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The influence of odd–even car trial on fine and coarse particles in Delhi

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ABSTRACT

The odd–even car trial scheme, which reduced car traffic between 08.00 and 20.00 h daily, was applied from 1 to 15 January 2016 (winter scheme, WS) and 15–30 April 2016 (summer scheme, SS). The daily average PM1.25 and PM10 exceeded national standards, with highest concentrations (313 μg m⁻³ and 639 μg m⁻³, respectively) during winter and lowest (53 μg m⁻³ and 130 μg m⁻³) during the monsoon (June–August). PM concentrations during the trials can be interpreted either as reduced or increased, depending on the periods used for comparison purposes. For example, hourly average net PM1.25 and PM10 (after subtracting the baseline concentrations) reduced by up to 74% during the majority (after 1100 h) of trial hours compared with the corresponding hours during the previous year. Conversely, daily average PM1.25 and PM10 were higher by up to 3× during the trial periods when compared with the pre–trial days. A careful analysis of the data shows that the trials generated cleaner air for certain hours of the day but the persistence of overnight emissions from heavy goods vehicles into the morning odd–even hours (0800–1100 h) made them probably ineffective at this time. Any further trial will need to be planned very carefully if an effect due to traffic alone is to be differentiated from the large effect caused by changes in meteorology and especially wind direction.

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1. Introduction

The majority of cities worldwide are experiencing periods of elevated air pollution levels, which exceed international health—based air quality standards (CPCB, 2009; Kumar et al., 2013, 2016). Some of the highest air pollution levels are found in rapidly expanding cities such as Delhi in developing countries (Kumar et al., 2015). Exposure to high concentrations is linked to a broad spectrum of acute and chronic health effects in adults and children depending on the constituents of the pollutants (Heal et al., 2012; Rivas et al., 2017; Kumar et al., 2017). For example, WHO (2014) has reported ~7 million premature deaths worldwide due to indoor and outdoor air pollution in 2012. The developing countries of the Western Pacific and South East Asian regions bear most of this burden with 2.8 and 2.3 million deaths, respectively. In particular for Delhi, which is the focus of this article, increasing concentrations of particulate matter (PM) result in thousands of premature deaths and six million asthma attacks each year (Guttikunda and Goel, 2013). Recent work of Kesavachandran et al. (2015) reported that the outdoor exercisers in Delhi at locations with high PM2.5 (≤2.5 μm in aerodynamic diameter) concentrations are at a risk of lung function impairment due to their deposition in the smaller and larger airways.

Delhi and its National Capital Region (NCR) have a population of 25.8 million that is 7.6% of India’s urban population. Of this, Delhi...
city alone has a population of 17.1 million, which has grown at a
decadal growth rate of 47%. The total NCR area is 34,144 km²,
including Delhi city with an area of 1483 km² (Kumar et al.,
2011). This drastic growth in population has resulted in extensive
consumption of energy resource to meet their transportation and
others demands (Kumar and Saroj, 2014). Studies are consistently
showing high PM_{10} and PM_{2.5} concentrations in the ambient air of
Delhi, irrespective of the type of locations in Delhi city (Mandal
et al., 2014; Pant et al., 2015; Sharma et al., 2013a; Tiwari et al.,
2014). The adverse health impacts of high urban air pollution
need to be managed to improve living standards but recent studies
have ranked Delhi as the “worst” polluted city based on an envi-
nroment performance index (Hsu and Zomer, 2014).

There were 6.93 million road vehicles in Delhi in 2011 and these
are predicted to increase to 25.6 million by 2030 (Kumar et al.,
2011). The current road length in Delhi city is 33,198 km with 864
signalised and 418 blinkers traffic intersections. The road network
has increased from 28,508 km in 2000 to 33,198 km in 2015 while
the number of vehicles has more than doubled from 3.37 million in
2000 to 8.83 million in 2015 (Gol, 2016; NCR, 2013). Delhi had 7.3
million road vehicles in 2015 compared with only 2 and 3.7 million
in other megacities Mumbai and Chennai, respectively (Gupta,
2015). Interestingly, the day traffic density of 0700–1200 h is only 245
for Delhi compared with 1014 and 2093 for Mumbai and Chennai,
respectively (Gupta; Kumar et al., 2015). This increase has
resulted both in heavy traffic congestion and reduction in vehicular
speed on the roads of Delhi, besides leading to increased emissions
of pollutants such as PM\textsubscript{2.5}, PM\textsubscript{10} (<10 \mu m) and NO\textsubscript{x} (oxides of ni-
trogen) (CPCB, 2010; Gol, 2014). A brief summary of past studies
between 1997 and 2016 is shown in Table 1, which indicates the
concentrations of PM\textsubscript{10} and PM\textsubscript{2.5} exceeding the national ambient
air quality standards (CPCB, 2009). In Delhi city, CNC fuel was
introduced for all public transport vehicles in 1998 (Chelani and
Devotta, 2007). From 1998 to 2016, there has been an increase in
CNG fuel operated public and private vehicles. Since the diesel and
CNG-fuelled engines have a different operating con-
figuration and are the
most congested stretches in Delhi. Consequently, this resulted in a significant reduction of
30–50% of travel time during odd–even hours of the winter
scheme compared with prior to the scheme. Furthermore, overall
trafﬁc volume reduced by ~19 and 17% on odd and even days,
respectively, at Delhi–Mathura Road compared with that prior to
the scheme. A reduction of about 24% in cars was noted during the
odd and even days compared with those outside the scheme
(Velmurugan and Gupta, 2016). There is no traffic count study
available showing a reduction of trafﬁc volume from roads across
the whole of Delhi city during the odd–even schemes. While a
reduction in trafﬁc congestion on the roads of Delhi was reported
during the trial days, there is no clear consensus whether the trial
brought a reduction in the levels of PM\textsubscript{10} and PM\textsubscript{2.5} concentrations.
In this work, we comprehensively evaluate the data measured at
the four monitoring stations across Delhi before and after the trial
periods to understand the underlying factors affecting the con-
centration levels of PM during the trial days and the actual beneﬁts
brought by this scheme to reduce the levels of air pollutants.

2. Materials and methods

2.1. Study area

Delhi is located at an altitude of about 215 m above mean sea
level and is one of the seventeen declared non–attainment areas in
India (CPCB, 2006). Delhi experiences four major seasons across the
year: summer (March–May), monsoon (June–August), post–
monsoon (September–November) and winter (December–Feb-
ruary). In summer, the city experiences dry weather with the
temperature reaching up to 48 °C. The monsoon season experi-
ences more than 80% of the total annual rainfall (Perrino et al.,
2011). During winter, frequent ground–based inversion condi-
tions occur with temperatures going down to 4 °C. These are winter
months when the combination of inversion conditions coupled with
emissions from paddy ﬁeld burning upwind of Delhi (Kumar
et al., 2015), together with biomass burning within Delhi itself for
heating purposes (CPCB, 2006; Nagpure et al., 2015), bring almost
every year high pollution episodic conditions leading to frequent violation of air quality standards (CPCB, 2010; Pant et al., 2015). A recent study suggested that burning of biomass contributes approximately 26% and 17% of PM2.5 and PM10 concentrations, respectively, in winter as well as 12% and 7% in summer in Delhi city, respectively (Sharma and Dikshit, 2016).

Delhi is surrounded by neighbouring cities of the National Capital Region (NCR: Fig. 1). The major neighbourhood cities are Sonepat in the north–west, Bahadurgarh, Jhajjar and Rohtak in west direction, Gurgaon and Manesar in the south, Faridabad in south–east, and Noida and Ghaziabad in the east. In Delhi city, a total of 19 monitoring stations are run by the Central Pollution Control Board, Delhi Pollution Control Committee (DPCC) and the Indian Institute of Tropical Meteorology Pune (under the SAFAR programme). Most of these stations monitor pollutants of regulatory interest such as PM10, PM2.5, SO2, NOx, and O3.

2.2. Monitoring stations

As part of this work, we considered four air quality monitoring stations to evaluate the impact of the odd–even car trial on the concentrations of PM10 and PM2.5 in Delhi city. The monitoring sites are selected in such a way so that they can cover a wide range of areas (i.e., industrial, commercial, residential and institutional) in Delhi city. Moreover, these stations provided us simultaneous data of both the PM10 and PM2.5 for the periods considered in this study. NOx was not included in our analysis due to lack of parallel data for the considered periods and that it has multiple sources in Delhi, many of which such as local combustion for heating and cooking are poorly quantified. Of course, the availability of simultaneous data on pollutants and meteorology from additional monitoring stations would have further assisted to evaluate spatial effects of odd–even-trial at other locations in Delhi. The selected monitoring stations are located at Anand Vihar (AV, in the east of centre of Delhi), Mandir Marg (MM, centre of Delhi), Punjabi Bagh (PB, in the west of centre of Delhi and R. K. Puram (RKP, in the south of centre of Delhi) and all of them are operated by the DPCC. The AV station is located at the border of Delhi and Uttar Pradesh state. The surrounding area comprises a mixture of commercial, industrial and residential activities. It is located in the parking lot of an interstate bus transport depot and 150 m away from a heavy traffic road in the east district of Delhi, which has a population of 1,709,346 (Census, 2011). The MM station is located at one of the heavily trafficked kerbsides in New Delhi and surrounded by residential and commercial activities. The PB station is located 30 m away from the kerbside of an arterial road in West Delhi and surrounded by residential and commercial activities. The population of New and West Delhi is 1,42,004 and 2,543,243, respectively (Census, 2011). The RKP station is located away from the major road in South West Delhi and surrounded by residential activities. The population of south–west Delhi is 2,292,958 (Census, 2011). The detailed information of all the monitoring sites along with traffic volume on the nearest major roads are provided in SI Table S2.

2.3. Data collection

Continuous hourly average monitoring data for PM2.5 and PM10 concentrations along with the meteorological parameters (relative
humidity, ambient temperature, wind speed, and direction) for all months of 2015, January 2016 and April 2016 was obtained from the selected four stations. Some missing hours were observed in the continuous times series data (Table 2), which were discarded from the analysis. The PM$_{2.5}$ and PM$_{10}$ concentrations are monitored using BAM 1020 monitors, which work on the principle of beta attenuation (MOI, 2013); it is a USEPA recommended method and adopted by the DPCC (CPCB, 2011). The BAM analysers are calibrated for mass as well as undergoing flow rate checks on a weekly basis. The working principle and calibration details of the instrument are provided in SI Section S1. The hourly average meteorological parameters such as wind speed, direction, ambient temperature and relative humidity were collected from all the four stations (Section 2.2), which are operated by the DPCC. These instruments are calibrated every six months to ensure the quality of their data. The mixing height is one of the indicators of the atmospheric stability condition (Census, 2011; Perrino et al., 2011). The data for maximum atmospheric mixing height during each season in Delhi was taken from the Atlas of hourly mixing height and Assimilative capacity of atmosphere in India (MOI, 2013).

2.4. Statistical analysis

The hourly average concentration data were collected from the CPCB database for the study period of January–December 2015, 1–30 January 2016, and 1–30 April 2016. As summarised in Table 2, the selected periods provided a total of 10,224 h data for the analysis. The PM$_{10}$ and PM$_{2.5}$ monitoring data capture was 80–84% at AV site, 81% at MM, 84–87% at PB, and 85–88% at RKP (Table 2). The meteorological data were available for 89–91% of the time at each site, except MM with 84% data. The data were analysed and compared in the form of diurnal and seasonal patterns, mean and standard deviations for each of the selected sites using the R program (Carslaw and Ropkins, 2012). In addition, bivariate polar plots

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**Fig. 1.** The map showing Delhi–NCR region and location of monitoring sites (shown by yellow stars) in Delhi city. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
were drawn to assess qualitatively the effects of wind speed and direction on the measured concentrations for the full 2015 year. January 2016 (first odd—even car trial scheme during winter, referred hereafter as WS), and April 2016 (second trial during summer, SS). The concentrations are compared separately for odd—even (0800—2000 h) and non—odd—even (2000—0800 h) hours along with the corresponding hours of no odd—even trial year 2015.

3. Results and discussion

3.1. Diurnal behaviour of PM concentrations throughout the year

Table 3 presents a summary of PM2.5 and PM10 concentrations at the selected air quality monitoring stations in Delhi. We divided the study duration into six different periods to investigate the variability in their concentration and for comparison with the odd—even trial periods. These seasons included: (i) winter 1 (January—February 2015), (ii) summer (March—May 2015), (iii) monsoon (June—August 2015), (iv) post—monsoon (September—November 2015), (v) winter 2 (December 2015—January 2016; this included the first odd—even winter scheme, WS), and (vi) summer 2 (April 2016, which included the second odd—even summer scheme, SS).

PM2.5 at the AV station was found to be 222 ± 118, 134 ± 107, 89 ± 83, 133 ± 87, 313 ± 136 and 157 ± 127 μg m⁻³ for winter 1, summer 1, monsoon, post—monsoon, winter 2 and summer 2, respectively. As expected, PM2.5 was highest during winter seasons, followed by summer and post—monsoon seasons, with the lowest being during the monsoon season. The higher PM2.5 during winters is expected due to a relatively lower atmospheric mixing height (Supplementary Information, SI, Fig. S1), which inhibits the dispersion, compared with the other seasons (Tiwari et al., 2013). For example, the mixing heights (mean ± standard deviation) were about 2701 ± 261 m during summer, followed by 1741 ± 400 m during the post—monsoon, and only about 1107 ± 201 m during the winter (SI Section S2).

PM2.5 was higher during winter 2 compared with winter 1. This trend was also shown by the rest of the monitoring stations (Table 3) and may be explained by the higher wind speeds (1.4 ± 1.0 m s⁻¹) during the winter 1 compared with 1.0 ± 0.7 m s⁻¹ during winter 2 (SI Table S3). These observations suggest relatively better dispersion conditions during winter 1 than those during winter 2 to explain the differences observed in PM2.5 concentrations. In the case of summer, PM2.5 was higher during summer 1 compared with summer 2. This trend could be explained by both the relatively lower wind speeds and ambient temperature during the summer 1 (1.8 ± 1.2 m s⁻¹ and 29 ± 8 °C) compared with summer 2 (19 ± 1.2 m s⁻¹ and 33 ± 5 °C).

The PM10 at AV station was found to be highest during winter 2 (639 ± 241 μg m⁻³), followed by post—monsoon (519 ± 260 μg m⁻³), summertime (448 ± 308 μg m⁻³), winter 1 (445 ± 218 μg m⁻³), monsoon (329 ± 256 μg m⁻³) and summer 2 (344 ± 215 μg m⁻³) — this order changed from PM2.5 which had highest for winter 2, followed by winter 1, summer 1, post—monsoon, summer 2 and monsoon. Similar trends of PM2.5 and PM10 were also seen at the other three selected monitoring stations in Delhi city. This observation clearly confirms that PM10 and PM2.5 in Delhi are affected substantially by the season (Pant et al., 2015). For example, high PM10 in the post—monsoon compared with winter 1 has an additional contribution from the burning of agricultural residue in the surrounding states of Punjab and Haryana that are located in a dominant upwind direction (Trivedi et al., 2014). Likewise, burning of fire crackers during the festival (e.g., Dussehra and Diwali) months of October to November creates extra contributions to both PM10 and PM2.5 (Tiwari et al., 2013) while burning wood and cow dung cake for heating make additional contributions across winters (Kumar et al., 2015).

Besides the high seasonal variations, PM2.5 and PM10 also showed large diurnal variations (SI Fig. S2). This analysis was particularly helpful to see the effects of odd—even hours on ambient concentrations. The concentrations were observed to be high during the morning peak hours (0900—1000 h), and night hours (2100—0500 h) when traffic volume is relatively low but the inflow of heavy goods vehicles through the city starts at 2200 h until 0800 h (Gulia et al., 2015; Kumar et al., 2013). These are also the hours when the mixing height is low (SI Fig. S1) and winds are calm, resulting in weakened dispersion and hence the increased concentrations (Kumar et al., 2015; Tiwari et al., 2013). The effect of mixing height on the concentration was evident during the afternoon hours (1500—1700 h) when it was highest but both the PM2.5 and PM10 were at their lowest (SI Fig. S2). As expected, there were
no clear hourly peaks during the monsoon season, mainly due to the frequent occurrence of rain (SI Fig. S2).

3.2. PM concentrations in pre—, during and post odd—even trial periods

Bivariate concentration polar plots for PM$_{2.5}$ (SI Fig. S3) and PM$_{10}$ (SI Fig. S4) were drawn to understand the location and characteristics of different sources affecting each of the selected locations. For better visualisation and quick directional information on sources, adjacent bins with the mean concentration values have been modified by using the smoothing technique (Azarmi et al., 2015; Carslaw and Ropkins, 2012; Mouzourides et al., 2015). Therefore, the colour bars should not be interpreted as actual measurement values.

The PM$_{2.5}$ pattern was found to be different at all the studied locations throughout the years 2015 and 2016. For example, irrespective of wind speed, high concentrations were observed at AV when the wind direction was west—southwest. This could be primarily due to a contribution from a nearby bus depot that is ~120 m in the upwind south—west direction of the station (SI Figs. S3a—c). However, this pattern changed during the summer compared with the winter season. For example, in April 2015, PM$_{2.5}$ concentration peaks were observed when the wind direction was east—northeast during the summer months with an average wind speed of ~2 m s$^{-1}$ (April 2015; SI Fig. S3d). On the other hand, predominant winds were from south—west and north—west with an average wind speed of about 2—3 m s$^{-1}$ during April 2016 (SI Fig. S3e). Likewise, in January 2015 and January 2016, PM$_{2.5}$ concentration peaks were observed when the wind direction was south—west with average wind speeds of 2.2 m s$^{-1}$ and 1.5 m s$^{-1}$, respectively. In addition, peaks were also observed when the wind direction was east—northeast with a wind speed of ~4 m s$^{-1}$ during January 2015 and east—southeast with average wind speed of 1—2 m s$^{-1}$ during January 2016. We carried out a similar analysis for the remaining sites (MM, PB, and RKP), which is presented in SI Section S3, to understand whether the direct comparison of the odd—even periods with the preceding years would clearly reflect its effect on PM types. All these observations clearly indicate that the comparison of the odd—even trial period in January 2016 or April 2016, compared with the corresponding period in 2015 or 2016, will be affected by the different background concentrations, and therefore a difference in PM$_{2.5}$ (or PM$_{10}$) concentrations between these two months cannot be taken as a direct result of the odd—even trial periods in January and April 2016. Therefore as a necessary step, we estimated the baseline (local site background) concentrations at our selected sites.

3.2.1. Estimation of baseline PM concentrations at sites

Given the discussions above where difference in wind directions and wind speed makes it challenging to make a direct comparison of odd—even trial periods in 2015 and 2016, it is important to estimate the background concentrations of PM at each site so that these values could be deducted from the time series during the comparison (Section 3.3). We adopted the same approach, as used in our previous work (Hudda et al., 2014; Goel and Kumar, 2015), to estimate the baseline background concentrations as the lowest 5th percentile of the observed hourly PM$_{2.5}$ and PM$_{10}$ data (SI Table S4). The use of the lowest 5th percentile values of time series for estimation of baseline PM concentrations excludes the micro- and middle-scale impacts due to local sources, usually vehicles (Hudda et al., 2014; Goel and Kumar, 2016). These studies applied the 5th percentile value of the time series of PM concentrations and found that the baseline concentrations were relatively spatially uniform outside of the study impact areas, with a coefficient of variation being less than 5%. The baseline background concentrations of PM$_{2.5}$ at the AV station were estimated to be higher during the WS (113 µg m$^{-3}$) and SS (33 µg m$^{-3}$) compared with the corresponding values of 69 and 26 µg m$^{-3}$ during 2015. Likewise, PM$_{10}$ was found to be higher during WS (252 µg m$^{-3}$) and SS (81 µg m$^{-3}$) compared with the corresponding values of 103 and 60 µg m$^{-3}$, respectively, during 2015. Similar estimates were made for the other stations, as explained in SI Section S4, and the following trends were observed. Firstly, the baseline concentrations of PM$_{2.5}$ and PM$_{10}$ were always higher by 2.6—7.4 and 1.0—3.1 times, respectively, during the WS compared with SS. Secondly, the baseline concentrations for PM$_{2.5}$ (and PM$_{10}$) were higher by 1.1—1.7 (1.8—2.5) and 0.8—3.4 (1.4—3.1) times higher, respectively, in 2016 compared with the corresponding months in 2015. The above observations suggest that each site received different baseline concentrations during the odd—even car trial phases compared with the same months in a preceding year. The fact that the baseline concentrations of both

| Seasons               | Parameter | AV   | MM   | PB   | RKP  |
|-----------------------|-----------|------|------|------|------|
|                       | PM$_{2.5}$| PM$_{10}$| PM$_{2.5}$| PM$_{10}$| PM$_{2.5}$| PM$_{10}$| PM$_{2.5}$| PM$_{10}$| PM$_{2.5}$| PM$_{10}$|
| Winter 1 January—February 2015 | n | 1249 | 1206 | 1372 | 1375 | 1388 | 1378 | 1321 | 1381 |
|                       | Mean     | 222  | 445  | 162  | 201  | 178  | 320  | 180  | 302  |
|                       | STD      | 118  | 218  | 83   | 91   | 94   | 194  | 100  | 156  |
| Summer 1 March—May 2015 | n | 1906 | 1828 | 1710 | 1718 | 1979 | 1970 | 2114 | 2149 |
|                       | Mean     | 134  | 484  | 121  | 119  | 96   | 238  | 92   | 225  |
|                       | STD      | 107  | 308  | 44   | 102  | 67   | 169  | 60   | 159  |
| Monsoon June—August 2015 | n | 2024 | 1836 | 1995 | 1657 | 2543 | 1697 | 2041 | 2075 |
|                       | Mean     | 89   | 329  | 53   | 130  | 73   | 148  | 68   | 140  |
|                       | STD      | 83   | 256  | 53   | 107  | 54   | 114  | 56   | 124  |
| Post—monsoon, September — November 2015 | n | 1404 | 1341 | 1345 | 1342 | 1233 | 1332 | 1238 | 1260 |
|                       | Mean     | 133  | 519  | 78   | 152  | 101  | 220  | 101  | 228  |
|                       | STD      | 87   | 260  | 50   | 67   | 63   | 111  | 62   | 125  |
| Winter 2 December 15—February 2016 | n | 2083 | 1870 | 1946 | 1943 | 2088 | 2147 | 2014 | 2155 |
|                       | Mean     | 313  | 639  | 216  | 358  | 260  | 460  | 261  | 437  |
|                       | STD      | 136  | 241  | 95   | 140  | 116  | 195  | 129  | 185  |
| Summer 2 March—May 2016 | n | 1406 | 1341 | 1345 | 1342 | 1233 | 1332 | 1238 | 1260 |
|                       | Mean     | 157  | 344  | 70   | 239  | 95   | 282  | 133  | 310  |
|                       | STD      | 127  | 215  | 47   | 110  | 74   | 131  | 80   | 158  |
PM$_{2.5}$ and PM$_{10}$ are large and affected by season, clearly suggests that the interventions such as odd–even trials will not be effective to cut down the overall concentrations unless measures to control the baseline concentrations from the inner (e.g., roadside biomass burning, construction and resuspension of road dust; Kumar et al., 2015) and peripheral sources (e.g., brick kilns, burning of agriculture residue, industrial emissions and biomass burning for cooking and heating; Nagpure et al., 2015) contributing to PM in Delhi are also controlled.

### 3.3. Odd–even trial impact on PM concentrations

In order to better understand the actual impact of odd–even car trial schemes, the diurnal variations of total and net ($\Delta$) PM$_{2.5}$ (Fig. 2) and PM$_{10}$ (Fig. 3) concentration were plotted for the WS and SS (SI Figs. S5–S6) in 2016 and compared with diurnal plots of 1–15 January 2015 and 15–30 April 2015. The net concentrations are essentially the total concentrations minus the baseline concentrations at each site, which differ during seasons and between sites (Section 3.2), and therefore need to be subtracted to see the real impact of the reduced car fleet during the odd–even trial period. These figures were further divided into odd–even (0800–2000 h) and non–odd–even (2000–0800 h) hours to visualise their temporal trend at each site. Polar concentration roses of $\Delta$PM$_{2.5}$ (SI Fig. S7) and $\Delta$PM$_{10}$ (SI Fig. S7) after subtracting the baseline concentrations were drawn to understand the direction of major road traffic affecting each of the selected locations.

#### 3.3.1. Winter trial

During the WS (1–15 January 2016), $\Delta$PM$_{2.5}$ was found to be relatively low during the odd–even hours (1100–2000 h) and high during non–odd–even hour (2000–0800 h) when compared with the corresponding hours of the previous year of 2015 (SI Section S5). For example, $\Delta$PM$_{2.5}$ across all the sites ranged from $-2$ to $-44\%$ during odd–even hours, but were higher by $2$–$127\%$ (0700–0800 h at MM site) during non–odd–even, hours compared with the corresponding values of the previous year (SI Section S6). This effect was the lowest ($-2\%$) and the highest ($-44\%$) at MM and RKP, respectively. Furthermore, hourly averaged $\Delta$PM$_{2.5}$ across all the sites was found to be higher during early odd–even hours (i.e., 0800–1100 h) compared with the corresponding values of last year. For example, $\Delta$PM$_{2.5}$ was higher by $9$–$83\%$, $17$–$99\%$, $7$–$88\%$ and $6$–$91\%$ during these hours at AV, MM, PB and RKP, respectively, compared with the corresponding values of the previous year (SI Sections S6–S7). It is clear from the above observations that the fine particles were reduced during the majority of hours, except early odd–even hours (0800–1100 h), compared with the corresponding previous year’s concentration. This trend indicates the persistence of overnight emissions into the early morning due to a lag effect. On the other hand, such a reduction was non-existent during the non–odd–even hours when the concentrations were found to increase by up to $127\%$ against the corresponding values of last year. Therefore, odd–even car trial schemes appears to help in reduction of ambient PM$_{2.5}$ and PM$_{10}$ despite an annual growth in traffic volume of $-7\%$ in winter 2 compared with winter 1 (Goel et al., 2015). No special circumstances were noted between the two periods, which would have affected the emission from the other sources such as industrial activities and roadside open biomass burning (Kumar et al., 2015). Similar to PM$_{2.5}$, PM$_{10}$ also showed the identical daily trend during the WS and SS. For example, $\Delta$PM$_{10}$ across all the sites during the WS ranged from $-5$ to $-49\%$ during the majority of odd–even hours (1100–2000 h), but was higher by $5$–$157\%$ during non–odd–even hours (2000–0800 h) compared with the corresponding values of the previous year (SI Section S8). Similar to $\Delta$PM$_{2.5}$, $\Delta$PM$_{10}$ was found to be higher by $26$–$145\%$...
during the early morning odd—even hours (0800–1100 h) compared with the corresponding values of the previous year (Fig. 3).

Congestion and road user charging schemes have been implemented successfully in cities such as London with an aim to reduce traffic count on roads in specially defined zones. This scheme reduced CO₂, NOₓ and PM₁₀ emissions by ~16, 13 and 7%, respectively, in the year 2003 compared with prior scheme implementation in the previous year (EEA, 2008). In another study, Hasheminassab et al. (2014) found a decrease by 24 and 21% in PM₂·₅ emissions from the year 2008 during these odd even hours compared with the corresponding values in the year 2007 due to implementations of stringent emission standards. Our above observations clearly indicate that the odd—even trials appear to have generated cleaner air for certain hours of the day compared with the corresponding values of the previous year. However, the persistence of overnight emissions from the heavy goods vehicles into the early morning hours points to a need for tighter control on the entry of these vehicles during the early morning hours when the atmospheric conditions are the least favourable for mixing of the emitted pollutants. For example, a survey by CSE (2015) provides evidence of a substantial number of vehicles entering and exiting the Delhi city. This survey included the period of 20:00 h to 08:00 h and nine different points. The survey reported that the about 85,790 light and heavy goods vehicles enter and exit from all the studied points. During the day time, entry of commercial vehicles in the Delhi city is banned.

3.3.2. Summer trial

During the SS (15–30 April 2016), ∆PM₂·₅ were also found to be relatively low during the afternoon odd—even hours (1200–2000 h) and high during non—odd—even hours (2000–0800 h) when compared with the corresponding hours of the previous year (SI Fig. S5). For example, ∆PM₂·₅ across all the sites fell by ~1 to ~74% during these odd—even hours, but was higher by 1–82% during non—odd—even hours compared with the corresponding values of the previous year (SI Section S6). The smallest (~1%) and the largest (~74%) values were seen at AV and PB, respectively. Similar to WS, hourly averaged ∆PM₂·₅ was found to be higher by ~35–176%, 2–33%, 56–135% and 57–73% during early odd—even hours (0800–1200 h) at AV, MM, PB and RKP sites, respectively, compared with the corresponding values of the previous year. Likewise, ∆PM₁₀ was higher by 16–128%, 5–82%, 6–34% and 1–49% during non—odd—even hours at AV, MM, PB and RKP, respectively, compared with the corresponding values of the previous year (SI Section S6). The above observations suggest a change between ~1% and ~74% during the afternoon odd—even hours while such an effect was non—existent during morning odd—even and non—odd—even hours — as was observed during the WS.

A similar trend was observed for ∆PM₁₀. For example, ∆PM₁₀ across all the sites during the SS ranged from ~1 to ~63% during the majority of odd—even hours (1300–2000 h), but was higher by 1–43% during non—odd—even hours (2000–0800 h) compared with the corresponding values of the previous year (SI Section S3). Similar to ∆PM₂·₅, ∆PM₁₀ was found to be higher by 4–81% during the early morning odd—even hours (0800–1200 h) compared with the corresponding values of the previous year (SI Fig. S6).

3.4. Trend in PM against the preceding trial periods

In order to assess further the trends in PM concentrations during both the schemes against the preceding period at all the sampling sites, we adopted two approaches to choose daily average PM₂·₅ and PM₁₀ as reference values for comparison. The first approach included the daily average values of 25 December 2015 and 1 April 2016 as reference values for the WS and SS, respectively. In the second approach, we matched days with meteorological parameters (i.e., wind speed, wind direction, ambient temperature and relative humidity) during the year 2015 which were very similar to those during the odd—even trial periods (SI Table S5). This matching was performed by sorting the daily average data between ranges of minimum and maximum values at the respective sites. The number of days matched with the odd—even data at different sites during both the WS and SS are shown in SI Table S5. The daily averaged reference values of PM₂·₅ and PM₁₀ were then estimated for comparison with the odd—even trials for both the WS and SS at all the studied locations.

Both the approaches provided a comparable trend. For example, Figs. 4 and 5 show the variations in PM₂·₅ and PM₁₀ during odd—even hours compared with the corresponding values of the odd—even trial periods (SIFigs. S9–S10), respectively. Both the PM₂·₅ and PM₁₀ during the SS showed a similar trend. For example, the concentrations were usually higher (except on 9 and 15 January 2016) against the reference value, reaching up to ~3 times in 2016 compared with a reduction by up to half in 2015, compared with the reference value. These observations point to three key conclusions: (i) PM concentrations during the odd—even trial were usually higher compared with the preceding days of the odd—even trial in 2016. (ii) PM concentrations during 2015 were always lower reaching half of reference values on certain days in January 2015, and (iii) PM concentrations during SS were usually higher than those of the pre—trial period. As for the SS, PM₂·₅ (SI Fig. S9) and PM₁₀ (SI Fig. S10) showed relatively unchanged concentrations at most stations, except MM, against the reference value (daily average 1 April 2016) during both the months of April 2015 and April 2016. This indicated that the PM concentrations during SS did not change much during the odd—even period compared with a reference value for the pre—trial period. Likewise, PM₂·₅ and PM₁₀ during WS and SS, when compared with their reference concentrations that were estimated using the second approach, showed a usual increase during WS (SI Figs. S11–S12), except a decrease during SS (SI Figs. S13–S14) on some occasions on the odd—even days.

Combining the results of Sections 3.3 and 3.4 allows presentation of the trends in contrasting ways as to whether the odd—even trials reduced or increased concentrations of PM. For example, if the PM concentrations during the odd—even hours are compared against the previous year’s concentrations there has clearly been a decrease in concentrations (Section 3.3). However, concentrations of PM were found to increase during the odd—even hours if the reference value for comparison is taken as the days before the pre—trial period (SI Figs. S9 and S10).

4. Conclusions and future outlook

This study has evaluated the impacts of two recently implemented odd—even car trials during winter (WS; 1–15 January 2016) and summer (SS; 15–30 April 2016) in Delhi on the reduction of ambient PM₁₀ and PM₂·₅ concentrations. The data for PM₂·₅ and PM₁₀, together with the local meteorological parameters, for the 2015 and 2016 years were analysed with an aim to quantify the influence on PM₂·₅ and PM₁₀ due to the implementation of odd—even trial schemes during the two seasons.

The following conclusions were drawn

- A huge variability in both PM₂·₅ and PM₁₀ concentrations was found among the sites and seasons within Delhi. For example, the average PM₂·₅ ranged within a factor of ~6 with a minimum value of 53 µg m⁻³ (at site MM during monsoon) to a maximum value of 312 µg m⁻³ (at site AV during winter). Likewise, the
lowest and highest at 12 and 113 \( \mu g \) m\(^{-3} \) at RKP and MM stations, respectively. It indicates that the baseline concentrations of PM\(_{2.5}\) itself are 0.5– to 4.5–times higher than the mean 24 h WHO limit value of 25 \( \mu g \) m\(^{-3} \). Likewise, the baseline PM\(_{10}\) was found to be the lowest and highest as 31 and 252 \( \mu g \) m\(^{-3} \) at site RKP and MM, respectively. The corresponding baseline concentrations of PM\(_{10}\) itself were 0.6– to 5.0–times higher than the mean 24 h WHO limit value of 50 \( \mu g \) m\(^{-3} \). These observations clearly suggest controlling the baseline concentrations as a basic step towards improved air quality, as also discussed in our recent work (Kumar et al., 2013, 2015).

- During the WS and SS trial periods, \( \Delta PM_{2.5} \) and \( \Delta PM_{10} \) were found to decrease during the odd–even periods, but these were higher during the morning odd–even and the rest of the non–odd–even hours compared with the corresponding period during the previous year. This seems likely to be related to the time taken for dispersion of the pollutants emitted overnight. The effect of the odd–even hours during the WS ranged from a minimal reduction of –2% to a maximum reduction of –44% during peak traffic hours across the studied sites; this effect was relatively larger during the SS with the corresponding reduction of –2% to –74% estimated.

- \( \Delta PM_{10} \) followed the same trend as the \( \Delta PM_{2.5} \). The effect of the odd–even period during the WS ranged from a minimal reduction of –5% to a maximum reduction of –49% during peak traffic hours across the studied stations compared with the corresponding period during the last year. This effect was relatively larger during the SS when the corresponding reduction of –1% to –63% was noted.

- While the monsoon season showed the lowest ambient PM concentrations, the higher mixing height during summer assists in better mixing to reduce ambient PM concentrations. The winter episodic conditions are due to a low mixing height and are most likely exacerbated by the emissions from heavy goods vehicles during night time when the mixing height was lowest. Any traffic taken from the road during the odd–even trial will assist in reducing concentrations during the certain peak exposure times (early morning and late evening hours). However, the real gains can only be achieved by restricting the entry of heavy goods vehicles during night hours. These vehicles contribute up to 65% of total particle numbers (Kumar et al., 2011) and nearly half of the PM\(_{10}\) emissions from the exhaust of on-road vehicles in Delhi (Jain et al., 2016; Nagpure et al., 2016) and a likely reason to build up background concentrations during the night hours.

This work analysed the data available from the fixed–site monitoring stations to assess the effect of the odd–even trial on the PM concentrations. While a clear picture emerged from the analysis of odd–even trial efforts, further studies are recommended to target background measurements under different meteorological conditions and seasons. The monitoring of on–road traffic volume before, during, and after the odd–even trial periods through control studies in future could also help in determining the actual reduction in different types of on-road vehicles and their emissions. Furthermore, mobile monitoring around such interventions could provide better spatial resolution of concentrations and identify pollution hotspots within the city to prioritise specific emission control strategies. From the use of routine air quality data, it has not been possible to differentiate clearly the changes in air quality attributable to changes in road traffic from those due to other sources of emissions. It is recommended that before such a trial is next implemented, measures are put in place to enable either full source apportionment of the particulate matter, or as a minimum, measurement of chemical tracers for road traffic emissions.
Moreover, very careful planning of the study, including simultaneous data for air pollution, meteorology and vehicle count during such periods of interventions, will be needed if it is to differentiate between the effects of changes in emissions and meteorology upon the measured concentrations.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envpol.2017.03.017.

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