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Technical Report

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Prognosis on the Indian gasoline cars and two-wheelers and application of Gasoline Particulate Filter (GPF) to minimize particulate emissions

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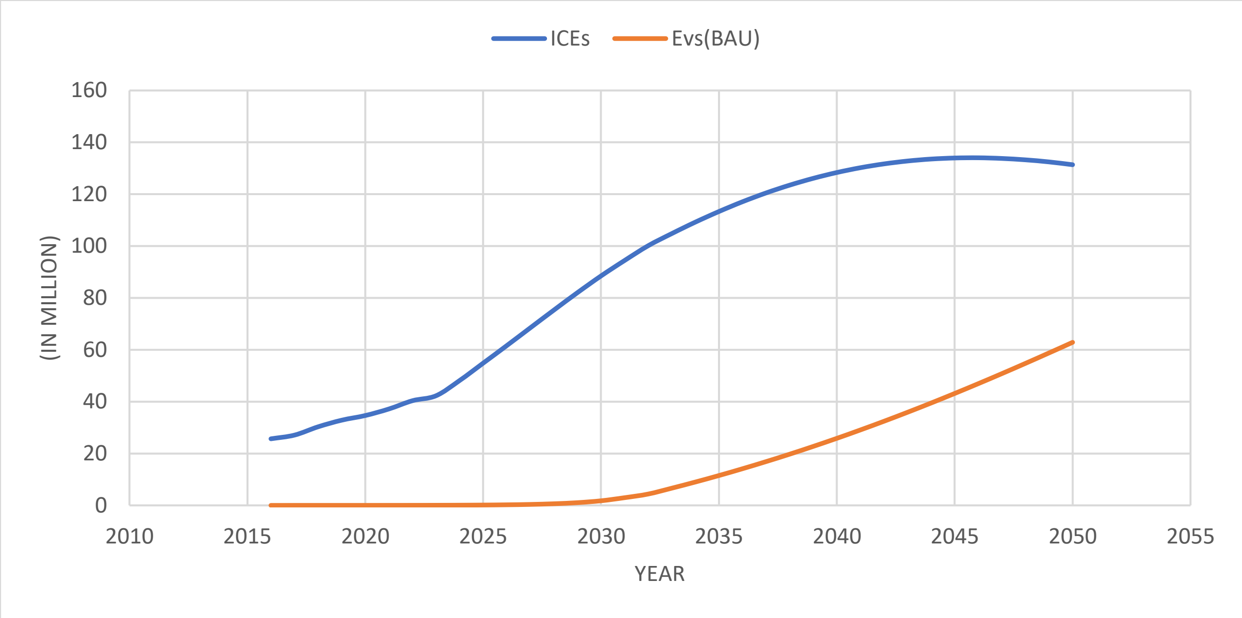
Executive Summary

Based on sales and survival function of passenger cars and two-wheelers, the current status and future growth of the on-road vehicle fleet (Internal Combustion Engines (ICEs) and Electric Vehicles (EVs)) have been examined (period: 2015 – 2050). The cars were classified into Bharat Stage (BS) emission regulation categories of BS1, BS2, BS3, BS4, BS6, and EVs over the years to estimate Particle Number (PN) emissions. For controlling PN emissions, the adoption of Gasoline Particulate Filters (GPFs) for BS6 vehicles was examined. It was also studied as to how effectively can the adoption of GPFs bring down the particulate emission inventory for the next two decades.

The total car (includes cars, jeeps, taxis) inventory (vehicle ownership growth) from 2015-2050 was projected by Gompertz growth function. The upper limit for the number of cars in the year 2050 was estimated as 150 cars per thousand population (conservative), that is, 200 million cars on road by 2050. The aggressive scenario could have 250 cars per thousand population. Of the total fleet, the numbers of EVs at time *t* were estimated using a logistic growth model.

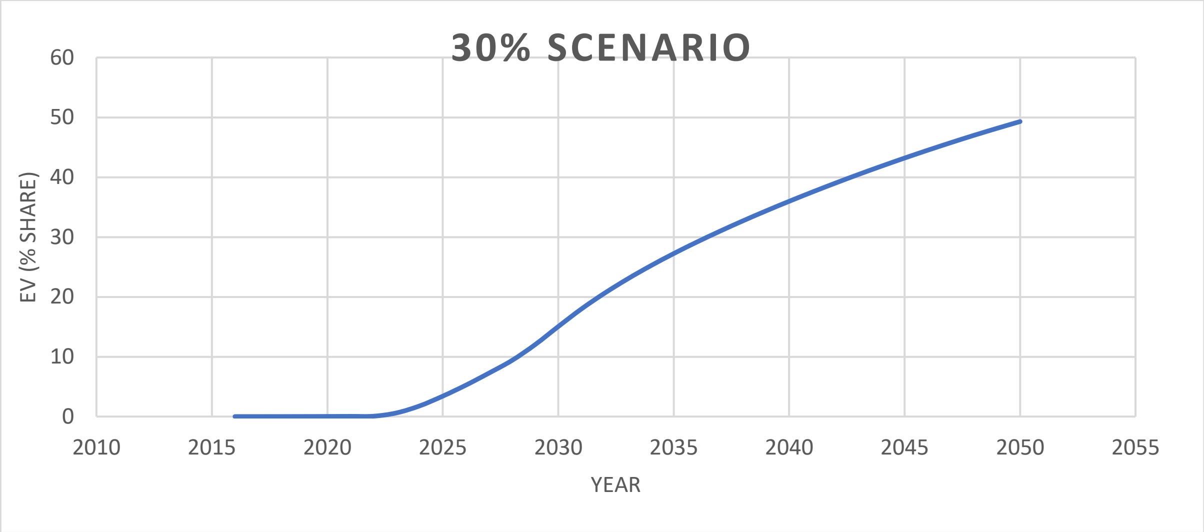
It was seen that there will be a sizeable number of cars in the categories of BS3 and BS4 in 2025 and even in 2030, about 25% of cars will be BS3 and BS4 and the rest BS6. Despite the introduction of BS6, the CO emission will increase with time because of more vehicles on the road and higher vehicle kilometer travel; BS6 emission for CO is not dramatically different from BS4. Although NO_x and PN emissions will drop and stabilize after the year 2030, primarily due to the larger fraction of BS6 and the fast adoption of EVs in 2-Ws (two-wheelers), the improvement would not be significant enough to see a tangible benefit in the air quality levels.

ICE and EV Fleet Evolution: The estimated number of cars in 2050 is 200 million. Although ICE cars will be replaced with EVs with time, one does not see a major share of EVs (about 33%) even in 2050 under the current business as usual scenario (BAU) scenario (see Figure below) and it will take a long time before the last of the ICEs cars are sent to the scrap yard.



On-road Car fleet of ICEs and EVs under current BAU scenario

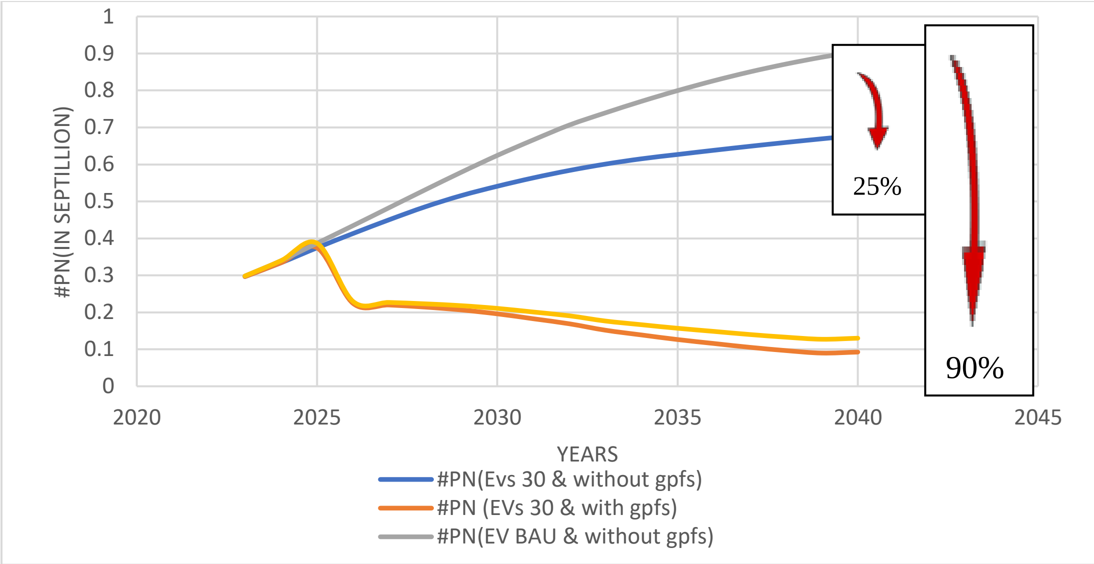
30% EV Sales by 2030: As per the current growth of EVs (i.e., BAU scenario), the number of EVs in 2030 will be insignificant (compared to the total fleet) and in 2040 and 2050 the share of EVs is estimated as 17 and 33 percent of total cars. The 30% EV sales scenario states that 30% of the total sales of cars from 2023 to 2030 should be EVs. This scenario is examined in detail in section 3.5 of the report. Findings tend to imply that extraordinary efforts are needed to achieve this scenario. Accelerated sales of EVs would be required from the year 2023 onwards. Under the accelerated 30% EV scenario, the share of EVs (on-road) by 2030, 2040 and 2050 will be around 15%, 35% (against 17%, BAU) and 50% respectively. It appears with the best of efforts for EV penetration, gasoline vehicles will be sold even after 2030 and a significant proportion of cars on the road will be running on a gasoline engine. If the EVs share must further increase, the accelerated growth of EVs sales has to continue for many more years even after 2030.



EVs as a percentage of total PVs on the road assuming 30% EV sales scenario by 2030

Since the gasoline engine would be dominating the passenger car market for a long time to come, it is important that we estimate the particulates they would be emitting as per the current emission norms. The outcome of this study was that the particulate pollution from gasoline cars (MPFI engines) could be significant. One of the options to counter this problem is the use of a Gasoline Particulate Filter (GPF). A gasoline particulate filter is a porous ceramic substrate where the alternate cells are blocked to form a checkerboard pattern. It forces the exhaust gases to pass through the porous walls and in the process traps the particulates. GPFs are expected to be widely used in the European Union (EU) and China to meet the PN emission standards (Suarez-Bertoa, et al. 2019).

Reduction in PN Emission: The scenario in which all BS6 PVs sold adopt GPFs is likely to result in a sharp PN reduction from 2026 and beyond (90 percent by 2040). The reduction in PN because of EV sales @30 scenario (in 2030) will be 25% (in 2040). It is advisable to explore the continuous adoption of GPF for BS6 PVs as a 90 percent PN reduction is expected in 2040.



PN emissions with EVs and adoption of GPFs in all new PVs

In summary, the overall reduction in particulate emissions will be from (i) the adoption of GPF and (ii) improving EV infrastructure. The introduction of EVs and the resulting reduction in PN emission will be gradual. Control of PN in ICEs through GPF or other means would be rather swift. The first action (i) can reduce PN emissions by 90 percent by 2040. However, the percent reduction in PN with EV will be limited to 25. Although EV adoption mitigates particulate emissions and should be accelerated, the adoption of GPF in ICEs could be more effective in controlling particulate emissions in the near to mid-term period.

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Chapter 1. Introduction

1.1 Background

After implementing BS6 norms in India, several automobile Original Equipment Manufacturers (OEMs) stopped manufacturing diesel engine vehicles because of technical, environmental, and economic concerns. The almost entire fleet of 2-Wheelers (2-W), which constitutes over 75 percent of vehicles on the road, is gasoline-powered. Post covid, the annual passenger vehicles (mostly cars) sales in 2022 are expected to touch 3.8 million (https://www.statista.com/statistics/608392/automobile-industry-domestic-sales-trends-india/). About 85-90 percent of the cars will be gasoline-powered and the Multi-point Fuel Injection (MPFI) technology will continue to have a majority share at least for the next decade. While Gasoline Direct Injection (GDI) vehicles will be regulated for particle number (PN) from 2023, the large fleet of MPFI is likely to remain unregulated (including a large older fleet) for PN. Therefore, a large emission of PN is expected from passenger vehicles on the road having MPFI technology. It may be noted that even BS6 vehicles have no regulation or limit for PN. However, it may become necessary that PN emission may become fuel neutral and technology to control PN will be required for BS6 vehicles with MPFI technology.

Although the gasoline vehicles are fulfilling the requirements of BS6 norms at type approval (TA) and certification level, compliance with stringent requirements for in-service real-driving emission (RDE) will be a challenge, especially for particulate matter (PM) and particle number PN concentrations. The focus on gasoline vehicles is also important from the vehicle kilometer travel (VKT) perspective. Of a total annual VKT of 1654 billion, 2-Ws and cars account for over 70 percent of VKT (Paliwal et al., 2016). Figure 1 presents the national-level annual emissions of $PM_{2.5}$ from vehicles; cars and 2-Ws combined account for 33 percent of total emissions. A large fraction of cars and the entire 2-Ws fleet is powered by gasoline, causing significant emissions.

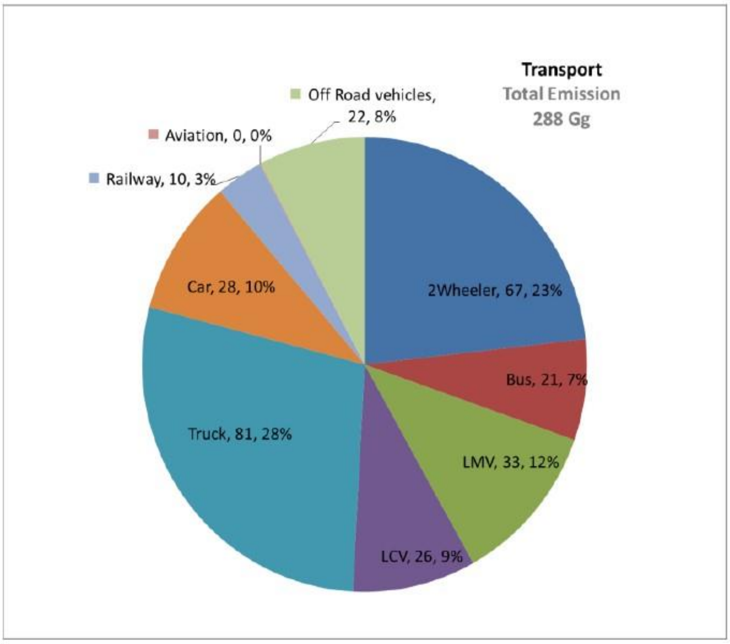


Figure 1: Source-wise emission contribution to the transport category (Madhesia, 2020)

Over the last few years, authorities and consumers have become increasingly interested in the growth of the electric vehicle (EV) sector, owing to their potential to cut CO, NOx, and PM emissions. It gives an impression, though not scientifically proven, that Internal combustion Engines (ICE) will be phased out and all transport emissions will cease to exist. Although most studies conclude favourably for EVs (https://www.epa.gov/greenvehicles/electric-vehicle-myths), not all share the view that EVs can offer climate change mitigation under all situations (Abdul-Manan et al., 2022). The larger point how exactly EVs will evolve in the future is still unknown. Predicting EV fleet over time is critical for many stakeholders, including automakers, policymakers, and energy suppliers. Furthermore, it is unclear how the decline in the fleet of ICEs and the expansion in the EV fleet would affect the emissions (Al-Alawi and Bradley, 2013).

For cars, NITI Aayog proposed the target of 30% of total car sales by 2030 would be EVs and the rest would be ICEs. In this scenario, ICE cars will be more than twice the current number of ICE sold (Figure 2). This is due to the high growth of automotive sales in India. This scenario will be even worse in case of a lower penetration of EVs by 2030. It appears that even in 2030 a major fraction of the car fleet will be ICE-powered with a sizeable fraction of BS6 vehicles. Thus, there would still be requirements to further control PM and PN from gasoline vehicles in 2-Ws and car categories.

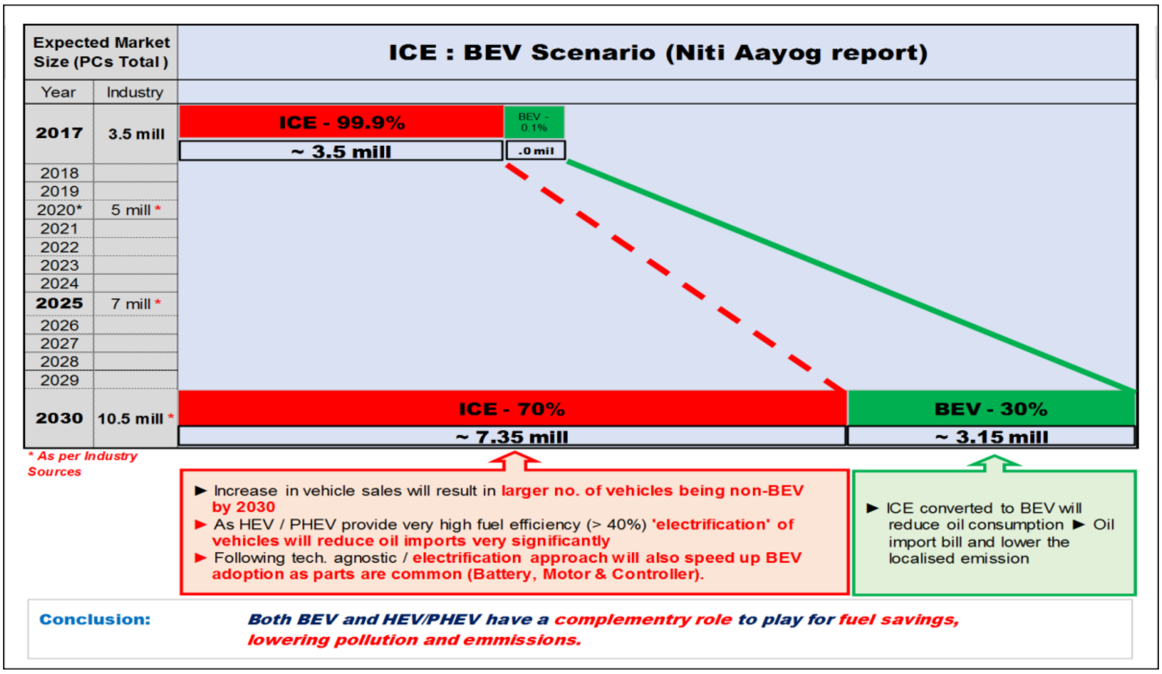


Figure 2: ICE: BEV Scenario

The BS6 and future regulations limits for PN (and PM) for GDI vehicles are equivalent to those for a diesel vehicle. However, there is no regulation for the particulate control of MPFI gasoline engines which have the majority share (~70%) in the passenger car segment. Since the personal growth of 2-Ws and passenger cars in India is one of the highest globally (Table 1), particulate control from these sources is paramount if India must achieve tangible improvement in air quality levels.

Table 1: Growth Projection

Personal Vehicles and Two Wheeler		
Segments	Growth Y-o-Y(%)	5 Year CAGR %
	FY 20 P	FY18 - 23 P
Cars	8-10%	6-8%
Utility Vehicles*	11-13%	9-11%
Motorcycles	7-9%	6-8%
Scooters	9-11%	7-9%

1.2 Objectives and Scope of the Study

The study has the following scope of work:

1. Predict the time series of 2-Ws and car sales and an on-road fleet of EVs and ICEs in India till 2050; and

2. Quantify the benefits of Gasoline Particulate Filter (GPF) adoption for cars in India in terms of the particulate mass (PM) and particulate number (PN) emission, considering realistic powertrain scenarios derived from scope 1.

Chapter 2. Literature Review and Methodology

In the past, International Energy Agency (IEA; Fulton and Eads, 2004) and Arora et al. (2011) have predicted the total vehicle fleet using the Gompertz growth function, by correlating vehicle ownership (vehicles per 1000 person) with an increase in Gross Domestic Product (GDP) of the country (Rietmann, 2020). In the current study, we have used the Gompertz growth function to estimate the total vehicle fleet on the road till 2050. We use this data to predict the EV fleet using the logistic growth model. To assess the ICE fleet on the road, corrections have been applied to account for survival rates of vehicles depending on the age of the vehicle.

Prior research has reported EV's market penetration. This research includes models depicting the diffusion of innovations, such as exponential or logistic growth models (Al-Alawi and Bradley, 2013), and stochastic models based on consumer preferences, such as discrete choice or agent-based models (Rietmann, 2020). Consumer preference models (CPM) are effective for illustrating decision-making, buying incentives, and potential impediments. CPM are, however, less transparent than diffusion models (DM). Al-Alawi and Bradley (2013) recommend that modeling of HEV (hybrid electric vehicles), PHEV (Plug-in hybrid vehicles) and EV penetration rates should include improved interfaces with consumer surveys, modelling of automakers' actions, state policy, competition among technologies, market volume, and vehicle classifications.

Once we arrive at the total quantity for the car fleet, we calculate the emissions from ICE vehicles on the road after breaking down the fleet into different BS-type vehicles and then into diesel and petrol categories. Based on this, the reduction in particulates that can be achieved through the adoption of GPF in gasoline cars is estimated.

2.1 Time series of total vehicles fleet

Vehicle ownership changes are proportional to a country's per capita GDP (Arora et al., 2011). However, as seen in Figure 3, this relationship between GDP and ownership is not linear. For the years 1991-2006, Figure 3 depicts the link between highway vehicle (HWV) ownership per 1,000 persons and GDP per capita for 19 countries. Vehicle ownership climbs slowly at low GDP levels, accelerates (beyond US$ 5,000 GDP per capita), and then slows as economies mature and saturation levels of vehicle ownership are reached (Arora et al. 2011). In the past, approaches like logistic, logarithmic logistic, cumulative normal, and Gompertz functions (e.g., Tian Wu et al., 2014) were employed to simulate vehicle growth.

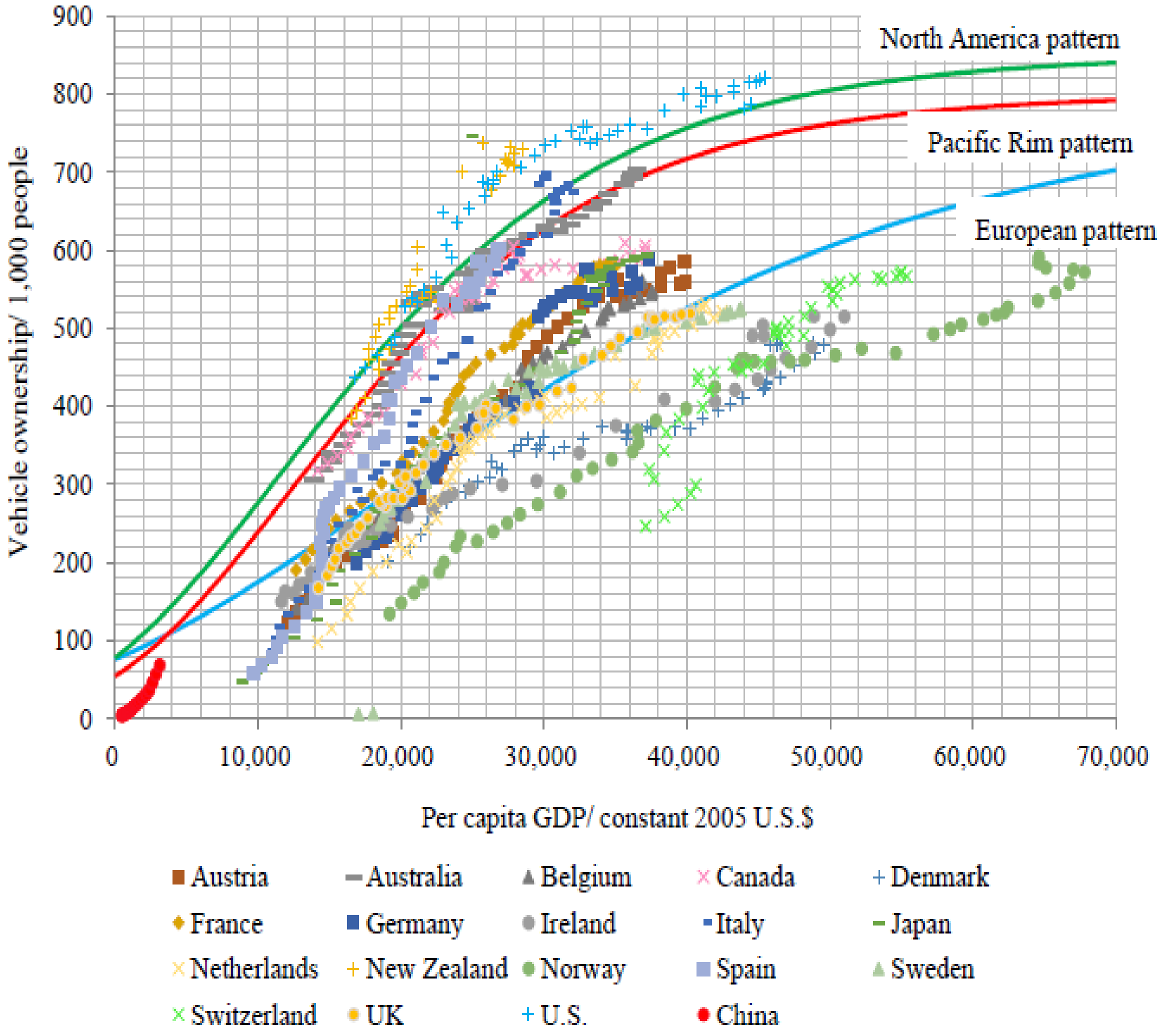


Figure 3: GDP vs Vehicle ownership (Tian Wu et al., 2014)

We have used the Gompertz function to estimate vehicle ownership (Wu et al., 2014). The Gompertz function is expressed as the following Equation (1):

$$Y=Z*\exp(q*\exp(r*g))$$ ………………………. **Equation 1**

Where Z is saturation level, q and r are negative parameters that determine the shape of the S curve, g is GDP per capita, and Y is vehicle ownership (per 1000 persons); these functions can be used for various future years to estimate Y given the GDP of the year.

2.2 Saturation level

The saturation level (Z) is a crucial parameter in the estimation of the number of vehicles. It is a country's maximum vehicle ownership rate (vehicles per 1000 persons). Although there is no standard technical way for calculating it, the saturation level for the UK and other industrialized countries is between 0.4 and 0.7 (i.e., fractional vehicle ownership per person, meaning 400 to 700 vehicles per 1000 person) (Guo et al. 2016). According to the Gompertz model, which was created using time series data from 26 countries, the car ownership saturation rate in most Organizations for Economic Cooperation and Development (OECD) countries was 0.62 in 2015 (Dargay et al. 2007). China's saturation level was estimated at 0.292. Huo et al. (2007) analyzed data from 18 nations and found that the United States had a saturation level of 0.8. The saturation level for European countries was 0.6, whereas for Japan it was 0.55.

The current study is carried out under BAU (business as usual) scenario, for cars (including passenger cars, jeeps, and taxis) and 2-Ws. The bottom-up approach is utilized in this study to project the vehicle population (2-Ws and Cars) separately for India till 2050. We have concentrated solely on private modes of transportation. The saturation level for 2-Ws and cars is taken from Arora et al. (2011). Car ownership saturation levels were predicted to be 150 vehicles per 1000 people (conservative growth scenario) and 250 vehicles per 1000 people (aggressive growth scenario) (Table 2). The saturation levels for 2-Ws were 250 (conservative growth scenario) and 350 (aggressive growth scenario) (Table 2) (Arora et al. 2011).

Table 2: Saturation Levels (vehicles per 1000 persons) (Arora et al. 2011)

Vehicle	Growth Scenario	Saturation Level(Z)
HWV's (Cars ,Jeeps ,Taxis)	Conservative Aggressive	150 250
Two Wheelers	Conservative Aggressive	250 350

Once we assume Z (Table 2), Equation 1 is used for estimating the q and r such that the available growth of vehicles fit well to the model; the method of least squares in errors (model vs actual vehicles) was applied.

2.3 Electric Vehicles Fleet

In the first step, total cars and 2-Ws inventory were predicted by Gompertz's growth function.

It provided an upper limit (L) for several vehicles in the year 2050. Of the total fleet, we have estimated the number of EVs at time *t* using the logistic growth model Equation (2) (Reitmann et al. 2020)

$$E(t) = \frac{L}{1+\left(\frac{L}{E(0)}-1\right)*e^{k*l*t}}$$ ………………………. **Equation (2)**

Where, E(t) is the Electric Vehicles inventory at time *t*, *L* is the saturation limit, E(0) is the inventory at the beginning of (i.e. t=0; i.e., the year 2015) and *k* is the growth factor.

Estimation of EVs is done only for the conservative scenario where the saturation limit for cars and 2Ws is 150 and 250 per 1000 persons respectively (Figure 4). *L* for cars and 2-Ws under a conservative scenario in 2050 was estimated as 194 million and 398 million respectively. Using L = 194000 and actual EV inventories from 2015 to 2022 for a logistic growth function resulted in E(0) = 1.1594038 and growth factor $k = 1.071 \times 10^{-7}$ for cars (note L and E(0) in Equation (2) are in per 1000 units).

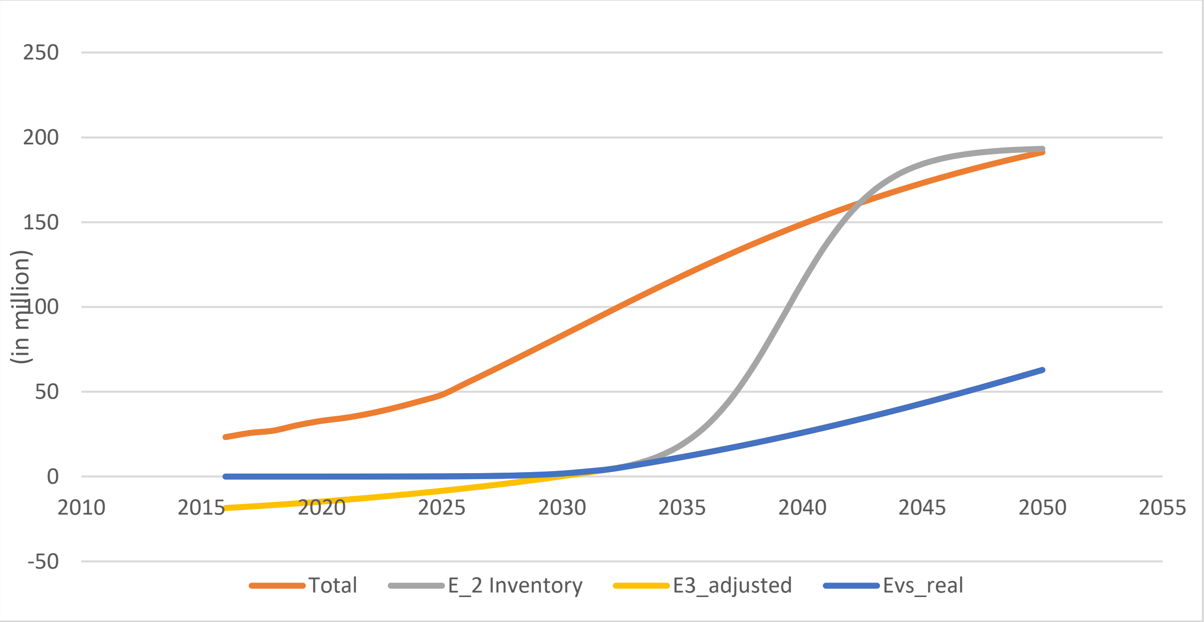


Figure 4: Modelled Growth of Cars and Share of EVs

The blue line in Figure 4 gives the EV vehicle inventory for cars with a saturation level of 150. Here, the grey line is E_2 derived from the following function (by putting the values of variables in Equation (3)

$$E_2(t) = \frac{194000}{1 + \left(\frac{194000}{1.1594038} - 1\right) * e^{1.071*10^{-7}*194000*t}}$$

……………………….. **Equation 3**

If we calculate sales for the year 2036 from the above grey line, it comes out to be around 11 million EVs and that is far more than the total vehicles sold in that or any year till that year. So, the logistic model is not performing correctly as EV sales should be much below the maximum number of cars sold. As a remedy, the slope of E_2 is flattened by a flatter function from 2032 onwards when both the functions (grey(E_2) and yellow(E_3) (adjusted EVs) curves) have the same EV inventory. So, the resulting EV inventory forecast would be a grey line till 2032 and a yellow line from 2032 onwards. The overall resulting real EV line (blue i.e., grey +yellow) is shown, after ignoring the negative growth seen as per the yellow line. For this analysis and logic, detailed calculations are explained below.

Consider the logistic growth model, Equation (2) again. Now, we have to find a lesser steep function E_3 (revised EV growth function) being tangent to E_2 at a chosen point (t*) where function values and their respective derivatives are equal (Figure 5). Therefore, the constraints are:

$$E_3(t^*) = E_2(t^*)$$

$$E_3'(t^*) = E_2'(t^*)$$

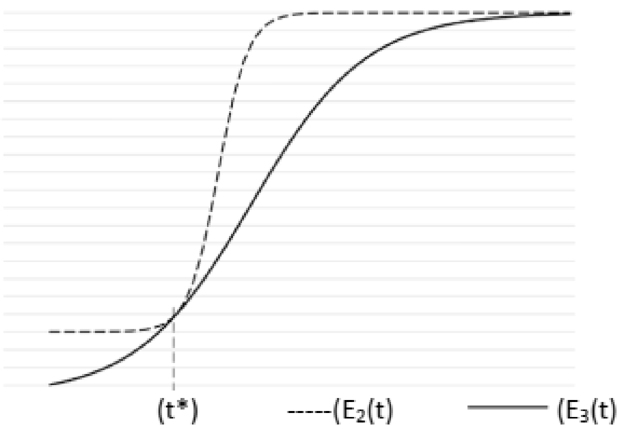


Figure 5: Flattening a curve

First, we will define a growth function E_3 with a higher saturation limit (L+C) and also subtract C from the function value. This will result in E_3 starting below t=0 and will however converge to the original saturation limit (L).

$$E_3(t) = \frac{L + C}{1 + \left(\frac{L + c}{E_3(0)} - 1\right) * \mathrm{e}^{-\mathrm{k}*(\mathrm{L}+\mathrm{C})*\mathrm{t}}} - C$$

………………………….. **Equation 4**

Solve Equation (4) for $E_3(0)$ with the condition $E_3(t^*) = E_2(t^*)$, i.e.

$$E_3(0) = \frac{(L + C) * (C + E_2(t^*))}{C + E_2(t^*) - \mathrm{e}^{\mathrm{k}*(\mathrm{L}+\mathrm{C})*\mathrm{t}} * E_2(t^*) + \mathrm{e}^{\mathrm{k}*(\mathrm{L}+\mathrm{C})*\mathrm{t}} * L}$$

…………….. **Equation 5**

The derivative of E_3 is

$$E_3'(t) = \frac{\mathrm{e}^{-\mathrm{k}*(\mathrm{L}+\mathrm{C})*\mathrm{t}} * k * (L + C)^2 * \left(\frac{L + c}{E_3(0)} - 1\right)}{(1 + \mathrm{e}^{-\mathrm{k}*(\mathrm{L}+\mathrm{C})*\mathrm{t}} * \left(\frac{L + c}{E_3(0)} - 1\right))^2}$$

……………………….. **Equation 6**

The derivative of E_2 is

$$E_2'(t) = \frac{k * L^2 * \left(\frac{L}{E_2(0)} - 1\right) * \mathrm{e}^{-\mathrm{k}*\mathrm{L}*\mathrm{t}}}{(1 + \mathrm{e}^{-\mathrm{k}*\mathrm{L}*\mathrm{t}} * \left(\frac{L}{E_2(0)} - 1\right))^2}$$

…………………………….. **Equation 7**

By applying condition, $E_3'(t^*) = E_2'(t^*)$, we estimate the revised growth factor k as

$$k = \frac{E_2'(t^*)}{\left(L - E_2'(t^*)\right) * (C + E_2'(t^*))}$$

…………………………………**Equation 8**

Now put the new value of k in the equation

$$E_3(0) = \frac{(L + C) * (C + E_2(t^*))}{C + E_2(t^*) - \mathrm{e}^{\frac{E_2'(t^*)}{\left(L - E_2'(t^*)\right)*(C + E_2'(t^*))}*(\mathrm{L}+\mathrm{C})*\mathrm{t}} * E_2(t^*) + \mathrm{e}^{\frac{E_2'(t^*)}{\left(L - E_2'(t^*)\right)*(C + E_2'(t^*))}*(\mathrm{L}+\mathrm{C})*\mathrm{t}} * L}$$

…………… **Equation 9**

With the values of $E_3(0)$ and k, we can predict the EV at different times/years. Hence, the resulting EV inventory forecast would be $E_2(t)$ till 2032 and $E_3(t)$ from 2032 onwards.

2.4 Survival Rate

For estimating the vehicles on the road (not just vehicles sold), we need to account for the survival function of the vehicles, given by

$$SF(a) = \frac{1}{1+e^{\alpha*\left(1-\frac{a}{L_{50}}\right)}}$$

……………………….. Equation 10

SF(a) is the survival rate function of the vehicle of age a; α is the shape factor (relates to retirement), and L_{50} age by which 50 % of the vehicles retired. (Apoorva et.al 2014) Pandey and Venkatraman (2014) varied function parameters α and L_{50} over a range of possible values to find an optimum solution, which gave the best least-squares fit between modeled and calculated (from age- distribution and sales data) survival rates (Figure 6). Table 3 shows the Survival rate of cars and 2-Ws at different years depending on the year of manufacturing/sale (see Table 3 for final results).

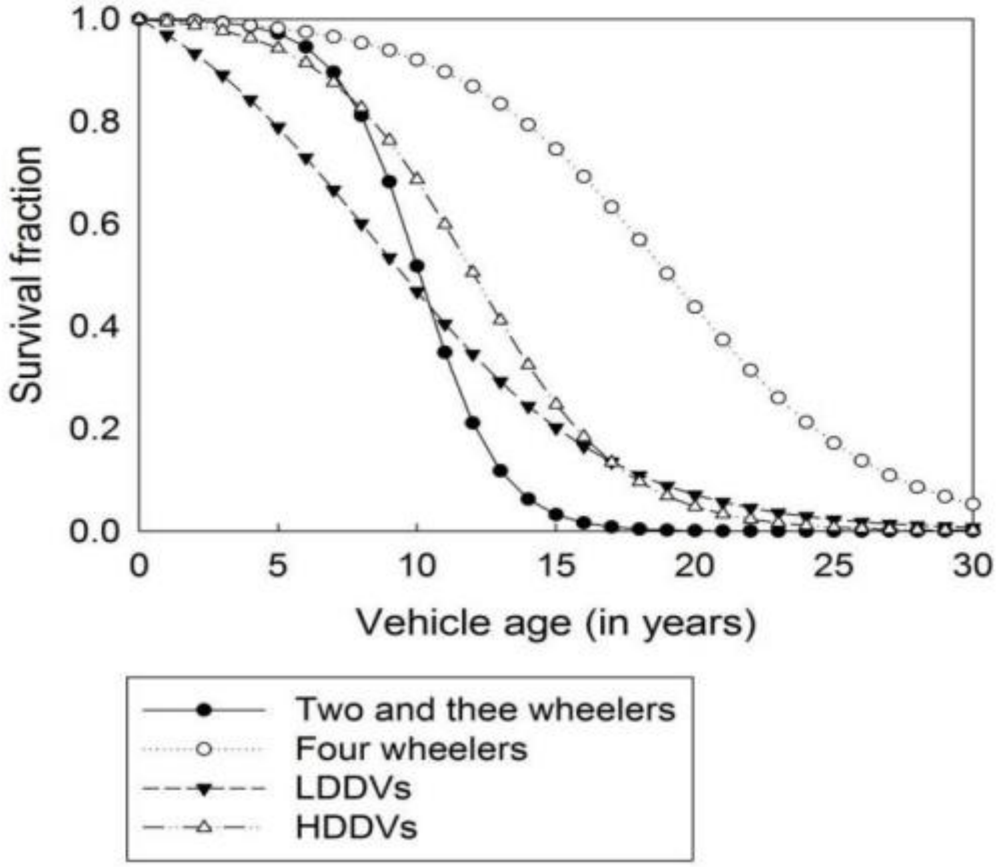


Figure 6: Survival rates and vehicle age (selected cars and 2-Ws for this study)

Table 3: The survival rate of cars and 2-Ws

Years passed	4-Wheelers Survival rate	Years passed	2-Wheelers Survival rate
0	1.000000	0	1
1	0.996979	1	0.993976
2	0.993958	2	0.990964
3	0.993958	3	0.987952
4	0.987915	4	0.984940
5	0.981873	5	0.978916
6	0.975831	6	0.945783
7	0.966767	7	0.891566
8	0.957704	8	0.810241
9	0.942598	9	0.680723
10	0.918429	10	0.515060
11	0.903323	11	0.346386
12	0.876133	12	0.210843
13	0.833837	13	0.111446
14	0.797583	14	0.060241
15	0.752266	15	0.030120
16	0.691843	16	0.015060
17	0.631420	17	0.006024
18	0.570997	18	0.003012
19	0.510574	19	0
20	0.435045	20	0
21	0.371601		
22	0.311178		
23	0.256798		
24	0.208459		
25	0.169184		

GDP (per capita in $) and population data were collected from World Bank. The Ministry of Road Transport and Highways (MoRTH) provides data for total vehicle registration. But that is the cumulative data for vehicles till now and we did not use it directly to predict vehicle fleets on the road. The MoRTH data were revised with the help of the survival function and then the revised data were used for the prediction of the fleet. Data on electric vehicles is taken from the website https://www.statista.com/statistics/1234761/india-electric-vehicle-sales-by-type/.

For example, we explain the number of vehicles in the fleet based on e-vehicle sales for 5 years

2002	t=1	sales 3(S1)
2003	t=2	5(S2)
2004	t=3------------------	6(S3)
2005	t=4	8(S4)
2006	t=5	9(S5)

Now, to find out the total number of vehicles in 2006 based on survival function (SF)

Vehicles (2006) = S5 + SF(5-1)*S1 + SF(5-2)*S2…………

2.5 Emissions

We have estimated the emissions from several vehicles on road by accounting for different BS technologies as per the following expression.

$$Emissions = No.of\ vehicles * VKT\left(\frac{km}{year}\right) * EF\left(\frac{gm}{km}\right) * 10^{-6}(\frac{tons}{gm})$$

……………………….. Equation 11

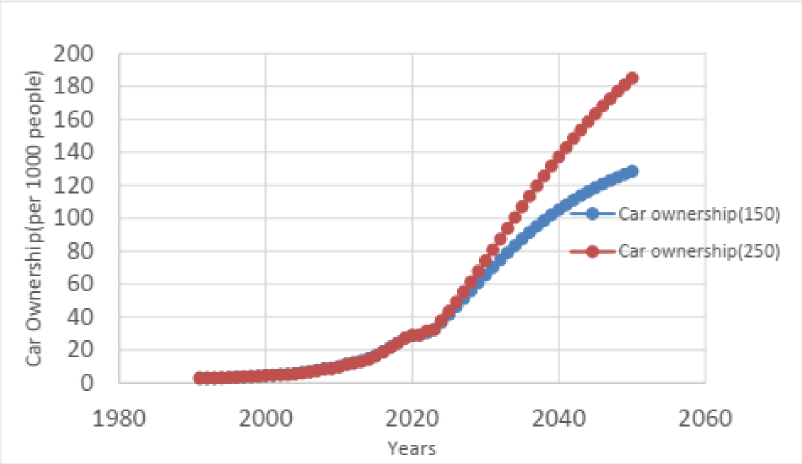
EF (emission factors) were taken from the website, https://dieselnet.com/standards/in/ld.php

While calculating emissions in a particular year (for example, year 2025), the number of vehicles on the roads was grouped BS technology-wise (using the survival function) followed by fuel-wise grouping (mainly gasoline and diesel). CNG vehicles and emissions are taken as negligible.

Chapter 3. Vehicle Fleet and Share of Electric Vehicles

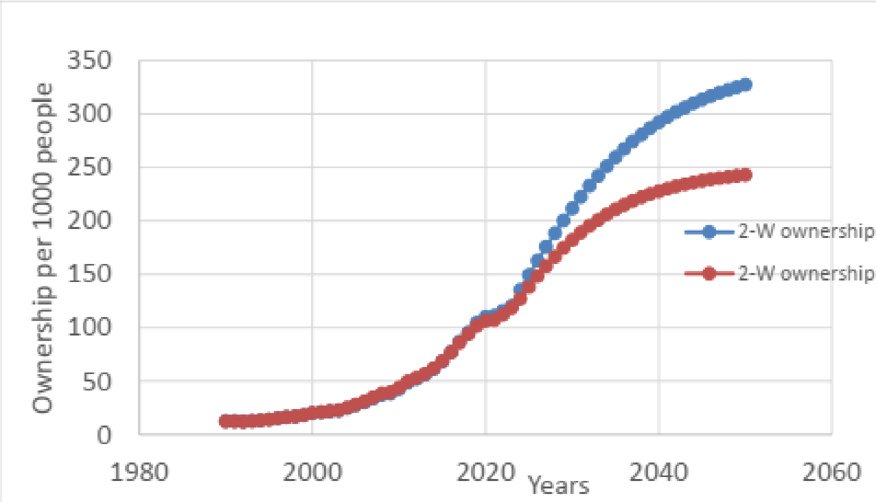
3.1 Total number of Vehicles

We have estimated the car and 2-W ownerships in different years based on Equation (1) for two different saturation levels (Figures 7 and 8) in terms of vehicles per 1000 persons.



Fitting Constants for Cars		
Z	q	R
150	-5.5194	-0.00018
250	-5.9004	-0.00015

Figure 7: Projected Vehicle Ownership for cars at two saturation levels



Fitting Constants for 2-Ws		
Z	q	R
250	-4.80974	-0.00026
350	-4.93166	-0.00022

Figure 8: Projected Vehicle Ownership for 2-Ws two saturation levels

For all further calculations, only the conservative estimate for the cars and 2Ws is considered. The number of vehicles per 1000 persons was converted to the total number of vehicles by multiplying it by the population in the corresponding year (Figures 9 and 10).

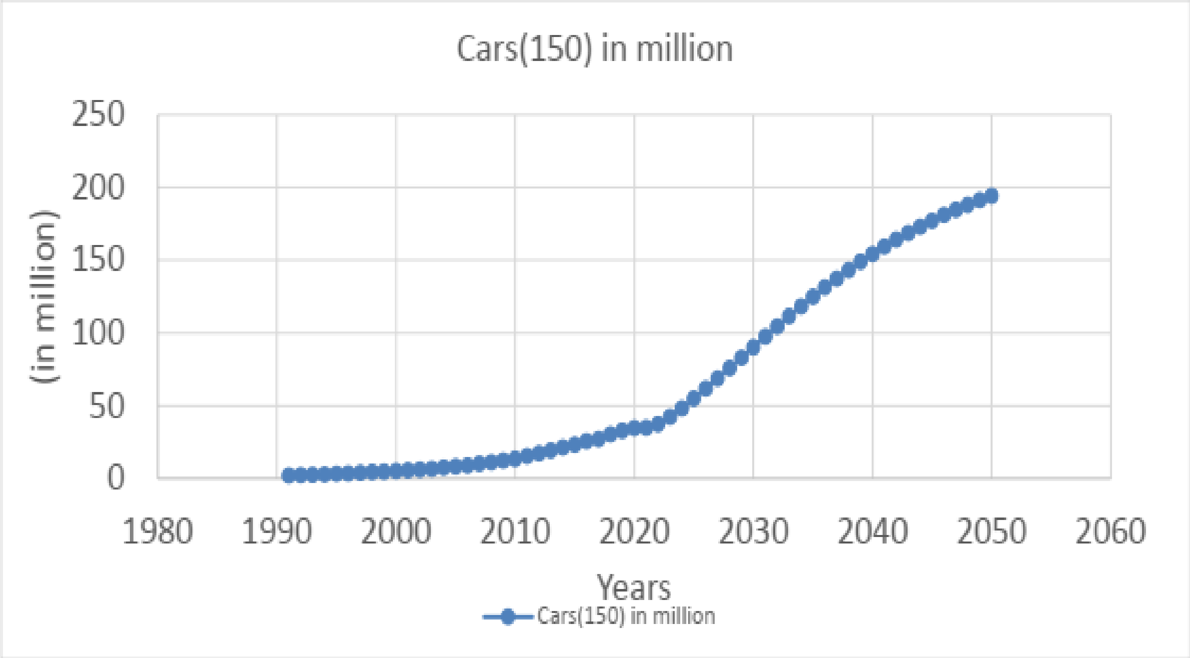


Figure 9: Vehicles (Car) in million fleet

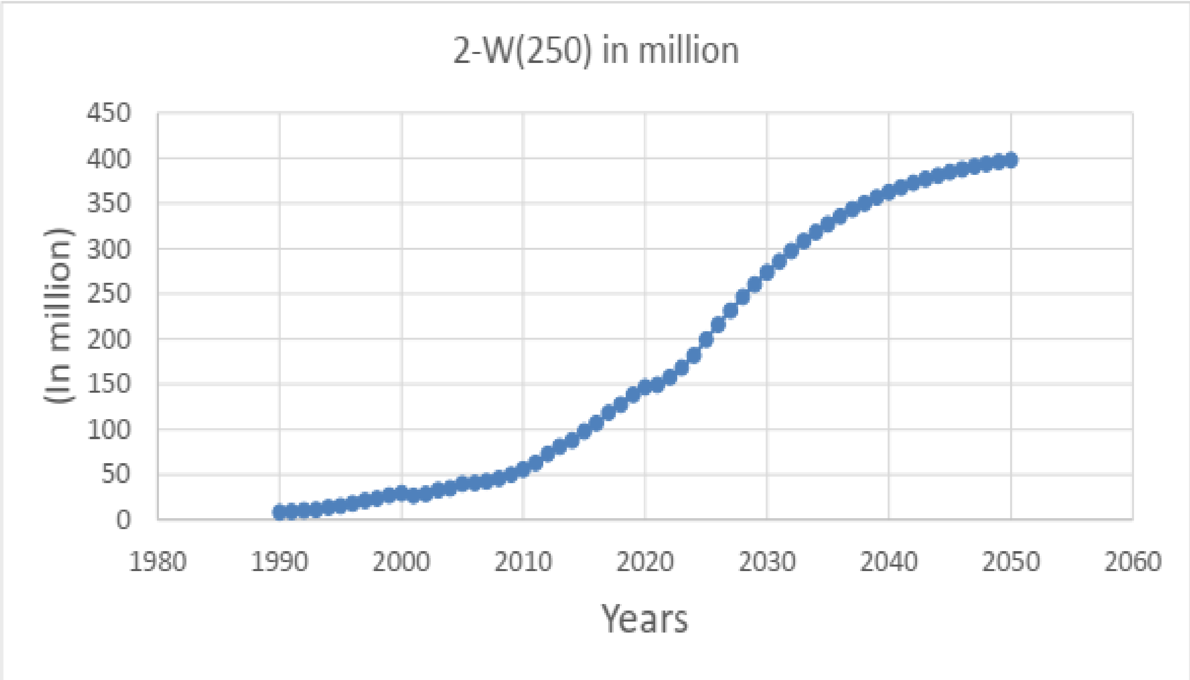


Figure 10: Vehicles (2Ws) in million fleet

The model suggests that there would be 200 million cars in 2050 and over 400 million 2Ws.

3.2 Electric Vehicles

The total vehicles per 1000 person, based on population, were converted into total vehicles on the road (in millions). Of the total vehicles, the EV share of cars (cars, jeeps, taxis) (Figure 11) and 2Ws (Figure 12) were projected based on the business as usual (BAU) scenario.

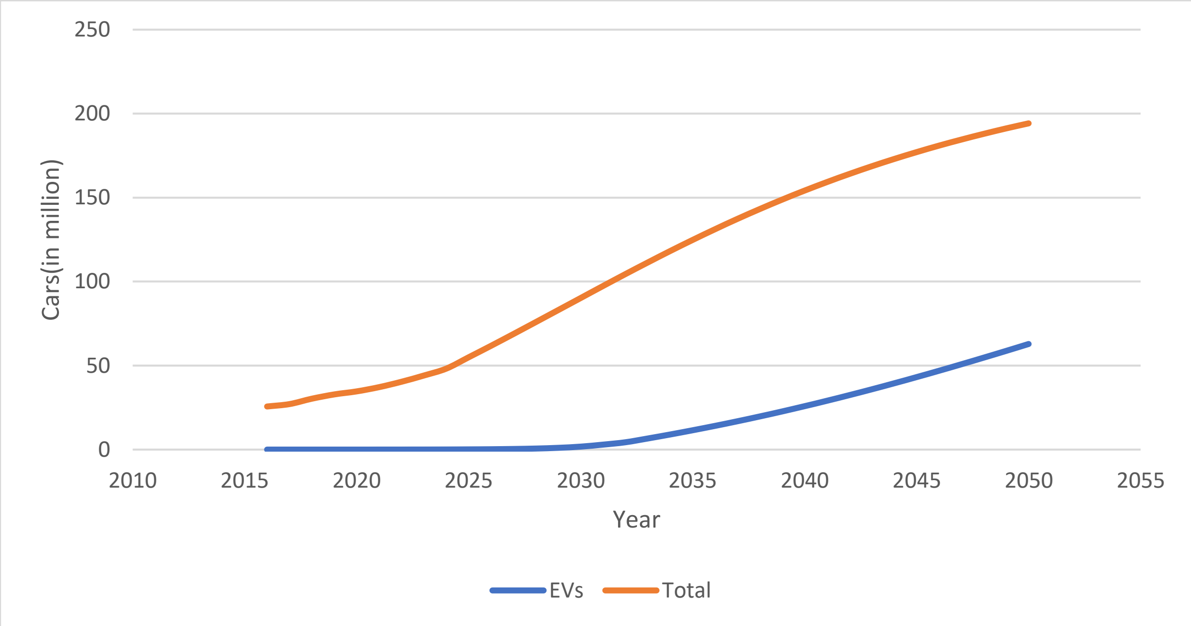


Figure 11: Total and EV Cars (BAU scenario) Inventories

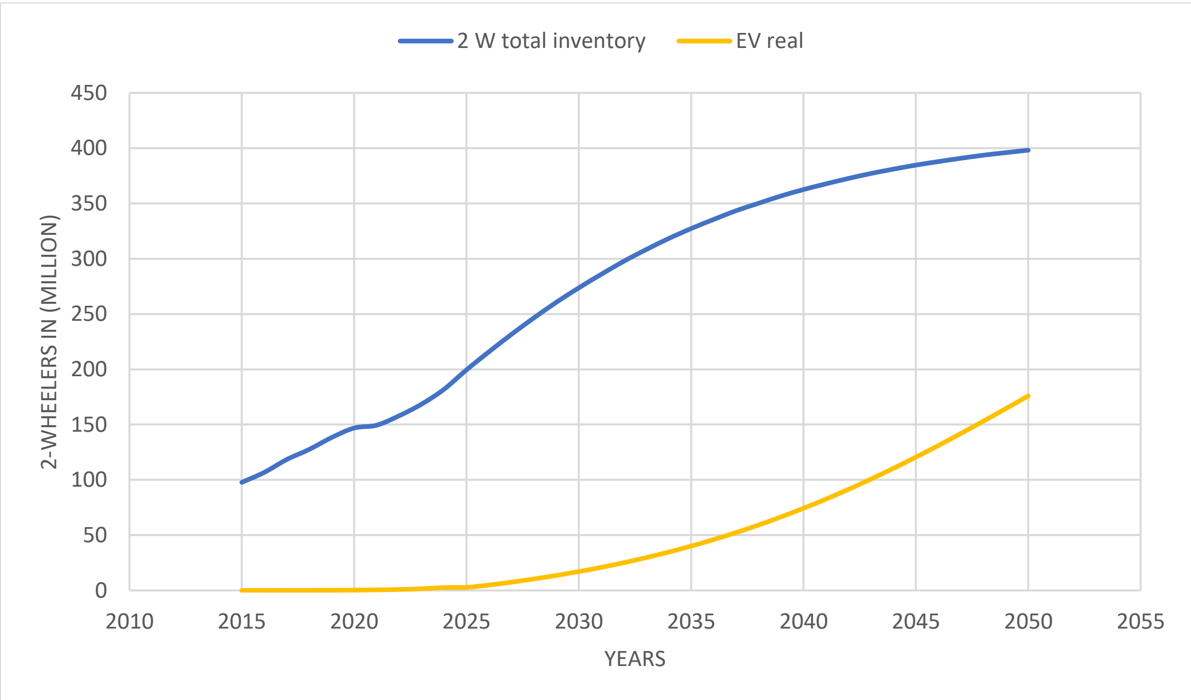


Figure 12: Total and EV 2Ws (BAU scenario) Inventories

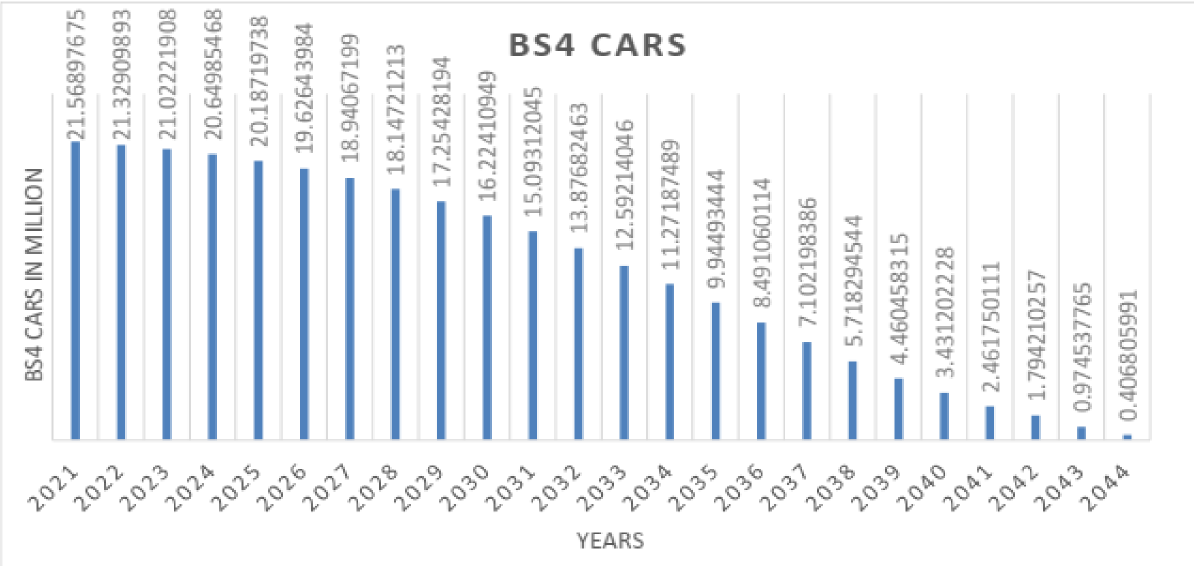
The model suggests that in 2050 there would be about 62 million EV cars and about 175 million EV 2-Ws.

As per the current growth of EVs (i.e., business as usual scenario (BAU)), the number of EVs in 2030 will be insignificant (compared to the total fleet) and in 2040 and 2050 the share of EVs is estimated as 17 and 33 percent of total cars (Figure 11).

3.3 BS Technology-wise break-up of vehicles

Based on the year in which the BS standard was enforced, the number of vehicles sold in different years, and survival function (Figure 6 and Table 3), the distribution of BS4, BS3 for cars, and 2-Ws are shown in Figures 13 and 14. The overall inventory of BS-wise distribution of Cars until 2030 is shown in Figure 15. It is seen that there will be a sizeable number of vehicles in BS3 and BS4 in 2025 and even in 2030 about 25% of cars will be BS3 and BS4.

The ICCT (2010) has estimated the PM emissions from different BS vehicles till 2035 (Figure 16), suggesting that about 40% of emissions will be from BS4 vehicles.



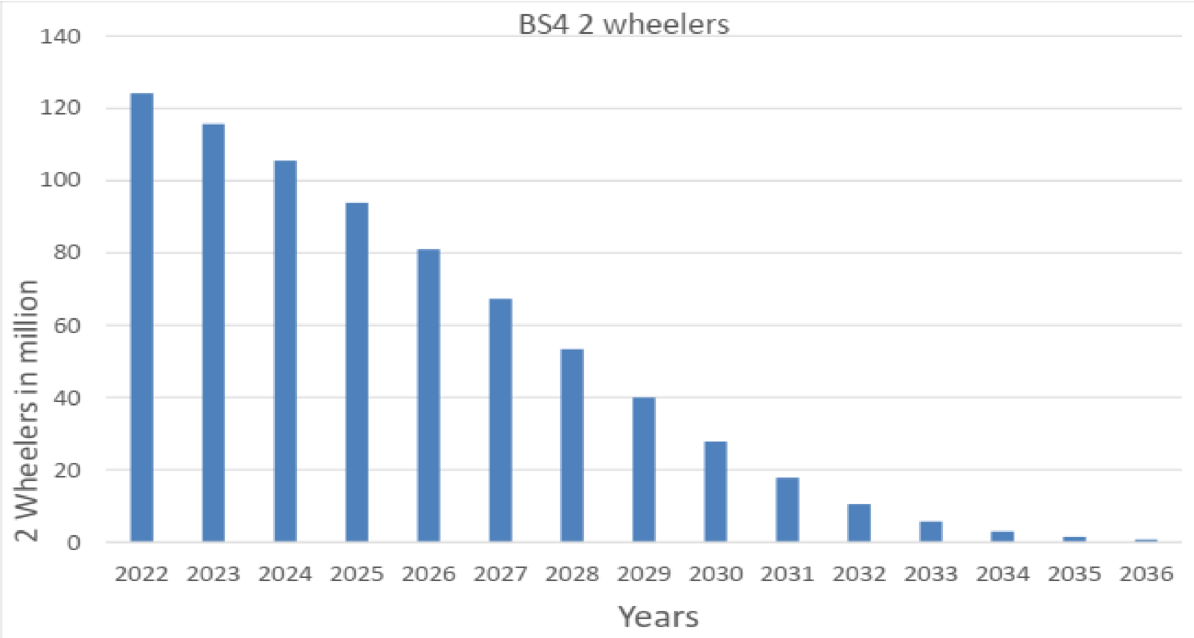


Figure 13: Distribution of BS4 for Cars and 2Ws

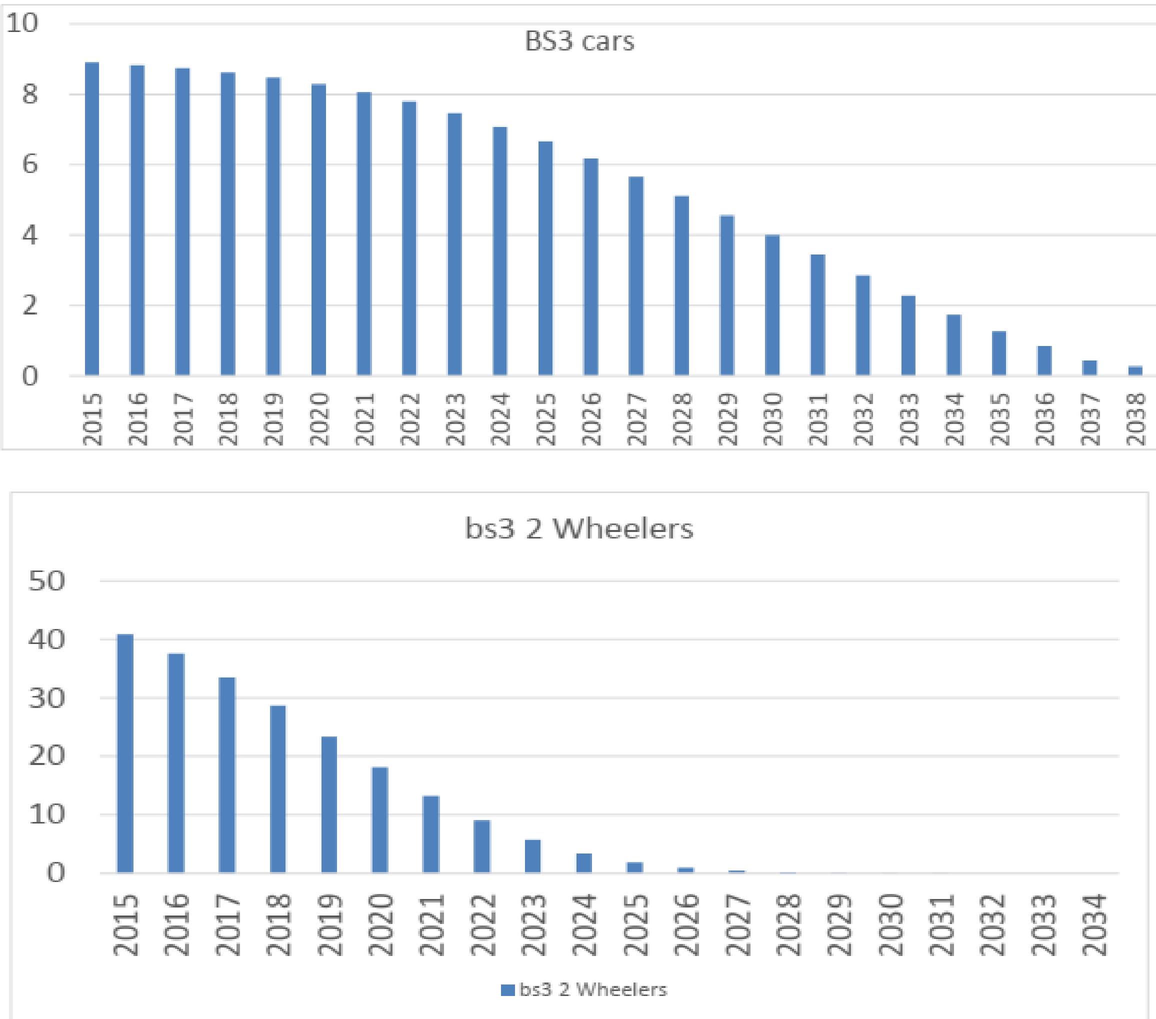


Figure 14: Distribution of BS3 standard Cars and 2Ws

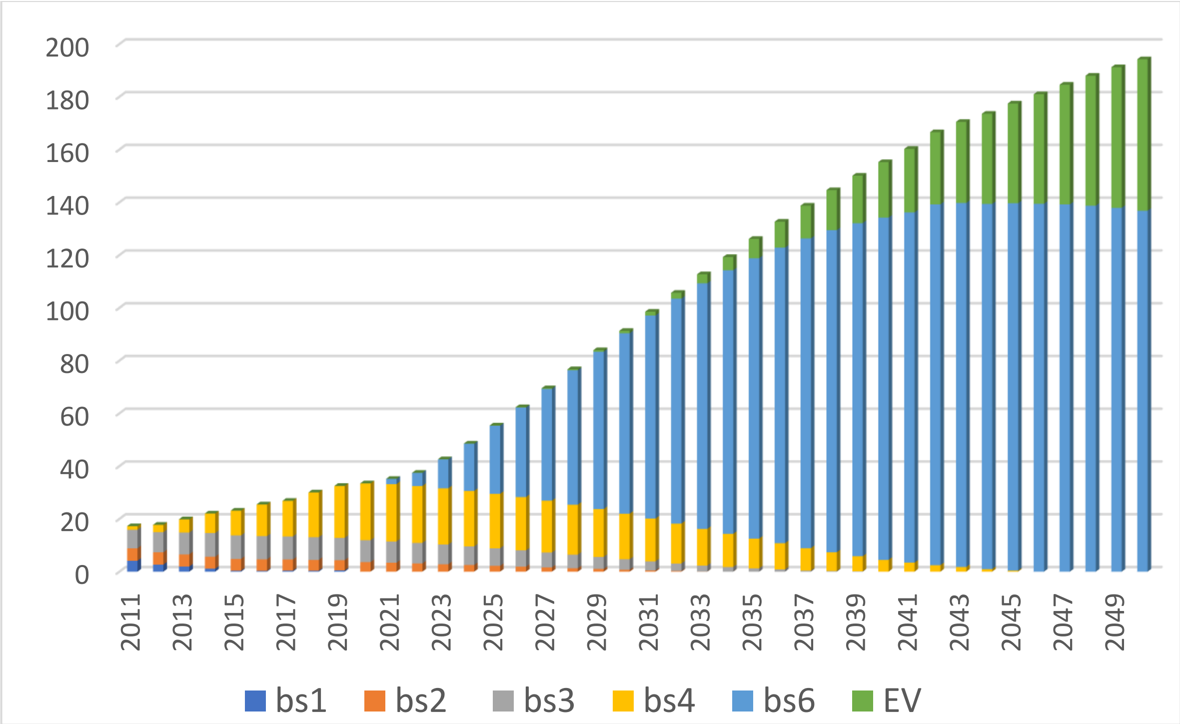


Figure 15: Cars with BS technology type and EVs on roads (units per 1000 person)

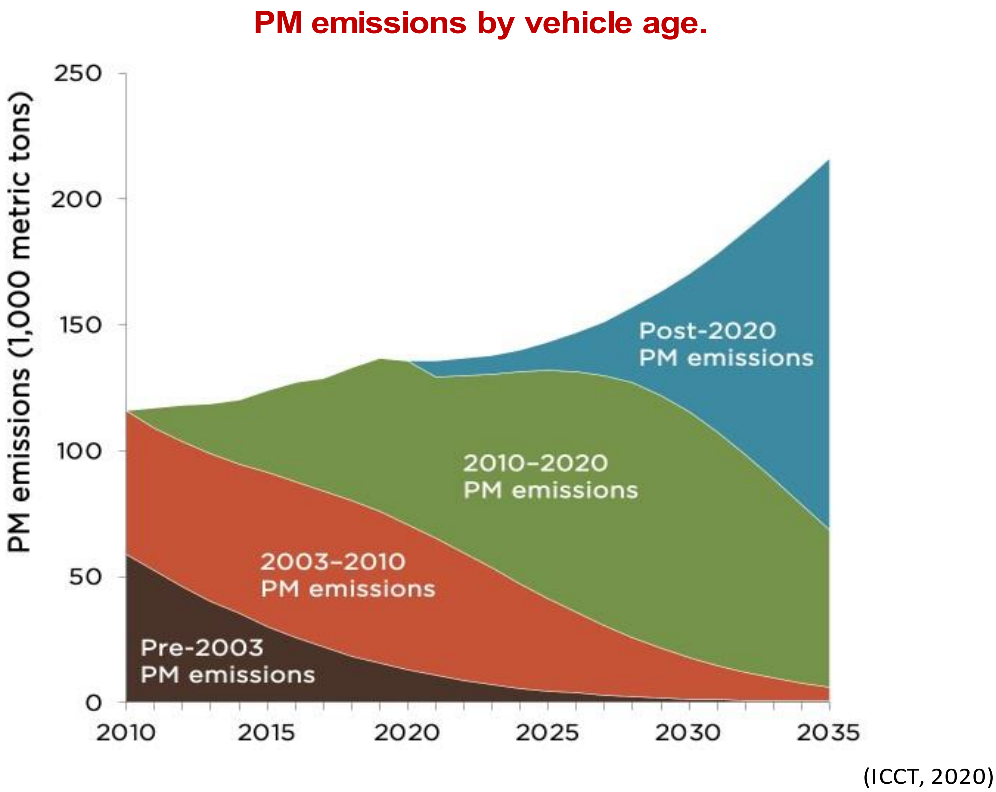


Figure 16: PM emission from vehicles with different BS Technology vehicles

3.4 Emissions

Using Equation (11), the emissions of CO, NOx, and PM have been estimated from cars and 2Ws (Figures 17 and 18). It is seen that despite the introduction of BS6, the CO emission will increase because of more vehicles on the road and higher vehicle kilometer travel. Even though NO_x and particulate emissions would start dropping after the year 2030, the improvement would not be significant enough to see a tangible benefit in the air quality levels

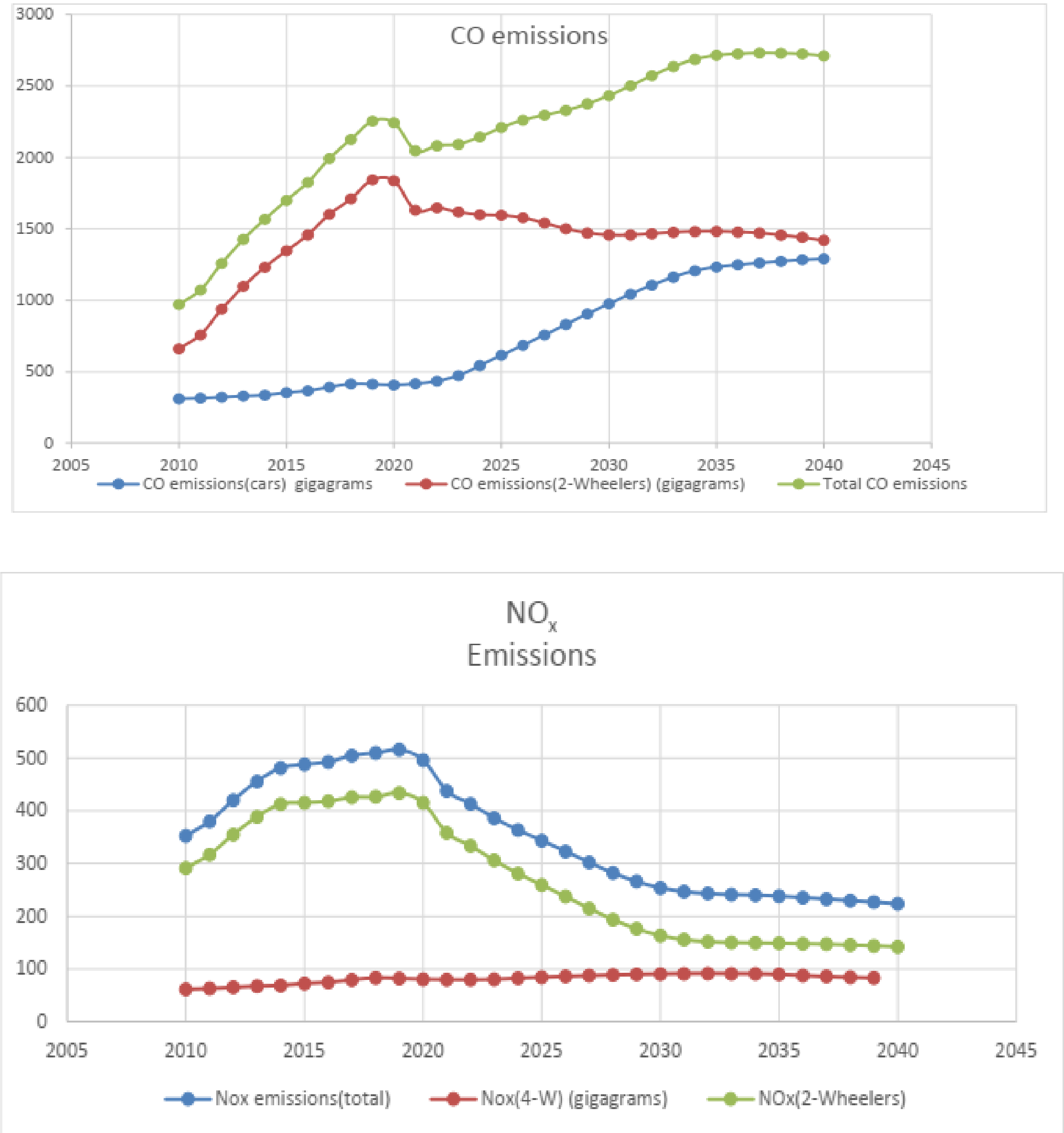


Figure 17: CO and NOx emissions (Gg) (gasoline)

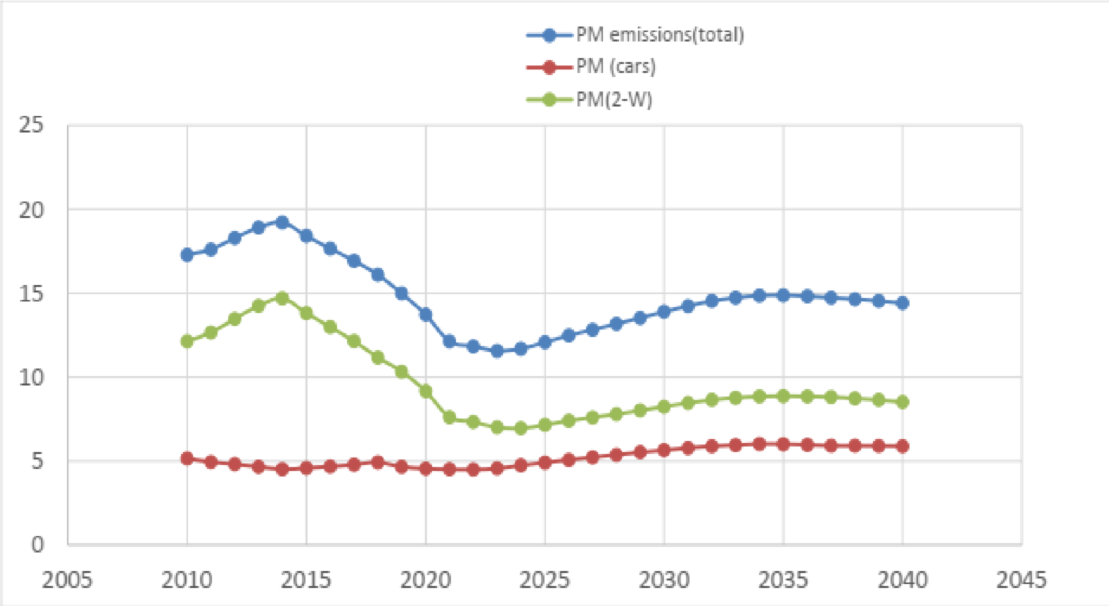


Figure 18: PM emissions (from gasoline in Gg)

3.5 EVs @30% Scenario

The 30% scenario focuses on achieving sales of electric cars (cars, jeeps, taxis) as 30% of total sales by 2030. To achieve this, we take the timeframe from 2023 to 2030. Total sales of PVs in this timeframe are predicted as 51 million sales. Then the EV sales required would be around 14~16 million (30% of 51million). Such sales are feasible but still practically difficult as shown in Table 4.

Table 4: EV Sales required (in millions) to reach the @30% scenario

YEAR	Sales (of total cars in million)	Sales of EV Cars as % of total car	Sales EV cars required (million)
2023	4.922445	5	0.246122
2024	5.896751	10	0.589675
2025	6.763431	15	1.014515
2026	6.842862	20	1.368572
2027	7.014214	25	1.753553
2028	7.105001	30	2.1315
2029	7.15344	40	2.861376
2030	7.161669	50	3.580834
	Total ~51 million		Total ~14million

Figure 19 shows the on-road vehicle fleet if we achieve the 30 @30% scenario. The fleet of EV cars would be around 14 million which will make up 15-16% of the total fleet in 2030. The proportion of gasoline cars remains quite significant.

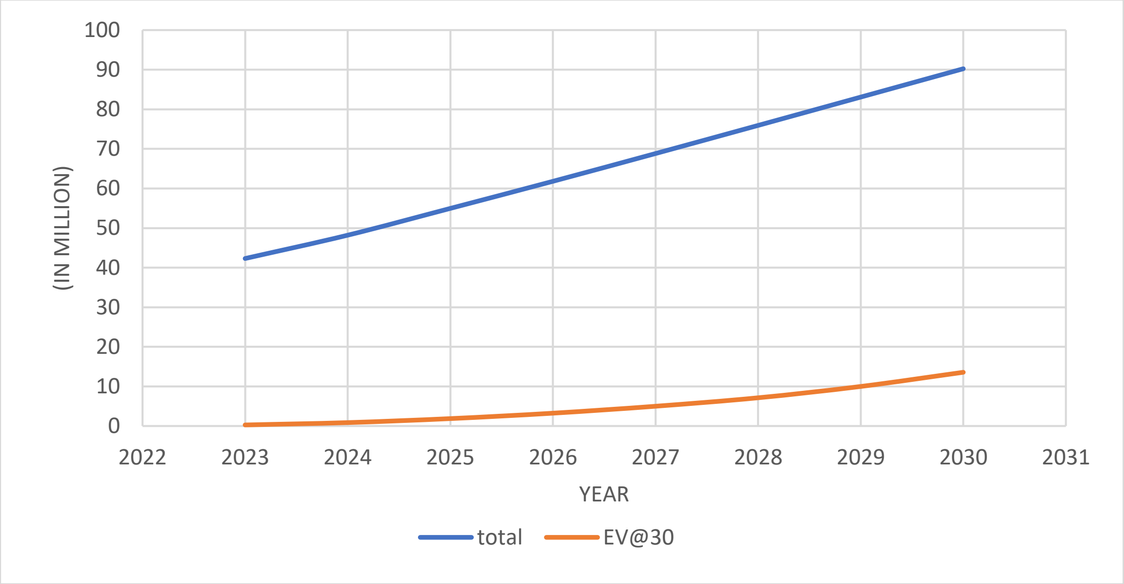


Figure 19: On-Road vehicle fleet with @30% Scenario

Figure 20 shows the vehicle fleet once @30% scenario is achieved in 2030 and BAU thereafter. This suggests that percent share of EVs will be 35% in 2040 and 50% in 2050.

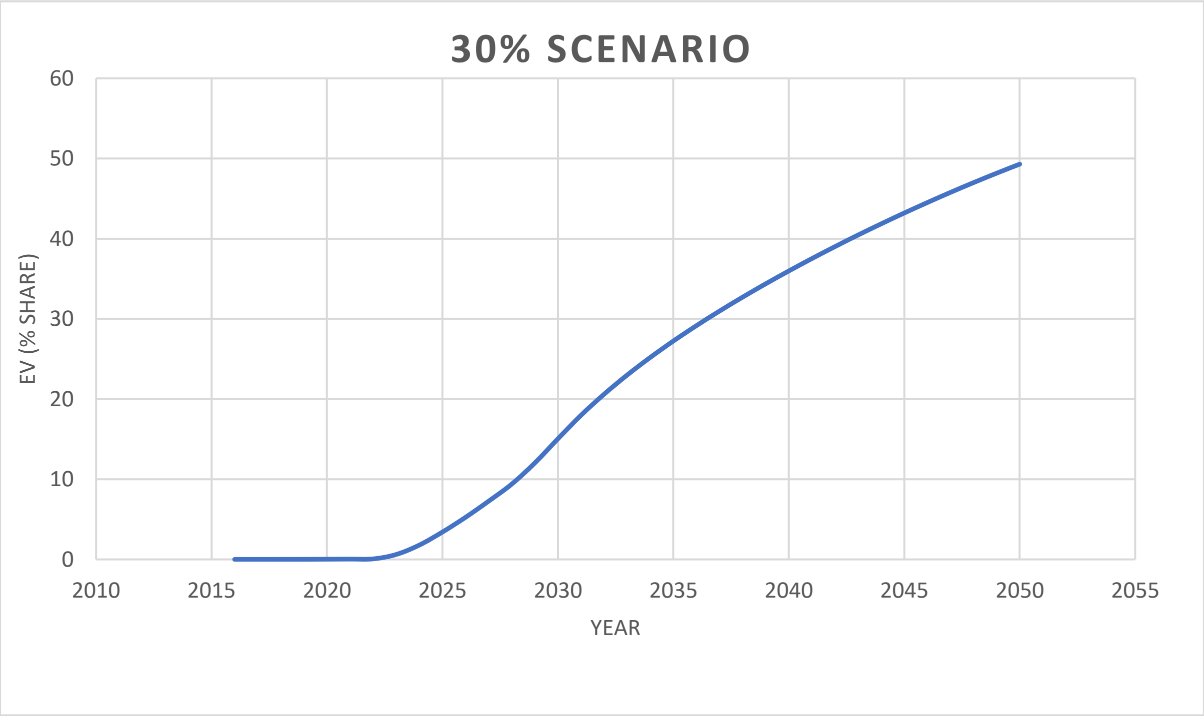


Figure 20: On-Road EV fleet with @30% EVs Sales and BAU thereafter

Figure 21 shows the monotonically increasing share of EVs with a 30% scenario over the years and the declining rate of increase of ICE. The number of ICE will first start to stabilize at around 100 million cars in 2040 and then the numbers begin to decline. However, the number of ICE cars in 2040 will be higher than EVs and just about the same (i.e. 50% each) in 2050.

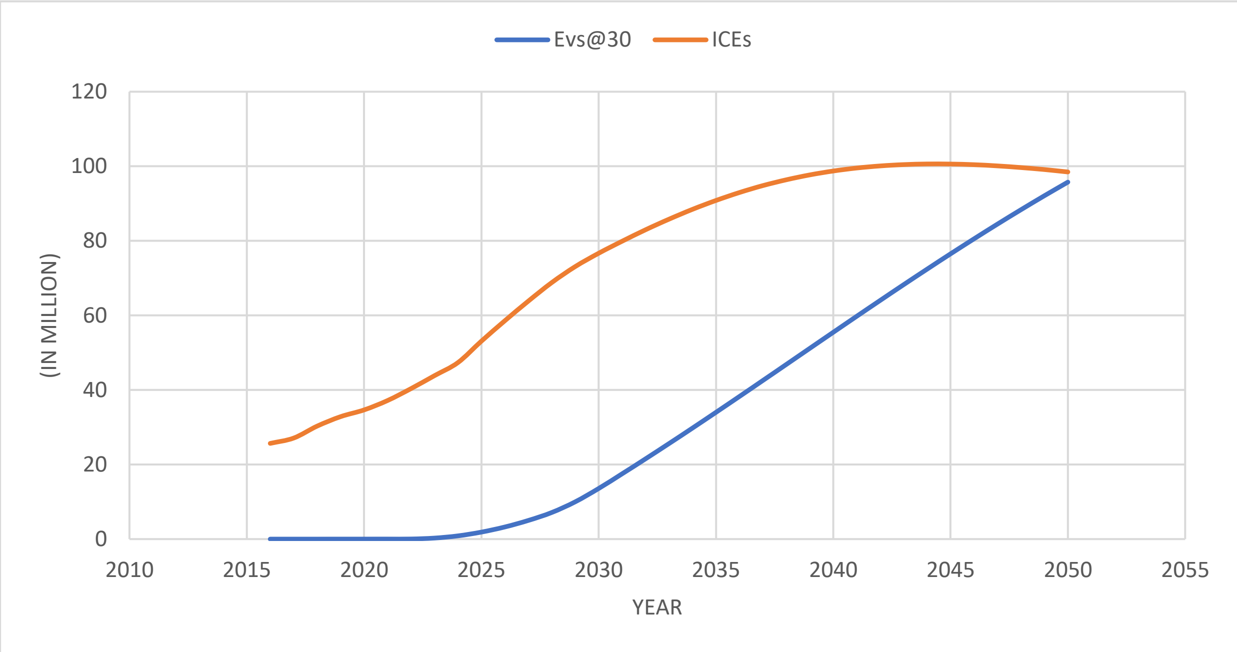


Figure 21: ICEs and of EVs (@30 Sales scenario)

Chapter 4. Estimation of Particle Number Emission with GPFs, EVs and without GPFs

Now that we understand that a large fleet of gasoline cars and 2Ws would be plying on roads and emitting particulates for a couple of decades at the very least, there is an exigent need to understand and adopt the technologies that have a potential to minimize the particulate emissions. In this chapter, we estimate the potential reduction in PN emissions in different years by adopting GPF in gasoline-powered ICE of new BS6 PVs.

#PN Number calculation

On average gasoline vehicle without filter emits 690 x 10^9 (690 billion) particles per km but with the filter, it emits 90 x 10^9 (90 billion) particles per km ((Source: Emission Analytics (Septillion Particle Problem) (2022) & ICCT (2016)).

For vehicles (without GPF)

#PN(in septillion) =630*10^9(particles/km) *no. of vehicles (in billion)*VKT(km/yr)

= particles/year (in septillion or *10^{24})

For vehicle (with GPF)

#PN(in septillion) =90*10^9(particles/km) *no. of vehicles(in billion)*VKT(km/yr)

= particles/year (in septillion or *10^{24})

Scenario 1: Taking all PVs of BS6 sold adopt GPFs from 2025 onwards

This scenario includes BAU for EVs and from 2025 onwards all PVs sold (except EVs) adopting GPFs. Figure 22 shows the estimated impact of the GPF applications in the reduction of PN. The estimated reduction under this scenario is about 85% for PN.

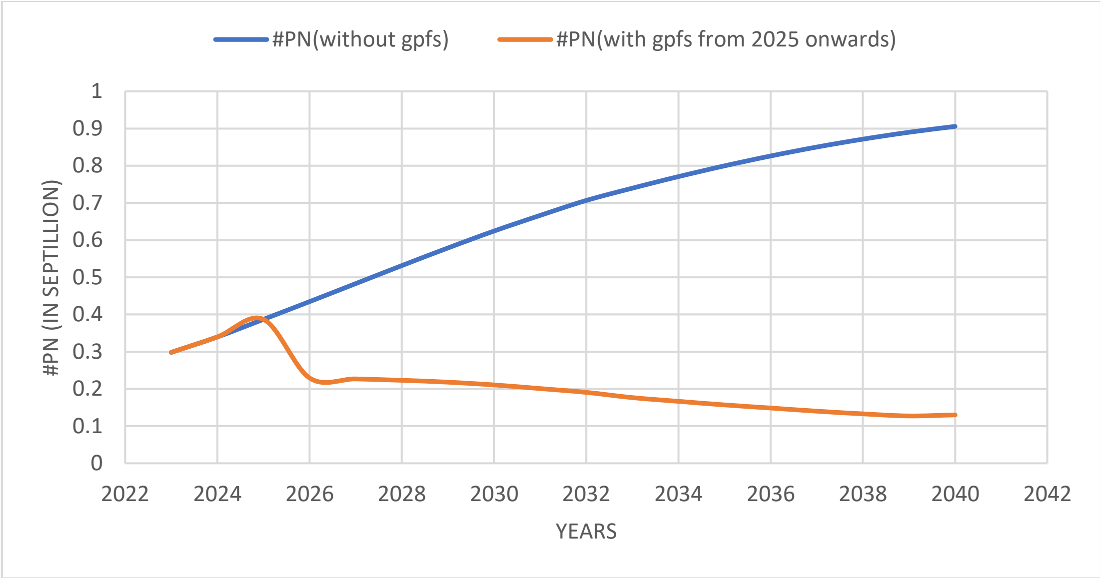


Figure 22: Scenario 1 GPF Adoption (2025 onwards)

Scenario 2: All BS6 PVs sold adopt GPFs from 2025 onwards and EVs (@30% in 2030

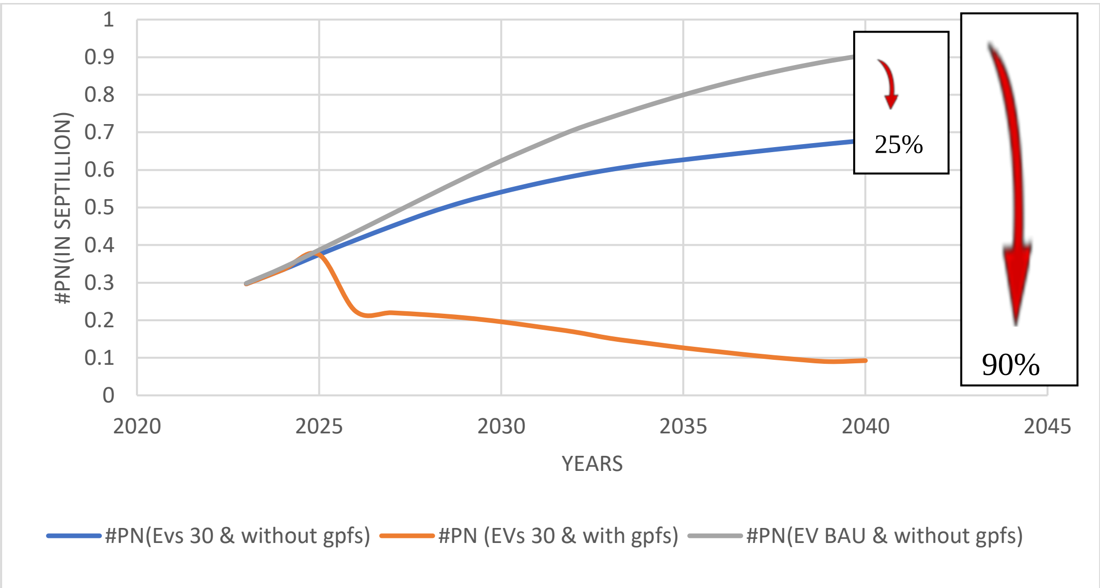


Figure 23: Scenario 2 GPF Adoption (2025 onwards) + EVs@30

The overall reduction in PN emissions will be the outcome of two actions (i) the adoption of EVs and (ii) the adoption of GPF. Figure 23 illustrates the PN reduction over the years with these two actions. In this scenario, EV@30 is also included. It is shown in Figure 11 that the introduction of EVs will be gradual in the BAU scenario and so will not effectively reduce the PN emissions. There is a significant reduction to 90 percent in PN when the adoption of GPF and EVs go hand-in-hand.

Chapter 5. Conclusions

This study, based on sales and survival function of passenger cars (operating on gasoline), presents the status and future growth of the on-road vehicle (car) fleet (both for ICEs and EVs) during 2015 – 2050. The total cars (including cars, jeeps, and taxis) and 2-Ws inventory (vehicle ownership growth) in different years were predicted by Gompertz growth function. The upper limit for the number of vehicles in the year 2050 was estimated as 150 cars per thousand population (conservative), that is, 200 million cars on the road by 2050. The aggressive scenario could have 250 cars per thousand population.

It was seen that there will be a sizeable number of vehicles in BS3 and BS4 in 2025 and even in 2030 about 25% of cars will be BS3 and BS4 and the rest will be BS6. Regarding particulate emissions, this would start to reduce after the year 2030, the improvement would not be significant enough to see a tangible benefit in the air quality levels.

It was estimated that as per the current growth of EVs (business as usual scenario (BAU)), the number of EVs in 2030 will be insignificant (compared to the total fleet) and in 2040 and 2050 the share of EVs is estimated as 17 and 33 percent of total cars.

The scenario where EV sales account for 30% of total passenger car sales, in the time frame 2023 – 2030, is examined. Extraordinary efforts are required to achieve 30% sales of EVs by 2030. Once @30% scenario is achieved in 2030 and the BAU scenario thereafter, the on-road percent share of EVs will be 35% in 2040 and 50% in 2050. The number of ICE will first start to stabilize at around 100 million cars in 2040 and then the numbers begin to decline. However, the number of ICE cars in 2040 will be higher than EVs and just about the same (i.e., 50% each) in 2050.

It appears with the best of efforts for EV sales, gasoline vehicles will be sold even after 2030 and a significant fraction of on-road vehicles will be ICEs. If the EVs share has to further increase, the accelerated growth of EVs sales has to continue for many more years even after 2030.

Since gasoline ICEs are expected to be used for the next two decades at least, there should be an assessment of the emissions inventory (especially particulates) they would be releasing into the atmosphere. Like European Union, India needs to explore the possibility of fuel/technology neutral regulation as a large portion of the PV segment remains unregulated with respect to particulates. From a technology standpoint, we have access to an advanced Exhaust After-Treatment System (EATS). EATS solutions like GPF can be extremely effective in mitigating emissions from these engines. A GPF is a porous ceramic honeycomb structure that filters the particulates from engine exhaust and allows only clean air to enter the atmosphere. GPFs are expected to be widely used in the European Union (EU) and China to meet the PN emission standards.

The potential reduction in PN emissions, in different years, by adopting GPF in gasoline-ICE was examined. The scenario considered was BAU growth of EVs, and from 2025 onwards, all BS6 PVs sold adopt GPFs. The estimated impact of the GPF adoption shows about 90% reduction in PN emission.

The overall reduction in PN emissions will be the outcome of two actions (i) the adoption of EVs and (ii) the adoption of GPF. The introduction of EVs will be gradual and this alone will not be effective in reducing PN emissions. Even if we take EV@30 in the scenario, the EVs share in PN reduction is 25 percent. It appears that when the adoption of EVs and GPFs (in ICEs) happens simultaneously, a significant reduction of over 90 percent in PN inventory levels can be achieved (which will prevent ~0.81×10^{24} #PN emission). It can be stated that while EV adoption should be accelerated, however, to obtain significant PN reduction and tangible improvement in air quality levels, advanced EATS solutions like the GPF should be considered.

Chapter 6. References

B. Al-Alawi, Thomas H. Bradley. 2013. Review of hybrid, plug-in hybrid, and electric vehicle market modeling Studies Published 1 May 2013 Engineering Renewable & Sustainable Energy Reviews

Salil Arora, Anant Vyas and Larry R. Johnson (2011) "Projections of highway vehicle population, energy demand, and CO_2 emissions in India to 2040"

Tian Wu, (2014) Analysis of Future Vehicle Energy Demand in China Based on a Gompertz Function Method and Computable General Equilibrium Model https://onlinelibrary.wiley.com/doi/10.1111/j.1477-8947.2011.01341.x

Apoorva,Chandra (2014) "Estimating emissions from the Indian transport sector with onroad fleet composition and traffic volume"

Statista, (2014). Average annual mileage of passenger cars in India as of December 2014 (in kilometers) https://www.statista.com/statistics/608392/automobile-industry-domestic-sales-trends-india/

Rietmann N, Hügler B, Lieve T (2020) "Forecasting the trajectory of electric vehicle sales and the consequences for worldwide CO_2 emissions" Journal of Cleaner Production Volume 261, 10 July 2020, 121038

Sharma M and Singh R (2021). Indian Drive Cycles and RDE Program for Effective Emission Norms, Controls and Policies. Dept. of Civil Engineering, Indian Institute of Technology Kanpur,(https://home.iitk.ac.in/~mukesh/Publications/Indian%20Real%20Driving%20Emission%20Reprort%202021.pdf)

Paliwal U., Sharma M. Burkhart, J. (2016). Monthly and Spatially Resolved Black Carbon Emission Inventory of India: Uncertainty Analyses. Atmospheric Chemistry and Physics; An International Journal of European Geosciences Union. Volume: 16 Issue: 19, 12457-12476

Rietmann N. (2020) Breaking the conventions: Routes toward green consumer behavior http://ux-tauri.unisg.ch/EDIS/Dis5011.pdf

Guo et al. (2016) Scenario analysis to vehicular emission reduction in Beijing-Tianjin-Hebei (BTH) region, China, https://www.sciencedirect.com/science/article/pii/S0269749116304705?via%3Dihub

Maddhesia J 2020, National Emission Inventory of PM2.5 on GIS Platform Master of Technology, Thesis, Department of Civil IIT Kanpur

ICCT (2016) and Emission Analytics (Septillion Particle Problem) (2022) For emission factors, https://dieselnet.com/standards/in/ld.php