Comparative Analysis of Carbon Emissions: ICE vs. Electric Vehicles Across Indian States

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Abstract - *Proponents of Electric Vehicles (EVs) often argue that their adoption is a simple and effective step toward decarbonizing transportation. However, the environmental advantages of EVs are highly dependent on the source of electricity, which can vary significantly across different regions. In this paper, we aim to analyze and compare the emissions produced by EVs and Internal Combustion Engine (ICE) vehicles including petrol, diesel, and CNG variants across various automobile categories and states in India. Our analysis reveals that states like Tamil Nadu and Karnataka, which have a higher share of renewable energy sources, show significantly lower emissions from EV usage. In contrast, coal-dependent states such as Jharkhand and Chhattisgarh exhibit higher EV emissions compared to ICE vehicles [1], [2]. Across vehicle categories, it is evident that Mopeds, Bikes, and Three-Wheelers are ideal candidates for electrification due to their consistently low emissions in all states [3]. These findings underscore the need for state-specific strategies and policies for energy and transportation along with grid decarbonization and vehicle-to-grid integration to ensure a truly sustainable transition to EVs [4], [5].*

Key Words: Electric Vehicles (EVs), Internal Combustion Engine (ICE) Vehicles, Carbon Emissions, Coal Dependency, Renewable Energy, Grid Decarbonization, State-Specific Energy Policies, Vehicle Electrification, Two Wheelers, Three Wheelers, Lifecycle Emissions, Sustainable Transportation.

1.INTRODUCTION

Electric vehicles (EVs) are perceived as the best possible solution to tackle emissions originating from transport; however, the strictly environmental advantages of EVs are painstakingly sensitive to the energy's origin, which differs greatly on India's vast terrains. In this paper, we try to analyze and contrast the emissions of EVs and Internal Combustion Engine (ICE) vehicles comprising Petrol, Diesel, and CNG versions of different types of vehicles across the various states of India. From the analysis, we learn that states abundant in renewable energy sources such as Tamil Nadu and Karnataka tend to have the lowest emissions from EVs, whereas coal-dependent states such as Jharkhand and Chhattisgarh show a much greater emission levels of EVs compared to ICE [2], [3]. A study of different categories of automobiles and motorcycles indicates that Two-wheelers (Mopeds and Bikes) and Three-wheelers are the best candidates to switch to EVs as they exhibit the least amount of emissions by far in comparison to other states [4]. Such analysis provides clarity on the need for state-specific energy and transport systems and policies that are centered around decarbonizing the grid and segment electrification, which substantively changes the dynamics of adopting EVs.

Nevertheless, the positive impacts on the environment resulting from EVs adoption are not the same for every region and state due to the varying impact of the electricity grid. The electricity used in charging the EVs can either be derived from renewable sources like solar and wind or fossil fuel-based sources like coal and gas [5], [6]. Like most countries, the state-level emissions differences in India are influenced by geographic and energy infrastructure diversity. While some states like Tamil Nadu and Karnataka use a large share of renewables in their power mix, Jharkhand and Chhattisgarh are mostly dependent on coal [6]. This means that where adoption of EVs in coal-heavy states would result in higher emissions, estimation of emissions in states with cleaner fuel use would show them to have lower emissions when compared to petrol/diesel ICE vehicles, especially when compared to CNG-powered vehicles [6].

This study seeks to bridge this gap by estimating emissions on a state level and stratifying the analysis per vehicle segment (Four Wheelers: SEDANS and SUVs; Heavy Wheelers: MINI TRUCKS and TRUCKS; Three Wheelers; and Two Wheelers: Mopeds and Bikes) with intention to define target states for EV adoption [2], [3].

2. METHODOLOGY

2.1 Internal Combustion Engine (ICE) Emissions

The vehicles were categorized into four segments: Four Wheelers, Heavy Wheelers, Three Wheelers, and Two Wheelers. Data on the most popular vehicles for each segment, including their mileage (in km/liter), was collected from official manufacturer websites and automotive platforms [1], [2], [3]. Fuel types considered were Petrol, Diesel, and CNG. Emission factors (in kg CO_2/liter) were obtained from the Gujarat Carbon Footprint Calculator.

2.2 Emission Calculations

The emission per kilometer for each vehicle was calculated as:

$$E_{per\ km} = \frac{E_{per\ km}}{Mileage} \quad \text{eq (i)}$$

The Python script automated the following tasks:

- Parsing mileage data for multiple vehicles and averaging across fuel types [5].
- Computing emission per km for individual vehicles.
- Generating a summary table with average segment-wise emissions.

2.3 Electric Vehicle (EV) Emissions

2.3.1 Vehicle Segmentation and Data Collection

Data on the range (in kilometers) and battery capacity (in kWh) of EVs was collected for each segment. Sources included manufacturer websites and platforms such as Zigwheels and Switch Mobility [6], [7].

2.3.2 Efficiency Calculation and State-Level Energy Data

The efficiency (in km/kWh) for each vehicle was calculated as:

$$Efficiency = \frac{Range\ (km)}{Battery\ Capacity\ (kWh)} \quad \text{eq (ii)}$$

Python scripts were used to:

- Process state-wise electricity generation and emission data from ICED NITI Aayog [8], [9].
- Compute the emission per kWh for each state:

$$E_{per\ kWh} = \frac{Total\ Emissions\ (kg\ CO_2)}{Total\ Electticity\ Produced\ (kWh)} \quad \text{eq (iii)}$$

- Calculate emission per km for EVs:

$$E_{per\ km} = \frac{E_{per\ kWh}}{Efficiency\ (km/kwh)} \quad \text{eq (iv)}$$

2.3.3 Averaging Across Segments

Python scripts automated:

- Efficiency calculations for all vehicles in a segment [5].
- Averaging emissions per km for each segment across states.

2.4 Comparison

2.4.1 Histogram Analysis

Histograms were generated using Python's visualization libraries (e.g., Matplotlib, Seaborn) to compare emissions across states for different fuel types (Petrol, Diesel, CNG, Electricity) and vehicle segments [5].

2.4.2 Segment-Specific Insights

Python's data analysis capabilities enabled:

- Identification of state-specific trends in emissions [10].
- Segment-wise visualization for vehicles like Sedans, SUVs, and Trucks.

3. RESULTS AND DISCUSSION

This section compares the carbon emissions of Electric Vehicles (EVs) and Internal Combustion Engine (ICE) vehicles across different Indian states, with a breakdown by vehicle type. The analysis includes graphs to illustrate the trends, highlighting states like Goa and Kerala that show zero or minimal emissions due to imported electricity. Any associated error margins or potential biases have been acknowledged and are addressed in a separate section later in this paper [9].

To make the data more readable and easier to interpret, the large composite graphs generated for each vehicle category were divided into smaller, focused subgroups (Group 1, Group 2, and Group 3). This grouping approach was used to ensure that comparisons between states and fuel types remain visually clear and readable, especially given the large number of data points across various Indian states. Each group highlights a specific subset of states, allowing for a more detailed examination and interpretation of emission trends without overwhelming the reader. The graphs were created using Python visualization libraries such as Matplotlib and Seaborn.

3.1 Four Wheelers

3.1.1 Sedans

The emissions from Sedans highlight a clear distinction between EVs and ICE vehicles:

- **EV Sedans:** States like Tamil Nadu and Karnataka, powered by renewable energy, have the lowest emissions (~0.08 kg CO_2e/km). In contrast, coal-reliant states like Jharkhand and Chhattisgarh exhibit higher emissions (~0.14 kg CO_2e/km) [11].

- **ICE Sedans:** Petrol, Diesel, and CNG emissions remain constant across states due to uniform fuel-based emission factors. Petrol and Diesel Sedans produce ~0.12–0.15 kg CO_2e/km, while CNG Sedans have slightly lower emissions (~0.11 kg CO_2e/km) [1].

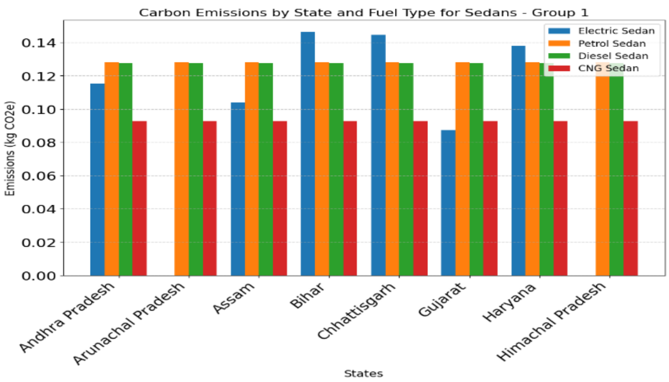

Fig - 1: Carbon Emissions by State and Fuel Type for Sedans – Group 1

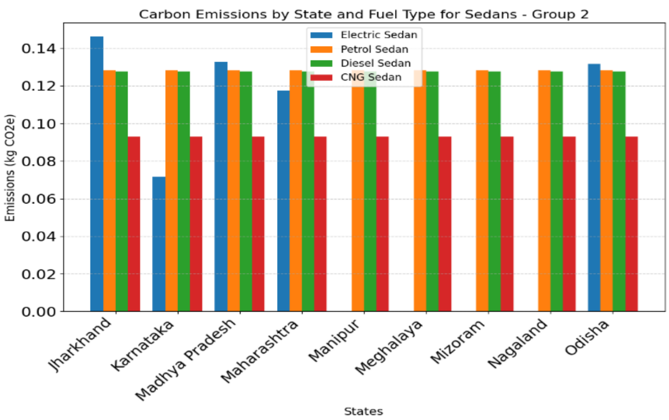

Fig-2: Carbon Emissions by State and Fuel Type for Sedans – Group 2

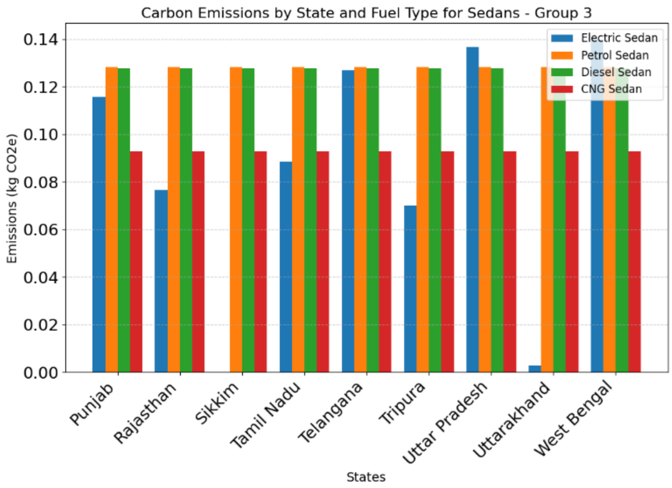

Fig-3: Carbon Emissions by State and Fuel Type for Sedans – Group 3

- **Insight**: EV Sedans outperform ICE Sedans in renewable-rich states like Tamil Nadu, but in coal-dependent states like Jharkhand, their emissions often exceed those of CNG Sedan.

3.1.2 SUVs

Similar trends were observed for SUVs:

- **EV SUVs**: Lowest emissions were recorded in states like Himachal Pradesh and Tamil Nadu (~0.08 kg CO_2e/km). Coal-dependent states showed emissions as high as 0.16 kg CO_2e/km, making EV SUVs less advantageous in those regions [12].

- **ICE SUVs:** Diesel SUVs consistently exhibited the highest emissions (~0.15 kg CO_2e/km), followed by Petrol and CNG SUVs (~0.12–0.14 kg CO_2e/km) [1].

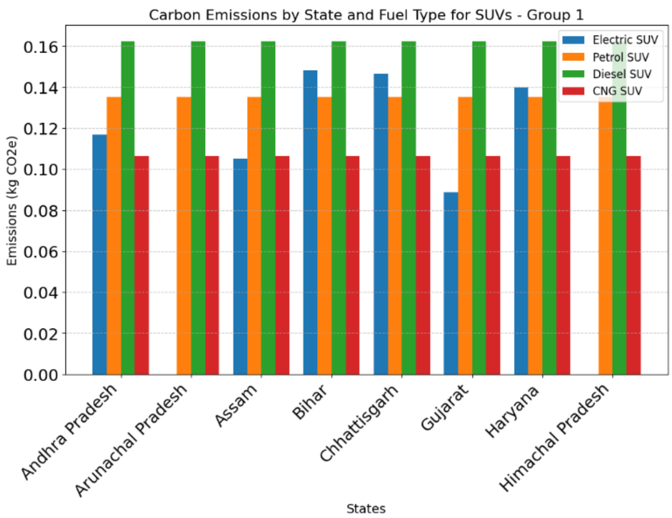

Fig-4: Carbon Emissions by State and Fuel Type for SUVs – Group 1

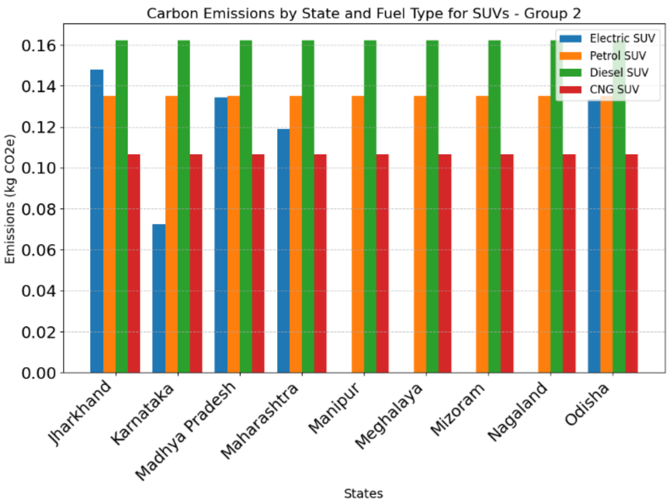

Fig-5: Carbon Emissions by State and Fuel Type for SUVs – Group 2

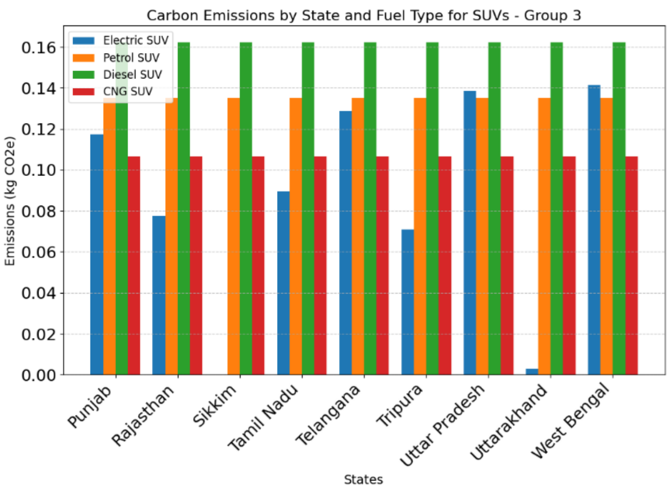

Fig-6: Carbon Emissions by State and Fuel Type for SUVs – Group 3

- **Insight**: EV SUVs are the cleanest option in renewable-energy states like Himachal Pradesh, but in coal-dependent states, their emissions can exceed those of CNG and Petrol SUVs.

3.2 Heavy Wheelers

3.2.1 Mini Trucks

The emissions of Mini Trucks highlight the suitability of EVs in renewable-energy-dominated states:

- **EV Mini Trucks:** Emissions varied from 0.06–0.12 kg CO_2e/km depending on the state's energy mix [11].
- **Diesel Mini Trucks:** Emissions were consistently high at ~0.15 kg CO_2e/km across all states [1].

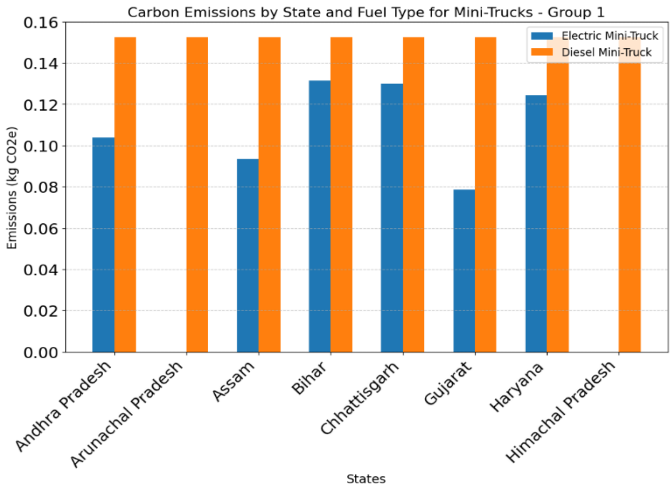

Fig-7: Carbon Emissions by State and Fuel Type for Mini Trucks – Group 1

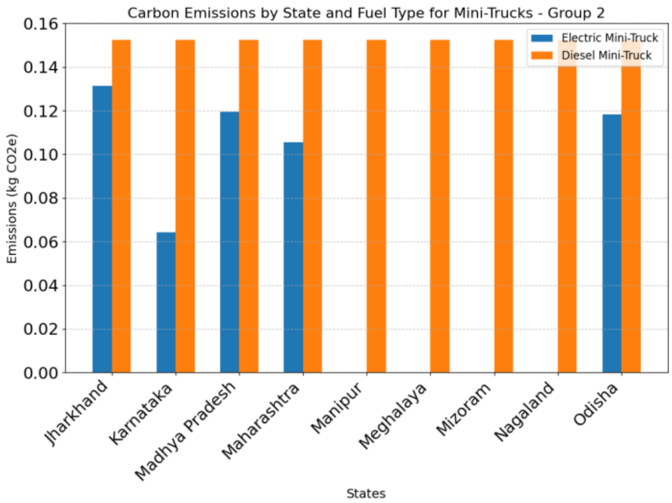

Fig-8: Carbon Emissions by State and Fuel Type for Mini Trucks – Group 2

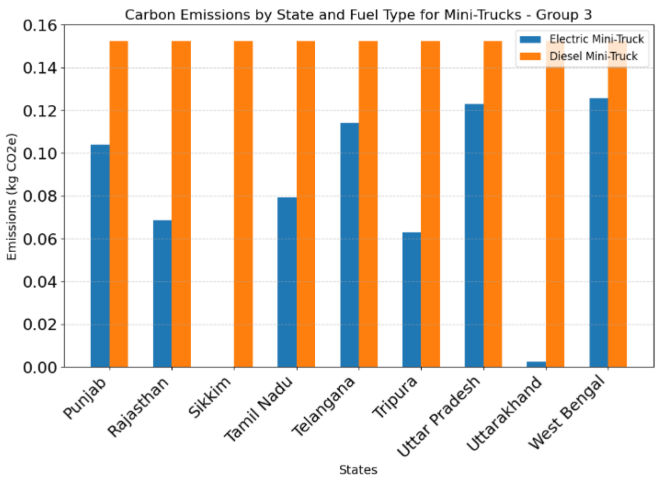

Fig-9: Carbon Emissions by State and Fuel Type for Mini Trucks – Group 3

- **Insight**: Electric Mini Trucks outperform Diesel Mini Trucks in renewable-heavy states, with emissions as low as 0.06 kg CO_2e/km, but show comparable emissions in coal-reliant states.

3.2.2 Trucks

Truck emissions showed high disparity due to differences in mileage estimation methodologies [5], [10]:

- **EV Trucks:** Emissions ranged from 0.5–0.7 kg CO_2e/km in renewable-heavy states. This mileage estimation was based on engine testing during manufacturing, which may not reflect real-world performance.

- **Diesel Trucks:** Emissions were consistently ~0.4 kg CO_2e/km across states due to more realistic, in-use mileage testing.

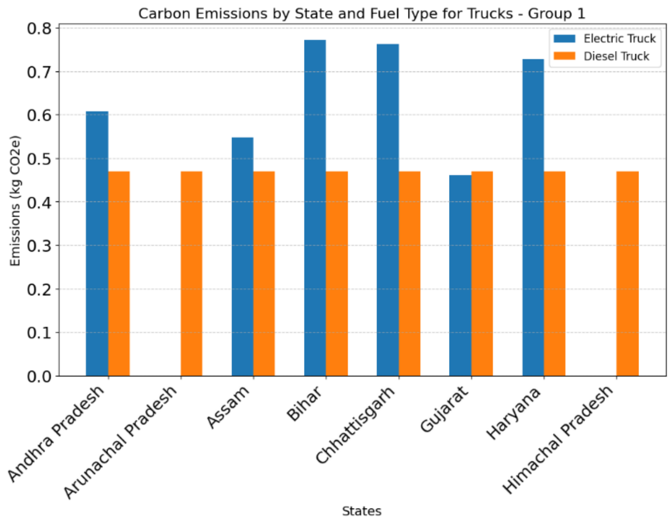

Fig-10: Carbon Emissions by State and Fuel Type for Trucks – Group 1

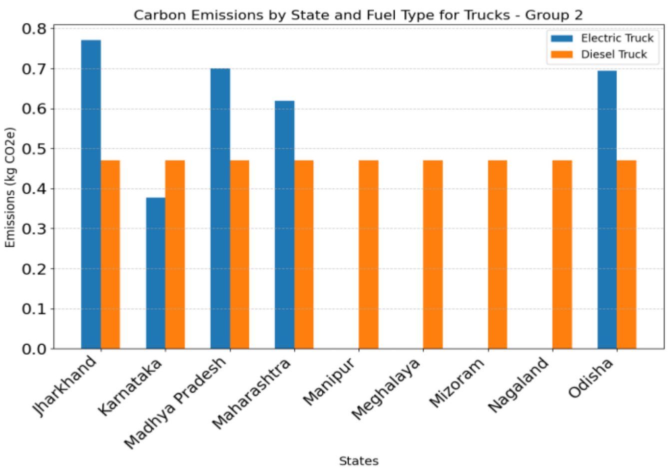

Fig-11: Carbon Emissions by State and Fuel Type for Trucks – Group 2

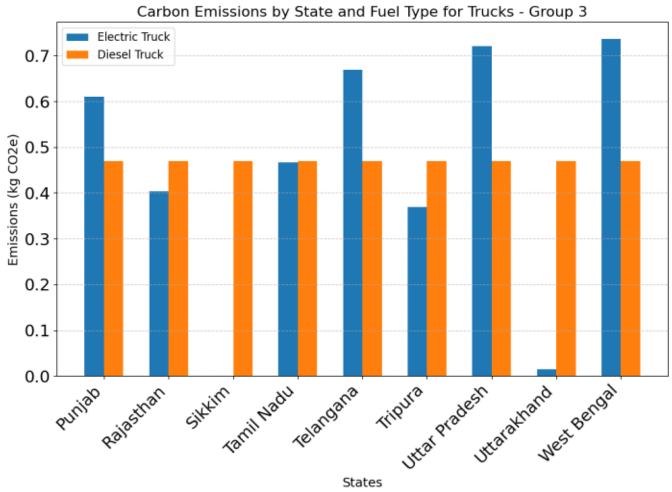

Fig-12: Carbon Emissions by State and Fuel Type for Trucks – Group 3

- **Insights**: EV Trucks have the potential to outperform Diesel Trucks in terms of emissions, but standardized mileage testing is needed to ensure fair comparisons.

3.2.3 Three Wheelers

Three Wheelers demonstrated a clear advantage for electrification:

- **EV Three Wheelers:** Emissions were significantly lower, ranging from 0.04 kg CO_2e/km in renewable-heavy states to 0.06 kg CO_2e/km in coal-reliant states [11].

- **Diesel and CNG Three Wheelers:** Emissions remained constant across states (~0.08–0.09 kg CO_2e/km) [1].

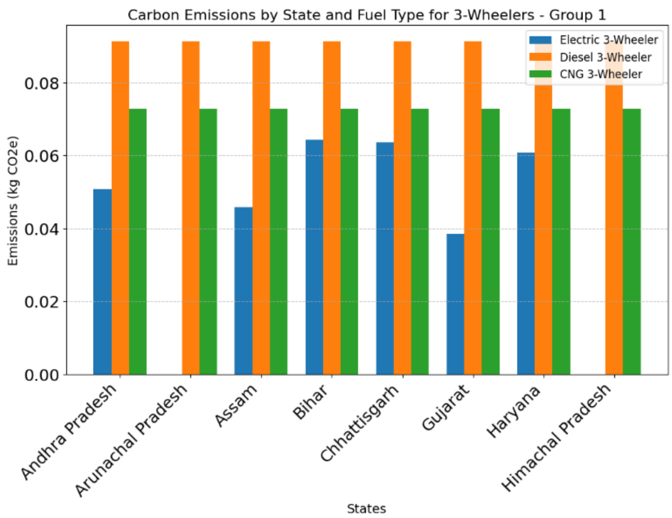

Fig-13 Carbon Emissions by State and Fuel Type for Three Wheelers – Group 1

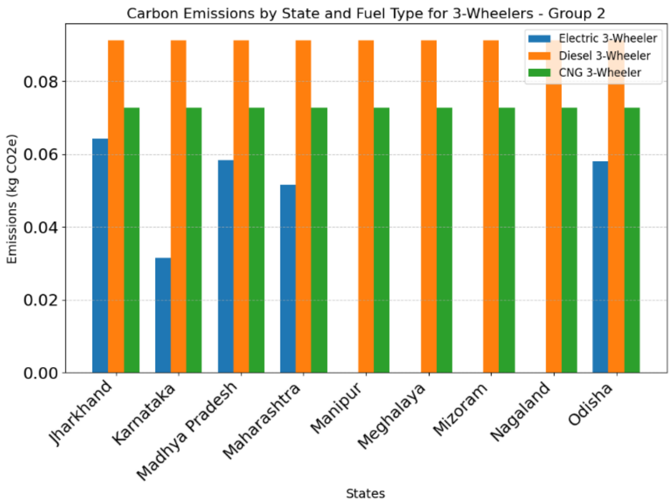

Fig-14: Carbon Emissions by State and Fuel Type for Three Wheelers – Group 2

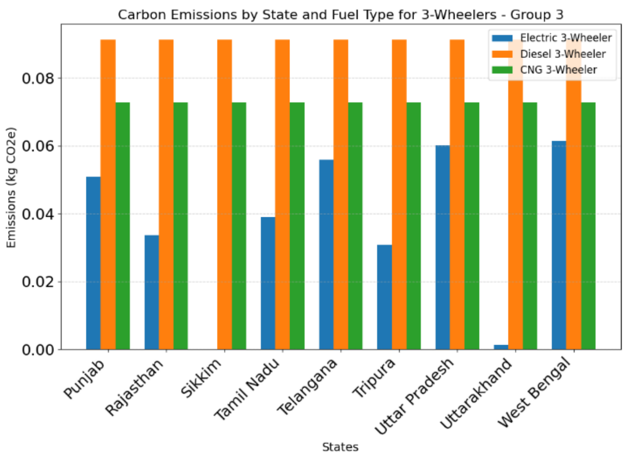

Fig-15: Carbon Emissions by State and Fuel Type for Three Wheelers – Group 3

- **Insights**: EV Three Wheelers are the most viable segment for electrification, offering consistent emission reductions across all states.

3.4 Two Wheelers

3.4.1 Mopeds

Electric Mopeds consistently outperformed Petrol Mopeds:

- **EV Mopeds:** Emissions were lowest in states like Tamil Nadu and Karnataka (~0.01–0.03 kg CO_2e/km) [11].

- **Petrol Mopeds:** Emissions were consistently higher at ~0.05 kg CO_2e/km across states [1].

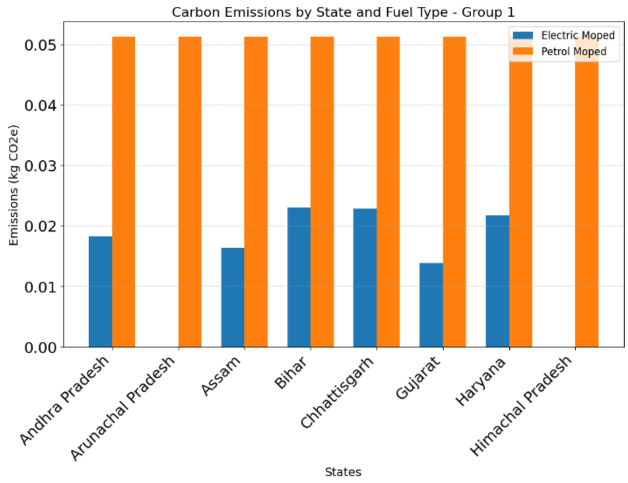

Fig-16: Carbon Emissions by State and Fuel Type for Mopeds – Group 1

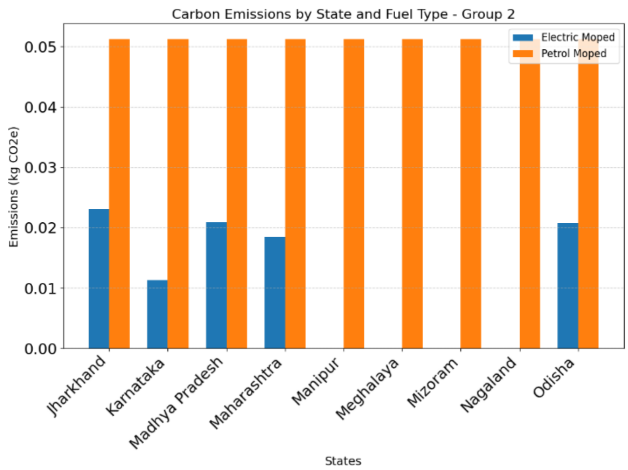

Fig-17: Carbon Emissions by State and Fuel Type for Mopeds – Group 2

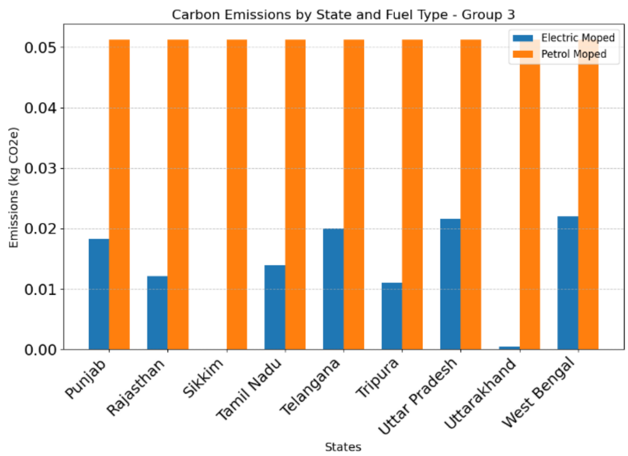

Fig-18: Carbon Emissions by State and Fuel Type for Mopeds – Group 3

- **Insight:** Electric Mopeds outperform Petrol Mopeds across all states, with emissions as low as 0.01–0.03 kg CO_2e/km in renewable-heavy regions like Tamil Nadu and Karnataka.

3.4.2 Bikes

Bikes followed similar trends as Mopeds:

- **EV Bikes:** Emissions ranged from 0.01–0.03 kg CO_2e/km in renewable-energy states, with slightly higher values in coal-dependent states.

- **Petrol Bikes:** Emissions remained constant at ~0.05 kg CO_2e/km across states.

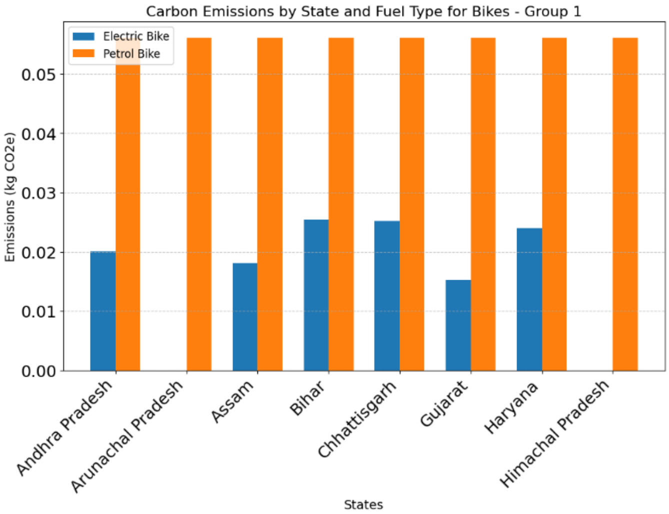

Fig-19: Carbon Emissions by State and Fuel Type for Bikes – Group 1

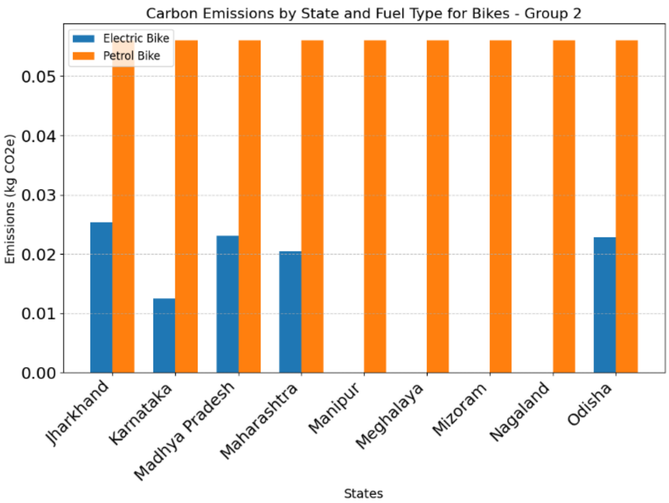

Fig-20: Carbon Emissions by State and Fuel Type for Bikes – Group 2

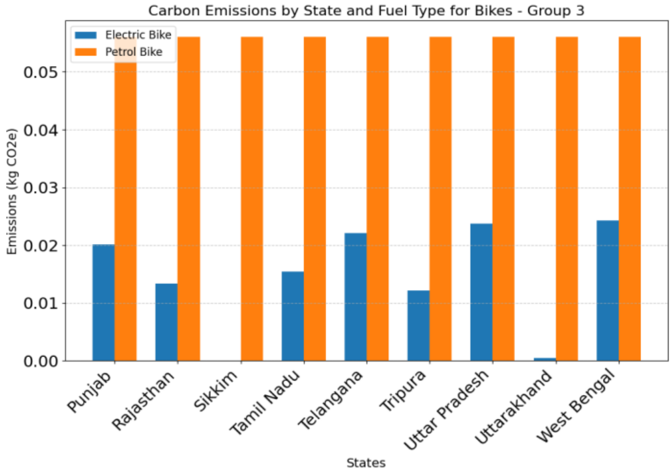

Fig-21: Carbon Emissions by State and Fuel Type for Bikes – Group 3

- **Insights**: Electric Two Wheelers, including Mopeds and Bikes, offer substantial emission reductions and are highly recommended for widespread adoption.

3.5 Error Margin Analysis and Potential Biases

The data and information used in this research is gathered and derived from a combination of manufacturer specifications, state-level electricity grid emissions, and various real-world data sources. It is important to acknowledge and consider the potential biases and errors that may exist within these datasets:

1. **Vehicle Performance and Efficiency Data:**
   - Overestimation in Controlled Tests: Mileage reported by manufactures is often based on ideal conditions, which can lead to overestimated real-world efficiency by about 10–30% [3].
   - Incomplete Vehicle Information: Missing or inconsistent efficiency/range values in certain vehicle categories may skew emissions estimates [3].
   - Extreme EV Consumption Outliers: Certain electric vehicles (EVs) display unusually high energy consumption per kilometer, potentially skewing average results for their segment [3].
   - Variability in ICE Mileage: The fuel efficiency of internal combustion engine (ICE) vehicles can vary and depend on factors like maintenance, usage patterns, and fuel quality, resulting in overall deviations of up to 20% [3].
   - Battery Degradation Impact: Over time, EV batteries lose capacity, which can increase real-world energy consumption by 5–15%, it is a huge factor that is often overlooked [4].
   - Fluctuations in Grid Emissions: Relying solely on static state-wise grid emissions fails to account for seasonal and demand-related changes, leading to potential errors of 5–20% in estimating EV emissions [2].

2. **CO_2 Emission Data:**
   - Annual Gaps: Gaps in state records can impact trend accuracy for interpolation methods utilized, resulting in differences of roughly 5–15% [2].
   - Emission Trend Changes: Significant emissions due to new policy implementation or additions to infrastructure can lead to approximate uncertainty of ±10% [2].
   - Electricity Emissions from Imports: Certain states, like Goa, Delhi, and Uttarakhand, do not account for emissions associated with imported electricity, which can lead to an underestimation of total emissions by 10–20% [2].
   - Emission Estimates from Privates: Private and industrial emitters are not completely captured in the report, which allows for a 5–10% underestimation of emissions [2].
   - Fixed Conversion Factors: Set standard emission rates ignore the differences in the quality of coal and the efficiency of the plants, which results in errors between 5–12% [4].
   - Grid Emission Change Variations: The assumption stationary mix fuel tends to disregard seasonal changes in the source of power which can lead to differences of 5–15% in actual emissions [2].

3. **Electricity Generation Data:**
   - Incomplete Records: Gaps in yearly data from some states can lead to a 5-15% uncertainty within generation trends [2].
   - Substitution from Other Sources: Seasonal and policy changes in energy sources cause a variation of 10% in the annual mix estimates [5].
   - Skipped Grid Losses: Reduction in power generation due to transmission losses being ignored will result in an underestimation of power use by 5-12% [2].
   - Overvalued Renewables: States overreporting generation output when the wind turns to solar, causes the actual generation to drop by 10-20% due to the weather and maintenance [5].
   - Thermal Inefficiency Gaps: Blame it on aged coal plants in some states, with their outdatedness causing the plants to increase emission by 5-15% more than the standard estimates [4].
   - Omitted Power Surrounding: Emissions caused by electricity coming from bordering states are taken for granted resulting in underestimate of Delhi and Goa's impact by a shocking 10-25% [2].

4. **Emission Factors Data:**
   - Absence of Data: Various states not having the complete record for CO_2 leads to a staggering 10-30% inaccuracy within estimations [4].
   - Methodologies Cut Out: Discrepancies appearing between estimates and calculations would lead to states records emission ranges anywhere between 5-15% [4].
   - Fixed Assumption Factors: Standard emission factors fail and ignore fuel and plant differences bringing up a considerable 5-12% [4].
   - Ignored Carbon Cuts: Emissions unaccounted for reforestation or renewable credits causes net emissions being overestimated by a ridiculous 10-20% [5].
   - Imported Emissions Excluded: States like Kerala and Goa omit emissions from imported power, underreporting by 10–25% [2].

3.5.1 Notes on Zero Emission States

The emissions for grid electricity in states such as Goa and Kerala, where energy imports were recorded, was a zero value [2]. Therefore, these states could not be included in the analysis. With no trustworthy government or authoritative sources for electricity import emission factors, these states were omitted from the comparison of emissions processes.

3.5.1.1 Summary of Observations

1. Factors to Consider for Each State: The make-up of the power grid determines the emission profile of an electric vehicle. States rich in renewables like Tamil Nadu, Karnataka, and Himachal Pradesh are very supportive of EVs, while coal-dependent states of Jharkhand and Chhattisgarh have EVs which are more carbon emitting because of coal powered electricity [1], [2], [5].

2. Segment Feasibility: Two Wheelers and Three Wheelers are the most promising candidates for electrification in all regions since they have lower emissions than their internal combustion engine (ICE) counterparts even in regions that rely on coal [3].

Dependence on Coal: In coal dominant regions, electric trucks, particularly the heavier vehicles, have the potential to emit more CO_2e than CNG or Diesel-burning trucks, which is not the case in other regions. Therefore, the environmental advantage of EVs is masked. Pairing electrification with reductions of emissions from fossil fuel power plants is necessary for true sustainability [4], [5].

4. FUTURE SCOPE

A robust foundation is laid by the findings of this research, which represents much of the mainstream understanding. This paper emphasizes that all concepts of state-specific energy policies should be integrated with the electrification of the transport sector [5], [6]. The environmental benefits of Electric Vehicles (EVs) can be demonstrated in states rich in renewable energy, but significant challenges remain in states dependent on coal [6]. Further research could focus on the following:

4.1. Grid Decarbonization:

Encourage the incorporation of renewable energy in states where coal plays a dominant role in the energy mix to minimize emissions related to electricity production. This would enhance the sustainability of electric mobility across the entire country [9]. It can also be supported by decentralized renewable energy solutions, wherein electric vehicle charging is powered by solar energy, thereby reducing reliance on coal-generated electricity [9], [13].

4.2. State-Specific Policy Development:

Develop state-specific incentives that help develop electric vehicle infrastructure, based on the advance of electric vehicle adoption in states with significant renewable energy usage [5], [6]. In the interim, also promote the use of compressed natural gas (CNG) vehicles in coal-dependent regions as a cleaner alternative to traditional fuels [6]. Offer state-specific incentives for the integration of renewable energy to further foster the development of EV infrastructure [9].

4.3. Lifecycle Emissions Analysis:

Broaden the scope of the study to include a complete lifecycle assessment of EVs and ICE vehicles, considering impacts from battery manufacturing, recycling, and disposal [4], [10]. Explore alternative battery technologies that have lower environmental impacts and are more sustainable in the long term [10].

4.4. Standardized Testing for EV Efficiency:

Develop standardized testing procedures for evaluating the real-world range and energy consumption of electric heavy-duty vehicles, especially trucks, to enable reliable comparisons with internal combustion engine vehicles [11].

4.5. Incorporation of Imported Electricity Emissions:

The analysis of electricity import emissions should become a part of future assessments for electricity-deficient states such as Goa and Kerala. A comprehensive evaluation arises from assessing both the sources of imported power and their associated emission factors [2], [6].

4.6. Advanced Data Analytics:

Advanced technologies in analysis and machine learning are used to predict the adoption of electric vehicles in different Indian states, and simultaneously assess the environmental impact under different network configurations [14] [15]. Using a decarbonization impact model, we efficiently determine areas that require political intervention by examining vehicle-related emissions [9] [12].

4.7. Exploring Alternatives to Coal:

Investigate alternative fuel options such as hydrogen fuel cells, especially in regions and sectors where EVs may fail to reduce emissions due to coal-based electricity generation [5]. Research on hybrid solutions like Plug-in Hybrid Electric Vehicles (PHEVs) should also be encouraged as short-term, transitional technologies [10].

Directing future research toward these areas will support a smoother transition to sustainable transportation systems. It will ensure that the implementation of EVs aligns with each state's energy profile and environmental targets [5], [6].

5. CONCLUSION

Vehicle emissions are highly contingent on the composition of the energy grid, so this research emphasizes the need for state-specific strategies as Americans adopt Electric Vehicles (EVs). EVs have a significant environmental advantage in renewable power-rich states like Tamil Nadu, Karnataka and Himachal Pradesh. While these benefits are substantial, they are much lower in coal-producing states such as Jharkhand and Chhattisgarh due to the relatively higher emissions from coal-based electricity generation [1], [2], [5].

Further, the results all point to the conclusion that electrification in the transport sector is definitively not a one-size-fits-all solution for emission reduction. In coal-heavy regions, ICE vehicles fueled by cleaner fuels (CNG etc.) may emit less than EVs in the near future [6]. Among all vehicle categories, Two-Wheelers (Mopeds and Bikes) and Three-Wheelers appear to be the most suitable for electrification, consistently delivering lower emissions across all Indian states [3], [4].

The research indicates that moving towards sustainable transportation necessitates an all-encompassing approach, which includes:

1. Decarbonizing the grid by investing in renewable energy sources.
2. Implementing state-specific policies that foster EV adoption in areas with cleaner energy while advocating for internal combustion engine alternatives in regions reliant on coal.
3. Emphasizing the need to standardize testing methods and conduct lifecycle emissions evaluations to guarantee precise comparisons [6], [12], [14].

By integrating energy and transportation policies, India has the potential to attain a more equitable and environmentally friendly strategy for vehicle electrification, guaranteeing enduring advantages for both the environment and society.

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