



Medium-term projections of vehicle ownership, energy demand and vehicular emissions from private road transport in India

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Abstract

Rapid growth of private vehicle ownership in emerging economies like India has major implications on transport infrastructure, energy demand and emissions targets. This study attempts to model the relationship between income and vehicle ownership for two-wheelers and cars in India. Further, the study aims to project various medium-term scenarios of vehicle ownership, fuel demand, and vehicular emission based on economic growth rates and electric vehicle adoption scenarios. Road infrastructure requirements and subsequent CO₂ emissions are also forecasted. Using time series data from 1960 to 2019, a nonlinear Gompertz function is estimated. Subsequently, a bottom-up methodology is used to forecast energy demand and emissions. This study proposes and utilises an incremental addition to vehicle stock approach to estimate on-road vehicles. In addition, it also incorporates longer time series to include the exponential growth of private vehicles in the previous decade. Further inclusion of electric vehicles and its related electricity demand and emissions are presented. The results indicate an addition of 107–145 million vehicles to existing fleet by 2030. During this decade 200–250 million vehicles are projected to ply on-road annually resulting in a peak fuel demand of 60 million tons and CO₂ emissions of up to 174 million tons. However, with the adoption of EVs and ownership approaching saturation levels, both fuel demand and vehicular emissions are forecasted to peak before they subsequently decline. Lastly, appropriate transport policy measures and investment spheres are required to direct concentrated efforts. Hence, a discussion of how to reduce dependency on private vehicles and regulate vehicular emissions is also suggested.

Keywords Vehicle ownership · Energy demand · Gompertz function · Greenhouse gas emission · EV · Transport policy

JEL Classification Q47 · Q54 · R42 · R48 · R49

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1 Introduction

India has witnessed rapid growth in vehicle population over the years. Since 1960, the number of total registered vehicles in India has grown significantly from 605 thousand to 295 million in 2019 at a compound annual growth rate (CAGR) of 10.87 per cent. A large part of this growth has been driven by private vehicle ownership, which includes two-wheelers and four-wheeler light motor vehicles i.e., cars. Over the last six decades, private vehicles have grown significantly from 358 thousand to 259 million in 2019 at a CAGR of 11.6 per cent. Two-wheelers, which accounted for 21 per cent of all private vehicles in 1960, have grown at a CAGR of 14 per cent to account for 85 per cent of total private vehicles in the country. On the other hand, the number of registered cars has grown by 38 million during this period. In contrast, the growth rate of public transit i.e., buses, has remained low around 6.2 per cent, with vehicle stock increasing from 280 thousand to 2 million. During the last decade (2009–2019), the addition of new public transport vehicles witnessed a further slowdown with only 500 thousand buses added to the existing fleet at a CAGR of a mere 3.2 per cent.

Steady economic growth and a growing population have propelled demand for travel. Rapid urbanisation and land use patterns have already exerted enormous pressure on the existing public transport systems, which, along with rising living standard, has resulted in an ever-growing demand for private vehicle ownership in India. In the coming years, India's small vehicle fleet relative to its large population is expected to grow rapidly (IEA, 2020; SHAKTI, 2019). This will carter the need of growing travel demand in lack and/or absence of an efficient mass transit network in both urban and rural space. Figure 1 shows the growing share of private vehicles as a part of aggregate vehicle stock in India, which has increased from 59 to 88 per cent in the last six decades. Since the turn of the century, the stock of private vehicles has grown more than seven times from 40 to 286 million. Contrastingly, the share of buses in the aggregate vehicle stock has declined from 9 per cent to a meagre 1 per cent in which presents a massive concern.

In the past, developed nations have witnessed a positive relationship between private vehicle ownership, economic development, and rising population. It can be ascertained that vehicle ownership rate and economic growth do not follow a linear relationship. At lower levels of national income, a rise in income enables vehicle ownership rate to grow slowly

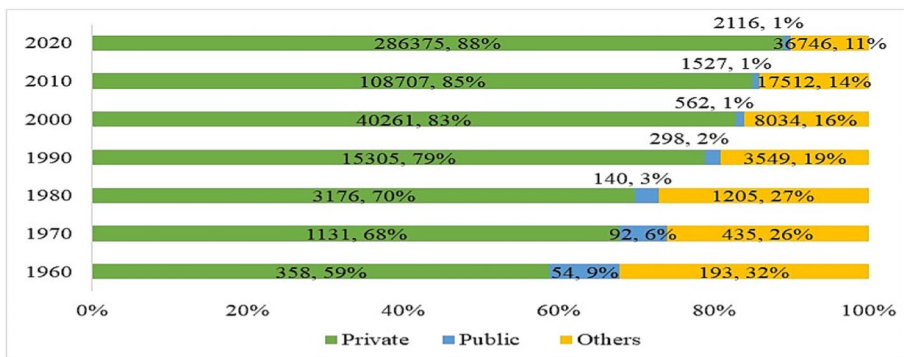


Fig. 1 Modal split of aggregate vehicle stock (in '000). *Others include tractors, trailers, light motor vehicles, trucks and lorries

until a certain level (take-off zone). Beyond this critical level, the ownership rate starts to grow rapidly primarily due to aspirations of improved standard of living, higher disposable income, greater travel demand, and the nature of urbanisation. This rapid growth continues until infrastructural bottlenecks start to limit road transport where insufficient road infrastructure discourages personalised travel in megacities (Ramanathan, 2000). It is at this point (saturation level) growth of vehicle ownership starts to slow down; number of new vehicles on-road follows similar pattern eventually attaining saturation. Thus, following an S-shaped curve.

India is home to approximately 1.3 billion people and is the fifth largest economy in the world (World Bank, 2023). India is also witnessing a rapid growth in private vehicle ownership. If evidence from developed nations hold, existing rapid surge motorisation can continue in the future in India with growth in economy and living standards. This could have varied implications within and outside the transport sector. Currently, the transport sector contributes to around half of India's oil demand (IEA, 2021) and accounts for a substantial share of total energy demand in India, with only the United States of America, China, and Russia committing a higher proportion of their energy to transportation (IEA, 2016). Meanwhile, the transport sector is also responsible for 13.5 per cent of total energy related CO₂ emissions in India of which road transport accounts for 90 per cent of sectoral energy consumption (IEA, 2020). Apart from GHG, local air pollution that results in detrimental health effects and premature deaths is another form of negative externality that the transport sector contributes. According to the World Air Quality Report published by IQ Air (2019), twenty-one of the world's thirty most polluted cities are in India, and none of them met the WHO's annual pollution exposure target during their study period.

The transport sector is one of the largest sources of CO₂ emissions globally with annual emissions more than 20 per cent of global emission in 2016 (FICCI, 2020). This is predicted to increase rapidly by 2050 due to significant growth of automobiles adoption and usage. Given the rapid rise of private vehicle adoption in India in parallel with accelerating economic growth, makes the transport sector in India critical from an energy use and decarbonisation perspective (CEEW, 2022). Consequently, the policy initiatives undertaken by India in its transport sector will not only have local implications (in reducing the adverse health impacts of local air pollution) but will also influence on global efforts to achieve the long-term temperature targets.

Hence, understanding India's transport dynamics and future vehicle ownership scenarios (and potential on-road vehicle stock), and its implications on energy requirements and emission of local and global pollutants is highly policy relevant. As policies implemented today will dictate the energy use and carbon emissions from this sector in the future, they will play a crucial role in the context of the Net-Zero emission targets announced by India during COP 26 in Glasgow in 2021. Therefore, strategizing effective control measures to address rising vehicle ownership on already cramped Indian roads and reduce emissions from road transportation requires a detailed investigation of the status quo and future projections. This will facilitate in designing of appropriate policies directed towards transport-oriented urban land use, addressing ambient air quality, and setting up suitable control measures to achieve GHG emission reduction targets.

The focus of this work is to utilise longer time series data (1960–2019) of private vehicle population in India to model the income-ownership relationship, estimate fuel demand and build an emission profile for local and global pollutants emitted from the use of private vehicles. Additionally, various scenarios of future medium term private vehicle stock—two-wheelers and cars—are projected till 2030 using an incremental addition to vehicle stock approach along with alternative rates of per capita GDP growth, fuel efficiency

and EV penetration. Lastly, an attempt to estimate road infrastructure requirements and resulting CO₂ emissions is forecasted.

To set the context of discussion in subsequent sections, Sect. 2 summaries recent literature. Section 3 explains the methodology adopted in this study along with sources of relevant data used. Section 4 provides a discussion on the results of various scenarios and highlights comparisons with results of recent literature. Section 5 provides concluding observations along with a brief on the role of appropriate transport policy measures to assist in reducing dependency on private vehicles and controlling vehicular emissions.

2 Literature review

In the past various studies have modelled the relationship between vehicle ownership, economic growth and/or population. One of the earliest studies, Button et al. (1993) modelled vehicle ownership for low-income countries categorised into five groups based on income levels. Using a logistic function to represent per capita ownership as a function of GDP, time trend and country specific dummies assuming a range of saturation levels depending on income levels. They highlighted that car ownership and use rises inevitably as low-income countries become more prosperous. Dargay and Gately (1997) modelled and forecasted growth in car ownership for OECD and select Asian economies. Highlighting the implications of rising vehicle ownership on energy demand and emissions based on Gompertz distributional function, they predicted a decline in the existing difference between OECD and non-OECD countries on car-based transportation, fuel consumption and CO₂ emissions as income rises in developing countries. In a subsequent study, Dargay and Gately (1999), they also highlighted that fastest growth rates of ownership were found in low-income countries, and particularly for those with highest growth rates of income including China, India, South Korea, and Taiwan due both to faster growth in per-capita income and higher income elasticities of car and vehicle ownership.

On a broader geographical scale, Fulton and Eads (2004) used ASIF (Activity, Modal Share, Energy Intensity and Carbon Intensity of Fuel) methodology to forecast fuel consumption and emission pathway based on car and two-wheeler ownership projections using logistic functional global economies divided into various regions. Adopting similar assumptions for fuel economy and travel rate, ADB (2006) projected vehicle ownership, subsequent fuel demand and carbon emissions for China and India using regression coefficients estimated from registered vehicles and per capita income and GDP association. Wu et al. (2014) presented forecast of vehicle ownership in China till 2050 based on historical data from 1963 using a Gompertz functional form to model relationship between GDP per capita and vehicle stock against a background of increasing energy use and CO₂ emissions associated with potential demands of on-road vehicles. They found China's vehicle stock had developed a S-shaped curve where saturation was achieved around 2050.

One of the earliest studies in India by Ramanathan (2000), emphasised on possibility of a S-shaped relationship between population and vehicle stock for Indian cities. The study asserted that, number of vehicles in Indian cities could increase along a S-shaped pattern with population growth and such pattern could lead to rising questions on ease of mobility, inefficient energy use and environmental concerns for urban setting. Further, role of economic growth was hypothesised as a determining factor for such a pattern of growth in vehicle stock. Singh (2006), used logistic and Gompertz functional forms to project passenger kilometre per capita. Energy demands were calculated for business as usual

and efficiency gain scenarios based on improvements in energy intensity of vehicles. A five-fold increase in energy requirements and four-fold rise in carbon equivalent emissions between 2000 and 2021 was estimated in this study.

Boucher and Mazraati (2007) modelled car ownership using various functional forms, viz., Logistic, Quasi-logistic and Gompertz for India. They estimated fuel consumption scenarios till 2030 and fuel demands were forecasted to triple from 2015 to 2030, while vehicle population to grow 2–3 times during the same period. However, their results diverge widely from other literature due to very high assumed level of saturation (850 per thousand population), combined with high energy intensity (13 L per 100 kms). Banerjee et al. (2009), employed a bottom-up approach to explore various scenarios of growth, assuming vehicle stock and fuel intensity to determine fuel use and resulting CO₂ emissions. In the most progressive scenario, car ownership in India by 2030 was projected to 70 cars per thousand people and corresponding CO₂ emission to range between 300 and 430 million tons per year.

Arora et al. (2011) projected highway vehicle stock (HWV) and two-wheelers using a nonlinear Gompertz function in relation to per capita GDP. They forecast India's HWV stock to be third largest in the world by 2040, while yet not attaining saturation level and thus vehicle population would grow beyond 2040. Subsequently, fuel demand was predicted to rise by 4–6 times and CO₂ emissions to grow by roughly 6–11 times. Singh et al. (2019) projected growth scenarios of future private vehicle stocks comprising two wheelers and cars in India up to 2050 under different saturation levels obtained from Arora et al. (2011).

These studies have mostly relied on nonlinear Gompertz functional form used by Dargey et al. (1997), quasi-logistic functional form used by Button et al. (1993), and logistic functional form used by Bouachera and Mazraati (2007) to model such pattern of relationship. The income-ownership relationship is modelled using a non-linear¹Gompertz functional framework in this study. According to the literature, despite a few drawbacks of Gompertz functional models such as lack of interpretability of estimated coefficients, limited applicability to long-term projection, and parameter sensitivity. This functional form better fits the historical data and is more flexible than other models, particularly in allowing different curvature at lower and higher levels of income (Dargay and Gately, 1999). Furthermore, Bouchera and Mazraati (2007) point out that the sensitivity of parameter selection (assumed saturation level) may not have a significant impact on forecasts for nations like India and China, which are at the very beginning of the curvature. Furthermore, in order to circumvent long-term projections, this study restricts its forecast scenarios to the medium term till 2030 and provides a comparison of intermediate-year projections to actual observed values highlighting the robustness methodology employed in this study.

Despite a rich literature on income-vehicle ownership association in Indian context, they do not capture the exponential rise of private vehicle stock witnessed in the last decade. During this period, private vehicles have roughly doubled in size in India. Incorporating

¹ Nonlinear functional forms are commonly used for indicating the s-shaped relationship between economic variables and vehicle ownership. Simultaneously, there are metaheuristic optimising algorithms, such as Prairie Dog Optimisation, Astute Black Widow Optimisation and the Global Best-Guided Firefly Algorithm for Engineering Problems, that can be used to determine the optimum pathways to achieve an objective given a set of constraints. However, the present study estimates potential energy and emission scenarios using a bottom-up approach based on the association between economic variables and vehicle ownership. See Ezugwu et al. (2022) and Ahmed et al. (2022) for discussion on optimising algorithms and its application.

this trend in modelling framework will provide a better fit and reduce the uncertainty for projected years. Hence, this study utilises a time series data spanning sixty years from 1960 to 2019. This will help in better capturing historical association along with recent trends in the vehicle ownerships, compared to existing literature that depend on a more limited time series data. Further, a critical component where this study deviates from existing literature is in employing a new approach to determine number of private vehicles plying on roads at a particular point in time. Existing literature has primarily focused on using “Rule of Thumb” to approximate on-road vehicles. However, such approximation would lead to over/underestimation based on various levels of vehicle ownership rate (discussed later). Hence, this study uses incremental addition to vehicle stock approach which helps to overcome the limitations of traditional approach by incorporating governmental norms (such as permitted life of vehicle etc.) in the analysis. This will also help in arriving at a more accurate projection of fuel demand and emission of pollutants based on a bottom-up² approach. It may also be noted that, the process of estimating relationship between an economic variable and vehicle ownership, and further forecasting future vehicle stock requires a set of assumptions to be made on critical components viz., fuel efficiency, growth rate of per capita income, etc. To better capture the wide range of possibilities in the projections of such parameters, the study adopts three different GDP per capita growth scenarios, and standards set by Bureau of Energy Efficiency-Government of India, for fuel efficiency. Lastly, with the onset of electric vehicles into the mobility sphere, it was necessary to acknowledge their existence, forecast their growth, and estimate carbon emissions from their use. Hence, the study uses multiple scenarios of electric mobility adoption with diverse penetration rates. The following sections will highlight all these in greater detail.

3 Data

Data on various components of this required multiple secondary sources to be examined. In order to estimate the income-ownership relationship, historical GDP per capita data (Constant USD 2010) was obtained from World Bank, data on annual vehicle registration was compiled from Road Transport Statistical Yearbook (MoRTH, 2019), population projections were obtained from World Population Prospect (UNDESA).

For projections of future private vehicle stock of both two-wheelers and cars, three different scenarios of GDP per capita were projected starting from 2019;

- (a) Constant 3 per cent growth rate—Conservative Scenario,
- (b) Growth rate based on SSP-2 obtained from IIASA (2016)—Moderate Scenario and,
- (c) Higher GDP growth rate based on TERI (2006)—Aggressive Scenario.

Other parameter values used in this study that obtained from literature is presented in Table 1 below:

² The bottom-up is a scenario-based approach that builds on the association between economic variable and vehicle ownership and, projects potential energy and emission scenarios. Simultaneously, there are simulation tools such as RETScreens, PRIMES and EVI-Pro which can be useful in predicting say EV charging stations required given a particular future scenario of vehicle ownership, simulating energy demand and supply, and managing energy usage. A discussion on such tools can be found in Ahmed et al. (2022) and Ahmed et al. (2023).

Table 1 Assumptions and parameter values used

Component	Two-wheelers	Cars
Saturation level	210 per thousand population	55 per thousand population
VKT ^a	6300 km per year	12,600 km per year
Fuel efficiency	50 kmpl ^b	18 kmpl for vehicles registered before 2022 ^c , 22 kmpl thereafter
Emission Efficiency	11 gm CO ₂ improvement from 2016	60 gm CO ₂ improvement from 2020
Battery capacity	3 KWh	30 KWh
EV range	100 kms per charge ^d	160 per charge ^e
Life span of vehicles	15 years	15 years

^aSingh (2006)

^bAverage fuel efficiency based onSIAM (2021)

^cBureau of energy efficiency (2015)

^dICCT (2021)

^eSIAM (2017)

Table 2 Emission factors for road vehicles (in g km⁻¹)

Gas	Cars	Two-wheelers
CO ₂	213	52.48
CH ₄	0.039	0.04
NO _x	0.026	0.003
PM	0.03 ^a	0.05 ^a
SO ₂	0.053 ^b	0.013 ^b
GEF	750 gCO ₂ /KWh till 2027, 600 gCO ₂ /KWh thereafter ^c	

^aCPCB (2007)

^bKandlikar and Ramachandran (2000)

^cTERI (2019)

Table 2 presents list of emission factors and grid emission factors used in this study which were compiled from IPCC (2006) unless stated otherwise.

4 Methodology

4.1 Projection of future vehicle stock

Choice of an appropriate functional form to represent the relationship is a key component in forecasting future vehicle stocks. Despite a few limitations associated with the Gompertz functional form, the literature suggests that the it can help in more effectively capturing changes along the critical levels. Dargay and Gately (1999) examined multiple functional forms and found that the Gompertz functional form provides more flexibility. According to Bouachera and Mazraati (2007), parameter selection (viz., assumed saturation level) may not significantly impact projections for nations such as India and China, which are at the bottom of the curve. As a result, the nonlinear relationship is modelled

using the Gompertz functional form specified in Eq. 1. Although several studies use estimated parameters to forecast long-term scenarios, this study prioritises medium-term projections as there could be various exogenous factors that can influence long-term results.

$$V^* = \gamma \exp^{\alpha \exp^{\beta \text{GDP}}} \quad (1)$$

where, V^* = long-run equilibrium level of the vehicle/population ratio.

GDP = Per Capita Income.

γ = Saturation Level measured in vehicles per thousand people.

α, β are negative parameters defining the shape of the curvature of the function.

Reducing Eq. (1) to its linear form, by taking log both sides, we get;

$$\log(\log(\gamma/V)) = \log(-\alpha) + \beta(\text{GDP}_t) \quad (2)$$

Here, (γ) the saturation point of vehicle ownership rate, is an important component for determining future vehicle ownership. It is an assumed level based on which estimation of the modelled relationship and subsequent projections of vehicle stock is made. The saturation level for two-wheelers was assumed to be 210 per thousand population from the existing level of 160 and 55 per thousand population for cars from existing 27.

An ordinary linear regression to determine the parameters of Gompertz function was estimated. Using the assumed GDP growth rates, future scenarios of vehicle stock was projected based on ownership rates and population projections.

4.2 Estimation of fuel and energy demand

Estimation of fuel demand and energy demand are based on these components: (a) Number of vehicles plying on-road, (b) Annual vehicle kilometres travelled (VKT), (c) Fuel efficiency—kilometre driven per litre of fuel consumed (for ICEs), and (d) Energy efficiency—kilometre driven per full charge (for EVs).

Based on the values from Table 1, fuel demand was derived using the following equation:

$$\text{FD}_{it} = (R_{it} * \text{VKT}) / \text{FE}_i \quad (3)$$

where,

FD_{it} is Fuel Demand at time period t by vehicle type i

R_{it} is number of vehicles on-road at time period t of vehicle type i

VKT_i is Vehicle Kilometre Travelled by vehicle type i

FE_i is Fuel Efficiency of vehicle type i and varies only for cars beyond 2020 as described in Table 1.

While, energy demand was derived using;

$$\text{ED}_{it} = (R_{it} * \text{VKT}) / \text{Cap}_i \quad (4)$$

where,

ED_{it} is Energy Demand at time period t by vehicle type i

R_{it} is number of vehicles on-road at time period t of vehicle type i

VKT_i is Vehicle Kilometre Travelled by vehicle type i

Cap_i is Battery capacity of vehicle type i

4.2.1 Approximation of vehicles on-road (R_t)

Number of vehicles on-road forms the basis of these forecasting processes of fuel demand and tailpipe emissions. Since, estimated vehicle stock based on modelled ownership rate in the previous section derives total registered vehicles in the country to date. It is necessary to segregate vehicles that ply on roads from this aggregate vehicle stock. It is logical that all registered vehicles will not be plying on roads. Vehicles registered in early years would have been phased out due to regular end of life of vehicle and governmental norms. Hence, it is crucial to adopt an approach based on which approximation of number of vehicles on road is determined.

A common practice is to use “Rule of Thumb” (RoT) approach where two-thirds of total registered vehicles are assumed to ply on-road and one-third vehicles are assumed to be obsolete. Studies in the past have generally employed this approach owing to its simplicity in terms of application. However, this is a crude measure that is prone to underestimation and overestimation at different stages of vehicle ownership rate. In order to address the limitations of RoT, an incremental vehicle added approach was devised and used in this study. The incremental vehicle approach estimates the number of on-road vehicles for a particular year based on vehicles registered during that year and 14 previous years. Hence, number of vehicles on-road for each year would comprise vehicles registered in the last 15 years (including the present year), as represented in the equation below.

$$R_t = \sum (N_t + N_{t-1} + \dots + N_{t-14}) \tag{5}$$

where,

R is Number of vehicles on-road for year t .

N is newly added vehicles during the year t .

This approach takes into consideration governmental norms relating to use of private vehicles in the country. The government of India deregisters petrol powered vehicles older than 15 years due to vehicle fitness and emission standards. These vehicles are not legally allowed to ply on roads unless applied for a re-registration which attracts stringent vehicle fitness tests. This is a more realistic approximation of the number of vehicles on-road due to low survival rates of vehicles beyond the government mandated life span.

Figure 2, illustrates comparison between incremental addition to vehicle stock approach and RoT. The difference is negligible in the initial years. However, they deviate and offer varied approximations beyond a certain stage. From turn of the century till 2024, RoT underestimates number of vehicles on-road and on contrary highly overestimating thereafter.

4.3 Estimation of local and global pollutant emissions

4.3.1 Conventional vehicles

Estimation of tailpipe emission was derived based on; (a) aggregate VKT of two wheelers and cars, (b) Emission Factors.

A bottom-up approach was adopted to estimate gaseous and particulate matter emission. The calculation of aggregate emissions based on actual number of vehicles plying

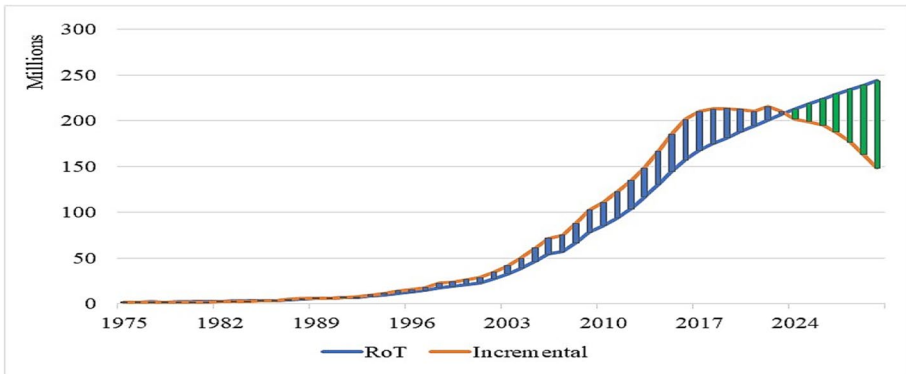


Fig. 2 Comparison of on-road vehicles under RoT and incremental addition to vehicle stock approach

on-roads, average distance travelled and corresponding emission factor is mathematically represented in the following equation:

$$E_{it} = (\text{Veh}_{jt} * \text{VKT}_j) * \text{EF}_{ij} \quad (6)$$

where,

E_{it} is Emission of a particular Pollutant i at time period t

Veh_{jt} is Number of vehicles per type j at time period t

VKT_j is Vehicle Kilometre Travelled by vehicle type j

EF_{ij} is Emission Factor corresponding to particular pollutant i from vehicle type j per km travelled.

4.3.2 Electric vehicles

The following equation was used to estimate CO_2 emissions from EV use.

$$\text{CO}_{2i} = \text{ED}_{it} * \text{GEF} \quad (7)$$

where,

CO_{2i} is Carbon dioxide emissions from vehicle type i

ED_{it} is Energy Demand at time period t by vehicle type i

GEF is Grid Emission Factors.

4.3.2.1 Penetration of EV Since the introduction of Faster Adoption and Manufacturing of Hybrid and Electric (FAME) scheme in India, EVs have become lucrative. During FY 2018–19 and 2019–20, nearly 50 thousand electric two-wheelers and two thousand cars were registered. With EVs being regarded as the future of road transport with growing environmental awareness and urgency in controlling emissions to achieve net zero target, inclusion of EV adoption into the existing framework becomes necessary.

Therefore, EVs were segregated from aggregate on-road vehicles stock. In order to map penetration of EVs in India, growth rates witnessed in already existing EV markets were used:

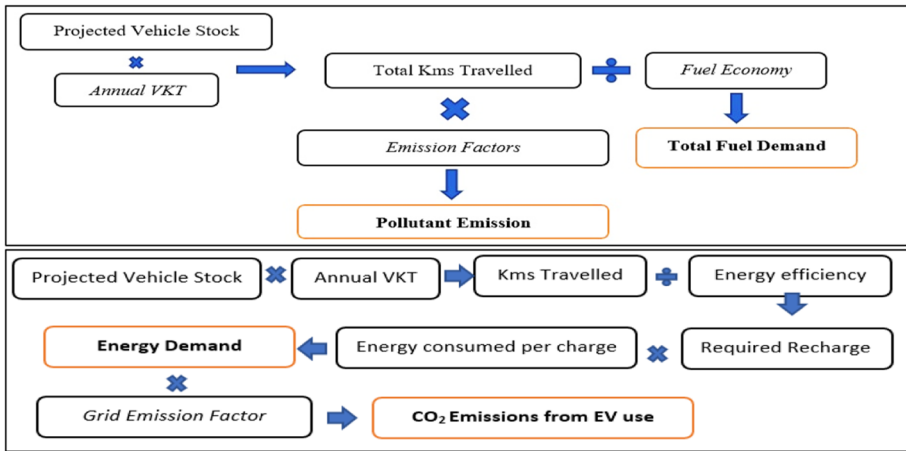


Fig. 3 Components used in projection of fuel demand and pollutant emission from ICE (top) and EVs (bottom)

- (A) *Electric cars* 56% CAGR till 2030 -witnessed in initial years in the USA- (IEA, 2021) and 9.6% thereafter which follows the internal combustion engine (ICE) vehicle’s growth rate.
- (B) *Electric Two-wheelers* 24% CAGR till 2035 adopted from Market Research Future (2023) and 10.4% thereafter which follows the ICE growth rate.

Figure 18 in Appendix A shows EVs (two-wheelers and cars) added each year based for all three per capita GDP growth scenarios.

Figure 3 presents a schematic diagram of methodology used in this study to estimate fuel/energy demand and pollutant emission based on conventional vehicle ownership and EVs.

5 Results and discussions

5.1 Relationship between vehicle ownership and GDP

The projection of private ownership rate obtained from estimating Eq. 2 was then used to calculate aggregate vehicle stock for three alternative scenarios of assumed per capita GDP growth rates viz., conservative, moderate, and aggressive. An S-shaped curve was observed for both two-wheeler and car ownership under all three scenarios, validating historical evidence from developed countries. Figures 4 and 5 illustrate this for conservative scenario. Historical data is used to represent ownership of vehicles till 2019, projected values of vehicle ownership rate are appended thereafter. Both two-wheelers and cars witnessed a slow growth of ownership rate till early 2000 beyond which an exponential growth is observed. A significant growth from 32 vehicles per thousand population in 2000 to 161 per thousand population in 2019 is seen in the case of two-wheelers. It is further projected to reach 196–209 per thousand population by 2030. Likewise, cars follow a similar pattern which grew from 5 cars per thousand population during the start of this century to 28 per

Fig. 4 Two-wheeler ownership curve

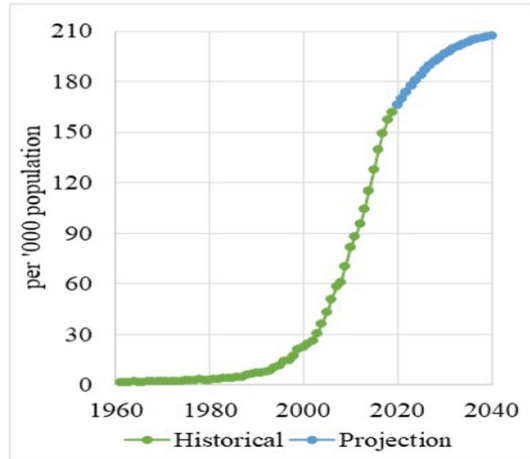
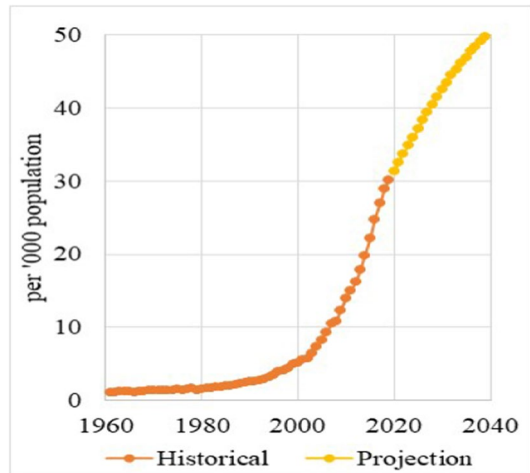


Fig. 5 Car ownership curve



thousand population in 2019. In the coming decade, it is projected to grow substantially to 43–54 cars per thousand population by 2030.

Results of these projections are discussed in the following section. Table 3, reports estimated parameters. Variables of interest of this study were found to be statistically significant.

5.1.1 Two-wheeler vehicle stock and ownership rate

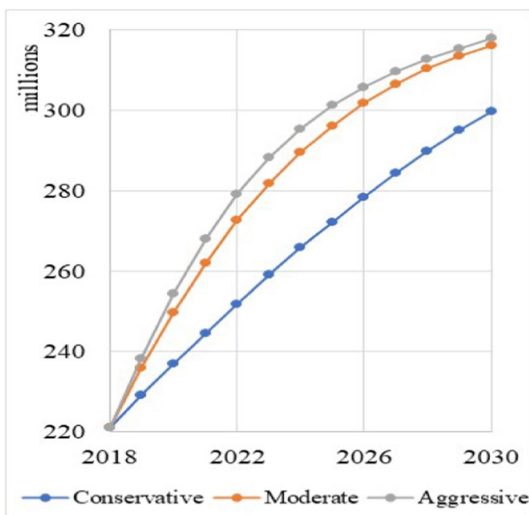
By 2030, two-wheeler vehicle stock in India is projected to range between 295 and 315 million from the current level of 221 million. Figure 6 shows the medium-term projection of two-wheeler vehicle stock up to 2030. The stock of two-wheelers during this period is expected to grow by 133–143 per cent based on different scenarios. Given population projection, ownership of two-wheelers is also projected to rise from 161 per thousand population to 196–209 units per thousand population in 2030. Saturation of two-wheeler

Table 3 Regression results

Variables/models	Two-wheelers (1)	Cars (2)
GDP per capita (β)	-0.00162*** (0.0000478)	-0.0010318*** (0.0000162)
Constant (α)	2.153*** (0.0441)	1.714*** (0.0 .0149)
Observations	60	60
R-squared	0.952	0.9859

Standard errors in parentheses
 * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Fig. 6 Projection of two-wheeler vehicle stock



ownership is projected to be attained by 2034 in an aggressive growth scenario. However, in a conservative scenario, saturation is expected to be achieved beyond 2050 which is illustrated in Fig. 7.

5.1.2 Vehicle stock and ownership rate of cars

The number of cars in India is projected to range between 64 and 81 million by 2030, growing from 38 million in 2019. Figure 8 shows a projection of future vehicle stock of cars for various growth scenarios. The forecasted results for all three scenarios show a 166%, 202%, and 211% rise compared to the 2019 level. This rapid growth translates to a significant rise in ownership rates from existing 28 cars per thousand population to 43–54 cars per thousand population (see Fig. 9). The Saturation of car ownership rate in India is expected to reach beyond 2060 in conservative scenario while under aggressive scenario, saturation will be achieved by 2050.

A comparison of the results of this study with recent literature is presented in Table 4. This study provides a lower and upper bound projection of medium-term vehicle stock. The projection of two-wheeler population in this study is greater than other

Fig. 7 Projection of two-wheeler ownership

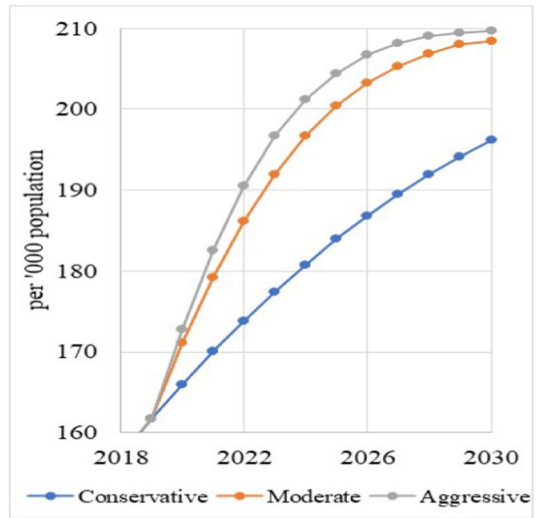
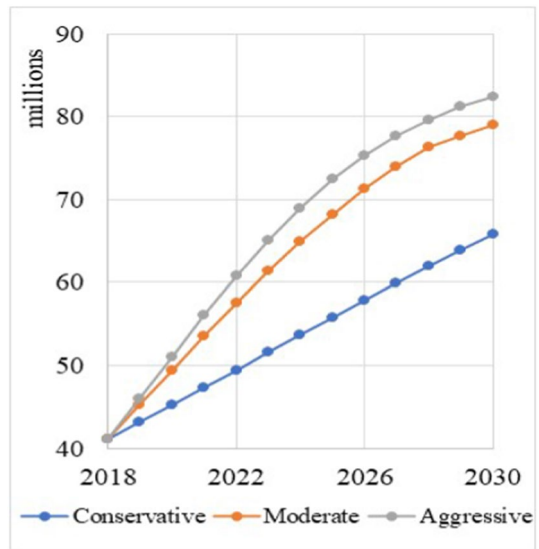


Fig. 8 Projection of car vehicle stock



studies except for the results of Singh et al. (2020) which fall within the range of this study for 2030. However, results of this study compared with actual numbers compiled using MoRTH publications and VAHAN dashboard for 2020 are closer than the projections of earlier studies. While actual number of vehicles based on MoRTH and VAHAN dashboard was 238 million two-wheelers, the projection of this study was significantly closer with 237 million two-wheelers. Meanwhile, stark divergence in estimates of this result with earlier studies like Fulton and Eads (2004) is primarily due to use of longer and more recent time series data which has contributed to improving the accuracy of the projections while absorbing the recent changes in rapid vehicle ownership—a point emphasized earlier. The results for cars depict a glaring difference as compared to

Fig. 9 Projected car ownership scenarios

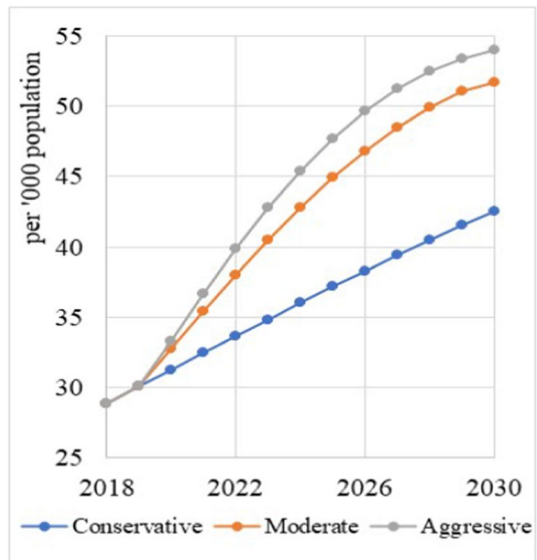


Table 4 Comparison of vehicle stock (in millions)

Study	2020	2025	2030	
Fulton and Eads (2004)	64	75	88	Two-wheelers
Arora et al. (2011)	177	–	264	
Singh et al. (2019)	210	–	313	
Current study (conservative scenario)	229	266	295	
Current study (aggressive scenario)	238	295	315	
Fulton and Eads (2004)	43	53	67	Cars
ABD (2006)	–	42	–	
Dargay et al. (2007)#	–	–	156	
Arora et al. (2011)#	111	–	194	
Singh et al. (2020)	60	–	149	
Current study (conservative scenario)	43	54	64	
Current study (aggressive scenario)	46	69	81	

#Projections include highway vehicles consisting of trucks, buses, trailers, and other heavy motor vehicles

earlier studies. This study projects car population to range between 64 and 81 million by 2030 which is substantially lower than the projections of Dargay et al. (2007) and Arora et al. (2011) due to the inclusion of highway vehicles in the mentioned studies. Further, the use of a higher saturation level compared to this study has propelled car ownership levels in Singh et al. (2020). Yet again, the projection of this study for the year 2020 of 43 million cars is closer to the actual figure for the same year published by MoRTH (2019) as compared to existing literature. This highlights the robustness of assumptions and indicates the advantage of using longer time series data.

Table 5 Comparison of car ownership rate across countries

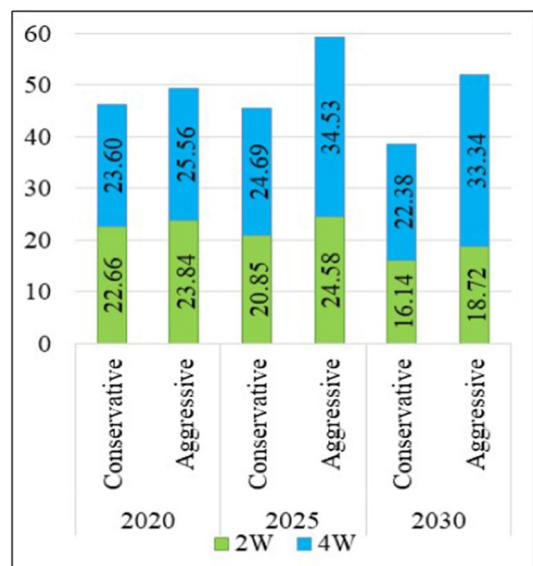
Area/region	2020	2030
North America	0.7	0.7
Latin America	0.14	0.36
Western European Union	0.62	0.65
Eastern European Union	0.64	0.7
Former Soviet Union	0.51	0.66
Africa	0.01	0.02
Middle East and Northern Africa	0.13	0.20
Pacific Asia OECD	0.52	0.58
Pacific Asia	0.27	0.42
China ^a	0.12	0.25
India ^b	0.028	0.054

Regional projections are compiled from Meyer et al. (2012)

^aBased-on Huo and Wang (2012) projections of vehicle stock. UNDESA (2022) was used to derive ownership rates

^bProjection of this study

Table 5 shows a global comparison of car ownership projections. The projection results show a considerable disparity in global ownership rates compared to India. While most developed regions appear to have reached saturation, ownership rates in the Global South, on the other hand, are likely to rise dramatically in the medium term. Africa, Asia Pacific, China, India, and Latin America are still in various phases of growth in car ownership, with these regions on track to virtually double their present ownership rates within a decade. If regions in the global south continue to follow the trend observed in developed nations, this could put them on the verge of a severe mobility crisis. Since, these are countries where transportation sustainability challenges are more apparent (Gruyter et al., 2016). This could eventually lead

Fig. 10 Fuel demand (in MT)

to large fossil fuel consumption and emission levels, which contribute to local air pollution and overall greenhouse gas emissions.

5.2 Fuel and energy demand

Rapid growth in vehicular ownership and its utilisation will have overwhelming pressure on energy requirements. During this decade 200–250 million vehicles are projected to ply on-road annually. This translates to an annual VKT of 1.2–1.9 trillion kilometres. This enormous demand for travel will put pressure on energy requirements where a substantial part of this travel demand is expected to be fulfilled by ICEs until EVs start replacing them, provided technological advancements happen swiftly, EVs become economically viable choice, and EV friendly policies are continued. Despite that, such a change in private vehicle ownership composition will incur a longer time frame. Hence, to address uncertainty over its penetration, this study presents cases with and without EV adoption while estimating fuel demand from the use of private vehicles.

5.2.1 Fuel demand: no EV adoption scenario

Figure 10 illustrates the fuel demand of private vehicles under no EV adoption scenario which is projected to peak by the latter half of this decade with 60MT of fuel consumed per annum. A constant decline in fuel demand is projected thereafter, primarily due to two-wheelers approaching saturation towards the end of this decade which is further accelerated by the peaking of on-road four-wheelers population. Lastly, improvement in fuel efficiency of new vehicles allows them to consume less fuel compared to older vehicles. Figure 11 shows the composition of fuel demand while, Fig. 12 shows various scenarios of aggregate fuel demand till the end of this decade.

5.2.2 Fuel and energy demand: EV adoption case

Two diverse scenarios of EV adoption were incorporated to estimate the reduced burden on fuel demand and pollutant emission.

- (a) Constant EV Adoption—Same number of EVs are added each year irrespective of per capita GDP scenario.
- (b) Differential EV Adoption—Number of EVs added each year differs for each scenario of per capita GDP.

In the first case, projected EVs for a particular year were the same for all three per capita GDP scenarios. This was subsequently segregated from newly added vehicles during that particular year. The latter case was based on the proportion of per capita GDP to aggressive scenario GDP. Using this ratio, number of EVs added each year was derived. The process of segregation was the same. Segregated ICEs were used to estimate fuel demand, while EVs were used to forecast energy demands.

5.2.2.1 Fuel demand With the adoption of EVs, the number of conventional ICE vehicles would be lower as compared to the previous scenario. Figure 13 shows the quantity of fuel saved based on various EV adoption scenarios compared to no EV adoption.

Fig. 11 Fuel demand composition

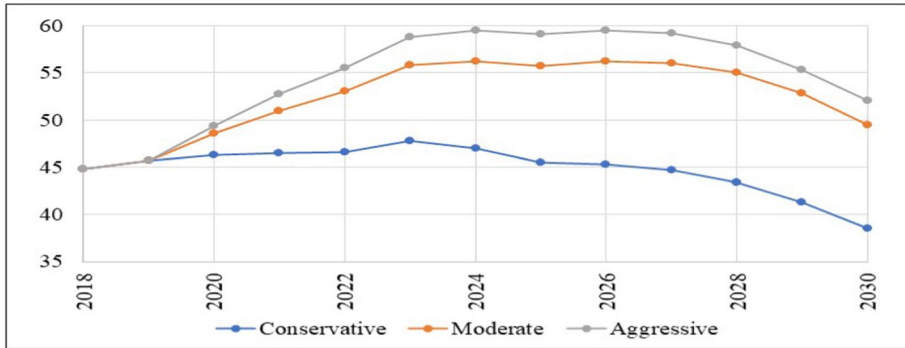
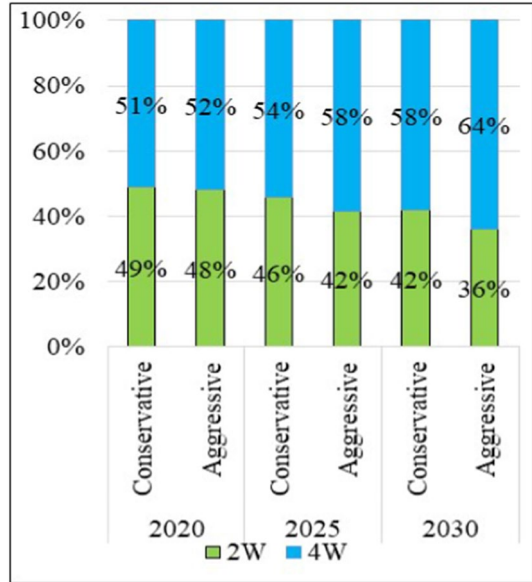


Fig. 12 Fuel demand scenarios (in MT)

5.2.2.2 Energy demand EVs require recharging of batteries, an average two-wheeler EV has a range of 60–80 kms, while cars ply 140–160 kms. This translates to 128–194 million recharges per annum by 2030 for two-wheelers based on different scenarios and 120–200 million recharges for cars. The resultant energy demand is depicted in Fig. 14.

5.3 Vehicular emissions

Measurement of GHG from the transport sector is essential for a very fast-developing economy like India in order to design and implement suitable technologies and policies with the appropriate mitigation measures (Ramachandra & Shwetmala, 2009). This study provides projections of local pollutants and GHG emissions.

Fig. 13 Fuel saved (in MT)

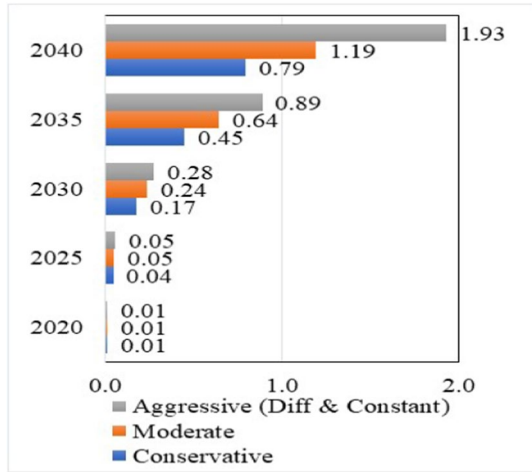
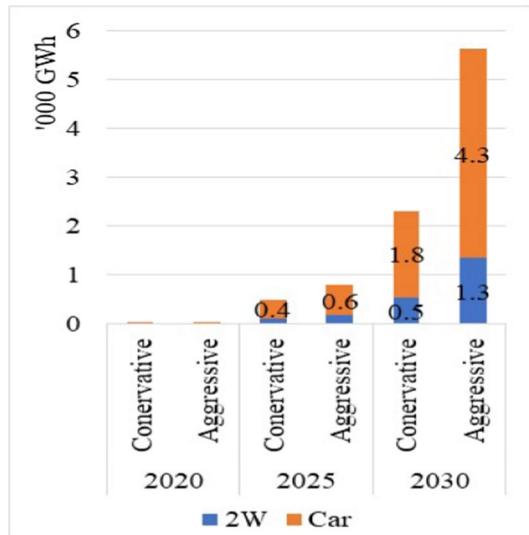


Fig. 14 Energy demand by EVs



5.3.1 Pollutant emission: no EV adoption case

An inventory for private vehicular emissions is presented in Table 6 and 7 where for local pollutants and other gases, and GHG, respectively.

Like fuel demand, emissions from private vehicle use are projected to peak in this decade. CO₂ emissions from tow-wheeler use are projected at 60MT, while cars are expected to have a larger share of emissions around 112MT per annum by 2027. A constant decline in emissions of both local and global greenhouse gas emissions is projected thereafter.

Table 6 Inventory of local pollutant and other gases (in '000 tons)

Year	Local pollutant						Other gases			
	NO _x		PM		SO ₂		CO		HC	
	Low	High	Low	High	Low	High	Low	High	Low	High
2020	14.4	15.5	69.4	73.4	37.2	39.9	866.3	866.3	1713.6	1713.6
2025	15.1	20.6	65.9	81.0	37.9	50.5	814.4	985.5	1594.9	1908.0
2030	13.9	19.9	53.6	66.5	33.9	47.0	650.3	787.8	1256.5	1493.7
2035	11.4	14.6	38.7	42.6	27.0	33.5	459.5	490.8	873.0	910.6
2040	9.9	6.8	30.3	19.3	22.9	15.6	352.4	221.3	659.2	408.0

Table 7 Inventory of GHG emissions

Year	CH ₄ (in '000)		CO ₂ (in MT)	
	Low	High	Low	High
2020	61.9	65.6	144	152
2025	59.6	74.6	135	172
2030	49.5	63.1	109	147
2035	36.6	41.5	79	97
2040	29.2	19.0	67	45

5.3.2 Pollutant emission: EV adoption case

While EVs are measures to reduce CO₂ emissions from the transport sector, they are not completely green. Recharging batteries require electricity which is sourced through non-renewables. The energy mix in India is dominated by fossil fuel. It is essential to consider CO₂ emissions from recharge EVs while forecasting emissions from private vehicle use. To forecast this indirect CO₂ emissions, GEF from TERI (2019) was used which allows for future improvements in the energy mix. CO₂ emissions from EV use if forecasted to range between 294 and 498 thousand tons by 2030, which substantially goes up to 1.4–3.4 million tons per annum by 2040 as shown in Fig. 15. Despite emissions from EVs amounting to a considerable size, switching from conventional ICEs to EVs reduces aggregate emissions as shown in Fig. 16. The lower bound reflects conservative per capita GDP scenario of differential EV adoption, while upper bound indicates aggressive scenario of differential EV adoption. By 2040, more than 1.6 million tons of CO₂ emissions from private vehicles can be reduced annually. This will be a vital contribution in the approach to net zero targets.

Presently, emission from private road transport account for less than half of all transport emission in India (IEA, 2021). Comparing with IEA (2021) sectoral emission forecasts based on their sustainable development scenario which tallies with the net-zero emission targets of India, suggests that: transport sector CO₂ emissions are expected to grow up to 26 per cent by 2030, whereas private vehicle emissions show relatively smaller growth as it is forecasted to peak by 2027 and decline thereafter such that by 2030, the decadal growth is less than 10 per cent. Further, between 2030 and 2040, IEA projections forecast a decline in decadal emission level from the sector at 11 per cent, whereas this study's forecast depicts a decline of 30 per cent if adoption of EVs and

Fig. 15 CO₂ emissions from EV (in MT)

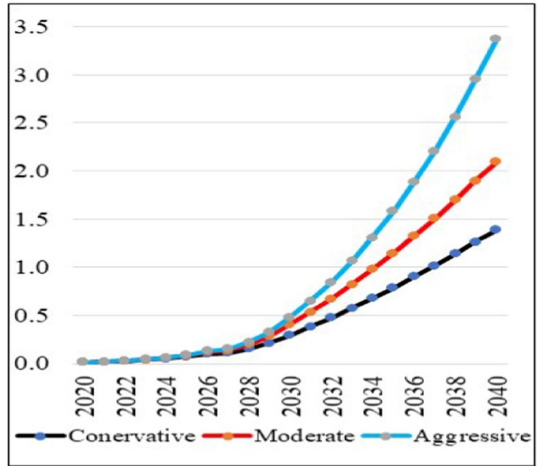
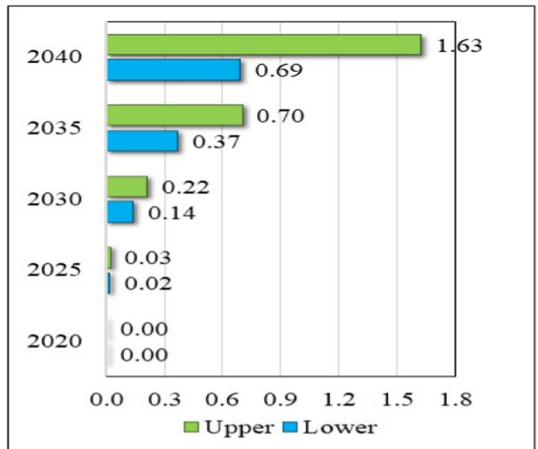


Fig. 16 Annual CO₂ emission reduction (in MT)



improvement in vehicle technology are achieved. This also results in reduction in share of private vehicle contribution to overall sectoral emissions indicating the alignment of emission pathways with the climate goals of India.

Figure 17 illustrates the local pollutant emissions reduced with the adoption of EV presented for the scenario of aggressive GDP per capita. An inventory of category-wise local and global GHG emissions is presented in Appendix B and Appendix C.

5.4 Road transport infrastructure

5.4.1 Requirement

As discussed earlier, the prevailing road infrastructure is inadequate for the current level of motorisation. However, endless investment in expanding the road infrastructure is not a

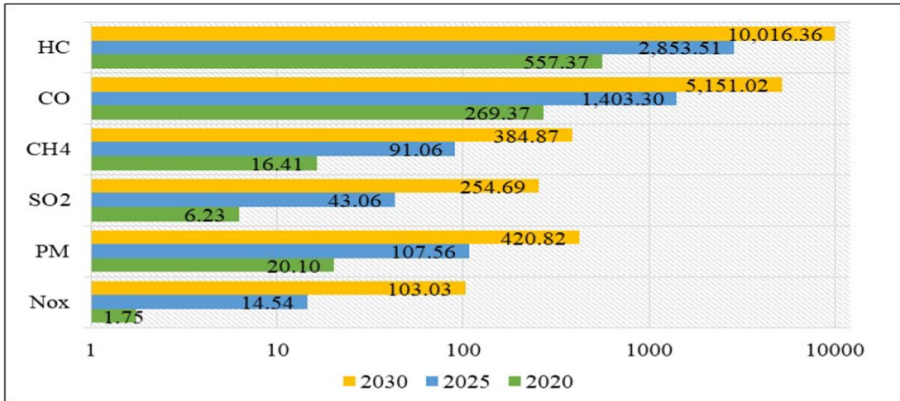


Fig. 17 Pollution sequestered (in tons). # Axis in log-scale

sustainable solution. Thus, an attempt to maintain the existing vehicular density is considered reasonable as there is a belief public transport will attract larger footfall than the current levels. Based on this, additional road infrastructure required to keep pace with growing private vehicle stock is estimated. At present, the road network in India spans around 6.4 million kilometres with a vehicle density of 40.6 vehicles per kilometre of road for private vehicles. An additional 3.7–4 million kilometres of roads are required to be constructed by 2040 to keep this ratio constant.

5.4.2 CO₂ emissions

Road infrastructure involves CO₂ emissions in various stages. CO₂ emission happens in three different stages viz., construction, transportation of raw materials, and maintenance. As it is difficult to map the source and use of raw materials, it is excluded. CO₂ emissions from the construction of new roads are estimated to be 3.38 bn tons and 42 million tons from maintenance based on the carbon footprint of road construction obtained from ADB (2010). This calculation assumes that national highways, state highways, and replacing kaccha roads with bituminous roads each account for one-third of new roads (Table 8).

6 Conclusion

This study projected various scenarios of future vehicle stock, estimated implications on fuel demand, and built an emission profile comprising from the current year to a medium-term future. To address uncertainties of vehicle growth and its composition,

Table 8 Road infrastructure and CO₂ emissions by 2040

	Additional road required Kms	CO ₂ emissions (in bn tons)		
		Construction	Maintenance	Total
Conservative	37,83,358	3.17	0.04	3.21
Moderate	40,15,930	3.37	0.04	3.41
Aggressive	40,34,617	3.38	0.05	3.43

multiple scenarios were developed. Three scenarios of per capita GDP growth rate and two EV penetration cases were established. Based on these projections, it was observed that by 2030, India could have an additional 74–94 million two-wheelers and 26–43 million cars during this period. Consequently, annual fuel demand is projected to range between 47 and 60 million tons. This could have crucial implications for India's future imports and energy security. Additionally, annual emissions of GHGs are forecasted to peak around 144–174 million tons of CO₂ per annum during this decade. Further, the benefits of EV adoption on fuel savings and emission reduction were highlighted. The voluminous fuel demand and emissions will have a significant impact on environmental quality unless the conservative saturation is met. This will be significantly challenged by the booming automobile industry in India. Appropriate transport policy measure in reducing dependency on private vehicles is extremely necessary. This will allow us to get back to 2018 levels of fuel demand by the end of this decade, streamline emissions to achieve net-zero commitments, and decongest Indian roads.

Current initiatives aimed at improving fuel efficiency and reducing carbon emissions—Implementation of BSVI by leapfrogging from BSIV and ethanol blending into petrol. Adoption of EV into the mobility sphere is also gathering pace with FAME which offers supply and demand side incentives. However, to meet climate commitments and reduce dependency on private vehicles, additional suitable policy measures are required. These can be categorised into (a) User Cost, (b) EV Push, (c) Public Transport Pull, (d) Transit Oriented Development (TOD), and (e) Others. This study concentrates on the aggregate level, hence policies that have universal applicability are discussed.

(A) *Increasing User Cost* 200–250 million vehicles are projected to ply on-road this decade. This translates to an additional 22 million cars and 26 million two-wheelers on roads from the existing level. Such a rapid rise on road private vehicles will exert enormous pressure on cramped roads. Ownership of private vehicles cannot be easily discouraged; however, it is possible to streamline its use through a combination of interventions (NTDPC, 2012). While regulating ownership is quite difficult, it is a double-edged sword that can disrupt the automobile sector and have a knock-on effect on the economy. On the other hand, exponential growth of will lead to an unsustainable transport environment. Hence, careful consideration is required in devising policies that aim at regulating vehicle usage.

- (i) MoRTH is contemplating the removal of FASTAG systems of user fee collection to replace it with GPS and a number plate-based toll collection mechanism where charges will be collected based on kilometres travelled. This mechanism can be extended to collect “carbon taxes” for all highway vehicles based on kilometre travelled.
- (ii) Urban spaces in India are struggling to handle vehicle stock. With a complex landform use, heavy traffic flow can have varied health implications for people residing in proximity. Areas with high population density -central business districts (CBDs)- are well connected with public transport systems. However, the lack of regulations ensures motorists opt for private vehicles. This can be regulated by categorising CBDs as “Low Carbon Zones” and implementing “congestion charges” which is successful have been various European cities.
- (iii) It is more convenient to use private transport extensively due to low/lack of on-roads costs that limit their use like parking charges. On-street parking are

cheaper alternative to covered parking. However, demand for parking is usually high for the prior. A measure to set parking fees based on demand and supply of parking lots should be considered where commercial spaces and cramped on-street parking will draw higher parking charges as compared to later which are built farther from focal points of these commercial hubs. Further, depending on the area where one gets a vehicle registered, one-time municipal “parking charges” are collected at the time of registration. These charges are low to affect vehicle ownership decision and hence needs to be reconsidered.

- (iv) Additional measures like annual “re-registration” and “pollution under control” charges must be implemented universally throughout the country. This will increase the cost of ownership and nudge regular maintenance of vehicles.
- (B) *EV push* Dependency on fossil fuel calls for a sizeable reduction.
- (i) There is growing consensus that the future of mobility is electric. While, alternative fuel vehicles are already part of Indian mobility sphere, their share is negligible at an aggregate level. These alternative fuel vehicles can assist in the gradual transition from gasoline to electric mobility which requires the promotion of CNG for intermediate public transport along with private vehicles.
 - (ii) Despite recent policies that aim at pushing EVs through FAME, lack of adequate infrastructure, charging facilities, and battery swapping options—which is prone to entitlement effect, hence can be a solution for commercial vehicles-, range anxiety and public awareness have been factors that are restricting growth of EVs. Hence, building infrastructure facilities with integrated fast charging and battery swapping zones, and mandating interoperability standards for charging ports, and swapping technologies needs to be at the forefront. As per CEEW (2020), the total cost of ownership of EVs is expected to decrease by 19–20 per cent compared to ICEs. Building awareness is required at a greater scale along with an organic EV push (without further subsidising).
- (C) *Public Transport Pull* Regulating private vehicle ownership to push travellers away from private vehicle use needs complimentary pull strategies from public transport systems. However, public transportation is faced with various issues such as availability, quality of services, etc. Presently, the share of public transport is remarkably low (see Fig. 1). A change is required from the status-quo to make public transport a favourable choice. The following areas could be addressed:
- (i) As per NITI (2018), India lags drastically behind with 1.4 buses per thousand population compared to other developing countries like Thailand and South Africa which have 8.6 and 6.5 buses per thousand population. The service level benchmark set by the Ministry of Urban Development suggests a desirable level of number of buses per thousand population to be 0.6. However, most cities in India are not closer to this level. For example, Chennai has only 3828 buses (MTC Performance Data) for a population of nearly 10 million in 2018. Hence, procuring buses must be scaled up rapidly.
 - (ii) Comfort and unpredictability have led to a massive shift away from public transport over the years. Since 2011, the occupancy ratio in State Road Transport Undertaking (SRTUs) has gradually declined. As per MoRTH

(2017), urban centres like Delhi, Mumbai, and Kolkata have occupancy ratios lower than the national average. Therefore, emphasis should be on making public transport reliable by incorporating modern solutions like *bus information systems* which provide real-time updates on bus arrival, congestion status of the road network, and expected travel time via mobile applications.

- (iii) Measures relating to public transport can be possible only if substantial public sector investment is streamlined or funded from revenues generated by SRTUs. However, the annual report by MoRTH (2021) suggests that the combined loss of all 56 STU in India accounts for 1.7 million crore rupees. SRTUs are stricken for finance as their operating costs exceed their revenues. This affects their ability to improve the quality of service and re-invest. Hence, non-operational revenue streams need to be explored. Advertising, issuance of naming rights, leasing existing facilities to private operators, etc. are some alternatives. The goal is to generate revenue by monetizing existing facilities and digital space without altering ticket prices.
- (D) *Land Use and TOD* To facilitate seamless connectivity, reduce demand for travel, encourage active mobility, and ensuring pedestrian safety; mobility planning must focus on TOD. Re-designing existing urban spaces needs to be given a thought such that transport networks offer easy transferability. The introduction of common smart cards to be used across transport modes, with digital payment options must be implemented in cities with metro facilities. Further, a comprehensive mobility plan must be undertaken/updated which can be used to calibrate various infrastructural investments.
- (E) *Beyond the conventional measures*
- (i) The newly announced scrappage policy provides incentives to owners in terms of benefits on the purchase of new vehicles. This is a welcome measure. However, the mandatory fitness test beyond vehicle age (15 years for personal and 10 years for commercial) offers a 5 year extension. Annual “re-fitness” tests should be mandated under the scrappage policy to ensure its success.
 - (ii) We saw in Sect. 5.4, a sizeable “road infrastructure” needs to be built. A need for rapid investment in building new-age roads with safety features and expanding existing road infrastructure is utmost necessary.

Appendix A

Annual addition of EVs under various GDP scenarios.

See Fig. 18.

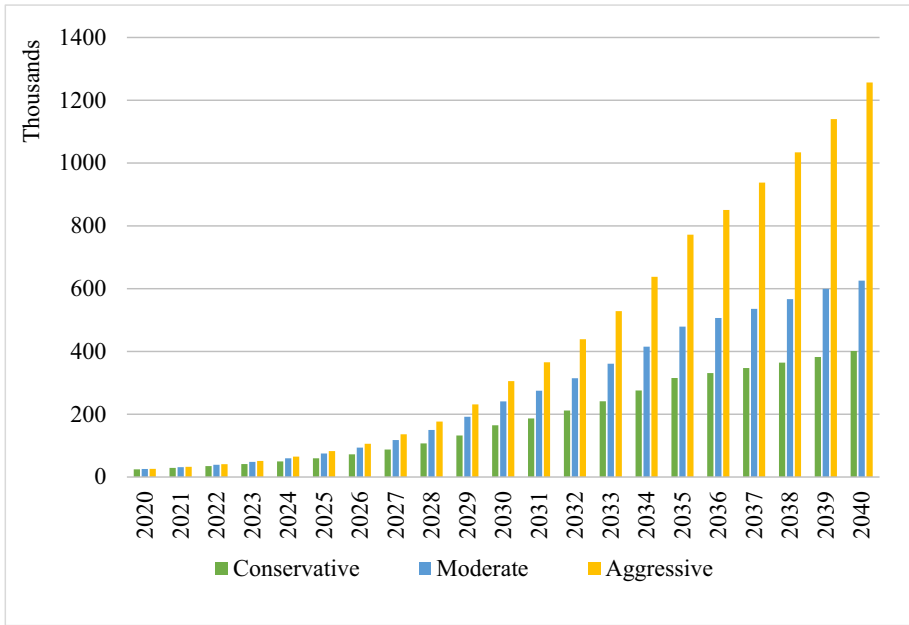


Fig. 18 EVs added each year

Appendix B

Inventory of local pollutant emissions.

See Table 9.

Table 9 Inventory of local pollutant emissions from private vehicles (in'000 tons)

Year	Vehicle type	NO _x		PM		SO ₂	
		Lower bound	Upper bound	Lower bound	Upper bound	Lower bound	Upper bound
2020	Two-wheelers	3.4	3.6	56.7	59.6	14.7	15.5
	Cars	11	12	12.7	13.8	22.5	24.4
	Total	14.4	15.6	69.4	73.4	37.2	39.9
2025	Two-wheelers	3.1	3.7	52.1	61.5	13.6	16
	Cars	11.9	16.9	13.8	19.5	24.3	34.5
	Total	15	20.6	65.9	81	37.9	50.5
2030	Two-wheelers	2.4	2.8	40.4	46.8	10.5	12.2
	Cars	11.5	17.1	13.2	19.7	23.4	34.9
	Total	13.9	19.9	53.6	66.5	33.9	47.1

Appendix C

Inventory of GHGs.

See Table 10.

Table 10 Inventory of GHG emissions from private vehicles (in'000 tons)

Year	Vehicle type	CH ₄		CO ₂	
		Lower bound	Upper bound	Lower bound	Upper bound
2020	Two-wheelers	45.3	47.7	55,049	57,461
	Cars	16.57	17.94	88,864	94,138
	Total	61.87	65.64	143,913	151,599
2025	Two-wheelers	41.7	49.2	47,669	55,362
	Cars	17.90	25.39	87,771	116,579
	Total	59.6	74.59	135,440	171,941
2030	Two-wheelers	32.3	37.4	33,257	38,568
	Cars	17.19	25.65	75,771	108,285
	Total	49.49	63.05	109,028	146,853

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Declarations

Conflict of interest The author has no conflict of interests to declare that are relevant to the content of this article.

Ethical approval Not Applicable.

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