Research highlights

- Air emissions from on-road vehicles have been estimated for megacity Delhi
- Activity based emission factors and primary vehicle data is used for emission modelling
- Private vehicles contributed larger emissions compared with public transport
- 2021-ALT-III scenario results in reduction of 39–76% air emissions compared to 2007 levels due various policy interventions
- Goods vehicle contribute to ~6% of the total VKT and responsible for ~57% of PM$_{10}$ and ~52% of NO$_2$
Vehicular exhaust emissions under current and alternative future policy measures for megacity Delhi, India

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Abstract

This study analyses the impact of integrated mass rapid transit system (IMRTS) and other policy measures on air emissions from vehicular sources in Delhi region. The impacts have been studied for the passenger and goods vehicles separately. For this purpose three alternative scenarios for the passenger vehicles and two alternative scenarios for the goods vehicles have been analysed for the year 2021. The interventions include stringent source emission norms, modal shift resulting from introduction of effective public transport alternatives, speed regulation measures and hiking of parking fee of private vehicles. These scenarios have been compared to the base year 2007. An important finding that emerged from the study is that stringent fuel emission norms and introduction of alternative public transport systems alone may not result in the modal shift and hence reduction in exhaust emissions. It is actually a combination of these measures and management measures such as increased parking fee and regulated uniform speed of public transport that results in desired benefits. Further, the inclusion of goods vehicle demand during transport policy formulation can help in controlling air pollution in new urban centers in India and in major developing regions of the world.

Keywords: Air pollution inventory; Road transport emissions; Integrated mass rapid transit system; Megacity Delhi; Passenger vehicles

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1.0 Introduction

Motor vehicles are one of the major sources that contribute to air pollution at local, regional and global scale [1]. The increasing shift in motorised mode of transport in megacities of the developing countries is raising the levels of air pollutants [2]. A report by the World Energy Council shows that growing megacities in developing countries will have increased commuting distance per person per day compared with the Organisation for Economic Co-operation and Development (OECD) countries which may result increase in air pollution in future [3].

Megacity Delhi, being the seat of political, economic and commercial activities, has an influx of population from different parts of the country. These reasons have led to a huge increase in travel demand and made Delhi as the most motorised city of India [4]. Further, increase in per capita income, mobility, city expansion, education facilities and proliferation of employment centres has created an imbalance between the growth of vehicles and road network [5-4]. This has resulted in issues of heavy traffic congestion and reduced vehicle speed [6] that are causing serious problems of air and noise pollution [7-9]. Emission contributions from vehicles place Delhi among the highest polluted cities of the world [2]. These increased levels are responsible for a notable amount of excess deaths and hospital admissions in Delhi [10-12]. Several initiatives have been undertaken by the national and local governments in the past to address the issues of traffic management and air pollution caused by vehicular sources [13]. These include command and control measures to reduce vehicular pollution such as phasing out of vehicles older than 15 years of age, use of unleaded petrol, mandatory use of compressed natural gas (CNG) in public transport and light duty commercial vehicles, and development of integrated mass rapid transit system (IMRTS) to cater to larger travel demands [14-17]. These measures have resulted in the reduction of ambient air pollutant concentrations including particulate matter ≤10µm (PM$_{10}$), carbon monoxide (CO), nitrogen oxides (NO$_x$), and sulphur dioxide (SO$_2$) in Delhi [2]. However, this reduction is still not up to an acceptable level and problems arising from urban transportation still prevail [2, 18]. Estimation and modelling of emissions from vehicular sources is the first step to assess the impact of these sources on the ambient air quality. It is therefore imperative to make accurate estimates of emissions from these sources.
The present study aims at modelling vehicular emissions under current and future alternative policy interventions. The base year for modelling emissions has been taken as 2007. The Master Plan of Delhi has been prepared with a perspective up to 2021 to cater to the increasing population and the changing requirements of the city. Thus, the BAU and alternative (ALT) scenarios have been generated for the year 2021 for modelling future emissions in order to assess the impact of policy interventions. The modelling has been done using the ASF model – Activity (in vehicle-km), modal Structure (i.e. Modes of vehicles, technology (2/4 stroke), type of fuel and vintage), and the emission Factors (in grams of criteria pollutants released per km vehicle travelled). The VKT data have been used for accounting the intensity of road transport usage or demand. The highlight of the study includes activity based emission factors and vehicle characterization data collected through primary field surveys in order to capture the vintage, engine technology, occupancy, modal-structure, fuel, make and mileage for modelling the emissions from various transport modes.

2.0 Methodology

2.1 Description of the study area

The study was carried in the national capital territory of the Delhi (NCTD) region (Figure 1). Delhi (28°36′50″N, 77°12′32″E) is the capital of India and is one of the major developing mega cities in the world. Due to rapid urbanization, the city saw a large-scale migration over the last decade. There has been an increase of ~21% in population between 2001 and 2011 census – 13.9 to 16.75 million. The rapid growth rate of both population and economy is putting enormous pressure on the city's existing transport infrastructure. For instance, the total count of road vehicles in Delhi during 2014-15 was ~8.82 million, with a ratio of 299 (two-wheelers) and 162 (cars) per 1,000 people. Furthermore, the number of goods vehicles in Delhi reached 0.22 million with a compound average growth rate (CAGR) of 6.31% during 2011-2012, with a larger movement of vehicles from NCR region. Recent reports suggest that nearly 1.5 million vehicles enter Delhi every year from the neighboring states for work or travelling purposes [14]. Delhi has the largest road network (~31,183 km road length) among other cities in India. Approximately, 46%, 27%, 8% and 2% of Delhi’s road length has the right-of-way between 10 and 20 m, 20 and 30 m, 40 and 60 m, and over 60 m, respectively. Traffic congestion still occurs frequently due to the large volume of traffic on city roads.

2.2 Vehicle characteristics survey
The data has been collected separately for the passenger and goods vehicles. The data on vehicle fleet characteristics has been collected using the cross-sectional sample surveys. The stratified random sampling technique was adopted to collect samples for five vehicle categories for emission calculations. These categories include two-wheelers (scooter and motorcycle: 2–stroke/4–stroke engine), cars (gasoline-, diesel- and CNG-driven), three-wheeler autos (CNG-driven with 2–stroke/4–stroke engine), and buses (CNG). The survey was conducted in nine districts of NCTD (central, north, south, east, northeast, south-west, north-west, west, and New Delhi) lying in its three statutory towns (Municipal Corporation of Delhi, New Delhi Municipal Council, Delhi Cantonment Board). This data has been described in the recent study on energy and carbon emission in Delhi region by Aggarwal and Jain [19]. Similar surveys were carried out to collect the vehicle characteristics for goods vehicles (light duty vehicles, LDV; and heavy duty vehicles, HDV) at various goods depots in industrial areas (in and around Delhi), local markets, fuel pumps, and maintenance workshops. The details of the vehicle characteristic survey can be found in supporting material (SM), Section S1 and Table S1-S2.

This information was integrated with the travel demand information (in VKT & passenger kilometre, PKM) procured from the in-depth study on ‘Transport Demand Forecast Study and Development of an Integrated Road Cum Multi-Modal Public Transport Network for NCT of Delhi’, commissioned by the government of National Capital Territory of Delhi region [14].

2.3 Traffic emissions modelling

The emission loads have been modelled for passenger and goods vehicles using the Activity-Structure-Fuel Mix (ASF) framework, which was also used in our previous work [19-20]. This is an adaptation of Activity-Structure-Energy Intensity-Fuel Mix (ASIF) framework [21], which is widely used in traffic emission modelling studies.

The ASF framework has been schematically shown in Figure 2 and uses the following as input variables: (i) the passenger and goods transportation Activity (in VKT), (ii) modal Structure (i.e. modes of vehicles, technology (2/4 stroke engine), type of fuel and vintage), and (iii) the emission Factors (in grams of criteria pollutants released per km vehicle travelled). Equation 1 provides the model used for estimating traffic emissions:
\[
E_{\text{Passenger\,Goods}} = \left( \frac{\sum_k \left( \sum_{ji} A_k \times S_{ij} \times F_{ji} \right)}{10^6} \right)
\]

Where, \( E \) is emission load per year from all modes of transport (tons/year); ‘\( k \)’ represents the mode-type; ‘\( j \)’ represents vehicle technology (2/4 stroke); ‘\( i \)’ represents the fuel type (gasoline/diesel/CNG); ‘\( A_k \)’ represents travel demand activity (in km); ‘\( S_{ij} \)’ represents the modal structure (in percentage); ‘\( F_{ji} \)’ represents emission factor (g/km); \( 10^6 \) is the conversion factor from gm to tons.

The present study has adopted Indian vehicle specific emission factors developed for Indian road conditions by testing 40 different vehicle categories. These vehicle emission factors were developed as a part of the source apportionment study conducted by the Central Pollution Control Board (CPCB) for major cities of India [22]. A comprehensive list of the applied emission factors under different vehicle categories can be found in SM Table S3.

2.5 Scenario generation

This study considers 2007 as the base year (2007-BASE) and 2021 as the year for future projections. Four scenarios have been generated for passenger transport for the year 2021 for modelling future emissions in order to assess the impact of policy interventions – BAU scenario (2021-BAU) and three alternative scenarios (2021-ALT-I, 2021-ALT-II, and 2021-ALT-III) – as detailed below.

2007-BASE: During the base year, lines 1 to 3 of the Delhi Metro (part of IMRTS), covering a distance of 65 km are taken as operational. The source emission norms BS II and BS III were introduced in the year 2003 and 2005, respectively, and have been duly considered in the computations. The passenger travel demand distributed across various travel modes such as car (gasoline-, diesel- and CNG-driven), motorcycle (2-stroke and 4-stroke engine; gasoline-driven), scooter (2-stroke and 4-stroke engine; petrol-driven), auto (2-stroke and 4-stroke engine; CNG-driven) and bus (CNG-driven) have been applied based on current modal shares collected through the field surveys.

2021-BAU: This scenario considers the existing growth rate of vehicles and does not take into account any policy interventions, except vehicle source emission norms (BS-IV), which were introduced in the year 2010. The VKT is distributed across different travel modes according to their current modal shares. We have assumed that the distribution of 15–, 10–
and 5–year old vehicles in the year 2021 will be 20, 35 and 45%, respectively. The assumption is based on the VKT vehicle classification data collected through the survey for the base year (see Table 1 and Section 3.1). Vehicular emission factors for the above-mentioned years have been assumed in accordance to BS III, and BS IV norms, respectively. The manufacturing of two-wheelers with two-stroke engines has been banned in India since 2000. Hence all such types of two-wheelers have been assumed to be phased out by 2015–2016 over their operational life of 15 years.

**2021-ALT-I:** Under this scenario, the BAU-2021 was augmented by one policy intervention – the introduction of BS-V vehicle emission norms in the year 2017.

**2021-ALT-II:** Under this scenario, the full phase of IMRTS implementation, which includes the 4 phases of Delhi Metro and Bus Rapid Transit (BRT) system, has been considered to be implemented by the year 2021, in addition to the assumptions taken in 2021-ALT-I. This policy intervention has been introduced in order to find effects of increased share of public transport on the reduction in the use of private on-road vehicles and resulting emissions of air pollutants.

**2021-ALT-III:** Under this scenario, two interventions have been added to the 2021-ALT-II scenario – (i) bus speed has been regulated to 25 km/h because of new infrastructural development of dedicated bus corridors, and (ii) parking fees has been hiked (from Rs 10-20 to Rs 60-200) for private vehicles. These assumptions have been made to assess the influence of increased share of public transport use.

**Goods vehicles:** The study has also considered three future additional scenarios for goods vehicles to assess their impacts on air pollutant emissions in the NCTD region. These scenarios include:

**2007-BASE-G:** This is a reference base case for goods vehicles which includes LDVs (CNG/diesel-driven) and HDVs (CNG/diesel-driven).

**2021-BAU-G:** Under this scenario, implementation of BS IV emission norms, discarding of vehicles more than 15 years of age, and conversion of diesel LDVs to CNG as per the governmental regulation in 2005-2007 were assumed, in addition to the considerations taken by 2007-BASE-G. These assumptions are similar to the ones made for the passenger vehicles in 2021. This scenario also assumes that the trend of growth rates of vehicles is similar to that of the base year 2007.
2021-ALT-I-G: Under this scenario, introduction to BS V in 2021 was added to the 2021-BAU-G scenario.

2021-ALT-II-G: Under this scenario, diesel particulate filter (DPF) in HDVs was added to the 2021-ALT-I-G scenario.

3.0 Results and discussions

3.1 Traffic fleet characteristics in Delhi

Figure 3 shows the modal occupancy and passenger trip lengths analysed from field survey data in the NCTD. The passenger trip length is the distance measured in km from the passenger pick-up location or point to the drop-off location [23]. The average occupancy of cars, two-wheelers, autos and buses was found to be 1.8, 1.2, 2 and 46, respectively through survey. This clearly indicates that private vehicles (both cars and two-wheelers) are not occupied to their full capacity as compared with the public transport system. The VKT by two-wheelers, cars, autos and buses in the year 2007 were ~46, ~40, ~10, and ~4%, respectively, suggesting that private vehicles need more road space as compared to the public transport system. This further results in more passenger-car units (PCU) on Delhi roads due to private vehicles and hence, results in increased number of vehicle stops and congestion, together with reduction in speed of vehicles. The PCU is a standard unit of measurement of traffic volume, taking the passenger car as the standard vehicle [24]. Table 1 presents the summary of modal share, age and fuel used for on-road vehicles in NCTD. Among the two-wheelers, scooters and motorcycles account for nearly equal share of 49.7% and 50.3%, respectively. Cars running on gasoline fuel have the highest share (~72% of total cars), followed by the CNG (~15%) and diesel (~13%). It was also observed that vehicles older than 15 years were still in-use, in-spite of the implementation of the current vehicle phasing out policy in Delhi.

The fleet characteristics data clearly show that while the private motorized vehicles, which have a large modal share and are under-occupied compared to the public transport vehicles, the buses run at occupancy levels more than their capacity. This indicates that there is a scope for improving the existing public transport by introducing new and efficient modes of public transport systems in order to encourage a modal shift from private to public transport.

3.2 Emissions from passenger vehicles under different scenarios

Figure 4 shows the tailpipe emissions from passenger vehicles for the base and future years. Pollutant emissions are higher in 2007-BASE as compared to the 2021-BAU scenario,
except for NO\textsubscript{2}. This is so because the percentage of old vintage vehicles, which follow BS-I and BS-II norms have higher NO\textsubscript{2} emission factors and are more in numbers in the 2007-BASE year than in the year 2021. Moreover, Delhi Metro PKM demand is found to increase to 11.5 times in the 2021-BAU scenario over the 2007-BASE year. It can be noted that the details on VKT and PKM demand under different scenarios have been discussed in SM, Section S.4 (Figure S1). About 3\% of the ~160 million-km PKM demand was met by Delhi Metro in the 2007-BASE year, as compared with 18\% of the ~281 million-km PKM demand in 2021-BAU. Consequently, ~32\%, ~17\% and ~18\% decrease in PM\textsubscript{10}, CO and HC emissions, respectively, is observed in 2021-BAU over the 2007-BASE values. The only exception is NO\textsubscript{2}, which shows an increase of ~37\% in 2021-BAU compared to the 2007-BASE year. The dominant reason for the increase in NO\textsubscript{2} emission is the change in engine technology of 2-stroke scooters to 4-stroke, which results into ~31 times more NO\textsubscript{2} emissions as compared to the older technology. The mode-wise emissions from various vehicle types for the base year and future scenarios, and per capita emissions have been provided in SM, Sections S.3 (Figure S2) and S.4 (Figure S3), respectively.

Under the 2021-ALT-I scenario, about ~50\% and ~15\% of the decrease in overall PM\textsubscript{10} and NO\textsubscript{2} emissions, respectively, was observed as compared to 2007-BASE year. This may be ascribed to the implementation of BS-V emission standards by the year 2017 that target only PM\textsubscript{10} and NO\textsubscript{2}. Under the 2021-ALT-II scenario, significant reduction in emissions of all the pollutants was observed as compared to the 2007-BASE year, i.e., ~56\% in PM\textsubscript{10}, 27\% each in CO and HC, and ~25\% in NO\textsubscript{2}. Such a reduction was anticipated by 2021 for all the four phases of Delhi Metro, BRT and LRT along with BS-V emission standards are assumed to be implemented in Delhi under this scenario. These changes have led to ~13\% decrease in VKT demand from all the passenger transport modes and hence the pollutant emissions. The decrease in VKT may be attributed to the: (i) increase in Delhi Metro PKM demand from 18\% to 28\%, and (ii) the decrease in PKM demand for both the private and public modes: 28\% to 23\% for cars, 15\% to 13\% for two-wheelers, and 35\% to 32\% of the buses, in 2021-ALT-II scenario compared to 2007-BASE. Our findings agree with the results of similar studies conducted elsewhere. For instance, Knowles [25] has found that Manchester Metrolink has attracted more passengers as compared to the forecasted numbers, which indicates positive impacts of intervention in terms of modal shift. Golias [26] analysed the introduction of the new Athens
Metro system and observed that the Metro system attracted ~53% bus passengers and ~24% private car users.

Finally, under the 2021-ALT-III scenario, there is a further decrease in overall emission levels from ~66% in PM$_{10}$ to ~21% in NO$_2$ as compared to 2007-BASE. A significantly high reduction in emission levels has been observed under this scenario due to major shift of passengers from private vehicles (decrease in PKM demand of cars and two-wheelers by ~24% and 49.4%, respectively) to public transport (increase in PKM demand of bus and auto by 28.6% and ~4%, respectively). This is relevant especially in the context of buses, where they run at constant speed in dedicated bus corridors, resulting in reduced emissions. The reduced emissions may also be attributed to disincentive in the form of hike in parking fee for the private vehicle users, increased reliability and efficiency of public transport modes like Delhi Metro and BRT. Similar results have also been reported by Chester et al. [27], where the introduction of BRT in Los Angeles resulted in an increase in boarding from 30% to 36% within five and seven years of implementation, respectively. Vedagiri and Arasan [28] have also found a modal shift of car travels to bus on introduction of the bus priority system. Recently, Wang et al. [29] have also reported similar modal shifts to BRT in Chinese's cities.

3.4 Comparison of emissions from goods and passenger vehicles

Total emission in 2007-BASE-G from goods vehicles are discussed first (see Figure 5a). The average VKT from goods vehicles were 2.7 million-km as compared with passenger vehicles i.e. 48.5 million-km (~18 times). The resulting PM$_{10}$ emissions from goods vehicles were ~1.2 times larger to those estimated for passenger vehicles (Figure 6b). However, the NO$_2$ emissions were found to be nearly same for both the goods and passenger vehicles (Figure 6c). Interestingly, HC and CO emissions were respectively about 3.5 and 2.3 times smaller for goods vehicles as compared to passenger vehicles (Figure 6d,e). This is because the goods vehicles primarily use low CO and HC emitting fuels such as diesel and CNG as compared to gasoline used by the majority of passenger vehicles. Similar results have been reported by Progiou and Ziomas [30] for the Greater Athens area. They found that passenger cars were the major polluters for CO (~59%) and HCs (~51%) as compared to HDVs, which contribute higher PM$_{10}$ (~66%) and NO$_x$ (~65%) emissions.

Figure 5 shows emissions for goods vehicles under the future scenarios. There is a substantial decrease in PM$_{10}$ emissions from goods vehicles under 2021-BAU-G (Figure 5b).
This is because the LDVs were converted into CNG in 2006-07 and had much lower emission factors of PM$_{10}$, CO and HC as compared with gasoline- and diesel-driven vehicles (see details in SI, Table S3). In the 2021-BAU-G scenario, the PM$_{10}$ and NO$_2$ emissions were found to be ~5 and ~1.5 times smaller, respectively, compared with 2007-BASE-G; this decrease was mostly due to implementation of BS-V emission standards. In 2021-ALT-II-G, there is a decrease in PM$_{10}$ emissions by ~22 times as compared to 2007-BASE-G, primarily due to implementation of DPF that resulted in this decrease from the HDVs.

The above results allow us to conclude that VKT from goods vehicles would be around ~5.2 million-km in 2021 as compared to ~61, 78, and 89 million-km by passenger vehicles under the 2021-ALT-I, 2021-ALT-II and 2021-ALT-III, respectively. These VKTs are nearly up to 17 times lesser compared to passenger vehicles in 2021; whereas, emissions are more for PM$_{10}$ and NO$_2$, respectively, of goods vehicles in comparison with passenger vehicles. Clearly, emissions from goods vehicles are likely to dominate the transport emissions despite much smaller share of the VKT by them (Figure 6). A number of studies have estimated emissions from goods vehicles in various cities under different scenarios. For example, Wang et al. [31] estimated emissions from on-road fleet (individual diesel vehicles, trucks and buses) in Beijing, China. They found that: (i) 5% of diesel trucks in their sample were responsible for 50% of the total black carbon emissions, and (ii) 20% of the trucks were accountable for 50% CO and PM$_{0.5}$ number (particles ranging from 5.6 to 560 nm) emissions, 60% PM$_{0.5}$ mass emissions, and over 70% of BC emissions. Likewise, a recent study by Kumar et al. [11] for nanoparticle emissions from road vehicles in Delhi concluded that heavy-duty vehicles release the majority (~65%) of total particle number emissions for only ~4% of total VKT in 2010. Hence, there is a need to focus on goods vehicles to reduce the overall pollutant emissions from the road transport sector. Several measures such as the construction of a freeway corridor for reducing intercity goods transport, increasing fuel economy and mandatory use of DPF for HDV can serve as a primary measures to solve the issues with goods transport in NCTD region.

4.0 Conclusions

The study reveals that the best policy alternative to bring an overall emission reduction for passenger vehicles is the 2021-ALT-III scenario, which includes a modal shift caused by the full implementation of IMRTS, stringent source emission norms, improved engine technology, higher parking fees for private vehicles and regulated bus speed of 25 km/h. This scenario
resulted in a decrease in overall VKT from about 85% (2021-BAU) to 26% (2021-ALT-III scenario) compared with 2007-BASE. The decrease in VKT was mainly due to the increase in the bus PKM demand from ~32% to ~44% as compared to 2007-BASE year and the corresponding decrease in PKM demand from ~28% to ~20% of cars and ~15% to ~8% by two-wheelers. Thus, stringent fuel emission norms, policy measures and the introduction of efficient and reliable public transport systems encourage a modal shift from private motor vehicle users to public transport; provide an appropriate measure that would help in reducing the VKT from private vehicles. As a consequence, this would reduce the emissions and the corresponding concentration levels of pollutants in the ambient air of Delhi city. For the goods vehicles the 2021-ALT-II-G resulted in maximum reduction in source emissions. It may be noted that though the VKT for the goods vehicles is only ~6% of the total VKT generated from passenger and goods vehicles together, the emission contribution of the goods vehicles to the PM$_{10}$ and NO$_2$ load is ~57% and ~52% respectively, of the total emission load. This is due relatively higher emission factors for goods vehicles compared to the passenger vehicles. Therefore, in order to bring down overall ambient emission loads, special attention needs to pay in bringing down the emission from the goods vehicles, especially HDVs. This can be done by improving the engine technology of goods vehicles, installation of DPF for HDVs and improving the quality of diesel such as ultra-low sulphur diesel (10 ppm).

An important finding that emerged from the study is that stringent fuel emission norms and introduction of alternative public transport systems alone may not result in the modal shift and hence reduction in exhaust emissions. It is actually a combination of these measures and management measures such as increased parking fee and regulated uniform speed of public transport, that results in desired benefits. The present study had a major focus on passenger vehicles in terms of alternative policy measures, with the case of Delhi region. Since a significant finding of the study is that the goods vehicles top with respect to overall emission load, it would a significant research proposition to conduct a comprehensive assessment of various alternative policy measures for the goods vehicles. This would enable regulatory bodies in India to draft a common policy road map (like draft auto fuel policy 2025) both for the passenger and the goods vehicles. Further, the inclusion of goods vehicle demand during transport policy formulation can help in controlling air pollution in new urban centers in India and in major developing regions of the world.
Competing interests

The authors declare that they have no competing interests.

Authors’ contributions

SJ conducted and coordinated the field survey, collection of vehicle information, research design, emission modelling and manuscript drafting. PA and PS participated in data analysis. SJ, PS and PK reviewed the whole manuscript and assessed scientifically. All four authors read and approved the final manuscript.

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<td>4900 (passenger)</td>
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</tr>
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<td>Private vehicles</td>
<td>Car (53%) and Two-wheelers (28%)</td>
</tr>
<tr>
<td>Public vehicles</td>
<td>Auto-rickshaws (12%) and Buses (6%)</td>
</tr>
<tr>
<td>Vehicle age distribution</td>
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<td></td>
<td>&lt;5 years</td>
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<tr>
<td>Overall</td>
<td>43%</td>
</tr>
<tr>
<td>Two Wheelers</td>
<td>47%</td>
</tr>
<tr>
<td>Car</td>
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</tr>
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<td>Auto-rickshaw</td>
<td>36.0%</td>
</tr>
<tr>
<td>Bus</td>
<td>65.5%</td>
</tr>
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</table>
SUPPLEMENTARY INFORMATION

Vehicular exhaust emissions under current and alternative future policy measures for megacity Delhi, India

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S.1 Traffic Characteristic Survey in Delhi

The study conducts surveys in Delhi region to capture the traffic characteristics such as vehicle age (vintage), engine technology (stroke), fuel type, and occupancy. The survey methodology and summary of collected information can be found in the research paper and supplementary information document of Aggarwal and Jain [1]. The current vehicle vintage ratio (by mode, technology, fuel and vintage) have been collected and summarized in Table S1-S2 for passenger and goods vehicles.

Table S1: Passenger vehicle characteristics in NCTD region (adopted from 1)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Technology</th>
<th>Fuel Use</th>
<th>Vintage *</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-Wheeler a</td>
<td>2 Stroke</td>
<td>Gasoline i</td>
<td>&gt;15 years</td>
<td>3.79%</td>
</tr>
<tr>
<td>Scooter</td>
<td></td>
<td>Gasoline i</td>
<td>10-15 year</td>
<td>12.29%</td>
</tr>
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<td></td>
<td></td>
<td>Gasoline i</td>
<td>5-10 year</td>
<td>8.07%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gasoline i</td>
<td>&lt;5 years</td>
<td>0.50%</td>
</tr>
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</tr>
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Table S2: Goods vehicle vintage ratio in NCTD region

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<th>Vintage</th>
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34

S.2 Activity based emission factors for Indian vehicle

The study uses emission factors for Indian vehicles which have been measured using the mass emission test setup. These vehicular emissions have been measured using the mass emission test setup including chassis dynamometer, CVS System (Constant Volume Sampler and Dilution Tunnel) and Analyzers (Exhaust Gas Analyzer for dilute emissions) from various classes of vehicles. More details about the method can be found in the source apportionment study report of CBCP [2]; while, the adopted emission factors have been summarized in Table S3:

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</tr>
<tr>
<td>2011-2015</td>
<td>0.046</td>
<td>4.180</td>
<td>2.740</td>
<td>3.99</td>
<td></td>
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<tr>
<td>2015-2017</td>
<td>0.037</td>
<td>4.180</td>
<td>2.740</td>
<td>2.27</td>
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<tr>
<td>1996-2000</td>
<td>1.965</td>
<td>19.300</td>
<td>2.630</td>
<td>13.84</td>
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</table>
The vehicle emission factors taken in the current study were taken from ARAI weighted-average factors, which do not account the impact of speed variation, congestion and driver behaviour during emission quantification. Therefore, it is very important to improve the existing emission factors by considering the above city's limitations, in order to estimate an ‘accurate’ level of air pollutant concentrations from Indian vehicles.

S.3 Vehicle and passenger travel demand under different scenarios

Figure S1 shows that the PKM demand will increase by ~80% in 2021\(^2\) as compared to 2007-BASE year, in which, private vehicles meet ~43% PKM demand and public transport caters to ~57% PKM demand. Similar figures were obtained for the 2007-BASE year, which are ~39% and ~61% of the private and public transport, respectively. It may be noted that even though the public transport system would meet ~57% of the total PKM demand in 2021 under the BAU scenario, it would generate ~14% of the total VKT, in comparison to the ~86% VKT by private vehicles (i.e., ~40% of cars and ~46% by two-wheelers). This is attributed to the finding that the PKM demand from Delhi Metro would increase by 11.5 times in 2021-BAU compared with 4.4 million-km in 2007-BASE case.

In case of 2021-ALT-I scenario, only BS V fuel quality norms have been included, which has no effect on VKT and PKM demand. However, this contributes in reduction of pollutant emissions due to decreased emission factors. The case of 2021-ALT-II assumes implementation of the IMRTS (i.e., four phases of Delhi Metro and BRT system) by 2021. This would result in decrease in an overall VKT from 84.5% in 2021-BAU to 61% in 2021-ALT-II against the 2007-BASE year values. The decrease in VKT may be ascribed to the findings that the PKM demand of Delhi Metro would increase from 18% to 28% in the 2021-ALT-II scenario, which would result in a decrease in PKM demand from 28% to 23% by cars, 15% to 13% by two-wheelers, and 35% to 32% by buses. These results suggest that there would be a major shift of users from private vehicles to Delhi Metro as they prefer a more reliable and comfortable transport system. Furthermore, the introduction of new policy interventions in the 2021-

\(^2\) The Delhi Master Development Plan 2021 (MPD, 2001) is the guiding document for various planning and development of infrastructure in Delhi region. This study has therefore aligned its research for the year 2021, to observe the impacts of proposed policy interventions on urban transport.
ALT-III scenario would result in a decrease in overall VKT demand from 84.5% in 2021-BAU to 26.5% in the 2007-BASE year. This decrease in VKT is mainly due to the reason that PKM demand from buses would increase from 32% to 44%, which is an increase of almost 50% as compared to 2007-BASE year. Hence this would result in a decrease in PKM demand from 28% to 20% of cars and 15% to 8% from two-wheelers. It can therefore be concluded, that modal shift from private to public transport, especially to the buses, is taking place due to the introduction of policy interventions. People prefer buses due to low fares as compared to Delhi Metro and policy intervention may result in an increase in reliability and frequency of bus service. These findings are in line with other studies that have assessed the impact of policy interventions and found modal shifts from private to public transport. For instance, Redman et al. [3] have found through qualitative review that the accessibility and reliability of public transport initiated a shift of private vehicle users (such as cars) to public transport. Similarly, Chester et al. [4] have also reported that introduction of BRT Los Angeles would result in an increase in boarding of Bus Rapid Transit (BRT) and Light Rail Transit (LRT) from 30% to 36% within five and seven years of implementation, respectively. Similar results have been reported for the megacities of Europe, Japan and USA, where the introduction of Mass Rapid Transit System (MRTS) has led to an increased shift of private vehicle users to a more reliable and comfortable public transport system [5].

(a) Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Two-Wheeler</th>
<th>Auto</th>
<th>Car</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>VKT</td>
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<tr>
<td>PKM</td>
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<td>VKT</td>
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<td>PKM</td>
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<td>VKT</td>
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<tr>
<td>PKM</td>
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<td>VKT</td>
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<td>PKM</td>
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<td>VKT</td>
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</tr>
<tr>
<td>PKM</td>
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</tbody>
</table>
Figure S1: Percentage variation of travel demand for the years 2011 and 2021

S.4 Mode wise air emissions

The results for passenger vehicles are illustrated in Figure S2. It was observed that emission decreases from 2007-BASE to 2021-BAU, however the decrease in not huge without intervention used in 2021-ALT-I to 2021-ALT-III.

S.4.1 PM$_{10}$ emissions

PM$_{10}$ emissions were found to be higher from private vehicles (63%; i.e., cars by 12% and two-wheelers with 51%) compared with buses (2%) and autos (35%) in the 2007-BASE (Figure S2a). PM$_{10}$ emissions from private vehicles were only about ~39% of the PKM demand, public transport (including Delhi Metro) supported ~61% of the total PKM demand but only produced ~27% of the total PM$_{10}$ emissions. This is because the occupancy of the public transport system is very high as compared to private transport modes (see Figure 4). The overall PM$_{10}$ emission reductions from all the passenger transport modes have been estimated to be ~50%, 56% and 66% in 2021-ALT-I, 2021-ALT-II, 2021-ALT-III scenarios, respectively, as compared to 2007-BASE values. This shows that the maximum reduction has been observed in 2021-ALT-I scenario due to implementation of BS V emission standards; nearly 5-16% reduction has been observed due to implementation of IMRTS and policy interventions under the 2021-ALT-II and 2021-ALT-III scenarios, respectively. Rojas-Rueda et al. [6] have observed similar results in their study – a shift of 20% from private to public transport (buses and metro) has resulted in a 5 % decrease in PM$_{2.5}$ concentrations. Ernst [7] has also found a modal shift from cars and motorcycles to BRT in Jakarta (Indonesia) that has resulted in PM$_{10}$ and NO$_x$ emission reduction by 31 kg/day and 212 kg/day, respectively. Likewise, Shabbir and Ahmad [8] have
observed a decrease of ~12, 16 and 20% of PM$_{10}$ emissions by the year 2020, 2025 and 2030, respectively, due to modal shifts as a consequence of policy interventions in Rawalpindi and Islamabad (Pakistan).

### S.4.2 CO emissions

Figure S2b shows the emissions of CO in the reference and future years. Private vehicles (cars and two-wheelers) were found to contribute the majority (85%) of the total emissions in 2007, leaving a small share for buses (9.1%) and autos (6%). This is an interesting finding considering that ~61% of the PKM demand is met by the public transport system, which includes Delhi Metro. Under the 2021-ALT-I scenario, no reduction in levels of CO emissions was observed as BS V standards do not have reduced targeted emission standards for CO. However, a reduction of ~27% and 36% in CO emission levels has been observed under the 2021-ALT-II and 2021-ALT-III scenarios, respectively. This may be attributed to modal shift from private to public transport under ALT-II and ALT-III scenarios – cars contributed only ~4% and ~16%, while two-wheelers contributed ~53% and ~72% in 2021-ALT-II and 2021-ALT-III, respectively, as compared to 2007-BASE year. In a similar study undertaken in China by Saikawa et al. [9], a reduction in CO emissions by 78% has been reported due to the implementation of the Euro-III emission norms as compared to BAU scenario for the year 2020. Likewise, Ozan et al. [10] estimated CO, NO$_x$ and CH$_x$ emissions from the transport sector, based on projected energy and transport demand under three policy scenarios in Turkey. A reduction of about 33%, 27% and 18% in CO, NO$_x$ and CH$_x$ emissions for Policy I, II and III, respectively, was noted as compared with the BAU scenario. These emission estimates have been made based on the projected energy and transport demand with an assumption that there will be a shift of private vehicle users and goods vehicles to public transport and railway transport under the three policy scenarios.

### S.4.3 HC emissions

About 77.2% of HC emissions were from private vehicles (i.e., ~15% from cars and 62% from two-wheelers) in the 2007-BASE year, while the public transport contributed only ~23% (i.e., ~19% from buses and ~4% from autos), as seen in Figure S2c. There are no targeted emission reduction standards for HC, and hence no reduction in HC emission levels was observed under the 2021-ALT-I scenario. However, a reduction of ~27% and ~33% of HC emissions were observed under the 2021-ALT-II and 2021-ALT-III scenarios, respectively. The reduction in HC emissions is primarily attributed to the change in engine technology in two-wheelers from a 2-stroke to the four-stroke engine, which results in 3 to 14 times fewer HC emissions compared with the older technology. This intervention resulted in a decrease of ~50% and ~70% of HC emissions for the 2021-ALT-II and 2021-
ALT-III scenarios, respectively, as compared with the 2007-BASE year; this was further augmented by a reduction of ~13% and ~41% in the VKT, respectively, for the two scenarios.

S.4.4 NO₂ emissions

Figure S2d shows NO₂ emissions in reference and future scenarios. Private vehicles (cars and two-wheelers) were found to contribute 43% of the total NO₂ emissions in 2007-BASE as compared to 47% by buses and 10% by autos. It may be noted that ~38% reduction in NO₂ emissions has been achieved only by the implementation of BS V emission standards under the 2021-ALT-I scenario. It has been estimated that overall NO₂ emissions reduction (i.e., 15.1%, 24.8% and 21% under the 2021-ALT-I, 2021-ALT-II, and 2021-ALT-III scenarios, respectively) is contributed by passenger vehicles (private and public transport) except the two-wheelers. The latter resulted in very high NO₂ emissions due to the change in engine technology in 2-stroke scooters (two-wheelers) to 4-stroke, resulting in 31 times more NO₂ emissions as compared with older two-wheelers technology in 2000. In a similar study, Ernst [7] found a modal shift from cars and motorcycles to BRT that resulted in NOₓ and PM₁₀ emission reduction by 212 kg/day and 31 kg/day, respectively. Shabbir and Ahmad [8] have also observed a modal shift from private to public mode under alternative scenarios. They found a decrease in NOₓ emissions by about 17%, 21% and 26% by the year 2020, 2025 and 2030, respectively. Similarly, Saikawa et al. [9] studied the impact of Euro III emission norms on emissions of CO, NOₓ, O₃, PM₂.₅, BC and OC in China. They observed ~50% decrease in emissions in the projected year (2020) compared to BAU scenario (2020).
Figure S2: Pollutant-wise emissions from various modes of transport under base and future scenarios

The emissions from the goods transport is given separately in Table S4, as it was not the main focus of the study, but has a great importance in reducing the associated air pollutants and impacts in urban areas.
Table S4: Detailed emission prediction for overall goods, light duty vehicles (LDV) and Heavy Duty Vehicle (HDV)

<table>
<thead>
<tr>
<th>Data</th>
<th>PM</th>
<th>CO</th>
<th>HC</th>
<th>NO₂</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Goods</td>
<td>LDV</td>
<td>HDV</td>
<td>Goods</td>
</tr>
<tr>
<td>2007-BASE-G</td>
<td>834</td>
<td>18</td>
<td>756</td>
<td>8228</td>
</tr>
<tr>
<td>2021-BAU-G</td>
<td>448</td>
<td>18</td>
<td>411</td>
<td>9714</td>
</tr>
<tr>
<td>2021-ALT-I</td>
<td>37</td>
<td>0</td>
<td>9</td>
<td>9714</td>
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</tbody>
</table>

S.5 Per-capita emission from passenger vehicles

Figure S3 shows the per-capita emission from passenger transport under various scenarios. It shows a decreasing trend from 2007 to 2021 for per-capita emissions ranging between 32% and 80% under various scenarios. The per-capita emissions have been compared with other studies carried out in Delhi by different researchers. Guttikunda and Calori [11] have reported emissions from various sectors such as transport, power plants, and industries for the year 2010 for PM$_{2.5}$ and PM$_{10}$ in Delhi. The per-capita estimated emissions (from transport sector only) for the year 2010 based on their study are ~2.4 g/day for PM$_{10}$, ~33 g/day for NO$_x$ and ~42.5 g/day for CO. Their estimates were about 10, 10 and 7 times higher for PM$_{10}$, NO$_x$ and CO, respectively as compared with those estimated in the current study. This is presumably because our study covers a Delhi metropolitan area, which is about ~6 times less as compared with the area considered by Guttikunda and Calori [11]. The other possible reason could be that the population (i.e. The denominator term) taken in estimating per-capita emissions in the current study is used for the NCTD only, which has ~40% lower population as compared to those covered by the other study for Delhi and its satellite cities, including Gurgaon, Noida, Greater Noida, Faridabad and Ghaziabad. However, CPCB [2] has estimated PM$_{10}$ emissions at 147 tons/day and NO$_x$ emissions as 460 tons/day during during the year 2006-07. Per-capita emissions from this study were 0.53 g/day and 14.8 g/day for PM$_{10}$ and NO$_x$, respectively, for 2006-07, which is almost ~2 and 5 times higher as compared to the current study. Both, the CPCB and our study have used similar population, but the difference could be attributed to the dissimilarities given by the modelling approaches used; receptor modelling used by the CPCB for apportioning PM$_{10}$ emissions from road transport as compared with a direct modelling approach used in our study. Further, Sahu et al. [12] have reported PM$_{10}$ and PM$_{2.5}$ emissions in Delhi during Commonwealth Games 2010. They have used a domain of 70 km × 65 km for emission estimations and have reported 23 times higher PM$_{10}$ emissions than the present study. The highest per-capita emissions from this study are due to the reason that their study...
area is 3-fold (~4550 km²) higher as compared with the current study (~1480 km²). In addition, average
vehicle traveled taken into consideration in their study was also ~8 times higher as compared with our
study. This may be due to the reason that they have included all the cities covered under the NCR
region.

Figure S3: Per capita (per person) tail-pipe emission for passenger transport under various scenarios

Reference


11. Gutikunda SK, Calori G. A GIS Based Emissions Inventory at 1km x 1km Spatial Resolution for Air Pollution Analysis in Delhi, India. Atmos Environ 2013; 67:101–111