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Role of urban growth, technology, and judicial interventions on vehicle exhaust emissions in Delhi for 1991–2014 and 2014–2030 periods

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ABSTRACT

Between late 1980s and 2014, the Greater Delhi region has witnessed an increase in vehicular fleet, four sets of emission standards, and changes in engine technology and fuel usage. This paper presents and evaluate these measures on on-road vehicle exhaust emissions under four counterfactual scenarios – (a) no penetration of 4-stroke (4S) 2-wheelers (2Ws) (b) no introduction of compressed natural gas (CNG) (c) no implementation of emission standards post 2000 and (d) no dual emission standards (supply of better fuel in the metropolitan areas and a grade lower for the rest). Introduction of 4S engines reduced VOC emissions by 90%, thus being the most effective compared to the three emission standards (BS-II, III, and IV) combined. Introducing CNG reduced 50% of $PM_{2.5}$ and increased 20% of NO_x emissions in 2014, mostly from buses and light duty vehicles. Implementation of emission standards affected all pollutants, with 60% reduction in VOCs and 20–30% reduction for the rest. Dual emission standards increased the $PM_{2.5}$ emissions from heavy duty vehicles, as much as the reductions from passenger vehicles, thus negating the benefits of the latter. Under the proposed roadmap of emission standards and vehicular technology by the Auto Fuel Policy 2025 committee, $PM_{2.5}$ emissions in 2030 will be halved, CO emissions will reach three times, and VOC and NO_x emissions will at least stabilize,

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compared to 2014 estimates. If leapfrogged to BS-VI in 2017, there will be additional reduction in NO_x and VOC emissions.

1. Introduction

The Greater Delhi region, with a combined population of 22 million (Census-India, 2012), is among the most polluted cities in the world (WHO, 2014). A large share of this pollution originates from manufacturing industries, power plants, brick kilns, dust resuspension, and vehicle exhaust (CPCB, 2010). For year 2010, Guttikunda and Goel (2013) estimated, for certain locations in Delhi, more than a third of total $PM_{2.5}$ (particulate matter (PM) with aerodynamic diameter $< 2.5\ \mu m$) concentration can be attributed to road transport emissions. Further, Apte et al. (2011) reported that the on-road exposure of $PM_{2.5}$ concentration is 1.5 times that of the ambient concentrations. Delhi, like most cities in India, has a vibrant mix of motorized vehicles plying on the roads. In this context, the knowledge of the estimates of on-road emissions as well as their contribution becomes an integral part to formulate pollution management policies.

In Goel and Guttikunda (2015), an integrated, dynamic, and multi-pollutant modeling framework for estimating annual on-road emissions was presented, for a period of 40 years, between 1990 and 2030, with projections to 2030 under business as usual scenarios. The modeling framework is an activity based emissions inventory model, in which the PM, nitrogen oxides (NO_x), carbon monoxide (CO), and volatile organic compounds (VOCs) emissions were estimated using

$$E_{v,f,g,p} = NV_{v,g} \times S_f \times VKT_{v,g} \times EF_{v,f,g,p} \quad (1)$$

and sulfur dioxide (SO_2) and carbon dioxide (CO_2) emissions were estimated using

$$E_{v,f,g,p} = NV_{v,g} \times S_f \times VKT_{v,g} \times FE_{v,f,g} \times PC_{f,p} \quad (2)$$

where, v=vehicle; f=fuel (petrol, diesel, and gas); g=age group; p=pollutant; E=the total emissions (tons/year) calculated by pollutant (p), vehicle type (v), fuel type (f), and by age (g); NV=the number of vehicles on-road by vehicle types (v) and by age (g); S=the share (%) of vehicles on-road for each vehicle type (v); VKT=the annual average vehicle kilometers traveled by vehicle type (v) and by age (g); EF=the fleet average emission factor (gm/km) by vehicle type (v), fuel type (f), age group (g), and by pollutant (p); FE=the fuel economy (km/lit) by vehicle type (v), fuel type (f), and age group (g); and PC=the carbon content (kg/lit of fuel) and sulfur content (ppm) of the fuel. In this study, the key parameters in the equations were used for Delhi, based on primary surveys conducted at the fuel stations and data collected from the emission testing labs, to establish the age mix, fuel economy, vehicle usage, and updated dynamic emission factors for the fleet (Goel et al., 2015). The emissions were classified by vehicle types; into 4Ws (passenger cars, jeeps, and vans), 2Ws (motorcycles, scooters, and mopeds), 3Ws (three-wheeled scooter rickshaws with 3 to 7seats), buses (intra- and inter- city operations), HDVs (heavy duty trucks), LDVs (light duty trucks), and others (off-road tractors and trailers).

For the period of 1990 and 2013, the framework included the emission control measures, mix of command and control measures, elimination of lead, reduction of sulfur and benzene content from the fuels, implementation of catalytic converters for cars, introduction of the “pollution under check” (PUC) program, implementation of emission standards, retirement of old public transport fleet, and introduction of compressed natural gas (CNG) for public transport vehicles. A schematic diagram showing the chronological order of road transport related measures in Delhi is shown in Fig. 1 and that of emission standards for different vehicle types is shown in Fig. 2. Since most of the factors such as pollution control measures, changing fuel share, and growth of fleet act simultaneously, independent effects of each of these are not known. Further, from a multi-pollutant perspective, the effects of these factors are not unidirectional.

A review of studies between 1998 and 2013 (Singh et al., 1990; Bose, 1996; Gurjar et al., 2004; Mohan et al., 2007; Sharma et al., 2002; Das and Parikh, 2004; Mittal and Sharma, 2003; Bose, 1999; Nagpure et al., 2013; Jalihal and Reddy, 2006; Singh and Sharma, 2012; Sahu et al., 2011; Guttikunda and Calori, 2013), suggests that, none reported independent effects of pollution control measures on transport emissions. In this paper, we trace the evolution of transport infrastructure, vehicular fleet, and technological advancement in engines, from early 1990s through 2014. Further, using counter-factual scenarios, we present estimates of contribution of technological advancements and different

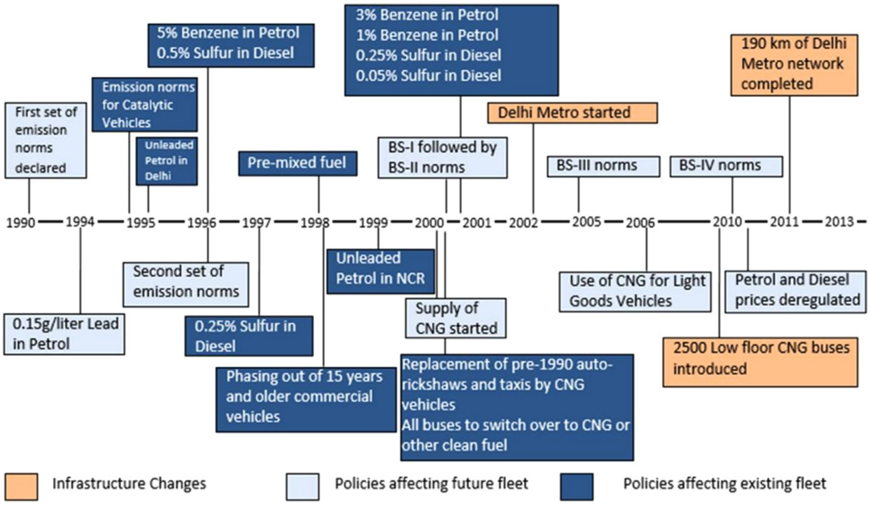

Fig. 1. Chronology of transport policies and infrastructure development in Delhi.

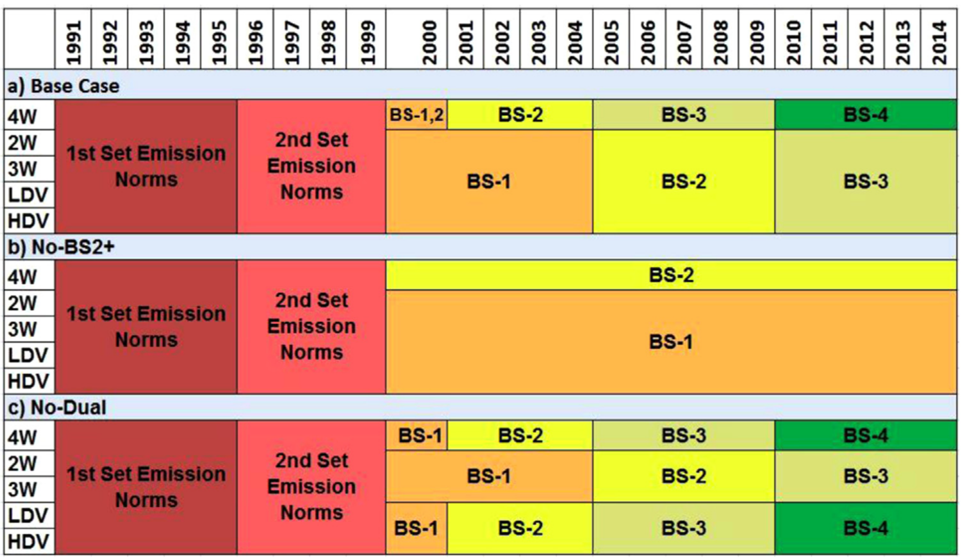

Fig. 2. Chronology of emission standards in Delhi.

policies to total on-road emissions and an analysis of the roadmap of emission standards proposed by the new Auto Fuel Policy through 2030 (Government of India (GOI) (2014)).

2. Study domain – the Greater Delhi region

Delhi, with a population density of 260 persons per hectare, is one of the most densely populated metropolitans in the world – 5 times denser than London, 4 times than Paris, and 12 times than New York. Fig. 3 presents a comparison of built up areas between 1991 and 2013, which increased from 715 km^2 to 1220 km^2, respectively. The built-up area was established using the Google Earth imagery for this study. Since 1991, the adjoining cities of Delhi have developed contiguous to the city boundary, which now along with the cities of Ghaziabad, Noida, Greater Noida, Faridabad, and Gurgaon, is referred to as the Greater Delhi region. The population of this working domain (80 km × 80 km) increased from 9.8 million in 1991 to 15.4 million in 2001 to 21.9 million in 2011, with Delhi being the largest with a population of 16.7 million in 2011 (Census-India, 2012). The urban and sub-urban connectivity is enhanced by networks of road, rail, and recently metro.

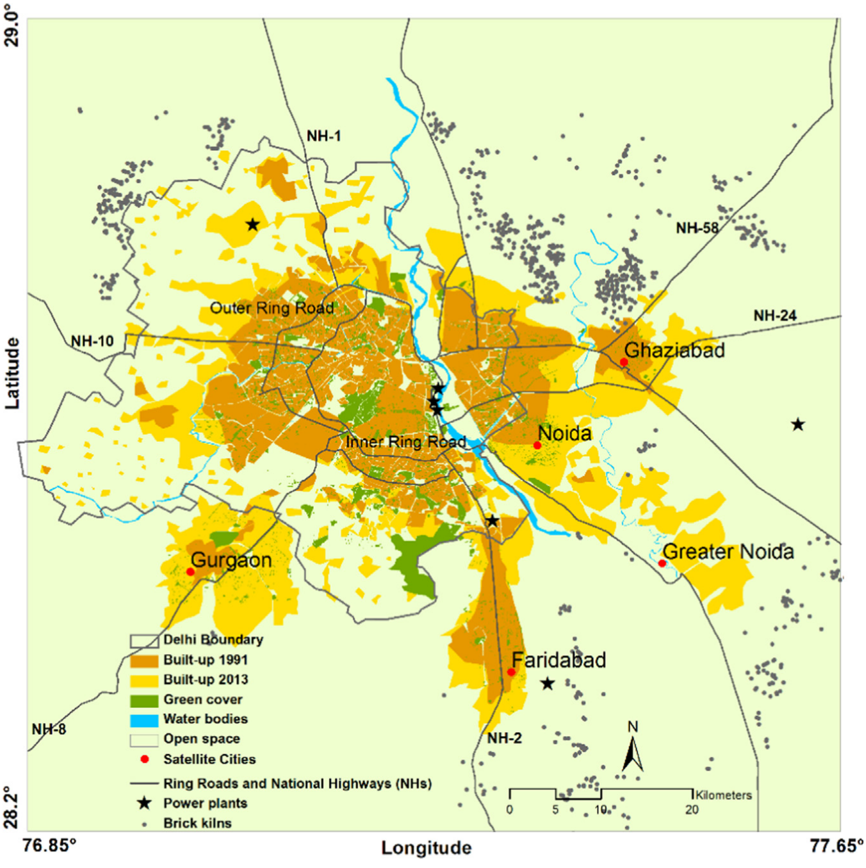

Fig. 3. The Greater Delhi region including the Delhi metropolitan area and its satellite cities – Gurgaon, Faridabad, Noida, Greater Noida, Ghaziabad and Rohini. Also highlighted are the main highways, brick manufacturing units (dots), and power plants (stars).

3. On-road vehicle fleet

3.1. Private Vehicles

The passenger vehicle ownership is among the highest in Delhi owing to its high per capita income (Census-India, 2012; ESD, 2013). Between 1991 and 2000, on an average 50,000 cars and 100,000 2Ws were registered every year which almost doubled in the following decade (2001–2010) to 110,000 and 180,000 per year, respectively, and further increased to 150,000 and 300,000 per year, respectively for 2011–2013 (DES, 2012; 2013). The number of registered cars and 2Ws increased from 0.4 million and 1.2 million, respectively, in 1990–91, to 2.3 million and 4.6 million, respectively, in 2011–12 (SoE-Delhi, 2012). As a result, the vehicle ownership in the Greater Delhi region increased from 150 (cars and 2Ws) per 1000 persons in 1991 to 200 in 2011. Through 2030, the number of in-use private vehicles is expected to grow at least 2.5 times between 2014 and 2030 under the business as usual scenario (Goel and Guttikunda, 2015).

3.2. Public transportation Systems

Delhi has two rail-based public transportation (PT) systems- the suburban railway and a metro rail network. The Delhi suburban railway system, introduced during 1982 Commonwealth Games, is 35 km ring (concentric to inner ring road in Fig. 3), and the Delhi metro rail system, started in 2002, is 190 km long with a ridership of 2 million per day in 2012 (was 82,000 in 2002).

The PT bus network consists of 750 bus routes and 6000 bus stops, operated by the Delhi Transport Corporation, Delhi Integrated Multimodal Transport System and some private contractors. In 2012, the bus ridership was 4.7 million per day. Private operations include chartered buses hired by offices, factories, and schools. These buses (approximately 5000) provide point to point services, covering 100–150 km per day. In addition, there are 3000 buses which carry out inter-city operations on a daily basis.

Para-transit system includes regular 3Ws (which seat up to 3), shared 3Ws (which seat up to 8), and mini-buses which seat up to 12 and work similar to buses except on shorter routes. In the satellite cities, formal systems are largely absent and most of their intra-city public transportation is carried out by informal systems. This is common for most cities in India, except a handful of major metropolitan cities (Guttikunda et al., 2014). With an operational 190 km of metro system, most of the 3Ws cater to short distance travel to-and-from the stations, and are also very popular for shuttling school children during the rush hours. The total number of 3Ws registered in the city was capped at 55,000, which was raised to 100,000 in 2013, with a mandated retirement age of 15 years. In comparison, registered number of auto-rickshaws in Mumbai is 250,000, with a population comparable to that of Delhi.

3.3. Freight transport

With 50,000 to 100,000 trucks moving through the city per day, the HDVs and LDVs are the largest contributors to the total emissions in the Greater Delhi region (Goel and Guttikunda, 2015). Of all the amount of freight traffic terminating to or originating from Delhi, 86% is carried on road, 13% by rail and rest by airways (RITES, 2013). Delhi attracts a large magnitude of road-based freight movement because of two reasons – (1) fast and convenient road-based connectivity through a series of NHs (Figs. 3) and (2) Delhi is a major wholesale trade and redistribution center for northern India. It is estimated that more than three-quarters of vegetables and fruits, and almost half of fuel, iron and steel, and food grains traded in Delhi are destined for other states (ESD, 2013). As a result, movement of goods traffic is not restricted to circulation within the city, but also the goods traffic which comes and then leaves the city.

Since a large fraction of freight traffic moving in Delhi is registered outside Delhi and carries out country-wide operations, the emission norms followed by such vehicles are not in compliance to those implemented in Delhi because of prevailing dual standards. For instance, while Delhi follows

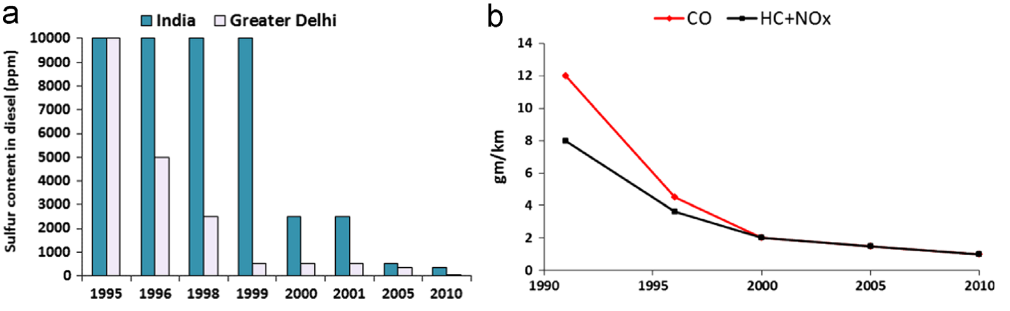

Fig. 4. (a) Differential sulfur standards for diesel in India (b) CO and HC+NO_x emission standards for 2Ws.

BS-IV standards (since 2010), rest of country (except for 38 other cities) still has access to BS-III fuel Government of India (GOI) (2014). See Fig. 4 for a chronological order of the sulfur content of diesel in India and in Delhi. Clearly, long distance trucks continue to use BS-III diesel, given its universal availability in India. Even the trucks with BS-IV engines registered in Delhi end up filling tanks with BS-III diesel, thus negating any benefits of new vehicular standards (Guttikunda and Mohan, 2014).

4. Technology and fuel advancements

4.1. 2-Stroke 2Ws

Until mid-1990s, most of the 2Ws sold in Delhi were 2-stroke (2S) scooters and mopeds. In these engines, fuel-air mixture ranged 15–40%, resulting in incomplete combustion, additional emissions, and reduction in overall fuel efficiency. This exhaust is dominated by a mixture of VOCs. In addition, in 2S engines, lubricating oil is mixed with the fuel, which is also released as visible smoke. It is estimated that unburned lubricating oil comprises 80 to 95% of total 2S PM emissions, because of which, the pollution from 2S vehicles became a serious concern during 1990s (Kojima et al., 2000; Iyer and Badami, 2007; Manufacturers of Emission Controls Association (MECA) 2008).

Starting from 1998, pre-mixed fuel (petrol mixed with the 2% lubrication oil) became available for 2Ws. This was required to prevent the 2S 2W owners adding up to twice the appropriate amount of lubrication oil, leading to significant additional pollution. Considering that sales of 4-stroke (4S) 2Ws increased only in mid-1990s and became significant only in early 2000s, in-use fleet of 2Ws was predominantly 2S-based during this reform. Since the excess use of oil causes deterioration of vehicle performance, this reform also helped vehicle owners without any significant cost difference in the fuel (Kojima et al., 2000; Bell et al., 2004).

4.2. Introduction of 4-stroke 2Ws

Introduction of 4S technology for 2Ws helped reduce the overall emissions from this sector. The 4S engines, unlike 2S, effectively separate the exhaust and intake strokes of the combustion cycle, and control the scavenging losses. As a result, both VOC emissions as well as fuel consumption are reduced relative to 2S. However, in 4S engines, NO_x emissions are higher due to higher (~5 times than 2S) combustion temperature resulting from a leaner air-fuel mixture (high oxygen to fuel ratio), which was necessary for increased fuel efficiency. Given that NO_x emissions and fuel efficiency are inversely related to each other, emission standards for 2Ws in India have not been mandated separately for HC and NO_x, but as a sum of the two (HC+NO_x), thus giving leniency for NO_x emissions. This is different from European Union and most other settings where two pollutants have separate standards. This is likely the reason that 2W fleet in India managed to be one of the most fuel efficient in the world Government of India (GOI) (2014).

The 2S to 4S shift was a rare instance when emission regulations proved beneficial for manufacturers (conforming to emissions standards), as well as its users (increasing fuel efficiency). As a result, sales of 2S 2Ws dropped from 80% in late 1990s to 6% by year 2004, and mostly restricted to 50–60 cm^3 engine size (Muralikrishna, 2007**;** Iyer, 2012). According to the PUC database for Delhi, described in Goel et al. (2015), 95% of in-use 2Ws in 2012 were 4S based.

4.3. 4Ws

Most technological changes in Indian car industry occurred in the late 1990s and early 2000s. Many joint-ventures of Indian and foreign manufacturers occurred in mid-1990s, following the economic liberalization (Sagar and Chandra, 2004), thus setting up base for fuel-efficient vehicles in 2000s. The landmark decision in 1996 was the mandatory catalytic converters in all petrol cars sold in the four metros (Delhi, Calcutta, Mumbai and Chennai). The use of catalytic converters also necessitated the use of lead-free and low sulfur fuels. This was followed by implementation of BS emission standards BS- I and II during 2000-01, and further BS-III in 2005 and BS-IV in 2010 (see Fig. 2). Up to BS-IV, there are no standards for PM emissions in petrol cars, unlike diesel cars.

4.4. 3Ws

Similar to 2Ws, change in technology from 2S to 4S was introduced for 3Ws. However, it was not successful among 3W operators, who use 3Ws as a means of livelihood, unlike users of 2Ws (Mohan and Roy, 2003). The operators had the following concerns against using 4S technology – (a) initial cost of a 4S engine was higher (b) 4S engines have many more parts thus leading to higher maintenance cost (c) vehicle acceleration was less in a 4S engine (d) 4S engine heated much more and (e) the fuel-efficiency benefits were not as significant as they were in case of 4S motorcycles (Rogers, 2002; Iyer, 2012).

In 1998, Supreme Court of India directed all public transport vehicles (buses, 3Ws, and taxis) to be converted to CNG **(**Kathuria, 2002**)**. During the CNG conversion, the 4S engines were re-introduced, pre-1991 3Ws were replaced by original equipment 4S CNG vehicles, while those from post-1991 were retrofitted with CNG retaining their 2 S engines. Before the CNG switch occurred, almost all the 3Ws in Delhi were 2S petrol driven (MOEF, 1997). Due to lower price of diesel, it was cheaper to operate a diesel-based 3W; however, they may not have been popular because of their inconvenience due to sound and vibration (Iyer, 2012). By year 2004, among the registered 3Ws, 65% were 4S and rest were retrofitted (EPCA, 2004). Over time, the retrofitted 3Ws were phased out and, according to the PUC database, constituted only 5% of all the operational 3Ws in 2012.

4.5. In-use vehicle fuel shares

According to a Supreme Court's order, 3Ws and taxis were allowed to run on mixed-fuels and to comply with mixed emission standards – taxis were allowed to comply with Euro II diesel standard and 3Ws were allowed to comply with low benzene petrol standard. This included retirement of fleet older than 15 years (Mehta, 2001). Thus, the definition of clean fuel and low emissions was mode dependent. However, all the 3Ws and taxis were eventually converted to CNG. It is not clear whether the push for 100% conversion is a result of successful venture of auto manufacturers to develop CNG-based 4S technology or more judicial interventions. Starting from early 2000s, all taxis, and from 2006, all new LDVs, operating in the Greater Delhi region were mandated to run on CNG.

In 2002, CNG was the cheapest fuel – priced less than half of petrol and 20% lower than diesel. The price gap between the existing fuels, cheaper operating costs, lower cost of retrofitting (to operate in dual fuel mode), more fuel pumping stations (from 30 in 2000 to 150 in 2009, to more than 300 in 2013), and increasing number of CNG variants of cars from the auto-manufacturers propelled rapid conversion of private petrol cars to CNG cars. According to PUC database, among the in-use fleet, share of CNG cars doubled in 5 years, from 14% in 2009 to 30% in 2013, and as a result, surpassed share of diesel cars (17% in 2013). During the same period, share of petrol cars reduced from 72% to 53%.

Between 2009 and 2013, number of diesel cars increased by 70%, CNG cars by 190%, and petrol cars reduced by 2%. This also explains the reduction of total petrol consumption in the city, which is less in 2012–13 compared to 2009–10 (DES, 2013).

5. Counterfactual scenarios

The integrated emissions model was utilized to simulate counterfactual scenarios, in which the model was run with a set of parameters which represent a scenario without intervention. For instance, in case of new emission standards starting in a particular year, the counterfactual scenario assumes that the standard was not implemented and the preceding emission standard was continued. We considered four major policies to evaluate their effectiveness on the on-road emissions in the Greater Delhi region

- *No-4S-2W*: Assuming no 4S engine penetration in 2W fleet. Introduction of 4S 2Ws was a crucial technological advancement, as PM and VOC pollution from 2S-based engines became a serious concern in India, with significant share of 2Ws in the motor vehicle fleet.
- *No-CNG*: Assuming no supply of CNG in the city and hence no CNG vehicles- which includes 3Ws, 4Ws, buses, and LDVs. We assumed that CNG cars are equally shared among petrol and diesel cars, 3Ws run mostly on petrol with a marginal share of diesel, and buses and LDVs continue to use diesel
- *No-BS2+*: No implementation of emission standards post 2000/01- BS-III and IV for cars, and BS-II and III for all other vehicle types, and continuation of first set of BS-I emission standards through 2014 (see Fig. 2)
- *No-Dual*: Assuming no lag between the implementation of emission standards between Delhi and overall India, leading to similar emission standards for 4Ws and trucks (LDVs and HDVs) (see Fig. 2). With highways passing through the city, even the inter-city vehicles add to city's pollution levels. The night-time truck movement leading high levels of PM pollution during early morning

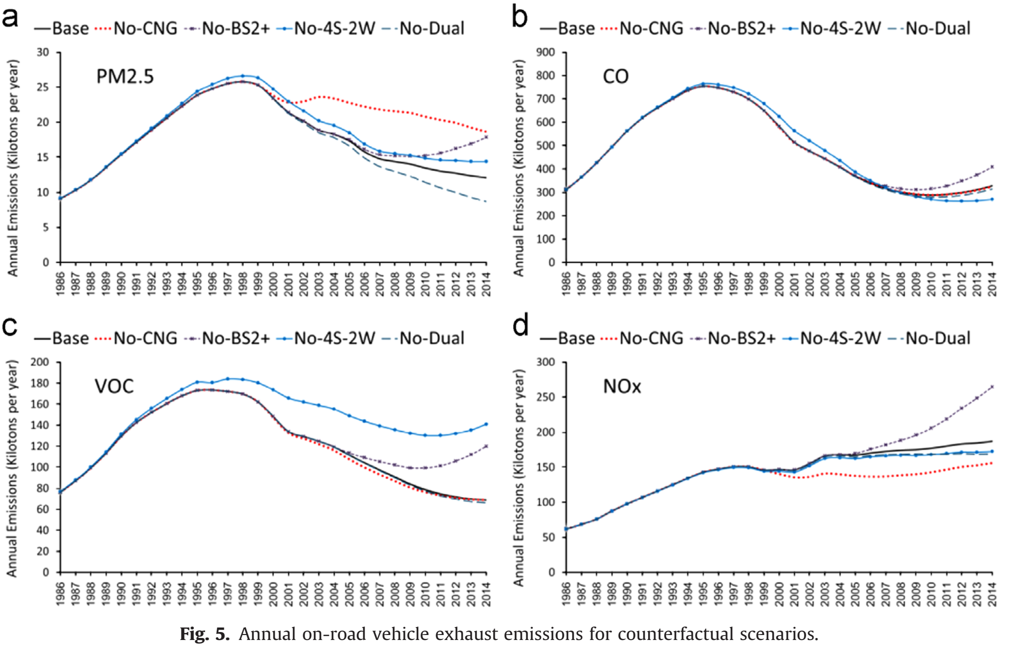

Fig. 5. Annual on-road vehicle exhaust emissions for counterfactual scenarios.

hours have been shown by Guttikunda and Calori (2013). In addition, with the prevalence of dual emission standards, vehicle owners during their inter-city travel are forced to fill their tanks with an inferior quality of fuel, leading to degradation of emission control measures in the vehicles.

The annual emissions under the business as usual and the counter-factual scenarios are presented in Fig. 5 and the share of total change in emissions for different vehicle types for year 2014 in Table 1.

Table 1
Effects of counterfactual scenarios on total on-road vehicle exhaust emissions in 2014.

		Change in base emissions for each vehicle type				Share of each vehicle type in total difference in emissions			
PM2.5	**Base emissions (Tons)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**
2W	1580	0	24	155	0	0	8	146	0
3W	210	152	187	0	0	4	8	0	0
4W	3075	18	49	0	0	6	31	0	0
BUS	840	373	44	0	−38	35	8	0	7
HDV	6240	−7	19	0	−38	−5	24	0	54
LDV	5175	103	21	0	−34	60	22	0	39
Total	17,130	52	29	10	−26	100	100	100	100
NO_x	**Base Emissions (Tons)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**
2W	20,650	0	3	−75	0	0	1	100	0
3W	19,780	−72	219	0	0	33	56	0	0
4W	13,930	5	32	0	0	−2	6	0	0
BUS	36,550	−15	27	0	−4	12	13	0	8
HDV	42,550	0	22	0	−17	0	12	0	39
LDV	107,370	−23	9	0	−9	57	13	0	53
Total	240,840	−18	32	−6	−8	100	100	100	100
CO	**Base Emissions (Tons)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**
2W	158,680	0	7	−37	0	0	14	100	0
3W	23,560	3	3	0	0	−23	1	0	0
4W	119,160	−3	45	0	0	123	67	0	0
BUS	17,120	0	30	0	−29	0	6	0	33
HDV	25,190	0	22	0	−22	0	7	0	37
LDV	51,240	0	8	0	−8	0	5	0	30
Total	394,940	−1	20	−15	−4	100	100	100	100
VOC	**Base Emissions (Tons)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**	**No-CNG (%)**	**No-BS2+ (%)**	**No-4S-2Ws (%)**	**No-Dual (%)**
2W	30,270	0	123	257	0	0	73	100	0
3W	19,770	−9	2	0	0	125	1	0	0
4W	16,200	2	74	0	0	−25	23	0	0
BUS	4800	0	14	0	−20	0	1	0	34
HDV	6650	0	11	0	−15	0	1	0	37
LDV	12,210	0	2	0	−7	0	0	0	30
Total	89,900	−2	57	87	−3	100	100	100	100

In case of $PM_{2.5}$ emissions No-CNG, No-BS2+ and No-Dual, made significant impact, with the former two leading to ~52% and ~29% increase in total emissions, respectively, and the latter leading to 26% reduction. This is followed by No-4S-2W leading to 10% increase in emissions. With No-CNG scenario, major increase in emissions occurred in case of buses (~370%), 3Ws (~150%), and LDVs (~100%). In case of No-CNG, buses and LDVs contributed to ~90% of the total change in emissions. For No-BS2+ scenario, most increase in emissions came from 4Ws (~30%), LDVs (~20%) and HDVs (~25%). As expected, all the difference in emissions for No-4S-2W is contributed by 2Ws.

In case of CO emissions, the largest increase comes from No-BS2+ (~20%) scenario, followed by ~15% reduction from No-4S-2Ws. No-CNG resulted in almost no change while No-Dual led to only 4% reduction. In case of No-BS2+, more than two-thirds of total change in emissions have been contributed by 4Ws, and 14% by 2Ws. No-BS2+ led to 45% increase in 4W emissions, 30% increase in bus emissions, and 7% increase for 2Ws, while No-4S-2Ws led to 37% reduction in CO emissions of 2Ws. In case of passenger cars, most reduction in the CO emission factors occurred with the implementation of catalytic converters in mid-1990s followed by implementation of BS-I and II; No-BS2+ assumed no implementation of BS-III and IV. In Goel et al. (2015), we presented trends of idling CO emissions for cars in which CO emissions dropped by a factor of more than three from late 1990s to 2001, following which the reduction has occurred gradually. The reduction in emissions from 2Ws also followed a similar pattern.

In case of VOC emissions, No-4S-2W (~90%) and No-BS2+ (~60%) led to the largest increase, while No-CNG and No-Dual led to negligible difference. No-4S-2Ws resulted in more than 2.5 times increase in VOC emissions of 2Ws. In case of No-BS2+, most changes are due to 2Ws (40%) and 4Ws (30%), with an increment of ~120% for the former and ~75% for the latter. For 2012, we estimated that one-third of total road transport VOC emissions are contributed by 2Ws, as a result of which any change in VOC emissions of 2Ws led to a significant change in total emissions (Goel and Guttikunda, 2015)

In case of NO_x emissions, major increase occurred in scenarios of No-BS2+ (~30%) and No-CNG (~20%), while the emissions reduced by ~8% in case of No-Dual and ~6% in case of No-4S-2W. In case of No-BS2+, major increase occurred for 3Ws (~220%), 4Ws (~30%), buses (~30%), and HDVs (~20%). Most reduction in No-CNG came from LDVs (~60%) and 3Ws (~35%). With No-4S-2Ws, there is a reduction of ~75% of NO_x emissions from 2Ws.

In addition to four counterfactual scenarios described above, the model simulated two additional scenarios – keeping the annual mileage values constant after 1995 and no deterioration of emission factors - effectively no ageing of fleet. For the two scenarios, while the annual emissions reduced significantly, the overall trend remained the same. Keeping a constant mileage led to ~25–30% lower emissions and no deterioration of emission factors (hence, no ageing) led to ~30–60% lower emissions.

5.1. *Learning from past policies*

A large number of emission control policies in Delhi have been formulated as a result of judicial interventions. The Supreme Court of India ruling in 1998 to convert public transport vehicles to CNG was the result of a Public Interest Litigation (PIL). This PIL resulted in a judgment laying down more than a dozen other emission control measures to be implemented in Delhi (Mehta, 2001; Bell et al., 2004). PILs have proved to be instrumental in addressing various environmental problems in India at various levels, and thus have empowered citizens and non-governmental organizations.

Between 1990 and 2014, implementation of emission standards (BS- III and IV in case of cars, and II and III for all other vehicle types) had the greatest impact on all the pollutants – $PM_{2.5}$, CO, NO_x and VOCs. Among vehicle types, standards made maximum impact on emissions from cars, followed by buses, and freight vehicles. CNG implementation reduced $PM_{2.5}$, while it increased NO_x. In case of buses, CNG replaced diesel, in case of 3Ws, it replaced petrol, and in case of cars, it replaced petrol as well as diesel. As a result, CNG implementation has varying effects (positive or negative) for different vehicle types. The penetration of 4S 2Ws is more effective in reducing the VOC emissions than the three emission standards combined together, highlighting the major contribution of 2Ws to VOC emissions, as well as significance of improved technology in reducing pollution. If standards were not implemented in a phased manner, it could have reduced as much $PM_{2.5}$ emissions as the combination of three emission standards.

The results in Fig. 5 and Table 1 also highlighted the importance of taking into account the variation of vehicular mileage of different vehicle types over time, as well as ageing of fleet, in order to estimate transport emissions. Also, note that the gap between the emissions of the counterfactual scenarios (for instance, implementation of emission standards) and that of baseline increases over time. This is because of a rapid growth rate of fleet size in addition to deterioration of emission control mechanisms in the vehicles, which result in higher emission factors with age. This also highlights the drawbacks of delaying implementation of emission standards.

5.2. Choice between CNG and low sulfur diesel

During the debate for CNG, ULSD (Ultra Low Sulfur Diesel with Sulfur content of less than 30 ppm) for buses was one of the alternatives to CNG. Prevalence of diesel adulteration with kerosene (Bell et al., 2004; Baidya and Borken-Kleefeld, 2009), among other reasons, encouraged policy makers to choose CNG as a fuel. However, after 15 years of introducing CNG in Delhi, ULSD is not available in India. Therefore, in retrospect, without implementation of CNG, $PM_{2.5}$ emissions from road transport in the city would have been up to ~60% higher.

However, a solution such as Delhi's is not very likely to be replicable in many cities. Use of a fuel for a smaller proportion of buses (by 2013, CNG-run buses are currently implemented only in less than 20 cities of India, MoPNG, 2013) provides no incentives for auto manufacturers to improve their vehicle design for the new fuel as it also impedes their efforts to attain economies of scale. In addition, implementation of CNG in a city is constrained by its supply. More than a decade after CNG was implemented in Delhi, at the end of 2012–13, there were only 25 cities with CNG network for vehicles, only 24,000 buses registered, which is less than 2% of the total registered bus fleet in India (MoPNG, 2013; MoRTH, 2012). The Supreme Court ruling to convert all Delhi buses to CNG, also mandated augmentation of the bus fleet to at least 10,000. However, after 15 years, the number of buses remain at 7000, due to lack of depots to park and lack of maintenance programs for continued support. Instead, a gradual improvement of diesel quality in India (reducing sulfur content) would have given enough time to auto manufacturers to upgrade their vehicle technology, as well as refineries in India to produce cleaner diesel. This would have led to an improved air quality in the overall country (Guttikunda and Mohan, 2014). Introduction of 4S technology is one of the examples where availability of technology made it possible for implementation of strict emission standards, which were highly needed given the ubiquity of 2Ws in Indian cities.

5.3. Prevalence of dual emissions standards

Emission standards in India have been implemented in a phased manner – starting with major metropolitan cities, followed by rest of India. Currently, for instance, Delhi and few other cities have 50 ppm sulfur diesel since 2010, while the rest of India has 350 ppm. The Auto Fuel Policy 2025 highlights two major reasons for implementation of emission standards in a phased manner

- Firstly, to account for the time required by refineries to upgrade their processes to produce fuel with lower sulfur content and the cost thereof, and also the time needed by auto manufacturers to upgrade their technology base.
- Secondly, given the link of fuel standards to emission outcomes, priority of implementation is given to the metropolitan centers where vehicle density is the highest.

However, such priority underestimates the contribution of inter-city trucks to overall road emission in Indian cities. In Goel and Guttikunda (2015), we estimated that more than 60% of total $PM_{2.5}$, CO, and SO_2 emissions are contributed by trucks (LDVs and HDVs). Thus, emission standards in India need to be set keeping the contribution of trucks to total emissions into account. Trucks are more likely to use fuel available in the rest of the country than that available in few cities because

- Trucks have long-distance haulage covering many states, therefore, they are inclined to use the fuel which has universal availability

- BS-III fuel as well as BS-III trucks are cheaper than BS-IV thus further encouraging the bias of truck users to use an inferior fuel Government of India (GOI) (2014)
- There is no restriction on the movement of BS-III registered trucks in areas with BS-IV regulations.

6. Road ahead through 2030

6.1. Auto fuel policy -2025

BS-III and BS-IV emission standards were implemented in India according to the roadmap laid down by the Auto Fuel Policy formed in 2003. In continuation of this, Auto Fuel Policy (AFP) - 2025 was formed in early 2014 which lays down the roadmap for implementation of national coverage of BS-IV, V and VI emissions norms for cars and heavy diesel vehicles, and BS-IV and BS-V for 2Ws and 3Ws. Similar to the previous emission standards, AFP-2025 also recommends implementation of standards in phases, with gradual coverage of geographical parts of the country.

Fig. 6 summarizes the recommended timeline of emission standards for different vehicle types in Delhi. According to the recommendations, by early 2017, there will be country-wide implementation of BS-IV. Since the policy document indicates that BS-V fuel will be available to some extent in the same year, we assumed that BS-V emission standard will be implemented in Delhi from that year, while country-wide implementation will begin only from 2020. Since there is no difference between BS-V and BS-VI, as far as fuel quality is concerned, there will be country-wide implementation of BS-VI norms by 2024. From BS-IV to BS-V, $PM_{2.5}$ emission factors for 4Ws and diesel trucks are reduced to fifth, and for diesel trucks, it is reduced further to half its value for BS-VI. For 2Ws, CO emission factors are increased by up to 90% from BS-III to BS-IV and then reduced to 10% higher than BS-III for BS-V. Emission factors $HC+NO_x$ are reduced by half in BS-IV and then further by half in BS-V. Starting from BS-IV, for 2Ws, AFP-2025 has also recommended setting separate emission standards for NO_x, in addition to a combination with HC ($HC+NO_x$).

6.2. Emission trends: AFP-2025 and alternate future scenarios

We used the timeline laid down by AFP-2025 and projected the on-road emissions in the Greater Delhi region from 2015 through 2030. We assumed that emission standards for diesel trucks are

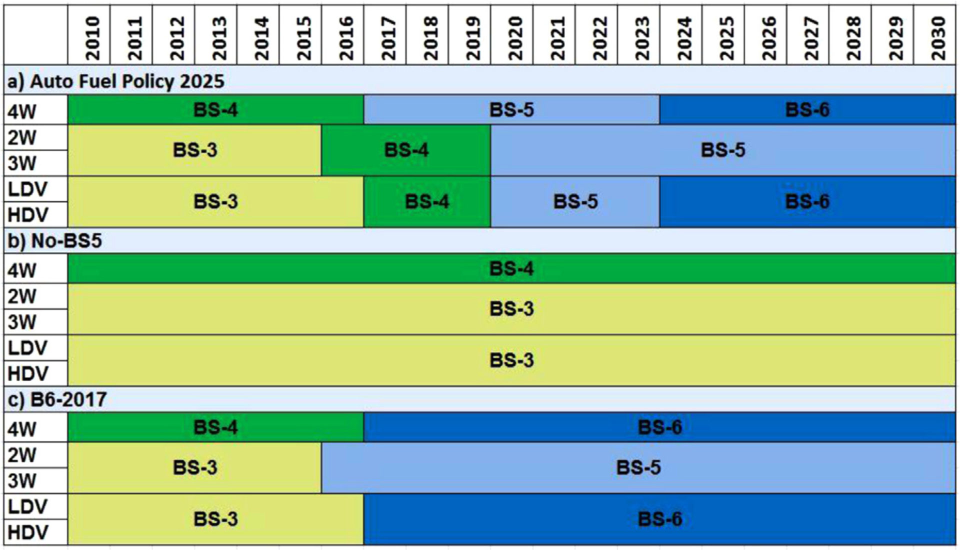

Fig. 6. Auto Fuel Policy-2025 and Alternate Future Scenarios.

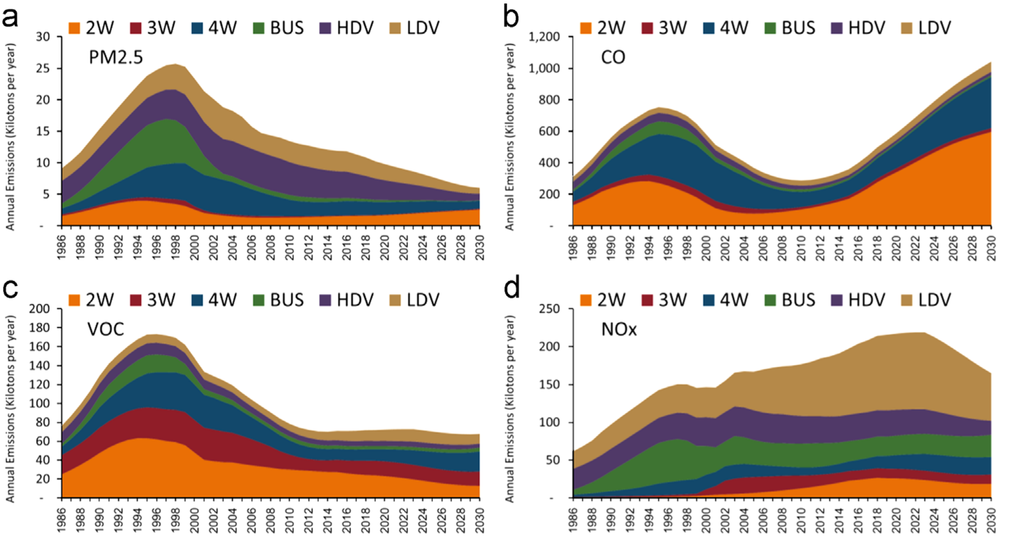

Fig. 7. Estimated annual on-road vehicle exhaust emissions in the Greater Delhi region between 1986 and 2030 (a) $PM_{2.5}$ (b) CO (c) VOC and (d) NO_x.

upgraded only when the new emission standard has been implemented nationally. In Fig. 7**,** we present emission estimates for years 1986 through 2030, using AFP-2025 recommended timeline of standards (Fig. 6). Table 2 shows the percentage increase in emission from 2014 to 2030 and also the distribution of emissions among different vehicle types for the two years.

Compared to 2014, $PM_{2.5}$ emissions will reduce to half in 2030, CO emissions will be 3 times, while VOC and NO_x emissions will reach almost to the same level. In 2030, share of 2Ws in total $PM_{2.5}$ and CO emissions increase compared to 2014, from 10% to 34% and from 41% to 55%, respectively, while the share of 4Ws will remain the same, and that of trucks and buses will reduce. For NO_x and VOC emissions, the distribution of emissions among different vehicle types will remain almost the same.

In order to put emission estimates resulting from AFP-2025 into perspective, we simulated two alternative future scenarios (Fig. 8). Firstly, we assumed continuation of current set of emissions standards (No-BS5) and secondly, leapfrogging to BS-VI emissions norms (BS-V for 2Ws and 3Ws) in 2017 for the whole country (B6-2017). Compared to No-BS5, for 2030, $PM_{2.5}$ emissions from AFP-2025 are reduced by 60%, VOC emissions are reduced to less than half, and NO_x emissions are reduced to half. However, CO emissions are increased by more than 10%. This is because CO emissions for 2Ws in BS-IV and V are higher than in BS-III. Thus implementation of AFP-2025 will reduce most pollutants significantly compared to continuation of current emission standards, even though in-use fleet size from 2014 through 2030 is estimated to be tripled (Goel and Guttikunda, 2015). With leapfrogging to BS-VI emission standards (B6-2017), $PM_{2.5}$ emissions as well as CO emissions in 2030 remain similar to AFP-2025, VOC emissions are reduced by 18% and NOx emissions are reduced by 40% from their estimates in AFP-2025. Thus leapfrogging to BS-VI has additional benefits compared to AFP-2025. With a significant reduction of NOx and VOC emissions, this scenario is likely to result in lowering surface ozone levels.

7. Implications

On-road vehicle exhaust emissions play a pivotal role in the circles of air quality management in India cities, because of increasing vehicle sales, higher mobility needs, and increasing linkages to human health effects. Based on the transport policies implemented in Delhi and in India, we learnt that the implementation of emission standards have made the biggest impact on all the major

Table 2
Estimated on-road vehicle exhaust emissions under the proposed Auto Fuel Policy-2025 and alternate future scenarios, compared to 2014.

Vehicle type	Emissions in 2014 (Tons/year)	Increase in 2030(%)	Share in 2014(%)	Share in 2030(%)
PM2.5				
2W	1580	76	10	34
3W	210	−23	1	2
4W	3075	−46	19	20
BUS	840	−86	5	1
HDV	6240	−73	35	19
LDV	5175	−60	30	23
Total	17,130	−50	100	100
NO_x				
2W	20,650	−2	9	9
3W	19,780	−18	8	7
4W	13,930	96	6	12
BUS	36,550	−4	15	15
HDV	42,550	−41	18	11
LDV	107,370	−3	45	46
Total	240,840	−5	100	100
CO				
2W	158,680	299	41	55
3W	23,560	36	6	3
4W	119,160	206	30	31
BUS	17,120	−21	4	1
HDV	25,190	−2	6	2
LDV	51,240	63	13	7
Total	394,940	193	100	100
VOC				
2W	30,270	−53	34	17
3W	19,770	3	22	24
4W	16,200	50	18	29
BUS	4800	0	5	6
HDV	6650	−20	7	6
LDV	12,210	26	14	18
Total	89,900	−7	100	100

pollutants. In addition, changing type of fuel used for public transport vehicles and 4S technology penetration for 2Ws, have also contributed significantly towards achieving reduction or stabilizing the emission levels in the Greater Delhi region.

However, implementation of emission standards in a phased manner, or dual standards, has negated some of the $PM_{2.5}$ reductions achieved from implementation of emission standards. PM has been documented to have the most significant effects on human health. Prevalence of dual standards also leads to inconvenience to auto manufacturers who have to deal with segmented market and use of two technologies at the same time. Thus it highlights the waste of resources and public health effects due to an inefficiently implemented policy. Policy makers have not taken cognizance of these effects and AFP-2025 has also recommended future implementation of emission standards to be carried out in a phased manner. However, it recommends having similar fuel prices when the two emission standards are prevalent so as to give no incentive to vehicle users with higher standard vehicle to fill their tanks with an inferior quality fuel.

According to the estimates, AFP-2025 will lead to reduction of $PM_{2.5}$ and CO levels to the same extent as the ambitious scenario of leapfrogging to BS-VI in 2017. However, implementation of the latter gives additional advantage in terms of further reduction of NO_x and VOC emissions. Since leapfrogging to BS-VI in 2017 is practically impossible, AFP-2025 can improve with simultaneous implementation of fuel standards across the whole country, rather than continuing with dual standards.

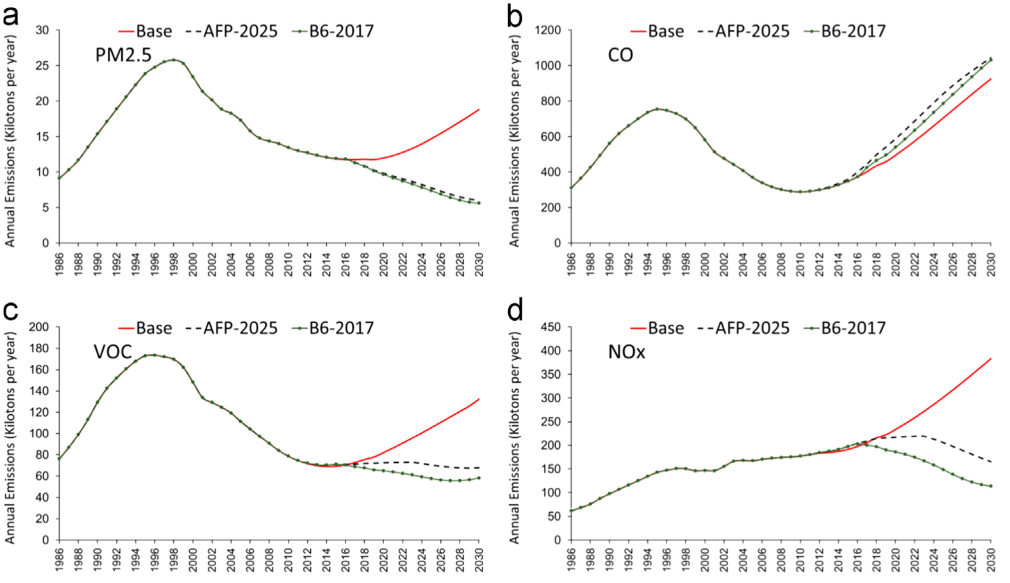

Fig. 8. Estimated on-road vehicle exhaust emissions under the proposed Auto Fuel Policy-2025 and alternate future scenarios.

The projected and scenarios presented in this study have assumed continuous growth of annual mileage as well as the vehicular fleet. Therefore, policies aimed at reducing the usage of vehicles, as well as their ownership, will have a direct effect on reducing the emissions.

In addition to improving standards of new vehicles, a large potential for reducing vehicular emissions in India remains untapped with the in-use fleet. While the pollution under control program has been implemented across the country, the inefficiencies in the testing procedure as well as other irregularities due to lack of quality assurance of testing services, render this program almost useless. Thus, the hopes of reducing future pollution should not be hinged solely on emission standards, but also on an efficient and strictly enforced vehicle testing program.

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