Alexandria Engineering Journal (2018) 57, 2649–2658

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ORIGINAL ARTICLE

Analysis of environmental co-benefits of transportation sub-system of Delhi

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Received 20 April 2017; revised 28 September 2017; accepted 15 October 2017
Available online 20 November 2018

KEYWORDS

Delhi;
Environmental co-benefit;
Policy intervention;
Transportation sub-system;
Urbanisation

Abstract Urban systems are the engines of economic growth. Urbanisation significantly contributes to economic, social, and physical transformation. This transformation is supported by infrastructure services. The pace of urbanisation and industrialisation of Delhi city has not only burdened transport system but also has produced detrimental impact on human development, environment and urban ecosystem. The basic concept of co-benefits is applied to understand the multiple dimension of transport policy beyond its intended benefit. Authors in this research have quantified the benefits and co-benefits of different implemented policies and technology intervention done by the government from 2001 to 2015 in Delhi, the capital city of India, and have observed that the emissions from all vehicles have been steadily increasing despite sincere efforts done by the planners due to increase in number of vehicles in the city. The paper concluded with plausible findings and strategies for emission reduction, and benefits and co-benefits of Delhi Metro system in the city.

1. Introduction

Urban settlements are characterised by high density of population actively engaged in certain economic activities on land defining land-uses. Looking at city from the organismic whole perspective, cities are complex systems having both spread and backwash affects. Urbanisation, though considered as an engine of economic growth, has rendered numerous benefits, and has rendered dimensions in human development [5]. Rapid urbanization requires massive provision of infrastructure, public transportation, housing and jobs for population, as well as a healthy environment. Energy is the basic need for development of any urban settlement. Transportation is the basic need for performing different activities in the urban space for economic development of the system. Transportation sector is the second largest energy consumer sector after the industrial sector, and it accounts for 30% of the world's total delivered energy. Transportation sector accounted for about 60% of the global oil demand and was responsible about 22% of the global CO_2 emissions in the year 2008. Road vehicles dominate oil consumption within this sector, and represent 81% of the total transportation energy demand [1]. Urban settlements face

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Peer review under responsibility of Faculty of Engineering, Alexandria University.

https://doi.org/10.1016/j.aej.2017.10.001
1110-0168

a large number of problems due to the unplanned population growth and lack of infrastructural facilities. Congestion is the backwash effect of urbanisation and industrialisation. Emissions from the combustion of fossil fuels contribute to both global climate change and local air pollution, and high concentration of pollutants causes serious public health issues, including asthma, bronchitis, pneumonia, decreased resistance to respiratory infections, and premature death [15].

Delhi city, which is located at 28.7041° N 77.1025° E, is a Union Territory and capital city of India, is considered for investigation. It has the geographical area of 1484 sq. Km, and is surrounded by the Haryana and Uttar Pradesh States (Image 1). This city attracts in-migration from the entire nation for employment opportunities as it is the political centre and also one of the major economic hubs of India. Delhi, with the limited resources, is dependent on the surrounding states for its basic needs. It has very strong network connectivity in the form of six national highways, five rail connectivity having junctions catering to huge traffic. International and national air transport is facilitated by the Indira Gandhi International (IGI) Airport. Delhi has very robust web of internal roads available in hierarchical system, internal railway and Metro system available for both public and exponentially growing private vehicles for supporting the average annual growth rate ranging from 9 to 13% of GDP (see Fig. 1).

The population, urban area, and the number of houses have grown almost double from 1991 to 2015. During this period, the road length has increased 1.5 times, whereas the vehicles have amplified approximately 5 times. It has been observed that the road capacity has increased disproportionate to the vehicular population; and the literacy rate has increased for more than 1.2 times, which lead to increase in the demand of infrastructure, and the demand is supported by the increase in the purchasing parity and willingness to pay for better infrastructure facilities bolstered by the increasing GDP.

The city functions like a dynamic system, so, impact of one element of the system will impact the behaviour of the entire system. A conceptual system dynamics model of the city, which includes population, GDP, transportation (both number of vehicles and road length), traffic congestion, pollution, human health, and policies in the form of technology advancement in fuel and vehicles, and mass transportation system (Metro Non-polluting) is presented in Fig. 2. The interactive functions among transportation, environment, and GDP of the system, which led to urbanisation is established and it can be easily understood from Fig. 2 (see Table 1).

Transportation sub-system of the city from 1991 to 2015 has been analysed, incorporating different policies implemented by the government from time to time in integration with physical, social (population), economic and environment sub-systems. The pressure of urbanisation and industrialisation in Delhi city has lead to increase in number of vehicles, which in turn touched the threshold limits of road capacity. Growth trend of passenger vehicles in Delhi from 1991 to 2015 is presented in Fig. 3. Analysis of capacity, productivity of different vehicles, average speed, and average trip length, mileage per year and fuel efficiency for different type of passenger vehicles for Delhi is presented in Table 2.

The increasing number of vehicles affected the environment sub-system and attracted the focus of policy makers. So, the

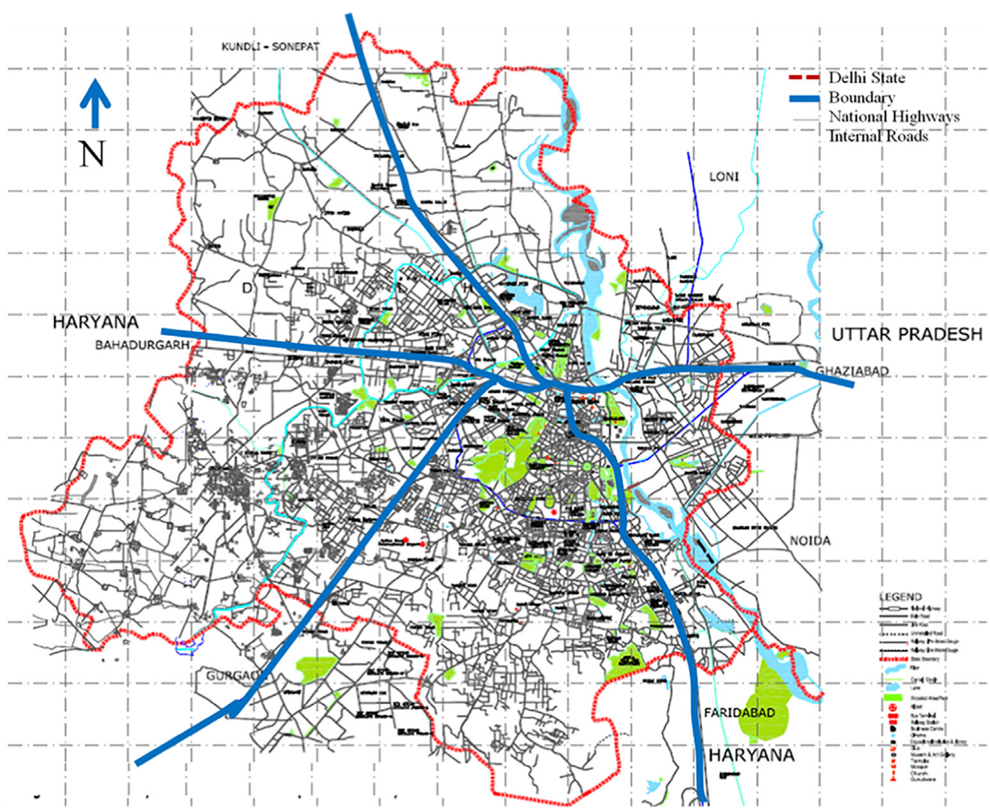

Fig. 1 The physical transportation sub-system in study area: National Capital Territory of Delhi (adopted from: Transport Demand Forecast Study and Development of an Integrated Road cum Multi-modal Public Transport Network for NCT of Delhi, 2010).

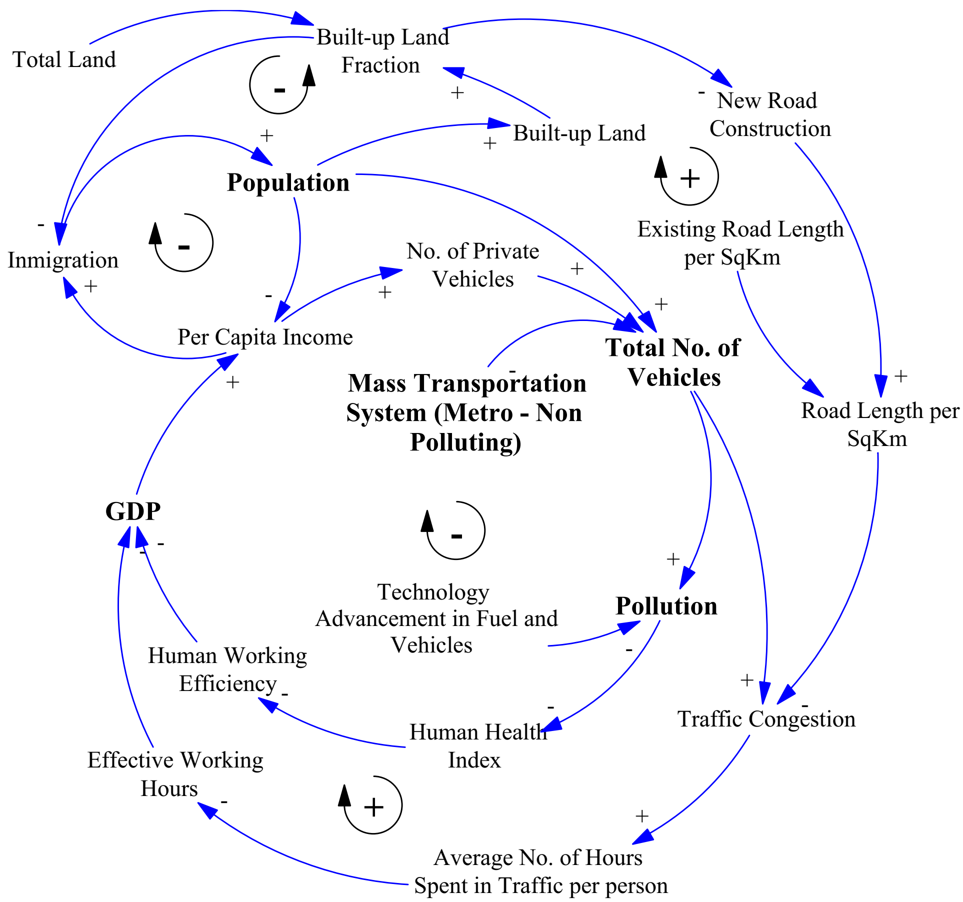

Fig. 2 Causal loop diagram to establish the functions between mass transit system (Metro) and urbanisation (Source: Authors).

Table 1 Scenario of population, literacy rate, houses, road length, vehicles and public transport modal split of the study area during the study period.

Sr. No.	Year	Urban Area/Total Area (Sq. Km)	Population	Literacy rate	No. of Houses	Road Length (in Km)	Total No. of Vehicles	Public Transport Modal Split percentage
1	1991	685.4	9,550,000	75.29%	1,860,748	22,842	1,962,998	
2	2001	924.7 (34.91%)	13,460,000 (40.94%)	81.67%	2,452,402 (31.8%)	28,508 (24.81%)	3,617,853 (84.3%)	64.1 (2001)
3	2011	1113.6 (20.43%)	16,896,000 (25.53%)	86.20%	3,313,904 (35.13%)	32,663 (14.57%)	7,452,985 (106.01%)	54.6 (2007)
4	2015	1113.6 (0.00%)	18,247,000 (8.00%)	86.20%	3,658,505* (10.4%)	33,260 (1.83%)	9,704,741 (30.21%)	43.48 (2012)

Source: Delhi Master Plan 2021, Delhi Statistical Handbooks [7], Economic surveys and extrapolated data*. **Figure is (%) presents percent increase considering previous value as base value.

study area has seen changes in emission standards for vehicle, fuel type for mitigating environmental degradation and infrastructural development of BRT and Metro for satisfying the increasing trips and soothing congested roads. Government has introduced new emission standard for vehicles and, alternative fuel vehicles in bus and taxi fleets as an attractive measure for reducing greenhouse gas emissions, and air pollutants, but the problem of overloading road infrastructure remained unattended. So, a dynamic equilibrium seeking solution optimally utilising available resources is the need of the hour. Less polluting and high occupancy vehicular transportation sub-system offers a solution to this problem. High occupancy public transport mode not only provides relief to congestion on urban streets and increases level of service but also endow with environmental co-benefit [2,3,18]. The infrastructural changes and different policies introduced by the government is presented in Fig. 4.

This forced the government to reform Delhi Transport Corporation bus fleet and implement mass transit system 'Metro' to ease the pressure on the road infrastructure (Department of Transportation, Delhi). Public mode of transportation especially Metro has high capacity as compared to private modes

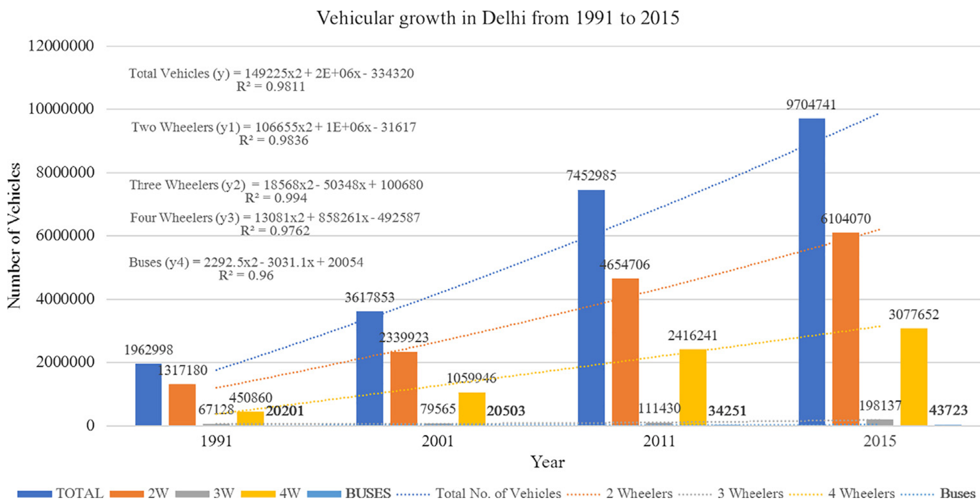

Fig. 3 Growth trend of passenger vehicles in Delhi from 1991 to 2015.

Table 2 Occupancy, PCU value, productivity, average speed and trip length, mileage and fuel efficiency of different vehicles in Delhi.

Sr. No.	Vehicle type	Occupancy[#] (Passenger/vehicle)	Passenger Car Units[*]	Productivity	Average Speed[$] (km/h)	Average Trip Length[$] (km)	Mileage per year (2012)[^] (km)	Fuel efficiency[^] (km/L)
1	2 W	1.5	0.5	3.0	25	33	12,000	48.5–52.3
2	3 W	2.5	0.7	3.6	22	150	54,700	22.08 ± 5 Km/Kg CNG
3	4 W	2.4	1	2.4	21	33	11,000	15.3–16.2 (P) 14–15.3 (D)
4	Bus	39.6	2	19.8	15	200	43,800	3.08 ± 0.6 km/kg CNG
5	Delhi Metro	903[**]	–	–	32	14.7[α] 12.5[^]		15.03 kWh/km[α]

[#] Sharma et al. [16].
[$] Goel et al. [9,8].
[^] Goel et al. [11,10].
[α] Doll and Balaban [6].
[*] IRC standard for Urban roads.
[**] Considering 2,600,000 passenger per day by 2880 trips of 216 metro trains (2015).

and doesn't produce pollution in the system as it is powered by electricity. The authors have quantified the benefits of alternative usage of fuel, new emission standard vehicles and mass transit vehicles (Delhi Metro) to satisfy the travel demand of growing economy considering the quality and quantity of fuel consumed.

2. Aim, objectives and methodology of the study

The study aims at to quantify the environmental co-benefits achieved by different transport alternatives implemented in the study area (Delhi city). Emissions generated by different modes of transportation in this city are calculated for recorded vehicle data in 1991, 2001, 2011 and 2015. Policies, parallel to the study period, in transportation sector implemented by the government in the study area are studied and correlated. Benefits of these policies and implemented projects are quantified and recorded along with the environmental co-benefits to be presented in the result section. Literature pertaining to the study area and problem at hand is reviewed for secondary data and the methods adopted in previous studies. As the data availability lacks, linear interpolation and extrapolation are done for projecting the data for different variables used in the study for the milestone years. Spreadsheet method, proposed in Sharma et al. [16], is used for calculation of vehicle taken off by the users of Delhi Metro. Bottom-up emission inventory ASIF (Activity–Share–Intensity–Factor) methodology, as used by many scholars [12–14,10,11] is employed to quantify the vehicle exhaust emissions. The milestone years of the study are decided based on having discussions with experts. The experts of the field are of the view that the results of a policy or infrastructure are seen based on whether a policy is long term or short term. As the study is for analysis of transportation sector for 25 years period, both long and short term policies are reviewed. The milestone years are kept at equal intervals, i.e., 1991, 2001 and 2011; and the year 2015 is considered to capture the current situation. The immediate effects of Bharat stage I, Bharat Stage II and implementation CNG and Metro systems have neutralised, and the milestone years have shown the real results of the policies and

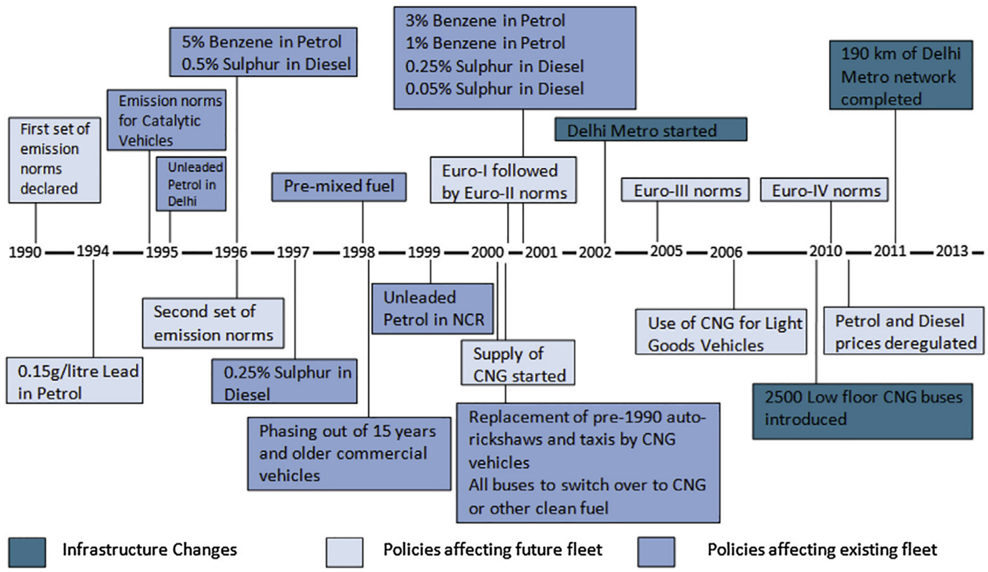

Fig. 4 Infrastructural changes and policies for reducing pollution during study period. Adopted from Goel and Guttikunda [10].

infrastructure changes. The validation of the results is, then, done by using the secondary data from the published government reports and results obtained from recent studies in similar line.

3. Benefits of Delhi metro

Delhi metro is growing at very fast pace, so is the ridership. Ridership shift from other modes to metro is taken for 2006, 2011 from Sharma et al. [16] and for 2013 from Doll and Balaban [6] respectively. The number of vehicle shifted has been calculated using Eq. (1), based on the occupancy and trip length data by different type of passenger vehicle presented in Table 2, and passenger shifted from that category and average trip length in metro are presented in Tables 3–5 (see Fig. 5).

$$\textit{Number of Vehicle shift per day} = \frac{\textit{Passanger shifted} * \textit{Average trip length by Metro}}{\textit{Average trip length by vehicle} * \textit{Occupancy}} \quad (1)$$

The trend of passenger vehicles shifted (Fig. 4) has been used to extrapolate number of passenger vehicles for 2015 to check the data on the pre-decided timeline used in the study. Table 6 reveals that approximately 2.3 lakh of vehicles have been shifted from road transportation due to implementation of Delhi Metro, whereas it is observed from similar study that the number of vehicles shifted is approximately 3.9 lakh (DMRC, Times of India).

Apart from reduction in number of vehicles by Delhi Metro, co-benefits have also been observed including time saved by the commuter in every trip using metro, conservation of fossil fuel, reduction in total accidents, etc., in Delhi. Physical exercise is also important observation in commuter using Metro. Approximately 30% of commuter have observed benefits equivalent to 30 min of physical exercise (Table 7).

4. Environment co-benefits

Energy being the feeder for functioning of transportation has been used to project the environmental co-benefits while solving problem of transportation sub-system. The quality and quantity of fuel consumed play pivotal role in achieving environmental co-benefits. ASIF methodology (a spreadsheet model based) has been used to calculate the vehicle exhaust emissions. The most important parameter considered for analysis of environmental pollution are Carbon Mono-oxide (CO), Hydro Carbon (HC), Nitrogen Oxides (NO_x), Carbon Dioxide (CO_2) and Particulate Matter (PM). The other parameter under consideration remained Benzene, Butadiene, Formaldehyde and Aldehyde.

Table 3 Number of Vehicles shifted by Delhi Metro in 2006.

Sr. No.	Vehicle Type	Occupancy factor	Avg. Trip length of Vehicle	Ridership shifted from vehicle type in 2006	Passenger trip shifted	No. of Vehicle shifted by Metro in 2006
1	2 Wheelers	1.4	37	15	72,600	14,015
2	3 Wheelers	2.4	45	5	24,200	2241
3	4 Wheelers	2.4	67	15	72,600	4515
4	Buses	42.9	160	65	314,600	458
5	Metro	(Avg. Metro Trip Length = 10 km)			484,000	Total = 21,229

Source: Sharma et al. [16], Delhi Metro Rail Corporation [4].

Table 4 Number of Vehicles shifted by Delhi Metro in 2011.

Sr. No.	Vehicle Type	Occupancy factor	Avg. Trip length of Vehicle	Ridership from vehicle type in 2011	Passenger trip shifted	No. of Vehicle shifted by Metro in 2011
1	2 Wheelers	1.5	33	20	332,000	83,838
2	3 Wheelers	2.5	150	5	83,000	2767
3	4 Wheelers	2.4	33	20	332,000	52,399
4	Buses	39.6	200	55	913,000	1441
5	Metro	(Avg. Metro Trip Length = 12.5 km)			1,660,000	Total = 140,445

Source: Sharma et al. [16], Delhi Metro Rail Corporation [4].

Table 5 Number of Vehicles shifted by Delhi Metro in 2013.

Sr. No.	Vehicle Type	Occupancy factor	Avg. Trip length of Vehicle	Ridership from vehicle type in 2013	Passenger trip shifted	No. of Vehicle shifted by Metro in 2013
1	2 Wheelers	1.5	51	25	547,500	105,206
2	3 Wheelers	2.5	109	5	109,500	5907
3	4 Wheelers	2.4	55	26	569,400	63,410
4	Buses	39.6	111	44	963,600	3223
5	Metro	(Avg. Metro Trip Length = 14.7 km)			1,660,000	Total = 177,746

Source: Doll and Balaban [6], Delhi Metro Rail Corporation [4].

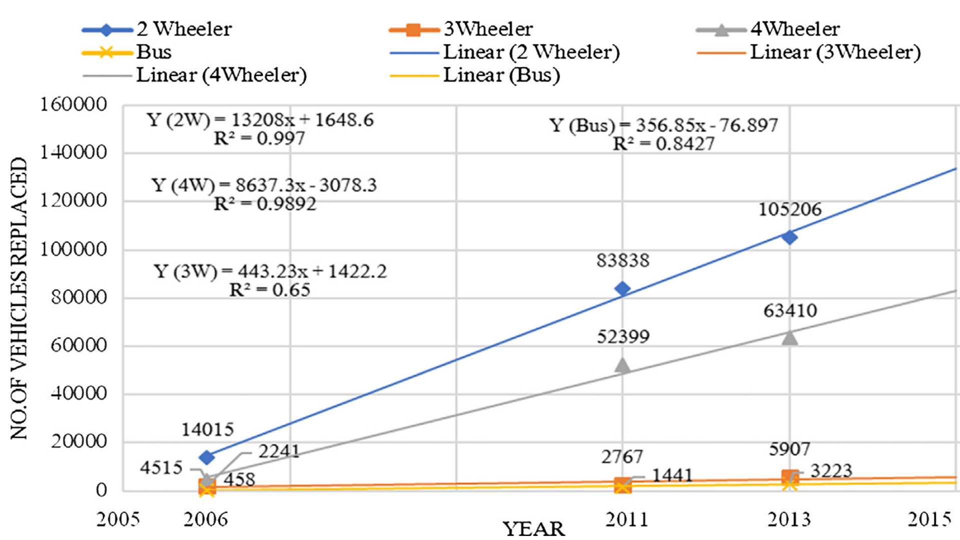

Fig. 5 Number of passenger vehicles shifted by implementing Delhi Metro in 2006, 2011 and 2013 showing trend-lines for different type of vehicles.

Eq. (2) is used for calculating CO, HC, NO_x, PM and other emissions other than CO_2, and Eq. (3) is used for calculating CO_2 emissions.

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

$$E_{(v,f,g,p)} = NV_{(v,g)} \times S_f \times VKT_{(v,g)} \times EF_{(v,f,p)} \times PC \quad (3)$$

where v = vehicle; f = fuel; 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 kilometres travelled by vehicle type (v); 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) of the fuel. The equations and explanations have been adopted from Goel & Guttikunda [10,11]. The total emission and emission per vehicle trends are shown in Figs. 6a–6o, for the compounds CO, HC, NO_x, CO_2, PM, Benzene, Butadiene, Formaldehyde and Aldehyde and total emission trends respectively. The assumptions made for calculating the emissions have been briefed in Table 8. The assumptions are based

Table 6 Number of vehicles shifted by Delhi Metro.

Sr. No.	Vehicle Type	No. of Vehicle shifted by Metro in 2006	No. of Vehicle shifted by Metro in 2011	No. of Vehicle shifted by Metro in 2013	No. of Vehicle shifted by Metro in 2015*
1	2 W	14,015	83,838	105,206	133,728
2	3 W	2241	2767	5907	**10,617
3	4 W	4515	52,399	63,410	83,295
4	Buses	458	1441	3223	3492
	Total	21,229	140,445	177,746	231,132

* Data extrapolated by using equations given in Fig. 3, by authors.
** Extrapolated by using 2011 and 2013 data only, by authors.

Table 7 Benefits of Delhi Metro reported by newspaper quoting DMRC as source, other than vehicles shifted and environmental co-benefits.

Sr. No	Year	Time saved by a commuter on every trip using metro	Total Fuel Saved	Annual reduction in fatal accidents	annual reduction in terms of accidents
1	2007			21	93
2	2011	28 min	1.06 lakh tonnes	125	937
3	2014	32 min	2.70 lakh tonnes	111	591

Source: TNN|Dec 25, 2014, Times of India [17].

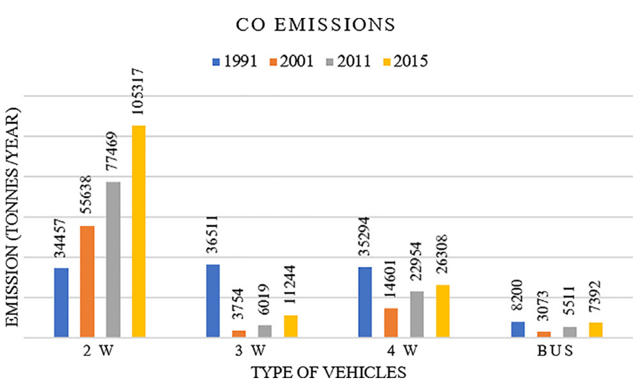

Fig. 6a Total CO emissions by Passenger Vehicles.

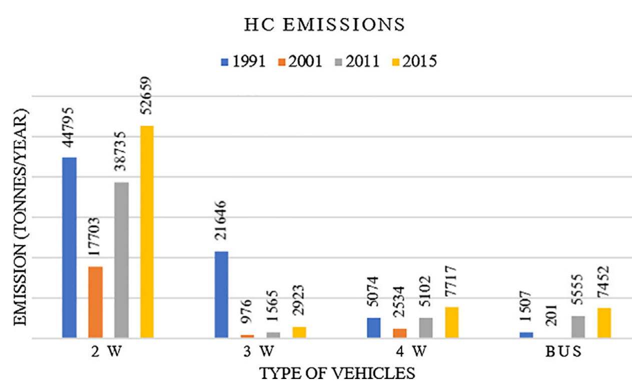

Fig. 6c Total HC emissions by Passenger Vehicles.

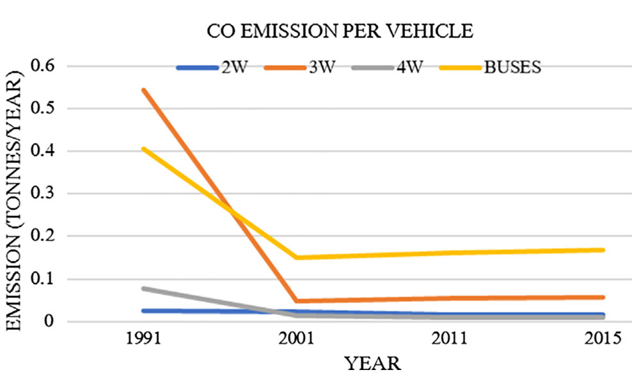

Fig. 6b CO emissions per Passenger Vehicles by category.

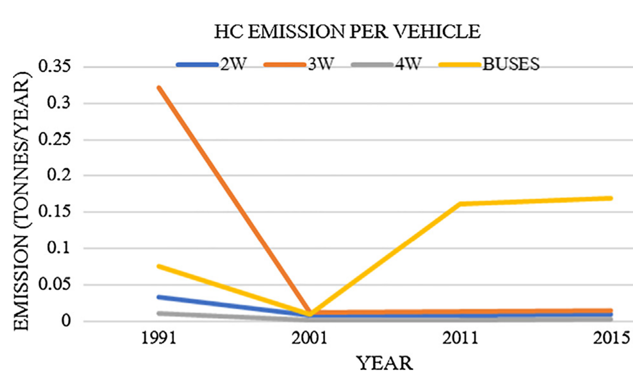

Fig. 6d HC emissions per Passenger Vehicles by category.

on the timeline of technology and policy changes adopted by government for emission reduction presented in Goel and Guttikunda [10,11].

5. Results and discussion

Total CO emissions from all vehicles have decreased except 2 wheelers and the reason is exponential increase in number of

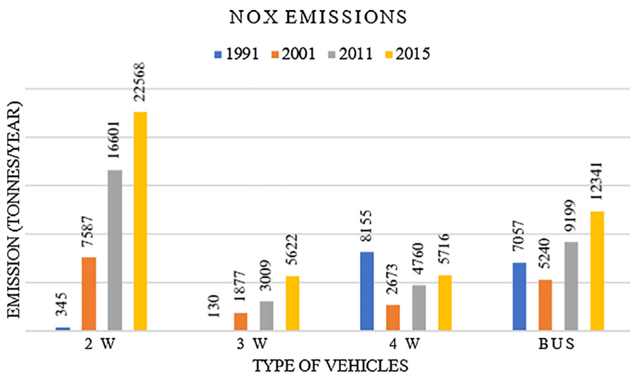

Fig. 6e Total NO_x emissions by Passenger Vehicles.

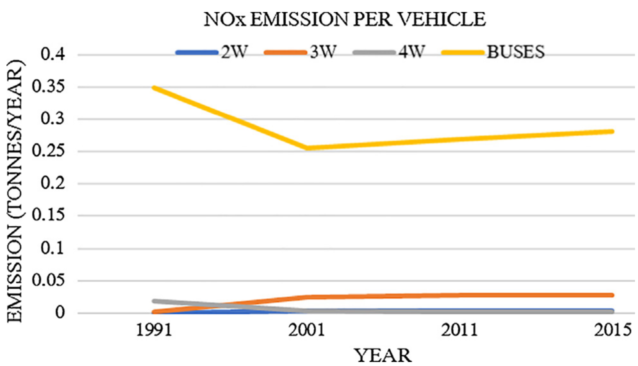

Fig. 6f NO_x emissions per Passenger Vehicles by category.

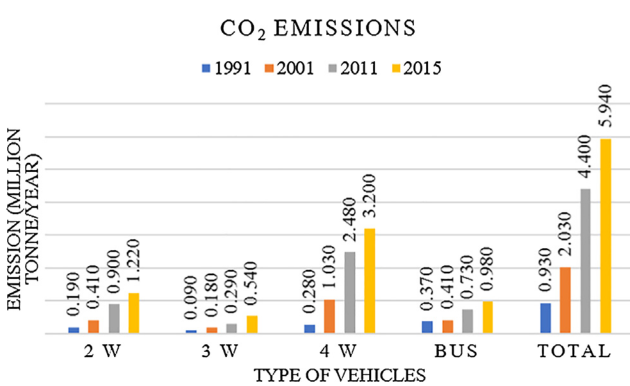

Fig. 6g Total CO_2 emissions by Passenger vehicles.

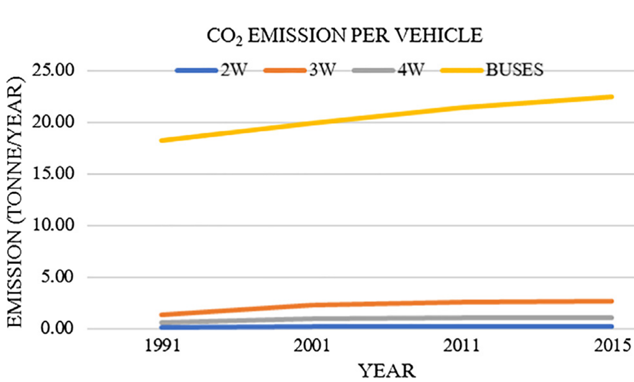

Fig. 6h CO_2 emissions per Passenger Vehicles by category.

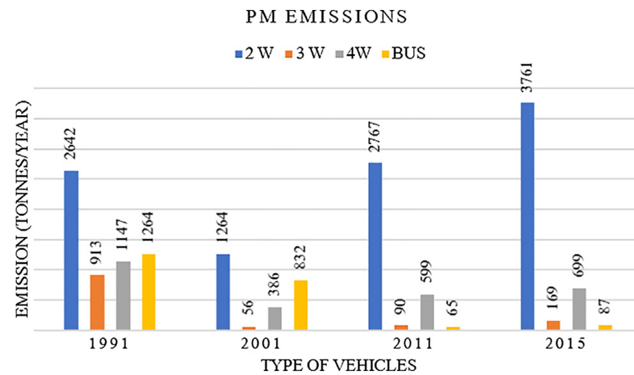

Fig. 6i Total PM emissions by Passenger vehicles.

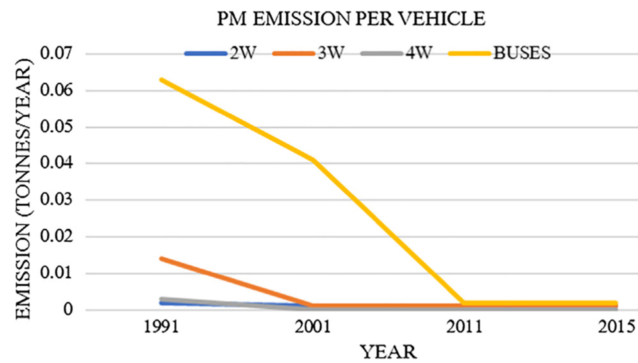

Fig. 6j PM emissions per Passenger Vehicles by category.

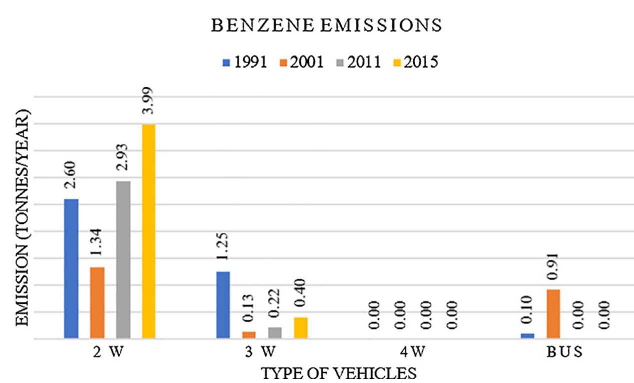

Fig. 6k Total CO, HC, NO_x, PM and CO_2 emissions by different type of Passenger Vehicles.

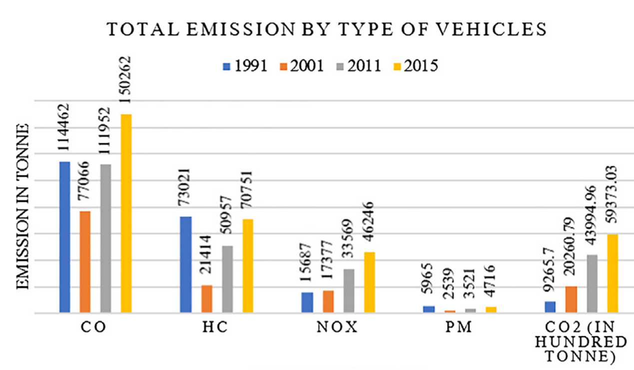

Fig. 6l Total Benzene emissions by Passenger vehicles.

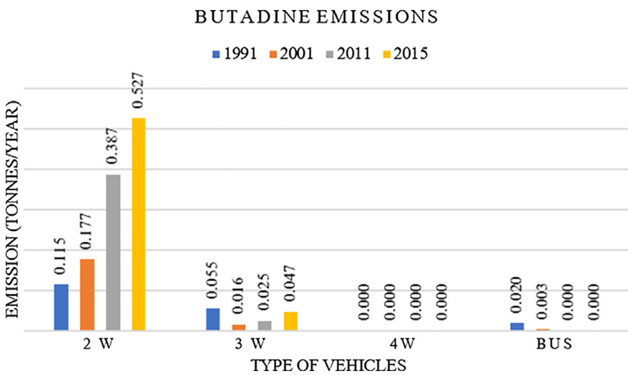

Fig. 6m Total Butadine emissions by Passenger vehicles.

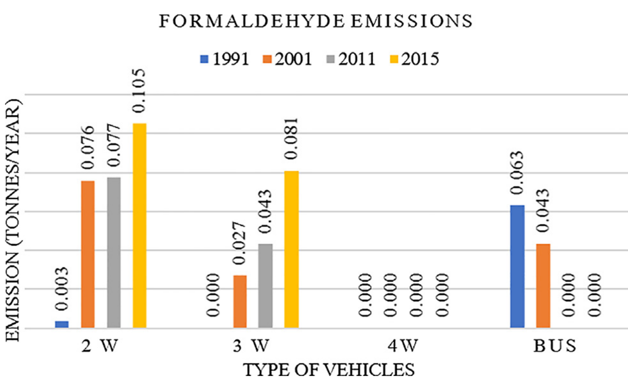

Fig. 6n Total Formaldehyde emissions by Passenger vehicles.

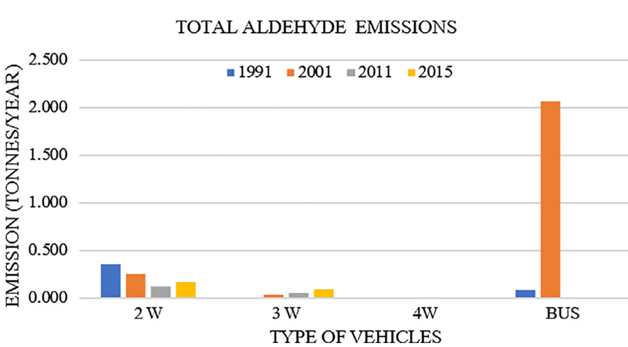

Fig. 6o Total Aldehyde emissions by Passenger vehicles.

2 wheelers otherwise per vehicle CO emission has shown reduction due to intervention of fuel change and technology change. Hydrocarbon emissions have decreased from the year 1991 to 2001, but then increased due to increase in vehicles, and buses have not been targeted for the reduction. NO_x emissions have decreased expect 3 wheelers as only change in fuel type is proposed for 3 wheelers but no specific policy targeting technology changes is proposed in this period.

Metro, the fifth mode of transportation, is electricity based mass transportation system, which is non-polluting in nature within the city, and also it is highly economical over a long period of time. The policies implemented during this period have targeted PM emissions reduction and have been successful in tremendous reduction in PM levels from passenger vehicles. Overall increase in emission is due to increase in total number of vehicles over the study period. The mass transit system e.g. buses and metro is planned in this period but removal of BRT in mid has resulted in loss of the anticipated emission reduction. Delhi Metro has significant contribution in removal of vehicles from road, but the increasing economy has fuelled up the demand for personal vehicles.

6. Conclusion

The total CO emission for all the vehicles except two wheelers have decreased from 1991 to 2001 and then again started gradually increasing (Fig. 6a), but this increase is due to increase in number of vehicles, which is evident from Fig. 6b, where CO emissions per vehicle have decreased due to adoption of advanced technology in vehicles and fuel quality. Hydro-Carbon (HC) emission showed a decline between 1991 and 2001 for all categories of vehicles. After 2001, HC emissions are on gradual increase due to increasing number of vehicles (Fig. 6c). The advance fuel technology helped in keeping the per vehicle HC emission constant despite increasing number of vehicles except for buses, as the HC emission are almost same in diesel and CNG buses (Fig. 6d). Nitrogen oxides (NO_X) emissions showed increasing trend both in total and per vehicle except for buses and four wheelers for the period of 1991 to 2001 (Figs. 6e and 6f).

Total CO_2 emission has shown contentious increase despite all policies and infrastructural changes (Fig. 6g). Per vehicle CO_2 emission also followed the simile trend in terms of emission by category of vehicles (Fig. 6h). The results on Particulate Matters (PM) emission have revealed drastic reduction for all categories of since the year 1991 (Figs. 6i and 6j). The

Table 8 Assumptions made in for analysing the emissions.

Sr. No.	Vehicles Type	1991	2001	2011	2015
1	2 Wheeler	All 2 S	4 S	4 S	4 S
2	3 Wheelers	100% petrol	100% CNG	100% CNG	100% CNG
3	4 Wheelers	Diesel – 20%	20%	20%	15%
		Petrol – 80%	75%	65%	45%
		CNG – Nil	5%	15%	40%
4	Buses	100% Diesel	100% Diesel	100% CNG	100% CNG
5	Delhi Metro	–	–	Electricity based, non polluting	

Source: Authors (compiled from various sources).

government intervention has been quite successful in reduction of PM in transport sector in the city.

Total CO, HC and PM emissions displayed decreasing behaviour between 1991 and 2001 period, whereas, after 2001 they are on uninterrupted rise (Fig. 6k). Total NO_x and CO_2 emissions kept on increasing since 1991 till date despite all policies and infrastructural changes by the government. As a result of all the government intervention in transport sector, benzene and butadiene emissions are reduced for all vehicles except two wheelers (Figs. 6l and 6m); formaldehyde emissions increased for two wheelers and three wheelers, but decreased for buses (Fig. 6n). Total Aldehyde emissions have also decreased for all passenger vehicles since the year 1991 (Fig. 6o).

These emission results from the present research are on lower side as compared to other scholars and Delhi Metro but are true representation of emission from passenger vehicles registered in Delhi. The present research analysed the emission from passenger vehicles supported only by registered vehicles in Delhi whereas the number of vehicles registered in other states have a significant share in total vehicular population.

The increasing population due to systems behaviour of the city demand more number of vehicles for satisfying the increasing transportation demand, which will further increase congestion and emissions in the system, so, to mitigate the backwash effects on system, development of non-polluting mass transit systems is the need of the hour. Delhi Metro is playing a significant role in removal of vehicles from road and has noteworthy co-benefits in form of emissions, health and GDP growth. So, the expansion of Delhi Metro and increase in functional efficiency will provide more soothing effect on urban transport infrastructure as well as urban environment. The government must target the reduction in number of vehicles using policies supporting use of public vehicles and discouraging private modes. The last mile affordable connectivity and all time availability in form of public transport will help in reduction of private vehicle use and need of future in the transport sector in Delhi city. Furthermore, the technology advancement in vehicular sub-system and fuel used must be researched for further reduction in per vehicle emission.

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