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Sustainable Driving: Zero-Emission Vehicles & Eco-Practices

Abstract

Addressing vehicular emissions is crucial for safeguarding both human health and the environment. This study explores strategies to mitigate CO_2 emissions from vehicles, focusing on adopting zero-emission vehicles (Electric vehicles) and promoting eco-friendly driving practices. By examining six scenarios, including measures to reduce emissions from existing Internal Combustion Engine (ICE) vehicles, the study predicts future CO_2 emission trends. Moreover, the analysis incorporates the social cost of carbon (SCC) and evaluates its environmental impact and toxicological implications. The findings highlight the effectiveness of transitioning to 100% electric vehicle fleets and implementing eco-driving practices in significantly reducing future CO_2 emissions. Additionally, embracing eco-driving techniques for current ICE vehicles emerges as a viable strategy for addressing current air pollution concerns while promoting a healthier environment.

Keywords

Electric vehicles • ICE vehicles • Eco-driving • Vehicular-emission • Decarbonization • Social cost of carbon • Carbon saving

Highlights

- The maximum reduction of on-road CO_2 emission can be achieved by replacing ICE vehicles with electric vehicles and simultaneously adopting economical driving practices to drive the current ICE vehicles.
- Only the 100% adoption of electric vehicles and eco-driving practices can help achieve the maximum reduction of total CO_2 emissions and minimize health and toxicological impact in the future.
- The use of 100% electrification along with eco-driving practices will also help reduce the economic loss due to carbon emissions.

Research Article

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Introduction

Automobiles stand as the primary contributors to greenhouse gas (GHG) emissions globally, with China, the USA, and India leading the charge at 25.9%, 13.87%, and 7.45%, respectively [1]. Notably, the transport sector, accounting for 24% of total fuel combustion CO_2 emissions in 2015, faces mounting pressure due to rapid urbanization and heightened travel demands, particularly in India [2]. This surge in travel needs exacerbates reliance on non-renewable energy sources, intensifying the strain on energy resources and leading to increased fuel consumption and electricity demand. India is undergoing a remarkable transformation in the realm of electric vehicles (EVs). The surge in EV registrations from 1.25 lakh units in 2020 to 10.25 lakh units by 2023 signifies a significant shift in the country's automotive landscape. This momentum was further emphasized in the 2022-23 Economic Survey, where the government outlined ambitious targets for the Indian EV market, projecting a robust 49% Compound

Annual Growth Rate (CAGR) from 2022 to 2030. The aim is to achieve annual EV sales of one crore units by 2030, reflecting the current state of India's EV ecosystem characterized by remarkable growth and substantial government support.

The behavior of today's consumer is pivotal in shaping the automotive market, with considerations such as safety, brand reputation, and cost influencing purchase decisions. This transformation is largely fueled by heightened environmental awareness, driving interest in EVs and other sustainable transportation options. Innovative solutions like fast-charging stations and community charging options are emerging to address the evolving needs of Indian consumers. However, several challenges hinder widespread EV adoption in India. These include the lack of clean energy, underdeveloped charging infrastructure, suboptimal battery technology, and persistent resistance to change. Additionally, power infrastructure and financing pose significant barriers to adoption. To address these challenges and effectively integrate EVs into India's transportation landscape, the country can draw inspiration from global leaders in EV adoption. By investing in infrastructure development, incentivizing clean energy adoption, and fostering public-private partnerships, India can create an environment conducive to sustainable mobility. Moreover, leveraging economic opportunities for stakeholders such as fleet operators, original equipment manufacturers (OEMs), and the real estate sector can further accelerate EV adoption.

While India grapples with challenges in transitioning to electric mobility, its rapid growth in EV registrations and government support underscores a promising future. By tackling key barriers and embracing innovative solutions, India has the potential to leverage electric vehicles to reduce air and noise pollution, enhance operational efficiency, and foster economic opportunities for all stakeholders. The transport sector in India consumes approximately 16.9% of total energy, primarily relying on internal combustion engines (ICE) vehicles, thereby significantly contributing to GHG emissions [3]. Notably, road transport bears the highest emission burden at 80%, while rail and air contribute 13% and 6%, respectively [4]. With global temperatures on the rise, urgent calls to reduce fossil fuel usage and associated emissions resonate worldwide, prompting the need for innovative clean energy solutions within the transportation sector. Recognizing the imperative to curtail GHG emissions, India has committed to reducing them by 33 to 35% below 2005 levels by 2030 [5].

Embracing electric vehicles (EVs) emerges as a pivotal strategy, offering enhanced efficiency and eco-friendliness. Transitioning from ICE vehicles to EVs not only promises a 37% reduction in GHG emissions but also envisions a US$60 billion decrease in oil bills, reducing dependency on fuel imports and acting as a bulwark against fluctuating crude oil prices and air pollution. To bolster EV adoption and achieve emission reduction targets, the Indian government has implemented several policies in recent decades. Initiatives like the Alternate Fuels for Surface Transportation (AFST) program and the National Electric Mobility Mission Plan (NEMMP) 2020 aim to stimulate EV distribution and support research and development. Additionally, schemes like the Faster Adoption and Manufacturing of (Hybrid &) Electric Vehicles (FAME) focus on technology development, demand creation, and infrastructure enhancement for EVs.

Moreover, endeavors such as the National Energy Storage Mission (NESM) and the National Policy on Electronics, 2019, seek to bolster technological advancements in EVs by fostering a conducive environment for industry competitiveness (Ministry of New and Renewable Energy, 2018; Ministry of Electronics and Information Technology). Several Indian states, including Delhi, Uttar Pradesh, and Karnataka, have formulated EV policies to incentivize EV uptake, complementing national efforts. Furthermore, the implementation of Bharat stage emission standards (BSES) regulates air pollutant emissions from ICE vehicles, progressively tightening emission norms over the years [6]. Notably, the upcoming BS VI norms, effective nationwide from April 2020, promise substantial reductions in vehicle PM and NOx emissions [7]. Addressing vehicular emissions necessitates multifaceted approaches, encompassing factors like road quality, vehicle age, and fuel type. Eco-driving emerges as a viable solution, defined as driving practices aimed at minimizing fuel consumption, pollution, GHG emissions, and accident risks. Studies indicate that eco-driving behaviors and training can improve fuel economy by 11 to 50% [8].

Moreover, eco-driving and CO_2 reduction yield social benefits, with the social cost of carbon (SCC) serving as a critical metric. India's SCC of $86 per ton of CO_2 underscores the economic implications of carbon emissions, highlighting the urgency of emission mitigation strategies [9]. This paper aims to evaluate EVs' role in mitigating India's vehicular emissions, emphasizing different adoption scenarios and eco-driving methodologies. By leveraging SCC values, the study intends to quantify CO_2 cost savings resulting from these strategies. The paper structure comprises an Introduction, Literature Review, Methodology, Results, Discussion, and Conclusion, offering comprehensive insights into emission reduction strategies for India's transportation sector.

Literature Review

Numerous studies have investigated the efficacy of electric vehicles (EVs) and eco-driving practices in mitigating global greenhouse gas (GHG) emissions. EVs offer the advantage of replacing fossil fuels, resulting in emissions-free operation [10]. Nanaki and Koroneos [11] conducted a study on three electricity production scenarios in the Greek market—high, medium, and low carbon. Their findings emphasized the significant environmental benefits of EVs, especially in carbon-free energy production settings. In a scenario with zero-carbon electricity, EVs contributed only 6.85% of GHG emissions and 5.76% of total air pollution, contrasting sharply with the substantial emissions from internal combustion engine (ICE) vehicles. Transitioning to all-electric vehicles powered by renewable energy via modern rechargeable grid infrastructure presents a viable strategy to reduce oil dependency and GHG emissions. Andersen [12] suggest that such a shift could reduce greenhouse gas emissions by up to 20%. Coupled with generating electricity from renewable sources, this reduction could potentially reach 40%.

Moreover, the long-term viability of EVs as an alternative to ICE vehicles is underscored by Brady and O'Mahony [13], who highlight the economic and environmental advantages of EVs utilizing renewable energy sources. However, studies such as Ma [14] caution that EVs may not always result in lower life cycle emissions compared to ICE vehicles, primarily due to GHG emissions associated with battery production. Despite this, Yagcitekin [15] emphasize the overall benefits of deploying EVs with renewable energy sources for sustainable development in the transportation sector. In India, the potential for EV adoption is substantial, with projections indicating significant energy demand and carbon emission savings by 2030 through shared, electric, and connected mobility initiatives. Various programs and schemes supporting electric mobility have been introduced to achieve these goals.

Efforts to mitigate road transport emissions extend beyond EV adoption. Ong [16] suggest strategies such as shifting passenger cars and motorcycles to public transport and promoting natural gas vehicles to reduce emissions. Additionally, studies on eco-driving emphasize its role in reducing fuel consumption and air pollution. Training programs and in-vehicle feedback systems are proposed methods to promote eco-driving behavior [17]. Further investigations into fuel consumption models and modal emission models highlight the impact of driving characteristics on pollution and fuel consumption [18]. In conclusion, while EVs offer long-term potential for reducing transportation emissions, their efficacy varies depending on factors such as electricity generation sources. Moreover, promoting eco-driving practices alongside EV adoption is crucial for emission reduction, especially in countries like India, where ICE vehicle usage remains prevalent.

Materials and Methods

Vehicular emissions are influenced by various factors including the type of transport, fuel type, combustion engine type, and vehicle age. In India, passenger and cargo vehicles predominantly utilize diesel fuel, while private two-wheelers (2Ws) and three-wheelers (3Ws) primarily run on petrol fuel. The growth and projected number of vehicles are shown in the (Figure 1)

Regulations in India impose an age limit of 10 years for diesel vehicles and 15 years for gasoline vehicles [19]. To project the CO_2 emission trends for future years in India, we gathered secondary data on vehicle numbers for different categories, including diesel cars, petrol cars, 2Ws, 3Ws, trucks, and buses, spanning from 2017 to 2019. Using this data, we extrapolated the trends up to the year 2050. Subsequently, we calculated the year-wise CO_2 emissions from 2017 to 2050 for various scenarios as shown in (Figure 2).

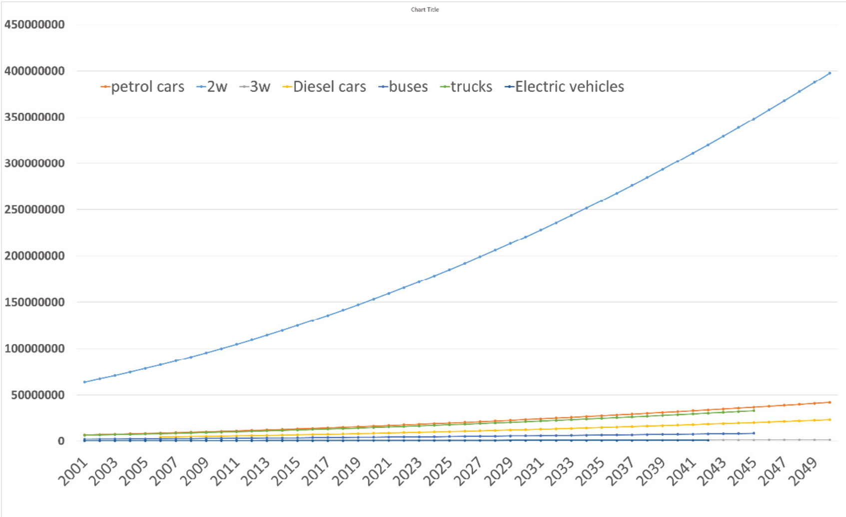

Figure 1: Growth and projected number of vehicles.

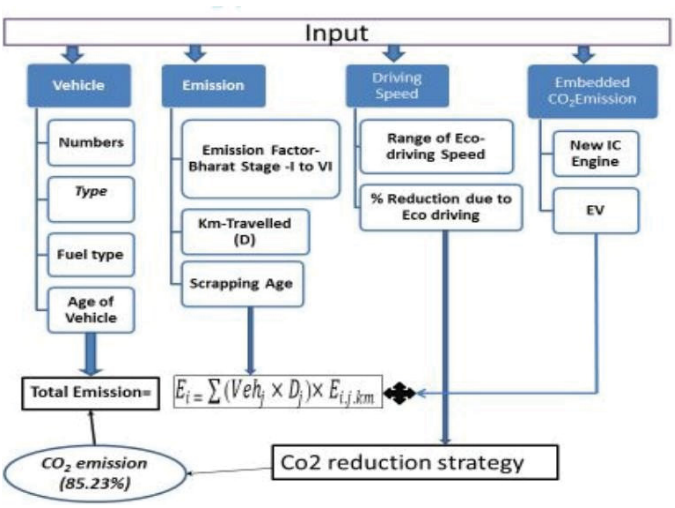

Figure 2: Flowchart showing the methodology.

Calculation of On-road emission from different vehicle type

Road emissions were quantified based on the vehicles numbers and distance travelled in year per vehicle type, which can be given by the equation no. (1)

$$E_i = \Sigma\,(Veh_j \times D_j) \times E_{i.j.km} \qquad (1)$$

Where,

E_i = emission of compound emitted from vehicle (i),

Veh_j = number of vehicles per type (j),

D_j = distance travelled in a year per different vehicle type (j),

$E_{i.j.km}$ = emission of compound (i) from vehicle type (j) per driven kilometer (Ramachandra & Shwetmala, 2009).

For the calculation of on-road emission, we split the different vehicles based on fuel-type i.e. (petrol, diesel and electric). we have also took the scrapping of vehicles in the calculation i.e.; the petrol vehicles will scrap after every 15 years whereas the diesel vehicles will scrap after every 10 years. We have assumed that the EVs have zero on-road emission and they will help in the reduction of the total on-road emission, if they replace the ICE vehicles.

Calculation of embedded CO_2 emissions from vehicle manufacturing

Embedded CO_2 refers to the carbon dioxide emissions associated with the manufacturing process of vehicles. Sullivan [20] discovered that approximately 50% of the total energy utilized in vehicle manufacturing is derived from the power grid. Consequently, a vehicle manufactured in a region heavily reliant on coal-based power plants would exhibit higher CO_2 intensity compared to one manufactured in an area utilizing renewable energy sources.

Studies generally indicate that the production of electric vehicles (EVs) generates more CO_2 emissions than that of internal combustion engine (ICE) vehicles. Qiao [21] reported that manufacturing a single electric vehicle emits around 14.6 metric tons of CO_2, whereas an ICE vehicle emits 9.2 metric tons. Furthermore, Hill [22] found that the production of an ICE vehicle results in emissions of 8.7 metric tons of CO_2, whereas an equivalent-sized EV production emits 15.5 metric tons. Similarly, according to the Ricardo report, the manufacturing of ICE and EV vehicles produces 5.6 and 8.8 metric tons of CO_2, respectively.

To calculate the embedded CO_2 of ICE and EV vehicles, we averaged the values obtained from these studies.

So,the Embedded CO_2 from ICE vehicles = $\frac{1}{3}(X_1+X_2+X_3)$ (2)

Where X_1 = 9.2 tCO_2 [21], X_2 = 8.7 tCO_2 [22], and X_3 = 5.6 tCO_2 [23]

And, the Embedded CO_2 from Electric vehicles = $\frac{1}{3}(Y_1+Y_2+Y_3)$ (3)

Where Y_1 = 14.6 t CO_2, Y_2 = 15.5 tCO_2, and Y_3 = 8.8 t CO_2

So, 12.9 tCO_2 emits in manufacturing per EV and 7.8 tCO_2 emits per ICE vehicle manufacturing.

Calculation of total emissions from vehicles

Total emissions encompass both on-road emissions and embedded emissions. In this study, we computed the annual on-road emissions from 2017 to 2050 and the embedded emissions linked to vehicle manufacturing per vehicle across various scenarios. These calculations were then utilized to derive the total emissions per year.

Calculation of CO_2 reduction due to eco-driving adoption

Numerous studies have demonstrated the effectiveness of eco-driving practices in reducing carbon emissions from automobiles. Arokiaraj [24] concluded that implementing eco-driving behavior strategies could lead to a substantial 16% reduction in carbon emissions and fuel consumption savings. Given that their study focused on Indian drivers, we adopted the same value for CO_2 reduction due to eco-driving and incorporated it into our emission calculations across various scenarios.

social cost of carbon (SCC)

Carbon emissions have significant implications for the Indian economy. The social cost of carbon (SCC) serves as a metric to quantify the monetary value of a policy's impact on climate change attributable to changes in carbon dioxide emissions within benefit-cost analyses. In instances where policies lead to increased emissions, the projected rise in emissions (measured in tonnes) is multiplied by the SCC value. The resulting figure 5 is then incorporated into the overall estimated costs associated with that policy [25]. Conversely, for policies aimed at reducing pollution, the reduction in pollution is multiplied by the SCC value, and the resultant Figure 5 is utilized to estimate the projected benefits of said policy.

According to research by Ricke et al [9], India's country-level SCC for carbon emissions stands at a staggering $86 per tonne of CO_2. This implies that for each additional tonne of CO_2 emitted, the Indian economy incurs a loss of $86. To assess the CO_2 cost savings across different scenarios, we employed the same methodology. Specifically, we calculated the cost of each policy or scenario by multiplying the increase or decrease in emissions (measured in tones) by the SCC value.

Results

This section presents the findings of the study. In Section 4.1, we explore the impact of electric vehicle (EV) adoption on on-road CO_2 emissions, while Section 4.2 delves into the analysis of the impact of EV adoption on total CO_2 emissions across various scenarios. To evaluate the influence of EV introduction on decarbonization, we conducted calculations on on-road and total CO_2 emissions under different scenarios spanning from 2017 to 2050. Our analysis assumes a gradual replacement of the existing vehicle fleet by the new vehicle fleet, with all new internal combustion engine (ICE) vehicles adhering to BS VI emission norms post-2019. As older ICE vehicles are phased out and substituted by newer, more efficient models, a gradual decline in carbon emissions is anticipated. Each scenario of EV adoption rate and ICE vehicle replacement is comprehensively outlined in Table 1. Additionally, Table 2 provides a breakdown of on-road emissions attributable to existing old vehicles, new vehicles, production emissions, and total production and emissions.

The six scenarios are detailed as follows: (Table 1 and 2)

Scenarios	Electric vehicles	ICE vehicles
1	Business-As-Usual	Business-As-Usual
2	Business-As-Usual	Targeted (no-new ICE production after 2034)
3	Business-As-Usual	Targeted (100% electrification of fuel after 2034)
4	Business-As-Usual	Eco-driving + Business-As-Usual
5	Business-As-Usual	Eco-driving + Targeted (no-new ICE production after 2034)
6	Business-As-Usual	Eco-driving + Targeted (100% electrification of fuel after 2034)

Table 1. Different combinations of scenarios for electric vehicles adoption.

Years	On road-emission	Total new vehicles	Production emission factor IC engine	Production emission	No of e vehicle	Production emission factor for EV	Total production emission for EV	Total emission=on road+ production emission
2017	3.27E+12	7021006	7.8	54763847	8162	12.9	105289.8	3.27E+12
2018	3.25E+12	7200528	7.8	56164118	8412	12.9	108514.8	3.25E+12
2019	3.22E+12	7380051	7.8	57564398	8662	12.9	111739.8	3.22E+12
2020	3.14E+12	7559574	7.8	58964677	8912	12.9	114964.8	3.14E+12
2021	3.14E+12	7739097	7.8	60364957	9162	12.9	118189.8	3.14E+12
2022	3.14E+12	7918620	7.8	61765236	9412	12.9	121414.8	3.14E+12
2023	3.13E+12	8098143	7.8	63165515	9662	12.9	124639.8	3.13E+12
2024	3.12E+12	8277665	7.8	64565787	9912	12.9	127864.8	3.12E+12
2025	3.11E+12	8457188	7.8	65966066	10162	12.9	131089.8	3.11E+12
2026	3.12E+12	8636711	7.8	67366346	10412	12.9	134314.8	3.12E+12
2027	3.13E+12	8816234	7.8	68766625	10662	12.9	137539.8	3.13E+12
2028	3.15E+12	8995757	7.8	70166905	10912	12.9	140764.8	3.15E+12
2029	3.17E+12	9175280	7.8	71567184	11162	12.9	143989.8	3.17E+12
2030	3.19E+12	9354802	7.8	72967456	11412	12.9	147214.8	3.19E+12
2031	3.21E+12	9534325	7.8	74367735	11662	12.9	150439.8	3.21E+12
2032	3.23E+12	9713848	7.8	75768014	11912	12.9	153664.8	3.23E+12
2033	3.24E+12	9893371	7.8	77168294	12162	12.9	156889.8	3.24E+12
2034	3.26E+12	10072894	7.8	78568573	12412	12.9	160114.8	3.25E+12
2035	2.96E+12	10252417	12.9	132256179	12662	12.9	163339.8	2.96E+12
2036	2.77E+12	10431939	12.9	134572013	12912	12.9	166564.8	2.77E+12
2037	2.58E+12	10611462	12.9	136887860	13162	12.9	169789.8	2.58E+12
2038	2.38E+12	10790984	12.9	139203694	13412	12.9	173014.8	2.38E+12
2039	2.18E+12	10970506	12.9	141519527	13662	12.9	176239.8	2.18E+12
2040	1.97E+12	11150029	12.9	143835374	13912	12.9	179464.8	1.97E+12

2041	1.76E+12	11329551	12.9	146151208	14162	12.9	182689.8	1.76E+12
2042	1.55E+12	11509074	12.9	148467055	14412	12.9	185914.8	1.55E+12
2043	1.33E+12	11688596	12.9	150782888	14662	12.9	189139.8	1.33E+12
2044	1.11E+12	11868119	12.9	153098735	14912	12.9	192364.8	1.11E+12
2045	8.78E+11	12047641	12.9	155414569	15162	12.9	195589.8	8.78E+11
2046	7.09E+11	12227164	12.9	157730416	15412	12.9	198814.8	7.09E+11
2047	5.37E+11	12406686	12.9	160046249	15662	12.9	202039.8	5.37E+11
2048	3.61E+11	12586209	12.9	162362096	15912	12.9	205264.8	3.61E+11
2049	1.82E+11	12765731	12.9	164677930	16162	12.9	208489.8	1.82E+11
2050	0	12945254	12.9	166993777	16412	12.9	211714.8	167205491.4

Table 2. Estimation of on-road emissions due to existing old vehicles, new vehicles, production emissions and total production and emissions.

Scenario 1: This scenario serves as the baseline, assuming regular growth rates for both new internal combustion engine (ICE) and electric vehicle (EV) production. Diesel vehicles are phased out every 10 years, while petrol vehicles are replaced every 15 years in accordance with government policy. On-road emissions are solely attributed to ICE vehicles, while EVs produce no on-road emissions.

Scenario 2: In this scenario, no new ICE vehicles are manufactured after 2034, while EV production continues to grow at a normal rate. Consequently, only existing ICE vehicles contribute to on-road emissions.

Scenario 3: In this scenario, it is assumed that all new vehicles introduced after 2034 will be 100% electric, with only existing ICE vehicles contributing to on-road emissions.

Scenario 4: Under this scenario, all vehicles operate under eco-driving conditions, with regular growth rates maintained for both ICE and EV production.

Scenario 5: Similar to Scenario 4, all vehicles practice eco-driving, but no new ICE vehicles are produced after 2034. EV production continues to grow at a normal rate, and only existing ICE vehicles contribute to on-road emissions.

Scenario 6: In this scenario, all vehicles adopt eco-driving practices, and all new vehicles introduced after 2034 are 100% electric. On-road emissions are solely attributed to existing ICE vehicles.

Impact of electric vehicle adoption on on-road CO_2 emission and health impact

We conducted an analysis to determine the on-road CO_2 emissions from diesel and petrol vehicles spanning the period from 2017 to 2050. Subsequently, Figure 3 graph illustrates the relationship between on-road emissions and years across six distinct scenarios. In all scenarios, we assumed zero on-road emissions from electric vehicles. (Figure 3)

Scenario 1, serving as the reference, depicted the highest annual increase in on-road emissions. This scenario assumes normal growth in ICE vehicle production, resulting in continuous CO_2 emissions. Conversely, scenarios 2 and 3 envisaged the cessation of ICE vehicle production by 2035 and its substitution by electric vehicles, respectively. As a consequence, on-road emissions are projected to reach zero by 2050 due to the scrapping of remaining ICE vehicles in 2049, leaving only electric vehicles on the road. Scenarios 4, 5, and 6 integrated eco-driving practices alongside vehicle electrification and the cessation of ICE vehicle production from 2035 onwards. Notably, these scenarios exhibited further reductions in on-road emissions attributable to eco-driving practices. Figure 3 illustrates the projected trend in on-road CO_2 emissions across different scenarios. Scenarios 5 and 6, incorporating both eco-driving and vehicle electrification showcased the most substantial reductions in on-road CO_2 emissions. Conversely, in Scenario 1 (Business as Usual), on-road emissions exhibited continuous growth.

This underscores the potential for mitigating future on-road CO_2 emissions through the replacement of ICE vehicles with electric vehicles and the adoption of eco-driving practices. The impact of embedded CO_2 is often accounted for in life cycle assessments of both Electric Vehicles (EVs) and Internal Combustion Engine vehicles (ICEs), where the embedded CO_2 is spread over the vehicle's entire lifetime. While this approach is suitable for determining whether a vehicle achieves carbon neutrality, it may not be ideal for evaluating the total CO_2 impact of a policy. During the manufacturing phase of a vehicle's lifecycle, CO_2 emissions occur upfront, rather than being spread out over the vehicle's lifetime, as noted by Hill et al [22]. Analyzing the impact of EV adoption on total CO_2 emissions (as depicted in Figure 4), we observe minimal differences in emissions among scenarios 1, 2, and 3 before 2035. This is primarily due to the predominant presence of ICE vehicles, which continue to contribute significantly to total CO_2 emissions. However, as ICE vehicle production ceases and EV adoption increases from 2035 onwards in scenarios 2 and 3, we witness the most substantial reductions in total CO_2 emissions compared to scenario 1. (Figure 4)

Moreover, combining eco-driving practices with vehicle electrification in scenarios 4, 5, and 6 results in additional reductions in vehicular CO_2 emissions. In terms of health impact, Arokiaraj et al [24] found that eco-driving strategies can reduce carbon emissions by 16% and save fuel consumption. Combining eco-driving with vehicle electrification in scenarios 4, 5, and 6 demonstrates significant reductions in both on-road and total CO_2 emissions. Specifically, scenario 4 achieves an 84% reduction, while scenarios 5 and 6 achieve an impressive 85.23% reduction compared to scenario 1 (BAU). This highlights the effectiveness of adopting both strategies concurrently. Additionally, Rietmann [26] concluded that India may achieve a 50% EV share of car inventory by >2035.

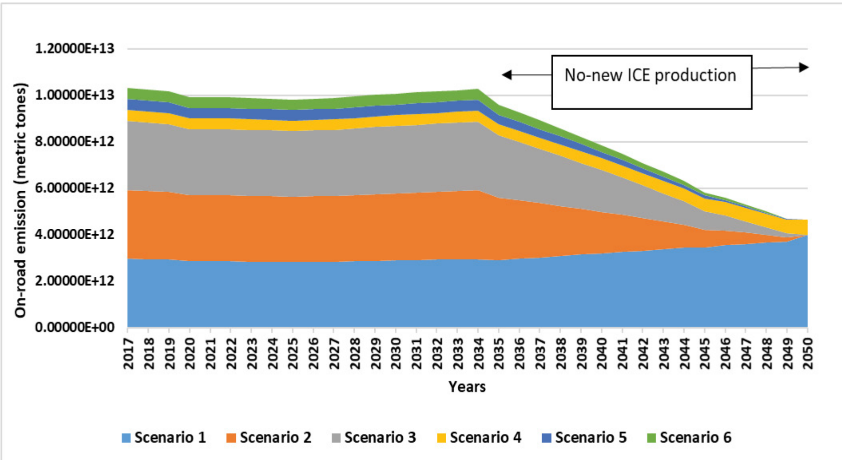

Figure 3: EV adoption impact on on-road CO_2 emission.

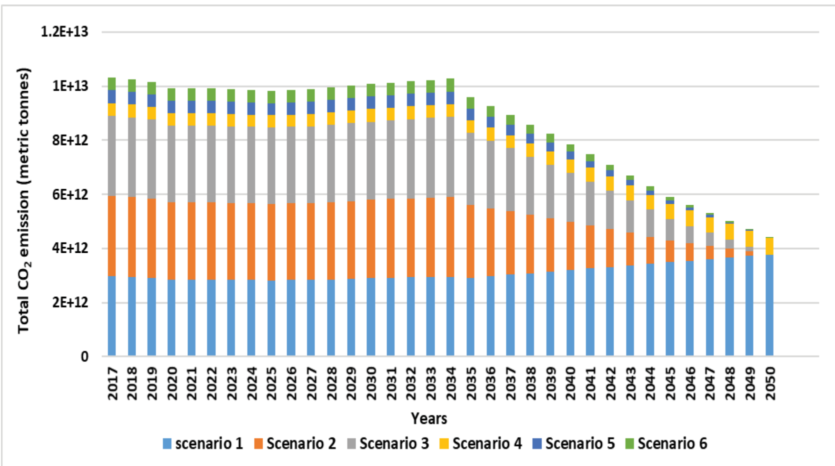

Figure 4: EV adoption impact on total CO_2 emission.

Our study suggests that switching production from ICE vehicles to EVs in 2035 would yield the highest reduction in CO_2 emissions. However, India faces challenges due to its heavy reliance on coal, which accounts for 56% of energy generation. Increasing EV production could exacerbate CO_2 emissions unless accompanied by a transition to renewable energy sources. Figure 4 illustrates the cost implications of implementing different scenarios in 2035 and 2050. Scenario 1 (BAU) incurs the highest cost in both years, while scenarios 5 and 6 exhibit the lowest costs. This underscores the cost-saving potential of scenarios 5 and 6, translating to significant benefits through emission reduction. (Figure 5)

Considering the study's findings, it's essential to address the health ramifications associated with vehicular emissions, particularly those originating from Internal Combustion Engine vehicles (ICEs). These vehicles emit a range of pollutants, including particulate matter (PM), nitrogen oxides (NOx), volatile organic compounds (VOCs), and carbon monoxide (CO), which pose significant health risks.

Particulate matter, particularly PM2.5, has the ability to infiltrate deep into the respiratory system and bloodstream, leading to a variety of respiratory and cardiovascular ailments, such as asthma, bronchitis, heart attacks, and strokes. Nitrogen oxides contribute to the creation of ground-level ozone, a primary component of smog, which can worsen respiratory conditions and cause lung damage. Volatile organic compounds react with NOx under sunlight to generate ground-level ozone and other harmful pollutants, exacerbating air quality issues and respiratory health problems. Carbon monoxide disrupts the blood's capacity to carry oxygen, resulting in symptoms like headaches, dizziness, and fatigue, and in severe cases, it can be fatal.

By reducing vehicular CO_2 emissions through the adoption of Electric Vehicles (EVs) and eco-driving practices, substantial co-benefits for public health can be realized. EVs produce zero tailpipe emissions, eliminating direct exposure to harmful pollutants such as PM, NOx, VOCs, and CO. Furthermore, eco-driving practices, emphasizing smoother acceleration, consistent speeds, and reduced idling, can lead to lower emissions of pollutants and improved air quality. The implementation of scenarios advocating for EV adoption and eco-driving, as delineated in the study, could significantly mitigate health risks linked to vehicular emissions. These strategies can enhance public health outcomes, diminish healthcare expenditures, and ameliorate overall community well-being by curbing exposure to harmful pollutants, particularly in densely populated urban locales where vehicular traffic is concentrated.

Discussion

The global interest in the rapid electrification of the transportation sector stems from the urgency to achieve climate change reduction goals, particularly in limiting global warming to below 1.5°C or 2°C. Our analysis reveals that increasing EV adoption rates and implementing prudent driving strategies post-2034 can significantly reduce CO_2 emissions (85.23%) compared to the Business as Usual (BAU) scenario. By 2035, only the combination of 100% EV sales and adopting eco-driving practices can attain the

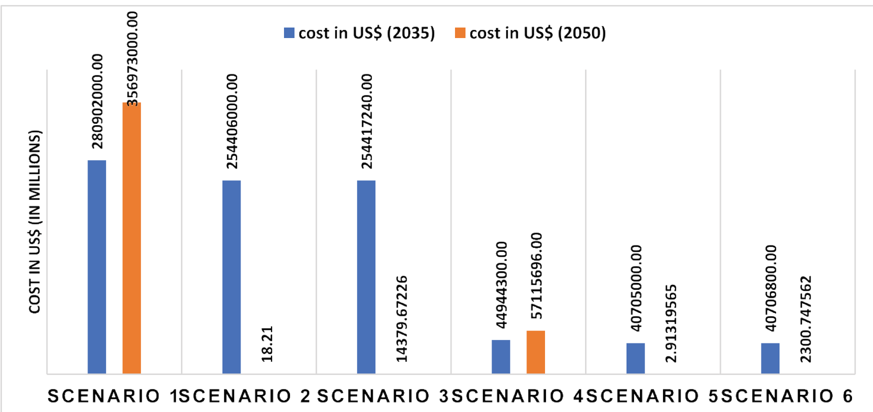

Figure 5: Cost of different scenarios (in US$).

necessary reductions in both on-road CO_2 emissions and total CO_2 emissions. Without these measures, there is a risk of continued increase in CO_2 emissions in the future. In India, where power generation relies heavily on coal, achieving long-term CO_2 emission reductions hinges on a substantial increase in EV uptake, alongside aggressive decarbonization of electricity used for EV charging and manufacturing.

Ceasing ICE vehicle production and transitioning to 100% electrification of vehicles, coupled with eco-driving practices, can effectively mitigate vehicular emissions and lead to economic savings through reduced carbon emissions. Studies on eco-driving conducted with various types of professional drivers yield diverse results. For example, machine drivers in Portugal achieved savings ranging from 0.3% to 2% [27], whereas in Greece, savings ranged from 10% to 15% [28]. Similarly, Rutty [29] examined the effectiveness of eco-driving with external drivers in Canada, where drivers achieved consumption savings between 4% and 10%. Yao [30] investigated eight professional drivers with a driving simulator in China and recorded savings of 8.4%. Eco-driving has effectively reduced energy consumption and CO_2 emissions in both large, congested cities and small towns, with savings ranging between 5% and 12% [31].

Conclusion

Based on the findings of this study, it is evident that urgent measures are needed to address the rising vehicular CO_2 emissions. Continuing with current motor vehicle usage trends will rapidly increase on-road CO_2 emissions in the coming years, making it challenging to achieve CO_2 reduction targets. Therefore, it is imperative to introduce a greater number of zero-emission vehicles into the market and promote eco-driving practices among vehicle users. The results of this study suggest that the most effective strategies for decarbonizing India's transportation sector and mitigating the greenhouse gas effects of automobiles involve the widespread adoption of electric vehicles and the implementation of eco-driving practices. Additionally, there is a critical need to transition towards renewable energy resources to reduce the CO_2 impact during the manufacturing of electric vehicles. Simultaneously, promoting eco-driving practices can enhance the fuel efficiency of Internal Combustion Engine (ICE) vehicles, further contributing to emissions reduction efforts.

Conflict of interest

The authors do not have any conflict of interest with other entities or researchers.

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