Clearing the air on Delhi's odd-even program

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Abstract

In January and April 2016, the government of Delhi piloted an "odd-even" traffic rule which mandated that only cars with odd (even) numbered license plates could ply on odd (even) dates. We use high frequency measures from air quality monitoring stations to estimate the program impact. Relative to surrounding satellite cities, fine particle concentrations in Delhi's air were lower by 13% during the January pilot. In contrast, the program did not affect Delhi's air quality during the warmer month of April. Taken together, this suggests that the main value of an ``odd-even" program is as an emergency measure during winter months when car emissions play a more prominent role in affecting air quality.

1.Introduction

Delhi, India's capital, is the third largest city in the world and India's largest city. It also routinely features among the world's most polluted cities. For instance, in 2015 Delhi's average concentration of fine particulates was 110 μg/m^3, 11 times the WHO prescribed annual average; and this fact led the Delhi High Court to compare Delhi to a "gas chamber" (The Times of India, 2015).

In December 2015, the government of Delhi announced a series of emergency measures including a pilot `odd-even' scheme to ration driving (The Hindu, 2015; The Indian Express, 2015). The scheme worked as follows: first, cars were classified into odd and even categories on the basis of the last digit of car licensing plates. Next, it was mandated that only vehicles with odd numbered license plates could ply only on odd numbered dates and even numbered plates on even dates. The scheme was effective during the hours of 8 am and 8 pm for the first 15 days of January 2016. [2] A second round of the odd-even program was implemented between April 15-30, 2016.

This paper estimates the impact of the odd-even program on air quality. To do so, we use high frequency data from monitoring stations to compare fine particulate concentrations in Delhi (where the odd even policy was implemented) to that reported for the neighboring towns of Faridabad and Gurgaon (where the policy was not implemented). Our analysis period spans the six months between November 2015 and April 2016.

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[1] We would like to thank Bhavna Rai for excellent research assistance.

[2] Vehicles driven by women or cars with more than two passengers were exempt from the policy.

We find that, relative to its neighboring cities, fine particulate concentrations in Delhi's air were lower by roughly 24-36 µg/m³ during the January odd-even scheme. These reductions were largest in the mid-morning (11am – 2pm) and we see no gains in air quality at nights (when rationing was not in effect).

In contrast, Delhi's air did not show any quality gains relative to its neighboring cities during the April phase of the program. A likely cause is that the warmer month of April is marked by greater dispersion of particulates, a fact that is reflected in Delhi's lower particulate concentrations during summer relative to the winter (Figure 2). In contrast, the winter month of January is marked by thermal inversion, a phenomenon where a layer of hot air covers cold air near the ground. This, in turn, causes air pollution to be trapped near the ground.

The paper is structured as follows. In Section 2, we present a brief background on air pollution in Delhi and the pollution mitigation programs introduced by the Delhi government or ordered by Supreme Court judgments. Data used for our analysis is outlined in Section 3, with methods described in Section 4. The concluding Section 5 discusses the results and its implications on the efficacy of the odd-even program as an air pollution measure in the city.

2.Background

Particulate Matter (PM) refers to tiny particles, either solid or liquid, which are suspended in the air.[3] Within this broad category, PM10 refers to particles that are smaller than 10 microns in diameters and PM2.5 to particles smaller than 2.5 microns in diameter. Smaller particles more easily penetrate human lungs and, therefore, present greater health risks. While there is no obvious `safe' level for particulates, the World Health Organization and the Indian Government set preferred norms for air quality – at present, these are 40 micrograms per cubic meter for PM10 and 60 micrograms per cubic meter for PM2.5.

Indian cities, however, routinely exceed these norms. Greenstone et al ,(2015) estimated 660 million Indians (or 54.5 % of the population) live in regions exceeding the national standards and reducing the pollution levels just to meet standards could increase life expectancy by 3.1 years on average. In this paper we focus on air quality in Delhi and neighboring cities and below we provide some background on Delhi's air quality as a precursor to our quantitative analysis.

2.1 Delhi: Sources of Pollution
Figure 2 shows the time-trend in Delhi's pollution over a 12-month period from May 2015 to April 2016. We see a sharp uptick in pollution in October, which corresponds to widespread crop burning in Delhi's neighboring agricultural states.

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[3] PM comprise organic and inorganic substances, and originate from many different sources. Sources of PM2.5 include combustion of fuels in various processes in industries, automobiles, cook-stoves as well as in the burning of solid wastes, concrete batching and construction activities, and abrasion of road surfaces.

PM concentration levels then remain high in the colder winter months – reflecting meteorological conditions, and increased inefficient winter heating. Pollution levels decline starting in the months of March and April with summer.

Source apportionment studies for Delhi's pollution typically offer a wide range of estimates on vehicular contribution to particulate matter, going from 8.7% (CPCB, 2011) to 62% (Srivastava, 2008) for PM10[i]. There are relatively fewer estimates for PM2.5. All studies, however, suggest that vehicular emissions form a larger fraction in winters. For instance, a recent comprehensive study commissioned by the Delhi government estimate vehicular contribution to PM2.5 at 6% during summers and 25% during winters (Sharma and Dixit, 2016). Vehicular traffic also affects resuspension of road dust; the same study estimates that resuspension of road dust accounts for 4% of PM2.5 concentrations in summers and 28% during winters (Sharma and Dixit, 2016).

2.3 Odd-Even Program

On Dec 1, 2015 Delhi government announced that the odd-even program for privately owned cars would be launched as a pilot during January 1-15, 2016. The program would be effective between 8 am in the morning to 8 pm in the evening, apart from Sundays. Cars with registration plates from outside Delhi were also required to comply.

Around the time the odd-even program was being introduced, the
Delhi government also announced other measures to reduce air pollution
- November 6, 2015: Environment Compensation Charge charged for commercial vehicles (light diesel vehicles and three-axle vehicles) entering the city limits. (Supreme Court, 2015a ; Department of Environment, 2015) On December 16, 2015, the Charge was doubled (Supreme Court, 2015 b)
- On December 16, 2015, Supreme Court banned the registration of new diesel cars (larger than 2000 cc) till March 31, 2016 (Supreme Court, 2015 b)
- From January 1, 2016, Delhi government increased the restriction on entry of trucks during the day. Entry hours were pushed from 9 PM to 11 PM (Department of Environment, 2015)

However, the odd-even program witnessed unparalleled media coverage and scrutiny regarding its impact on air quality. Disentangling the impact of the odd-even scheme from other policy measures therefore requires careful analysis. We examine both the hours during the policy implementation when impacts were most clearly observed and consider periods both before and after the odd-even scheme. As a short-term policy measure the effects of odd-even should exist only during the 15 day period in question.

If the program witnessed compliance with odd-even, vehicle volumes would mechanically reduce. The reduction of cars on the road would mechanically reduce vehicular exhaust emissions. However, the impact on ambient concentrations, which

is a function of several other factors, was unknown before the program. One source of skepticism about the program has been the extent to which vehicular restrictions in the city affect air pollution. We seek to answer this question here.

3. Data

Our analysis uses data from ten ambient air quality monitors in Delhi and three satellite cities just outside Delhi. Figure 1 shows the location of these monitors which are operated by the Central Pollution Control Board for Delhi and by the Haryana State Pollution Control Board for the neighboring towns of Faridabad, Gurgaon and Rohtak.

We compile hourly monitoring data for the six months spanning November 2015 to April 2016. Table 1 describes data availability for each monitor entering our sample.

Figure 2 shows significant variation in PM concentrations over the course of a single day: Concentrations are typically high in the early morning and forenoon hours, lower in the afternoon, and then increase again in the evening hours.

Figure 3 shows significant temporal variation in concentrations across days, reflecting weather conditions. Low atmospheric mixing heights and low wind speeds, for instance, increase concentrations. We also observe significant seasonal variation with improved air quality in summer and monsoon months.

Finally, Figure 4 shows significant within-city variation such that the seven monitors in Delhi typically show significant differences in air quality at the same time.

4. Empirical Strategy

Temporal and spatial variations in PM2.5 levels imply that a simple comparison of air quality before and during the program may be misleading. We, therefore, focus on difference-in-differences analysis where we examine how difference in air quality in Delhi and neighboring cities changes during the program relative to the time period before and after. We also consider a `triple difference' variant where we additionally examine whether during program days the impact is concentrated during hours that the program is effective (i.e. between 8 am and 8 pm)

More formally, we estimate a regression model that takes the form

$$Y_{tm} = \alpha + \beta.\, 1(m \in \text{Delhi}) + \gamma.\, 1(t \in \text{oddeven}) + \delta.\, 1(m \in \text{Delhi}) \times 1(t \in \text{oddeven}) + \lambda_m + \eta_t + \mu_h + \varepsilon_{tm}$$ - **Model 1**

Y_{tm} is the particulate (PM$_{2.5}$) concentration at time t (on hour h and day d) for monitor m. Explanatory variables include an indicator variable for the treatment area (*Delhi*), an indicator variable for the days that the odd-even program was in place (termed *oddeven*), and their interaction term. β and γ are the coefficients for

the treatment area and period indicator variables. The interaction coefficient δ estimates the program impact on particulate concentration..

This is the triple difference specification because the interaction term is the product of the indicator variable for Delhi, the indicator for days when the program was implemented and the indicator for the hours during which the restrictions were in force

We use monitor fixed effects to control for different average levels of particulate matter at each monitor. We use time fixed effects to account for differences in average levels across time of day, and from one day to the next.

 In addition, we have introduced several finer variants to the specifications in Model 1. These include models with
   - Time fixed effects at the day level, indicator variable for each hour of day to account for average hourly trends, and an interaction variable between the daily indicators and the times when the restrictions were in force. (Model 1-Table 2)
   - Time fixed effects at the hourly level (Model 2 in Table 2, and the models in Table 3)

Standard errors are clustered at the monitor level. To address the challenge of gaps in air pollution data from the monitors at different points of time, and therefore potential artifacts of this changing composition of the panel on the estimates themselves, we use bootstrapped standard errors with 200 repetitions.

Our empirical analysis is premised on the assumption that that in the absence of the program, pollution in delhi and neighboring cities would have evolved similarly. The relatively unexpected nature of the program and short program duration, combined with the geographic proximity of the satellite cities to Delhi, makes this a plausible assumption. As a robustness check, we also report a variant of model 1 with time fixed effects at the hourly level and with an interaction between Delhi and a linear time trend variable[ii].

In addition, we run 24 models for each hour of the day to get hourly estimates for impact on the concentration of particulates. The specifications are nearly identical to Equation 1. However, running 24 models in this manner relaxes the assumptions and reduces the sample size, thereby creating a more stringent test.

For each hour of the day, h,
$Y_{dm,h} = \alpha + \beta . 1(m \in Delhi) + \gamma . 1(d \in oddeven) + \delta_1.1(m \in Delhi) \times 1(d \in oddevenJan) + \delta_1.1(m \in Delhi) \times 1(d \in oddevenApril) + \lambda_m + \eta_{d,h} + \Omega.W_{dm.h} + \varepsilon_{dm}$ - **Model 2**

This model is run over the 6-month period with separate estimates for January and April rounds. Inclusion of the Delhi-time trend interaction has no effect on the

coefficient for the triple difference. The coefficient of the interaction is not significant for the results for the 6-month period, validating the parallel trends assumption. These results remain consistent with several different timeframes and specifications, and suggest that the model successfully identifies the impact of the program on pollution concentrations.

5. Results and Discussion

5.1 Regression results

The results (in Tables 2 and 3) show that there was a statistically significant and substantial reduction in PM2.5 concentrations during the days and hours that the odd-even program was implemented in New Delhi in the January round. The estimated reduction from the many specifications we cover in Section 4 ranges from about 24 $\mu g/m^3$ to 37 $\mu g/m^3$. In percentage terms, we estimate a reduction of 13%[iii].

From the hourly models, we find large, statistically significant reductions in concentration between 11 am – 2 pm, which could be attributed to reduction in traffic during the morning peak hours. During other times of the day, our estimates are noisy and we cannot rule out the possibility that they are zero. This may be due to dispersion (wiping out any local improvements in air quality) and other sources of PM2.5 (reducing the significance of reductions from traffic alone). Importantly however, no impacts were observed at night when the odd-even rationing was no longer in force.

This reduction in concentrations could be attributed to three factors: one, reduction in PM from vehicular exhaust of the cars taken off the road; two, reduced congestion and consequently, reduced idling and emissions from all the vehicles (allowed cars as well as buses and other vehicles) on the road; three, reduced resuspension of road-dust due to reduced vehicular volumes. [iv]

One concern here is that road traffic outside Delhi may also have reduced during odd-even because of significant commuter traffic from Delhi to the satellite cities and from these cities to Delhi. To the extent this occurs, our results will under-estimate the impact of the rationing, both in January and April.

On the other hand, the results in April look very different. We observe significant reduction during both the night and the day in the second (April) round of vehicle rationing. At the very least this underscores that while an initiative such as odd-even can work (over a short period), it will not always be useful. This is important to keep in mind and it is possible that in Delhi this type of policy mechanism is useful only during parts of the winter.

It is possible that one or more of the other interventions introduced by the government in December may have also contributed to the reductions in Delhi. We may be concerned that restrictions on trucks – on the volumes entering the city and

on the hours they could enter— may have confounded the impact of the program. Two factors make this unlikely. First, we find the impacts of odd-even restricted to the days it was in force. The restrictions on truck traffic continued beyond this period. Secondly, from the hourly model results (Figure 5), the conspicuous dip around noon is likely due only to car driving restrictions, and we do not observe significant reductions late in the night.

5.2 Differences between January and April

5.2.1 Meteorological factors
It is possible that despite similar compliance and similar reduction in *emissions*, concentrations may have been affected less in April than January. A plausible reason for this is greater dispersion during warmer months. Dispersion is faster when atmospheric mixing heights[v] are greater, as is the case in the summers compared to winters (Guttikunda and Gurjar, 2012). For this reason, modest increases and decreases in emission sources on-ground may disperse upwards and not translate into observable changes in pollution concentrations near the ground. On the other hand, in winter when dispersion is minimal, these changes are immediately noticeable. This suggests a limitation of the program itself: it is perhaps more appropriate as an emergency measure during the winters, than as a long-term pollution reduction measure, even if compliance rates are high.

5.2.2 Lower compliance and/or use of alternative vehicle
Alternative explanations for the differences in results between January and April could include lower compliance to the restrictions, and greater use of an alternative vehicle (an unrestricted second car, a taxi or a two wheeler) in the second round compared to the first. We discuss these together because they have similar measurement challenges, as will be explained shortly.

The first hypothesis is lower compliance in April. With a program of the scale of odd-even in Delhi, police enforcement is bound to have constraints; public enthusiasm plays a large role too. Were public participation to decline, these schemes may become largely ineffective.

The second hypothesis is that commuters were better prepared for the second round, in terms of alternative private modes of transport- a second car, a neighbor's unrestricted car or a two-wheeler. In the case of similar driving restrictions in Mexico City introduced in 1989, Davis (2008) compares vehicle registrations with new vehicle sales to show that the program there led to an increased adoption and use of used cars. Substitution to relatively older vehicles on restricted days for the principal vehicle may lead to a net increase in pollution.

Finding reliable data on non-compliance or substitution is difficult. For example, with traffic police records, a reduction in traffic *challans* from January to April could

indicate improved compliance or reduced enforcement or both. As a result, these records form an unreliable way to understand compliance.

Instead, traffic volumes and travel times could offer insights. Primary traffic surveys by the School of Planning and Architecture along several junctions around the city find that traffic volumes were higher during the second round of the program than the first round, and that there was a large shift to two-wheelers (Hindustan Times, 2016). They contrast this with the January round when commuters chose to carpool or use the public transportation.

However, there is some contradictory evidence that suggests that compliance did not reduce. Kreindler (Indian Express, 2016) uses high frequency queries on travel times from Google Maps along several routes and found that the two rounds show consistent reductions in speeds in both rounds. Furthermore, from a survey of 960 male drivers from across Delhi, Kreindler writes in the same article that there was little to distinguish participation between the two rounds.[vi]

5.3 Concluding remarks

The challenges in estimating the impact of this program stress the need for more carefully designed pilots, with reliable data collection and analysis. The limited number of air quality monitors in and around Delhi, and the low levels of data availability (Table 1) impede effective air pollution regulation in the city.

Even if the program resulted in reductions in traffic congestion and air pollution in the city, the odd-even program may not be a good long-term measure to reduce air pollution in New Delhi. As the program in January was known in advance to be a short-term pilot, commuter response may not be typical of what is expected over the longer term. In other cities where such a program has been implemented there is some evidence that commuters purchased and used a second car (Davis (2008) for Mexico City) or "cover or borrow license plates" (Wang et al. (2014) in the case of Beijing).

A more sustainable option to reduce vehicular usage and traffic congestion could be to institute congestion pricing in Delhi. Congestion pricing may be more equitable, and well targeted to parts of the city especially vulnerable to congestion and high local pollution levels. Such a program could also generate additional revenues that could then be redirected to other urgent traffic interventions in Delhi, including greater investments in public transportation as well as making the streets friendly to pedestrians and cyclists.

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Figure 1: Map with locations of the monitors in Delhi (blue) and in Haryana (yellow), which are used for analysis in this study.

Table 1: Data availability for the 10 monitors during November 2015- April 2016, and in particular for the two months where the odd-even pilot took place.

	January '16	April '16	November '15 - January '16	February '16- April '16
Delhi monitors				
Anand Vihar	98%	63%	96%	0%
Dwarka	96%	71%	90%	81%
IHBAS	27%	52%	62%	32%
Mandir Marg	81%	61%	92%	89%
Punjabi Bagh	90%	58%	92%	89%
RK Puram	99%	77%	95%	98%
Shadipur	95%	77%	98%	96%
Haryana monitors				
Faridabad	60%	59%	83%	82%
Gurgaon	10%	60%	3%	64%
Rohtak	52%	.	17%	.

1. Data availability= Number of hours of data available from each monitor for the period divided by number of hours during this period that satisfy the conditions below.
    I.   At least 1 monitor from Haryana (comparison group)
    II.   At least 4 monitors from Delhi (treatment group)
   III.   PM2.5 levels between 10 and 1000 $\mu g/m^3$
2. Four other monitors in Delhi (Civil Lines, DCE, ITO and IGI Airport monitors) have zero data availability on the CPCB website for the entire period.

Figure 2 Average concentrations in Delhi over the course of the year (from May 2015- April 2016).
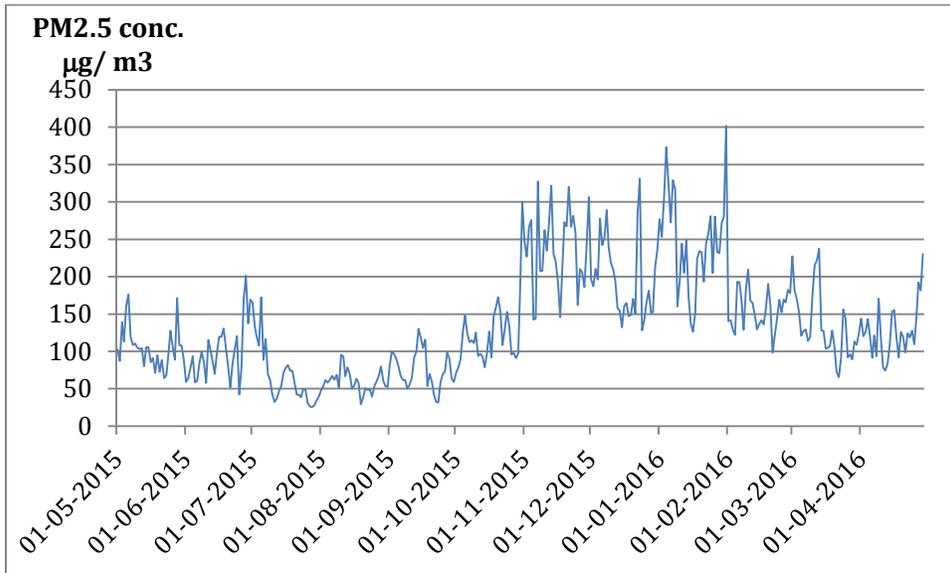

1. This uses data from air monitoring station in Delhi with availability of 50% or higher. Stations included here are Anand Vihar, Dwarka, Mandir Marg, Punjabi Bagh, RK Puram and Shadipur.
2. Daily averages have been computed by controlling for monitor fixed effects

Figure 3 Averages across the monitors Average PM2.5 levels in the 10 ambient air quality monitors.

Mean PM2.5 conc.
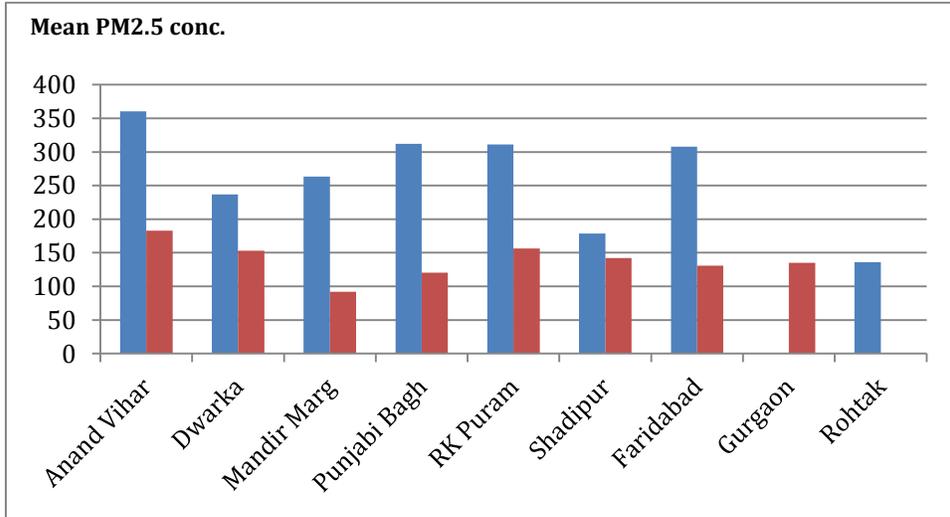
1. Monitor averages have been computed after controlling for time fixed effects

Figure 4: Average fine particulate matter levels in the months of January and April 2016 for the Delhi and Haryana monitors.
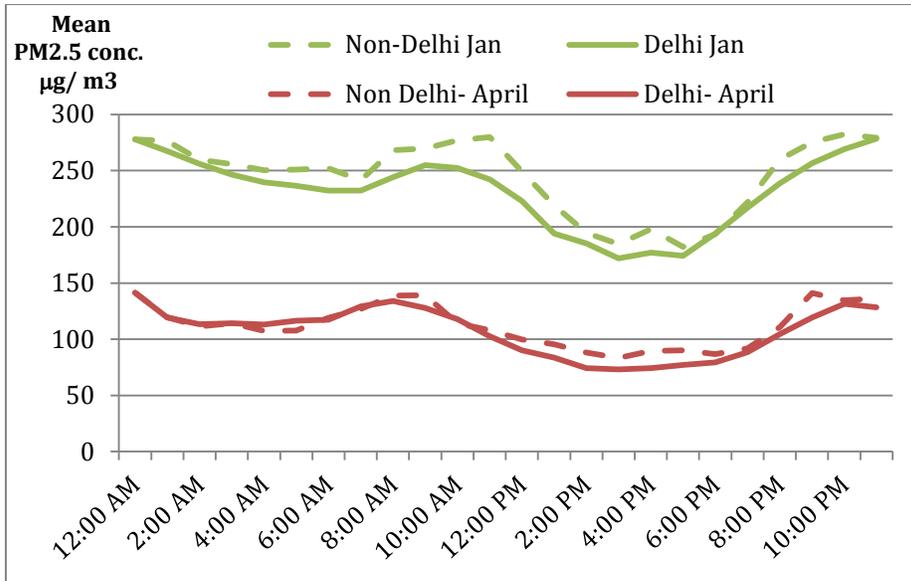
These have been computed by controlling for monitor fixed effects and time fixed effects (for every hour of observation) and by regressing concentrations on indicator variables for Delhi and for hour of day, and the interaction of the hour indicator variables with the Delhi indicator variable. This has been done to control for compositional variations.

Table 2 Results of regression models for the two rounds separately. The triple difference coefficient is significant for the January round, and not significant for the April round.

VARIABLES	January- (1)#	January- (2)	January- (3)	April- (1)#	April- (2)	April- (3)
Delhi X OddEvenDates	15.58	13.77	31.82	-4.000	-8.361	12.04
	(24.09)	(21.63)	(17.68)	(12.53)	(12.81)	(12.74)
DelhiX OddEvenDatesX OddEvenHours	-37.66*	-32.77**	-33.45**	-1.801	0.635	-0.642
	(22.21)	(10.37)	(10.83)	(15.20)	(9.283)	(8.920)
Delhi X Timetrend			1.112			-1.723
			(2.357)			(1.286)
Observations	3,667	3,667	3,667	3,438	3,438	3,438
R-squared	0.313	0.488	0.489	0.332	0.472	0.473
Number of monitors	8	8	8	9	9	9
Monitor FE	Y	Y	Y	Y	Y	Y
Day FE	Y	Y	Y	Y	Y	Y
Hour of Day FE	Y	Y	Y	Y	Y	Y
Day FE X OddEvenDates FE	Y			Y		
Day FE X Hour of Day FE		Y	Y		Y	Y

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

#- Bootstrapping with 200 repetitions, stratified on the Delhi indicator variable. Model 3 has hourly fixed effects and therefore controls for compositional differences effectively.

Table 3 Results of the regression model when run on a single pooled dataset with monitor and time (each hour of observation) fixed effects. Results are summarized below for the six month period of November 2015 - April 2016.

VARIABLES	(1) Six months joint estimate	(2) Six months separate estimates	(3) Jan and April joint estimate	(4) Jan and April separate estimates
Delhi X OddEvenDatesJan		-14.96		-6.020
		(21.54)		(24.29)
Delhi X OddEvenDatesApril		-3.940		12.84
		(17.15)		(13.01)
Delhi X OddEvenDatesJanX OddEvenHours		-24.42***		-31.69**
		(6.446)		(12.93)
Delhi X OddEvenDatesAprilX OddEvenHours		11.60		-6.794
		(12.27)		(15.53)
DelhiXOddEvenDatesBoth	-8.945		5.702	
	(13.56)		(13.65)	
DelhiXOddEvenDatesBothXOddEvenHours	-7.072		-18.59*	
	(8.371)		(9.234)	
Observations	21,197	21,197	7,105	7,105
R-squared	0.472	0.473	0.486	0.489
Number of monitors	8	8	10	10
Monitor FE	Y	Y	Y	Y
Day FE	Y	Y	Y	Y
Hour of Day FE	Y	Y	Y	Y
Day FE X OddEvenDates FE	Y	Y	Y	Y

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

The triple difference is highly significant only for the January round, and is not significant for the combined model (1). If January and April months are pooled together, the combined coefficient (in 3) is significant, but if separate coefficients are included in the specification, only the January triple difference is significant.

Figure 5: Results of the hourly models when run over the six-month period. The difference-in-difference coefficient has been plotted for each hour of the day with the hours with statistically significant results shown as a circled point on the graphs
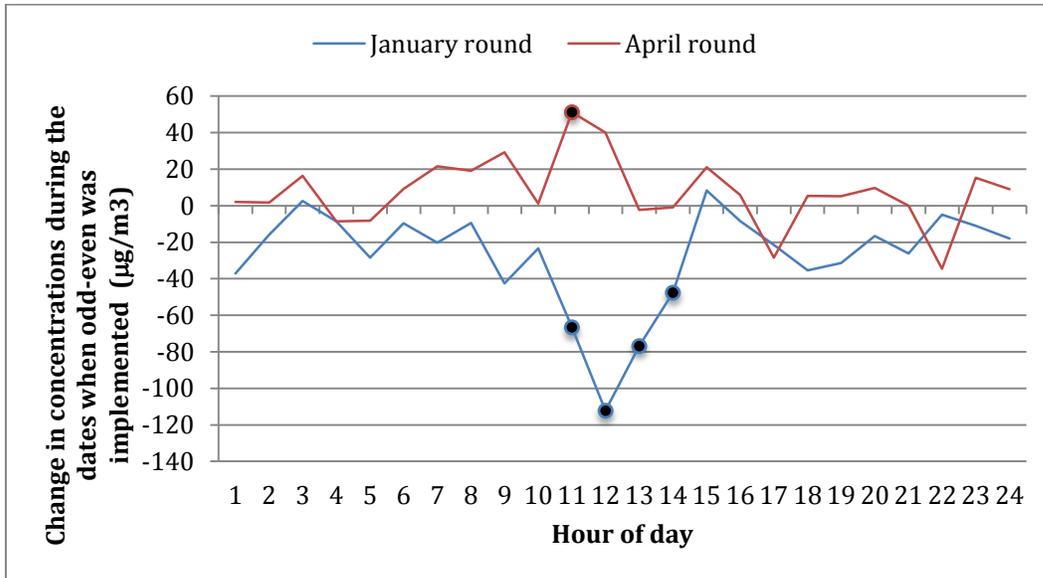
[i] These studies provide a wide range of estimates for vehicular contribution to PM10 ranging from 8.7% (in industrial locations)- 20.5% (residential locations) (CPCB, 2011), 27-31% (Khillare and Sarkar, 2012) and 62% (Srivastava et al, 2008). Goel and Guttikunda(2015) estimate that cars alone account for 19% of vehicular PM2.5 emissions.

[ii] If the pollutant concentrations within and outside Delhi are systematically changing relative to each other (for example, pollution in Delhi is going down due to multiple local mitigation efforts), the Delhi- time trend interaction should be significant. We include a linear time trend (days since November 1st) and an interaction term between the *Delhi* variable and the linear time trend to Model 1.

$Y_{tm} = \alpha + \beta.\, 1(m \in Delhi) + \gamma.\, 1(t \in oddeven) + \delta.1(m \in Delhi) \text{ X } 1(t \in oddeven) + \lambda_m + \eta_t + \tau.\, days + \rho.\, Delhi \text{ X } days + \varepsilon_{tm}$

[iii] Percentage reduction is estimated using a variant of the regression models described in the paper with the dependent variable as natural logarithm of PM2.5 concentrations. With these specifications the coefficient of the triple difference can be directly interpreted as the percentage change. Specifically, this estimate of 13% comes from a model using the combined 6 month data, with separate estimates for the two rounds.

[iv] With reduced congestion and hence, improved average speeds, it is possible that there is an increased resuspension of road dust. However, the net impact of reduced traffic is almost certainly going to be reduced emissions.

[v] There are several definitions for mixing heights. This height need not necessarily be the same as the height at which inversion happens, which is primarily a nocturnal phenomenon. One definition as per Seibert et al: "The mixing height is the height of the layer adjacent to the ground over which pollutants or any constituents emitted within this layer or entrained into it become vertically dispersed by convection or mechanical turbulence within a time scale of about an hour"

[vi] Kreindler finds that the April round marginally less effective along a few dimensions: a larger percentage of drivers used other four-wheelers (including taxis) than their principal vehicle on restricted days and fewer moved to public transportation (Indian Express, 2016)