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

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A B S T R A C T

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 $PM_{2.5}$ and PM_{10} 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 $PM_{2.5}$ and PM_{10} (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 $PM_{2.5}$ and PM_{10} were higher by up to 3–times 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 larger effect caused by changes in meteorology and especially wind direction.

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 $PM_{2.5}$ (≤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

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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 km^2, including Delhi city with an area of 1483 km^2 (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 environment 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 (GoD, 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 traffic density per km of road is only 245 for Delhi compared with 1014 and 2093 for Mumbai and Chennai, respectively (Gupta, 2015; 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 $PM_{2.5}$, PM_{10} (≤ 10 μm) and NO_x (oxides of nitrogen) (CPCB, 2010; GoI, 2014). A brief summary of past studies between 1997 and 2016 is shown in Table 1, which indicates the concentrations of PM_{10} and $PM_{2.5}$ exceeding the national ambient air quality standards (CPCB, 2009). In Delhi city, CNG 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 configuration (Semin, 2008) there was no shift of diesel-fuelled to CNG-fuelled vehicles during the sampling period.

The Delhi traffic fleet is heterogeneous in nature in terms of fuels, engine capacity, technologies, vintage and mixed usage patterns that make pollution emission inventory estimation a challenging task. More than one–third of PM_{10} emissions in Delhi is generated by dust re-suspension (Guttikunda and Goel, 2013). Vehicle exhaust emissions are a major source of $PM_{2.5}$, contributing up to 45% of total $PM_{2.5}$ emissions in the Delhi NCR in the year 2010 (Kumar et al., 2016). Supplementary Information, SI, Table S1 summarises the findings of source apportionment studies carried out for Delhi city in the recent past.

The management of urban air pollution remains a major policy challenge in megacities like Delhi despite the implementation of several mitigation policies such as shifting of fuel used by public transportation from diesel to compressed natural gas, CNG (Dholakia et al., 2013), transforming coal power plants to natural gas (CPCB, 2010) and restriction on entry of heavy duty diesel vehicles in the city during the day time (Gulia et al., 2015a). Numerous kinds of schemes of road space rationing such as Rodízio or congestion pricing have been implemented in Latin America and European cities as a measure to alleviate the pollution levels. For example, Rodizio restricts each personal car for 1 day per week to run on the roads of Sao Paulo during 0700–1000 h (local time) and 1700–2000 h (Kumar et al., 2016; Rivasplata, 2013). Likewise, a short–term odd–even day trial was applied in Beijing during the 2008 Olympic Games (Cai and Xie, 2011). A number of studies have critically reviewed various stories of best practices of urban traffic management to reduce urban air pollution throughout the world (Dablanc et al., 2013; EEA, 2008; Gulia et al., 2015a). The results of these studies indicate reduced congestion due to such trials but there was no clear consensus about their impact on pollution levels.

The assessment and evaluation of benefits on ambient air pollution due to the implementation of policy measures such as odd–even trials are important but also challenging in a complex city like Delhi. In order to tackle the very high pollution levels in Delhi during winters, a 15 day odd–even car trial was applied by the Delhi Government between 1 and 15 January 2016 (winter scheme, WS), and the same between 15 and 30 April 2016 (summer scheme, SS), for personal diesel and petrol cars. The trial allowed an exemption to about 20 different categories such as cars driven by women, electric and hybrid cars, cars of very/very important persons, two–wheelers, emergency vehicles, ambulance, fire, hospital, prison, and enforcement vehicles. Personal light duty vehicles such as cars/jeep contribute ~40% of the total road traffic and are the dominant traffic fleet type in Delhi (Sharma et al., 2013b; Gulia et al., 2015b). The trial was applicable between 0800 and 2000 h (local time) during the weekdays and Saturday and allowed only private cars with their registration numbers ending with an odd number running on the road on odd dates of the month and those with even number allowed to run on even dates. The Delhi Government applied a fine of Rs. 2000 (about 30 U.S. dollar) for every violation of the odd–even car trial scheme in line with provisions of the Motor Vehicles Act 1988 to make this scheme successful. This resulted in a 15–20% reduction in traffic volume compared with the traffic volume before the odd-even scheme across the Delhi–Mathura Road, which is one of 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_{10} and $PM_{2.5}$ 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 concentration 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–February). In summer, the city experiences dry weather with the temperature reaching up to 48 °C. The monsoon season experiences more than 80% of the total annual rainfall (Perrino et al., 2011). During winter, frequent ground–based inversion conditions 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