "back of the envelope" calculation suggests that the benefits of adopting the new gasoline standard significantly outweigh its costs. That benefit-cost conclusion is robust to a range of assumptions for the parameters involved.

The high efficiency demonstrated for the fuel standards could be due to several considerations. First, the new fuel standards were strictly implemented by the retailers and the cities under pressure from the NDRC. Second, drivers had little scope for storing cheaper, low-quality fuel for any considerable period of time, so the policy could not induce significant non-compliance from a large number of drivers. The fuel standard thus may be more cost effective than the driving restrictions imposed in some Chinese cities, which are shown to reduce daily labor supply. Restricting the number of vehicles driven each day is known to be very costly, so perhaps more emphasis should be placed on developing and implementing cleaner fuel and emissions technologies.

The efficiency of environmental regulations crucially depends on whether they can be strictly enforced without inducing behavioral responses. These important factors need to be taken into account when formulating policy and translating policy into practice. The findings imply that environmental regulations should put greater emphasis on cleaner technologies, of which cleaner fuel is a prominent example.

4.5 Fuel Standards and Emission Technology

The development of clean exhaust technologies is also important for reducing tailpipe emissions and potentially for minimizing climate change. But the transition from dirty to clean technologies may need well-designed government regulations given the competition between these two approaches (Acemoglu et al., 2016). As has been mentioned previously, in addition to more stringent fuel standards, China adopted new vehicle emission regulations during the period studied, pushing forward the use of better-performing engines. China's reform path provided a rare opportunity to examine how various policies are designed to shape the transition to clean technology.

To shed light on the relationship between fuel standards and vehicle emission regulations, whether or not adopting the gasoline IV standard led to more stringent vehicle emission regulations is investigated. Specifically, we examine the relationship between the $Gasoline4_{cd}$ variable and $Gasoline\ Car4_{cd}$ (the exhaust emission standard IV for gasoline vehicles), and also its relationship with the $Yellow\ Car_{cd}$ variable indicating the voluntary scrapping programs. Since all of these policies were adopted at the city level, the following DD estimation is evaluated.

$$V_{cd} = \beta \cdot Gasoline4_{cd} + \boldsymbol{\rho}\mathbf{LPolicy}_{cd} + \boldsymbol{\lambda}_c + \boldsymbol{\lambda}_d + \boldsymbol{\gamma}\mathbf{X}_{cd} + \varepsilon_{cd}, \qquad (5)$$

where V_{cd} denotes the vehicle emission regulations (i.e., $Gasoline\ Car4_{cd}$ or $Yellow\ Car_{cd}$ as previously defined); λ_c is the city fixed effects, controlling for all time-invariant heterogeneity among the cities; X_{cd} includes a series of time-varying controls as in equation (1) but measured at the city level (such as city-specific seasonality, city-specific weather conditions, and fuel prices); and ε_{cd} is again the error term. The standard error at the city level are clustered to control for possible heteroskedasticity and serial correlation.

Estimation results are reported in Table 6. As shown in column 1, the adoption of the gasoline IV standard predicted earlier implementation of exhaust emission standard IV for new gasoline vehicles. Similarly, in column 2, the estimate points to a positive contribution of the new fuel standard to the phasing out of older vehicles. When the Chinese government enforced the new fuel standards, it apparently built momentum for introducing tighter emission standards given the complementarity between fuels and engines.[12] Those follow-up measures are likely to have further enhanced the pollution reductions in the long term. Taken together, the reform of fuel quality has profound impacts on the vehicle emission regulations, through which a more rapid transition to cleaner technologies could be achieved.

[Insert Table 6 Effects of Fuel Standards on Gasoline Vehicle Emission Regulations here]

5 Conclusion

Air pollution is currently China's most severe environmental problem, with the population increasingly experiencing prolonged and dangerous smog events. Extreme concentrations of particulate matter, especially fine particulates and ground-level ozone, pose deadly threats to human health. With the dramatic growth of private motor vehicle fleets, vehicle exhaust has

[12] Note that data availability prevents empirically examining the effect of fuel standards on innovations in engine technology. The fuel regulations might, for example, have spurred consumer demand for better-quality engines. This, in turn, might have generated an endogenous technological innovation in the car market (Bresnahan and Yao, 1985; Acemoglu and Linn, 2004).

become a major source of ambient air pollution in Chinese cities. One pollution reduction measure has been to require the use of fuels with much lower sulfur content. In this paper, we assess the quantitative importance of this policy and shed light on how higher quality fuels may help address air pollution.

Taking advantage of the roll-out and strict enforcement of new gasoline standards across China, this study has shown that cleaner fuels do indeed translate into better air quality. The adoption of higher gasoline standards significantly reduces local air pollutant concentrations, including those of PM and ozone. Further, the health benefits outweigh the costs. More stringent gasoline standards also drive the progress of new emission regulations. These results have important environmental, economic, and health policy implications. The importance of stringent fuel quality standards for exhaust emissions is evident.

This study focuses on the technical aspects of regulations in mitigating vehicle pollution. Government officials' incentives in advancing this environmental agenda are also an important topic (Zheng and Kahn, 2013), but we leave that difficult enquiry to future research.

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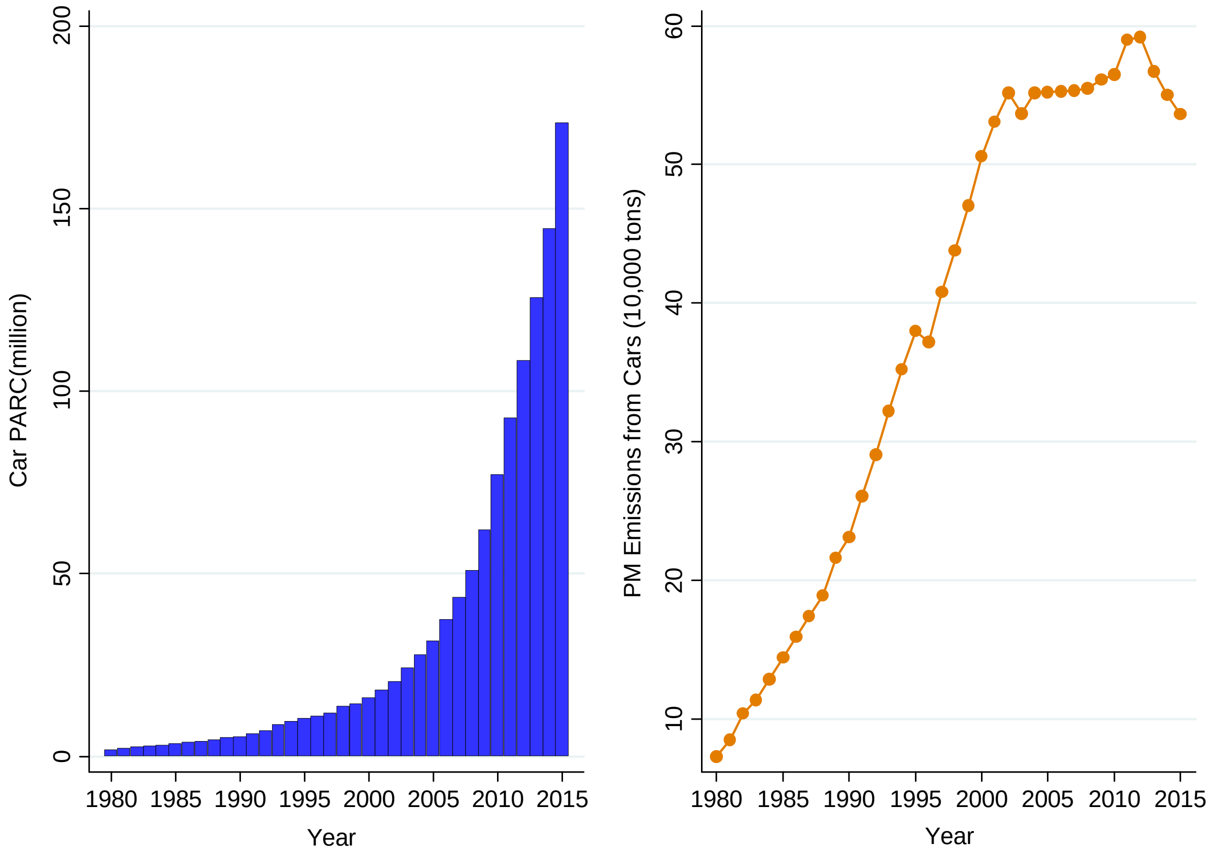
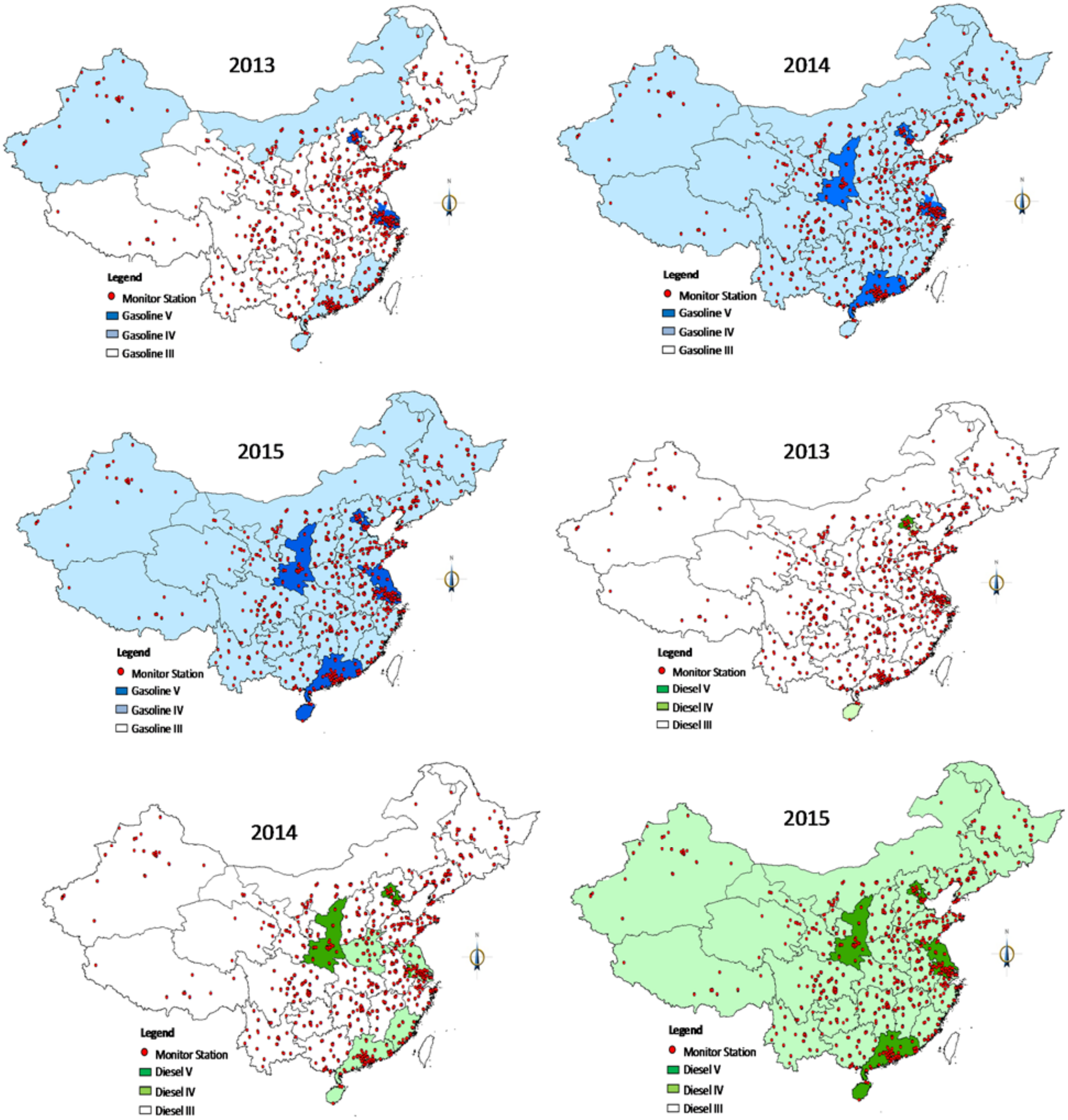
Figure 1: Motor Vehicle Ownership and PM Emissions in China



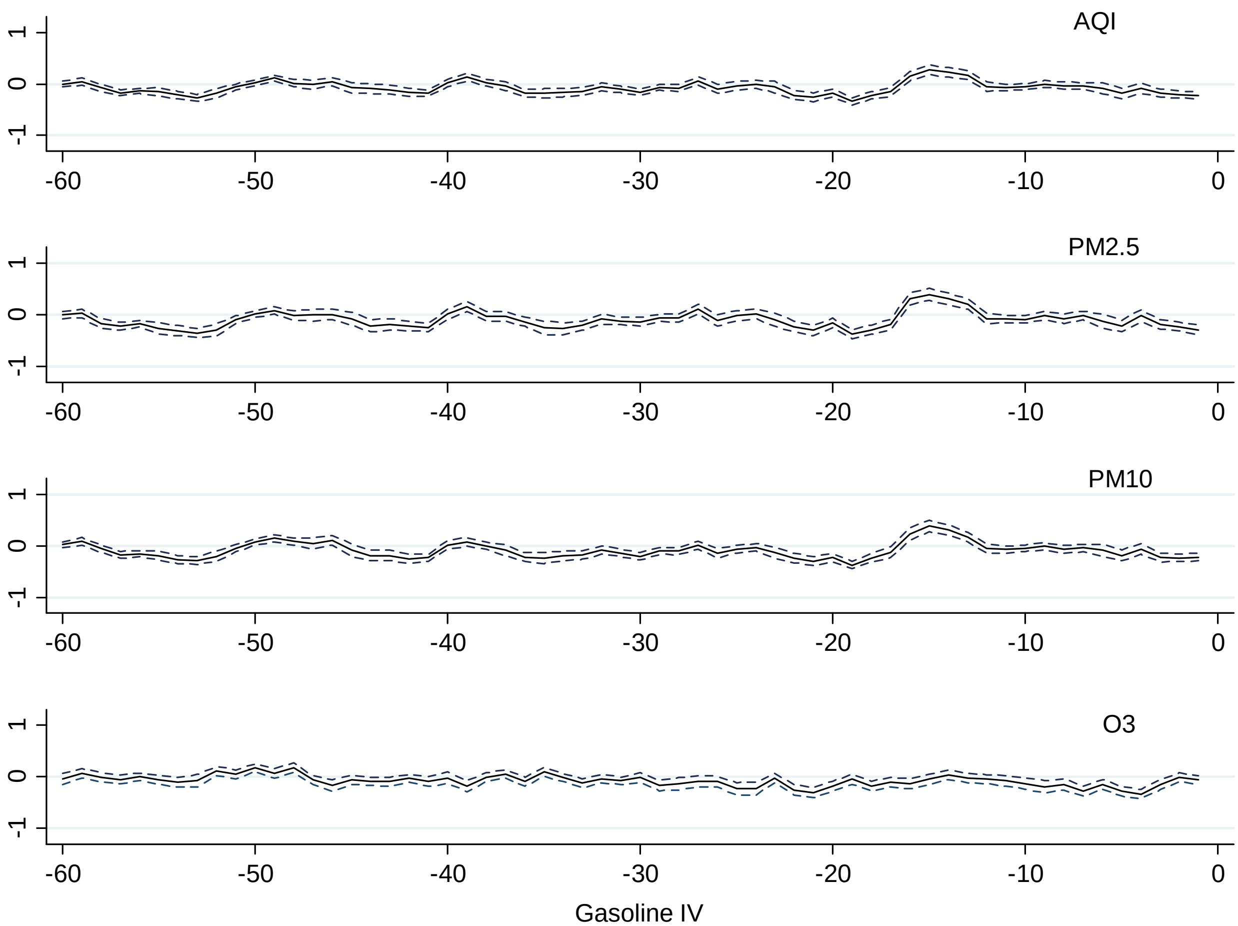
Data source: China Vehicle Emission Control Annual Report 2010-2016.

Figure 2 Evolution of Gasoline and Diesel Content Regulations in China



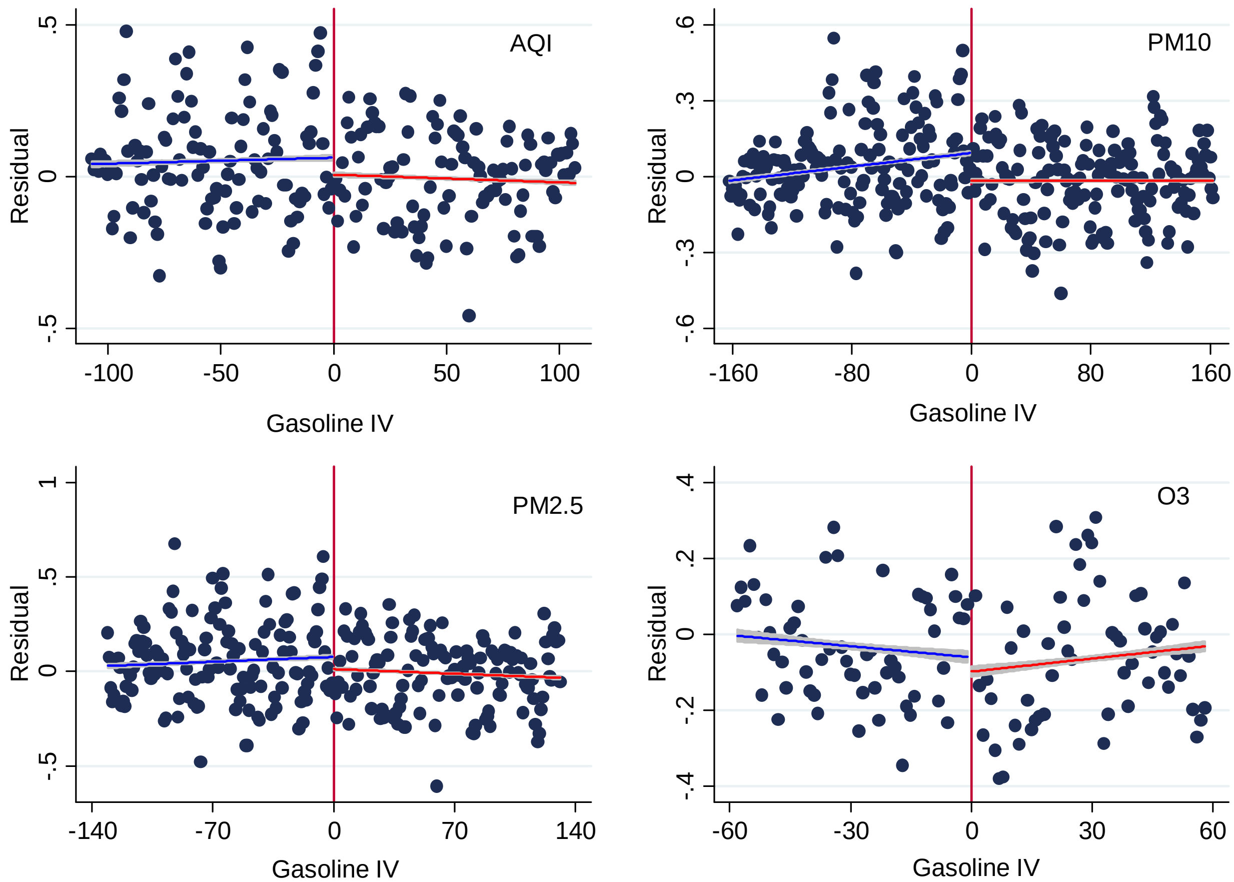
Notes: The figure displays the gradual implementation of new fuel standards in China from 2013 to 2015, beginning with the progression of gasoline standards from III to IV, and then from IV to V, followed by diesel standards upgrading in various cities.

Figure 3 Tests for Parallel Trends



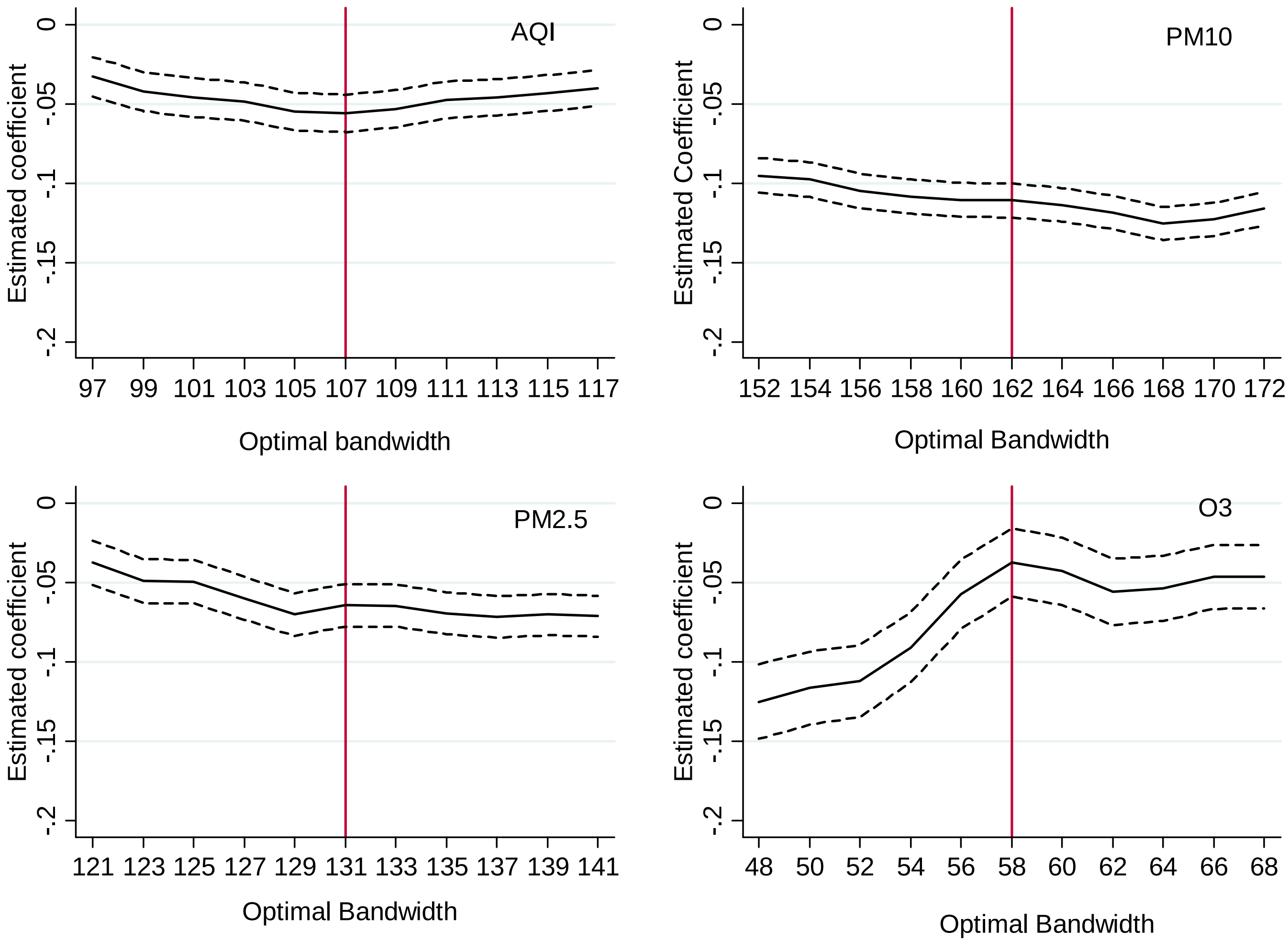
Notes: The figure plots the estimated coefficients of the pre-treatment dummies from equation (2) as well as their 95% level confidence intervals. The treatment and control groups show parallel pre-treatment trends up to 60 days before the implementation of the first fuel content regulation (i.e., the gasoline IV regulation).

Figure 4 Effects of Fuel Standards on Air Quality (RD Estimates)



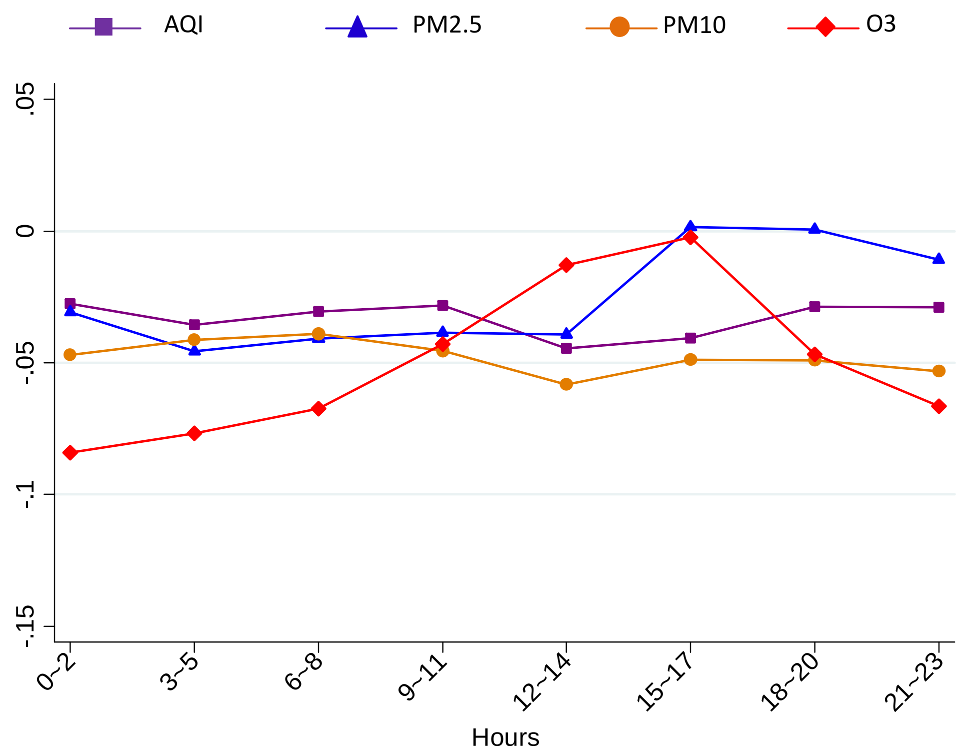
Notes: The method developed by Imbens and Kalyanaraman (2012) is used to calculate the optimal bandwidth. The estimation method is described in full in Section 3.2.2.

Figure 5 Sensitivity Test on Choice of Bandwidth



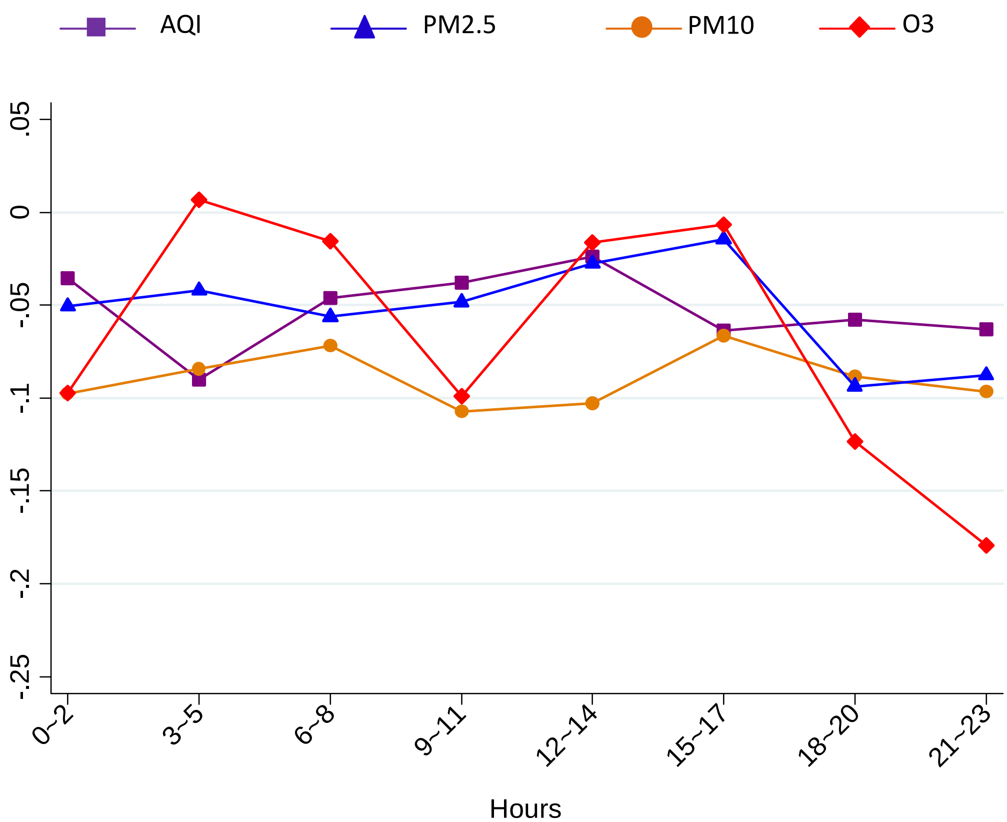
Notes: The method developed by Imbens and Kalyanaraman (2012) is used to calculate the optimal bandwidth. The estimation method is described in full in Section 4.2.

Figure 6 Effects of Fuel Standards on Air Quality through the Day



Notes: The intra-day effects of gasoline standard regulations are examined by dividing a day into eight time periods for which the coefficients from equation (2) are plotted.

Figure A1 Effects of Fuel Standards on Air Quality through the Day (RD Estimates)



Notes: The figure (the counterpart of Figure 6) plots the coefficients computed using the methods developed by Hahn *et al*. (2001).

Table 1

Fuel Standards Roadmap

Stage	Standard	Maximum sulfur level (ppm)	Standard Issued on	Implementation
China Gasoline III	GB 17930-2006	150	Dec 6, 2006	Phased-in by Dec 31, 2009
Gasoline IV	GB 17930-2011	50	May 12, 2011	Phased-in by Dec 31, 2013
Gasoline V	GB 17930-2013	10	Dec 18, 2013	Phased-in by Dec 31, 2017
China Diesel III	GB 19147-2009	350	June 12, 2009	Phased-in Jan 1, 2010–Jul 1, 2011
Diesel IV	GB 19147-2013	50	Feb 7, 2013	Phased-in by Dec 31, 2014
Diesel V	GB 19147-2009	10	June 8, 2013	Phased-in by Dec 31, 2017

Source: Intl. Council on Clean Transportation

Table 2
Variable definition and descriptive statistics

Variable	Definition	Mean	SD
Fuel Standard Regulations and Price			
Gasoline IV	=1 if a city has upgraded the gasoline content regulation from the Chinese standard III to the standard IV; =0 otherwise.	0.717	0.450
Gasoline V	=1 if a city has upgraded the gasoline content regulation from the Chinese standard IV to the standard V; =0 otherwise.	0.146	0.353
Diesel IV	=1 if a city has upgraded the diesel content regulation from the Chinese standard III to the standard IV; =0 otherwise.	0.521	0.500
Diesel V	=1 if a city has upgraded the diesel content regulation from the Chinese standard IV to the standard V: =0 otherwise.	0.067	0.250
Fuel_Price	Average retail price of gasoline and diesel (thousand yuan/ton)	7.950	0.976
Vehicle Emission Regulations			
Gasoline_Car IV	=1 if a city has upgraded the gasoline vehicle emission regulation from the Chinese standard III to standard IV; =0 otherwise.	0.898	0.303
Old Car	=1 if a city has started to phase out yellow label vehicles; =0 otherwise.	0.612	0.487
Air Pollutant Varibles			
AQI	Air Quality Index	87.934	57.130
PM2.5	PM2.5 concentration (μg/m3)	58.972	51.190
PM10	PM10 concentration (μg/m3)	99.665	76.317
O3	O3 concentration (μg/m3)	55.398	35.658
Weather			
Temperature	Prefecture daily average temperature (Fahrenheit)	58.460	19.629
Wind_Speed	Prefecture daily average wind speed (knots)	5.083	2.604
Precipitation	Prefecture daily average rainfall (0.1 inches)	0.124	0.392

Notes: Fuel standard regulations, vehicle emission regulations, fuel prices and weather variables are all at the prefectural level. The air pollutant variables are at the monitoring station level. Definitions, means and standard deviations are reported. Data sources are described in full in Section 3.1.

Table 3

Effects of Fuel Standard Regulations on Daily Average Pollutant Concentration

	Log(daily average pollutant concentration)			
	AQI	PM2.5	PM10	O3
	(1)	(2)	(3)	(4)
Gasoline IV	-0.032***	-0.023*	-0.051***	-0.030
	(0.012)	(0.013)	(0.016)	(0.025)
Station dummies	Yes	Yes	Yes	Yes
Day dummies	Yes	Yes	Yes	Yes
Station dummies × Day of week dummies	Yes	Yes	Yes	Yes
Station dummies × Week of month dummies	Yes	Yes	Yes	Yes
Station dummies × Month of year dummies	Yes	Yes	Yes	Yes
Weather condition controls	Yes	Yes	Yes	Yes
Gasoline V	Yes	Yes	Yes	Yes
Diesel IV	Yes	Yes	Yes	Yes
Diesel V	Yes	Yes	Yes	Yes
Gasoline_Car IV	Yes	Yes	Yes	Yes
Old_Car	Yes	Yes	Yes	Yes
Fuel_Price	Yes	Yes	Yes	Yes
Adjusted R^2	0.592	0.582	0.604	0.577
No. of observations	616,264	614,919	603,365	605,318

Note: Reported in parentheses are robust standard errors clustered by monitoring station. ***, ** and * represent significance at the 1%, 5% and 10% levels of confidence, respectively. The weather condition controls are the daily average temperature, rainfall, and wind speed at the prefectural level. All specifications control for the indicators of gasoline V standard, diesel IV standard, diesel V standard, exhaust emission standard IV for gasoline vehicles, the voluntary scrapping programs, as well as fuel prices.

Table 4

RD Estimates: Effects of Fuel Standards on Daily Average Pollutant Concentrations

	AQI	PM2.5	PM10	O3
	(1)	(2)	(3)	(4)
Gasoline IV	-0.056***	-0.064***	-0.111***	-0.038***
	(0.006)	(0.007)	(0.005)	(0.011)
Day	0.0002***	0.0004***	0.001***	-0.001***
	(0.000)	(0.000)	(0.000)	(0.000)
Gasoline IV × Day	-0.0004***	-0.001***	-0.001***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)
Optimal bandwidth	107	131	163	58
R^2	0.005	0.004	0.005	0.002
No. of observations	93,643	112,796	134,211	50,143

Note : Reported in paretheses are robust standard errors. *** indicates significance at the 1% level of confidence. Day is the normalized time variable. The method developed by Imbens and Kalyanaraman (2012) is used to calculate the optimal bandwidth. The estimation method is described in full in Section 3.2.2.

Table 5

Topography and the Effects of Fuel Standards on Air Quality

	Log(AQI)		Log(PM2.5)		Log(PM10)		Log(O3)	
	Slope low	Slope high	Slope low	Slope high	Slope low	Slope high	Slope low	Slope high
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Gasoline IV	-0.054**	0.002	-0.024	-0.001	-0.107***	-0.001	-0.051	0.044
	(0.021)	(0.023)	(0.023)	(0.025)	(0.025)	(0.031)	(0.041)	(0.045)
Station dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Day dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Station dummies × Day of week dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Station dummies × Week of month dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Station dummies × Month of year dummies	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Weather condition controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Gasoline V	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Diesel IV	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Diesel V	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Gasoline_Car IV	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Old_Car	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Fuel_Price	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Adjusted R^2	0.592	0.557	0.582	0.537	0.610	0.573	0.586	Yes
No. of observations	202,967	158,126	202,534	157,821	197,018	156,576	197,633	156,583

Note : Reported in parentheses are robust standard errors clustered by prefecture. *** and ** represent significance at the 1% and 5% levels of confidence respectively. The weather condition controls are daily average temperature, rainfall and wind speed at the prefectural level. All of the specifications controlled for the indicators of gasoline V standard, diesel IV standard, diesel V standard, exhaust emission standard IV for gasoline vehicles, the voluntary scrapping programs, as well as fuel prices.

Table 6

Effects of Fuel Standards on Gasoline Vehicle Emission Regulations

	Gasoline_Car IV	Old_Car
	(1)	(2)
Gasoline IV	0.131**	0.230
	(0.064)	(0.119)
Prefecture dummies	Yes	Yes
Day dummies	Yes	Yes
Prefecture dummies × Day of week dummies	Yes	Yes
Prefecture dummies × Week of month dummies	Yes	Yes
Prefecture dummies × Month of year dummies	Yes	Yes
Weather condition controls	Yes	Yes
Gasoline V	Yes	Yes
Diesel IV	Yes	Yes
Diesel V	Yes	Yes
Fuel_Price	Yes	Yes
Adjusted R^2	0.566	0.759
No. of observations	115,189	115,189

Note : Reported in parentheses are robust standard errors clustered by prefecture. ** indicates significance at the 5% level of confidence. All variables are at the prefectural level. In columns 1 and 2, the dependent variables are the implementation of exhaust emission standard IV for gasoline vehicles, and the voluntary scrapping program, respectively. The weather condition controls are daily average temperature, rainfall and wind speed at the prefectural level. All specifications control for the indicators of gasoline V standard, diesel IV standard, diesel V standard, and fuel prices.

Table A1

RD Estimates: Topography Effects of Fuel Standard Regulations on Air Quality

	Log(AQI)		Log(PM2.5)		Log(PM10)		Log(O3)	
	Slope low	Slope high	Slope low	Slope high	Slope low	Slope high	Slope low	Slope high
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Treatment	-0.108***	-0.074***	-0.102***	-0.024**	-0.123***	-0.097***	-0.082***	0.003
	(0.008)	(0.010)	(0.012)	(0.009)	(0.009)	(0.010)	(0.017)	(0.020)
Day	0.001***	0.001***	0.001***	0.000	0.001***	0.001***	0.0001	0.001***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
Treatment × Day	-0.001***	-0.001***	-0.001***	-0.0003***	-0.001***	-0.001***	0.001**	-0.002***
	(0.000)	(0.000)	(0.000)	(0.001)	(0.000)	(0.000)	(0.000)	(0.000)
Optimal bandwidth	165	164	173	275	163	192	64	81
Adjusted R^2	0.008	0.003	0.007	0.004	0.008	0.004	0.586	0.001
No. of observations	47,821	34,491	49,969	56,865	45,982	39,151	197,633	17,198

Note: Reported in parentheses are robust standard errors clustered by prefecture. *** and ** indicate significance at the 1% and 5% level of confidence respectively. The slope information pertains to a one kilometre radius around each monitoring station.