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Discussion Paper

Fueling India's Mobility Transition

A Life Cycle Perspective on Passenger Road Transport Options



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Abstract

The transportation sector is crucial for India's economic and social development but poses significant environmental and global warming challenges. This study conducts a comprehensive Life Cycle Assessment (LCA) of passenger vehicles in India, evaluating various propulsion technologies and modes of transport.

The analysis reveals that the dominance of fuel production, use, and vehicle maintenance are important factors contributing to overall greenhouse gas (GHG) emissions and cumulative energy demand (CED) across all vehicle types. Notably, electric and compressed natural gas (CNG) buses have emerged as the most effective near-term solutions, potentially reducing life-cycle GHG emissions per passenger-kilometer by 70%-72% compared with private passenger cars. This result is due to the efficiency and lower carbon intensity of mass transit systems. However, this study identifies the following critical issue: the reliance on nonrenewable fuels, which account for more than 90% of energy consumption during the operation phase, hinders significant emission reduction efforts and the alignment with India's net-zero goals. To overcome this barrier, this study recommends the following multifaceted approach: decarbonizing the power sector, promoting alternative fuels, enforcing stricter fuel efficiency standards, and enhancing the efficiency and utilization of passenger transport systems. The insights from this study provide a robust foundation on which policymakers, urban planners, and industry leaders can develop targeted strategies and implement evidence-based interventions for a sustainable, low-carbon mobility future in India.

Keywords: Life Cycle Assessment, passenger vehicles, sustainable mobility, India, net zero 2070.

Introduction

The transportation sector in India is not just a facilitator of socioeconomic development but also a sector at a critical juncture. With India being the world's most populous nation and a rapidly growing economy, the sector is grappling with the twin challenges of meeting the increasing mobility demands of its citizens and mitigating the environmental and climate impacts of its transportation systems (Nouni et al. 2021; Potluri and Tejaswi 2018)

This concern is not one of the future but rather a pressing issue that needs immediate attention. Accordingly, the Indian government has prioritized ensuring accessible, efficient, and sustainable passenger mobility, aiming to bolster economic growth, enhance quality of life, and address mounting environmental concerns. In this vein, India has pledged to achieve net-zero emissions by 2070 and simultaneously reduce the carbon intensity of its economy by more than 45% from its 2005 levels by 2030 (Roychoudhury 2023). Furthermore, India's commitment at the 26th Conference of the Parties summit to achieve 100% zero-emission vehicle sales by 2040, especially for cars and vans, underscores its transportation-focused decarbonization goals. As a result, these audacious targets are reshaping the growth trajectory of the country's transportation sector (Accelerating to Zero Coalition 2021).

The transformation of India's transport policies is a testament to the country's commitment to balancing multiple objectives, from its initial focus on building road infrastructure and promoting motorization to its recent shift toward sustainable transportation options. The evolution of these policies mirrors the country's efforts to address the complex and often conflicting demands of economic development, social equity, and environmental sustainability. This evolution is not a linear path but a series of strategic shifts in response to the changing needs and challenges of the sector (Roychoudhury 2023; Verma, Harsha, and Subramanian 2021).

The passenger transportation sector has been a focal point for these policy changes. Historically, the prevalence of private vehicles, notably two-wheelers and cars, has led to a gradual increase in India's carbon footprint and air pollution levels (Verma, Harsha and Subramanian 2021). While the increase in private vehicle ownership has facilitated greater mobility and accessibility, it has also intensified concerns about energy security, traffic congestion, and the environmental sustainability of the transportation system (IEA 2023).

In response, the Indian government has introduced a range of policy interventions and initiatives to promote more sustainable passenger mobility options. These policies have considered investments in public transportation infrastructure, the implementation of fuel efficiency standards, incentives for electric vehicle (EV) adoption, and the integration of multimodal transportation networks (Verma, Harsha, and Subramanian 2021). However, the environmental impacts of India's passenger transportation sector remain a significant concern, as road vehicles continue to be a major contributor to greenhouse gas (GHG) emissions, air pollution, energy demand, and other environmental concerns in the country (IEA 2023; Hossain et al. 2023).

In this light, it is crucial to understand the life-cycle environmental performance of different passenger vehicle technologies to inform policy decisions, industry strategies, and consumer choices regarding sustainable mobility solutions. Life Cycle Assessment (LCA) provides a comprehensive framework for evaluating the environmental impacts of a product or service, from raw material extraction to end-of-life (EOL) disposal (Matthews, Hendrickson, and Matthews 2014). By applying LCA to the passenger vehicle sector, policymakers and stakeholders can gain valuable insights into the trade-offs associated with different vehicle technologies, enabling

more informed and evidence-based decision-making (Koroma and Arora 2024).

Several LCA studies have been conducted to evaluate the environmental performance of passenger vehicles in India (Abdul-Manan et al. 2022; Ghate and Qamar 2020; Nouni et al. 2021; ITF 2023). However, the existing LCA literature on passenger transport in India is limited in scope and often focuses on a narrow set of passenger vehicle technologies. Moreover, these studies generally adopt a "tank-to-wheel" (TTW) or "well-to-tank" (WTT) approach, neglecting the upstream impacts of fuel and vehicle production and EOL treatment. This incomplete system boundary and narrow scope (regarding the set of passenger vehicle technologies assessed) can lead to the underestimation of the true environmental impacts of different mobility options.

To address these limitations, the current study conducts a comprehensive LCA of passenger vehicles in India, considering a wide range of propulsion technologies and modes of transport. This study aims to evaluate the life-cycle environmental performance of various passenger vehicle technologies in India and provide insights for policy decisions and industry strategies to achieve sustainable mobility solutions. The ultimate goal of this work is to inform the development of more sustainable mobility solutions for the country's growing population while generating much-needed empirical evidence to support informed decision-making. The following research question is asked:

- What are the life-cycle climate impacts and energy consumption profiles of the major passenger road vehicle technologies currently available in the Indian market, and what are the key policy implications for promoting more sustainable mobility solutions?

This research is crucial because it addresses the urgent need for sustainable mobility solutions in India, a country facing significant socioeconomic and environmental challenges due to its rapidly growing population and economy. This study provides essential insights for policymakers in developing effective transportation policies that align with India's ambitious goals of reducing carbon intensity and achieving net-zero emissions by evaluating the life-cycle environmental impacts of various passenger vehicle technologies. Additionally, the findings can guide industry stakeholders in prioritizing technologies that offer the most significant environmental benefits and inform consumers about the environmental implications of their vehicle choices.

The remainder of this paper is organized as follows. Section 2 describes the methods and data, followed by the LCA results and discussion in Section 3. Finally, Section 4 summarizes the main research conclusions and implications for policymakers.

Methods and Assumptions

Understanding the life-cycle performance of current passenger vehicle technologies in India is crucial for assessing the impact of transport policies on climate change. LCA is a key tool for comparing alternative technologies in environmental assessments (Koroma and Arora 2024), as it quantifies material and energy usage, emissions, and waste throughout the entire supply chain (Hauschild, Rosenbaum and Olsen 2017). LCA identifies critical "hotspots" in the system with the greatest environmental impact, prioritizing them for sustainability improvements. This study focuses on two significant impact categories outlined in Table 1.

Global warming potential (GWP) quantifies the impact of GHGs by measuring their ability to increase the degree of radiative forcing. GWP values, established by the Intergovernmental Panel on Climate Change (IPCC), represent the cumulative radiative forcing over a specific period relative to carbon dioxide (CO_2) emissions (IPCC 2021). GWP assigns values to gases based on their heat-trapping abilities compared to that of carbon dioxide (CO_2), which has a GWP of 1. For example, methane (CH_4) has a GWP of 25-30 over 100 years, meaning that it is 25 to 30 times more potent than is CO_2. Cumulative energy demand (CED) measures the total energy consumed throughout the life cycle of a product or process, assessing direct and indirect energy inputs. This approach helps evaluate energy efficiency and guide policy decisions, particularly in energy-intensive industries. This study uses the 100-year GWP values from the IPCC 2021 report and the CED impact assessment method in the SimaPro modeling tool, which is based on the Ecoinvent v3 database and extended by PRé Consultants, and relies on higher heating values (HHVs) for energy calculations (PRé Sustainability B.V. 2023).

Goal and Scope

The goal of LCA is to estimate the impacts of global warming and the energy demand of passenger vehicles in India in 2023. The study assesses vehicles with alternative powertrains (battery EVs [BEVs] and hybrid

Table 1. Impact categories and indicators considered.

Impact category	Impact indicator	Unit	Impact assessment method
Climate change	Global warming potential (GWP)	gCO_2eq	IPCC 2021
Energy consumption	Cumulative energy demand (CED)	MJ	

EVs [HEVs]), conventional fuels (petrol and diesel), and alternative fuels (compressed natural gases [CNGs] and petrol-ethanol blends), including the electricity used for EV charging. Table A1 (in the Appendix) details the characteristics of the representative vehicles considered. The main goal is to provide policymakers with insights into the energy demand and global warming reduction potential of current passenger vehicles in the Indian context.

This LCA study is attributional and comparative, following the ISO 14040 series (ISO 2020a; 2020b). The functional unit is defined as a person-kilometer, reflecting the purpose of passenger vehicles in transporting people. The system boundary includes the production stage (material extraction and manufacturing), operation stage (fuel production, use, and vehicle maintenance), and EOL stage (treatment and disposal) of vehicles in the Indian context. The recycling of valuable materials (mostly minerals and metals) at the vehicles' EOL state is not considered because of the cutoff modeling approach and limited data availability. However, the impacts of road infrastructure construction and maintenance during vehicle operation are considered.

Foreground inventory data for different passenger vehicle technologies are obtained from the literature (Table A1), whereas background system data are derived from the Ecoinvent v3.9 database via the SimaPro v9.5 modeling tool (Ecoinvent 2023; PRé Sustainability B.V. 2023). The Ecoinvent datasets used for vehicle manufacturing are based on average global market processes. However, the electricity generation processes for vehicle and component assembly are adjusted to reflect the average performance of the current (2022) all-India electricity mix. An exception is made for Li-ion battery (LIB) production, which uses average Chinese conditions, as China is the leading global supplier of traction battery components (Boon-Brett, Lebedeva and Di Persio 2017).

Vehicle Production and End-of-Life (EOL) Treatment

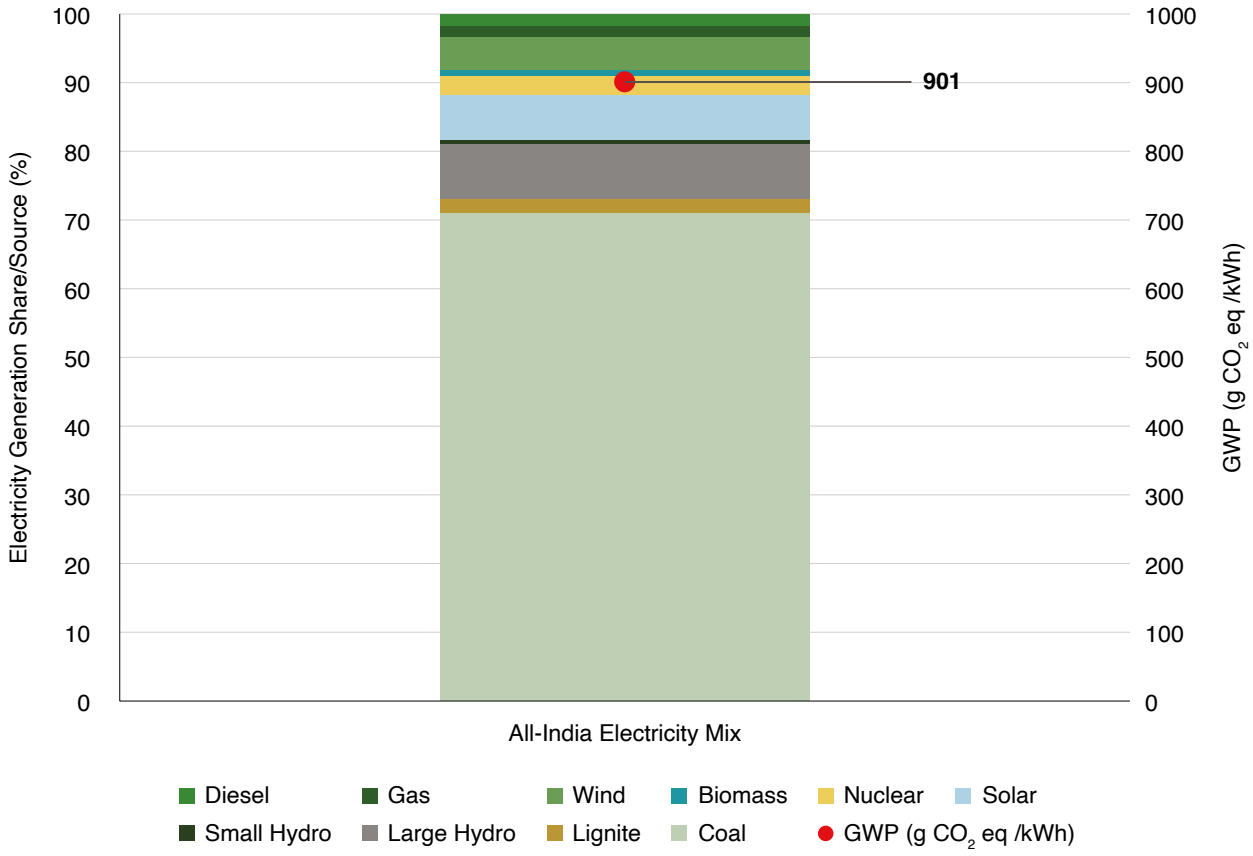
The passenger car production model uses a modular approach, including a vehicle glider, a drivetrain, and an EV traction battery. Most vehicle production aspects are assumed to be common, except for technology-specific powertrain components such as the electric drive (e-drive), internal combustion engine (ICE), and LIB. The main differences in the model are their respective weights and assumed lifetime mileages (see Table A1). The Ecoinvent dataset for passenger car gliders, which is based on the "Golf A4" dataset, is used for all the passenger cars considered (Schweimer and Levin 2000; Wernet et al. 2016). The production models for ICEs, e-drives, and LIBs are based on their representative manufacturing processes in the Ecoinvent database.

For buses, a common dataset scaled according to their empty weights is used, including the bus glider and ICE powertrain components. For electric buses, the ICE powertrain components are excluded, and the dataset is used as a proxy for the electric bus glider, scaled to the weight of the empty electric bus without the electric powertrain components. A similar approach is applied to scooters via the Ecoinvent process for motor scooter production, scaled according to their empty weights. The dataset includes glider and ICE powertrain components for ICE scooters. For electric scooters, the dataset is used as a proxy for the glider, excluding electric powertrain components, and scaled accordingly. This simplified assumption for electric buses and scooters is validated by comparing production impacts with recent literature (ITF 2023). The EOL stage includes only vehicle treatment and disposal, excluding recycling, due to insufficient data in the Indian context. However, the benefits of material recycling are captured via a portion of burden-free recycled materials following the cutoff system approach in the Ecoinvent database (Ecoinvent 2023; Steubing et al. 2016).

Vehicle Operation

During the use phase, both direct emissions from vehicle usage (TTW) and indirect emissions from fuel/electricity production (WTT) are considered. WTT emissions include those from producing electricity for EVs and diesel, petrol, CNG, and ethanol for internal combustion engine vehicles (ICEVs). The energy consumption for each vehicle type is based on the manufacturers' certified energy/fuel consumption, as detailed in Table A1. TTW emissions are modeled via the EURO 5 emission standards implemented in the Ecoinvent database. A static electricity mix is assumed for charging the EVs (see Figure 1) on the basis of official electricity generation data from India's Central Electric Authority (Central Electricity Authority 2023).

Figure 1. Indian gross electricity generation mix and resulting carbon intensity for 2023 based on data from the Central Electricity Authority (2023).



Source: Authors' analysis.

Fuel production for ICEVs is based on Ecoinvent datasets for manufacturing diesel, petrol, CNG, and ethanol-petrol blends specific to the Indian market. Vehicle maintenance, including oil and tire replacement, is modeled via Ecoinvent data. Road construction and maintenance, encompassing production processes for gravel, concrete, and bitumen, are also considered, with datasets derived from the Ecoinvent database.

Results and Discussion

Our LCA results underscore the environmental advantages of mass transportation systems, particularly electric and CNG buses, and the critical need to address the energy source and operational efficiency of passenger vehicles to support India's sustainability and net-zero objectives. This section presents and discusses our LCA outcomes in detail.

Global Warming Potential (GWP)

Figure 2 shows the life-cycle GWP emissions of all the assessed passenger vehicles as CO_2 equivalents per passenger-kilometer operating in India. Compared with passenger cars, buses demonstrate clear benefits in reducing the GWP per passenger traveled, with electric and CNG buses achieving approximately 72% and 71% reductions, respectively, compared with petrol-powered cars (ICEV-P). HEVs present the lowest GWP among the passenger cars assessed, followed by BEVs and PHEVs. Cars using the petrol-ethanol blend show a reduction in GWP proportional to the share of ethanol, with the 20% ethanol blend showing the greatest reduction relative to the petrol-powered car.

The operation stage is the most significant contributor to GWP for all the passenger vehicles assessed. For all the bus options, this life-cycle stage contributes to more than 94% of their GWP impacts. Passenger cars and electric scooters display a similar pattern, with the operation phase contributing 63 to 82% of the total impacts, except for motor scooters, where 91% of the impacts come from the operation stage. These findings suggest the prioritization of mass transportation (in this case, public buses) and enhancement of the operation phase performance of all passenger vehicles through optimized powertrain efficiency and low-carbon fuels/electricity to support India in achieving its net-zero targets.

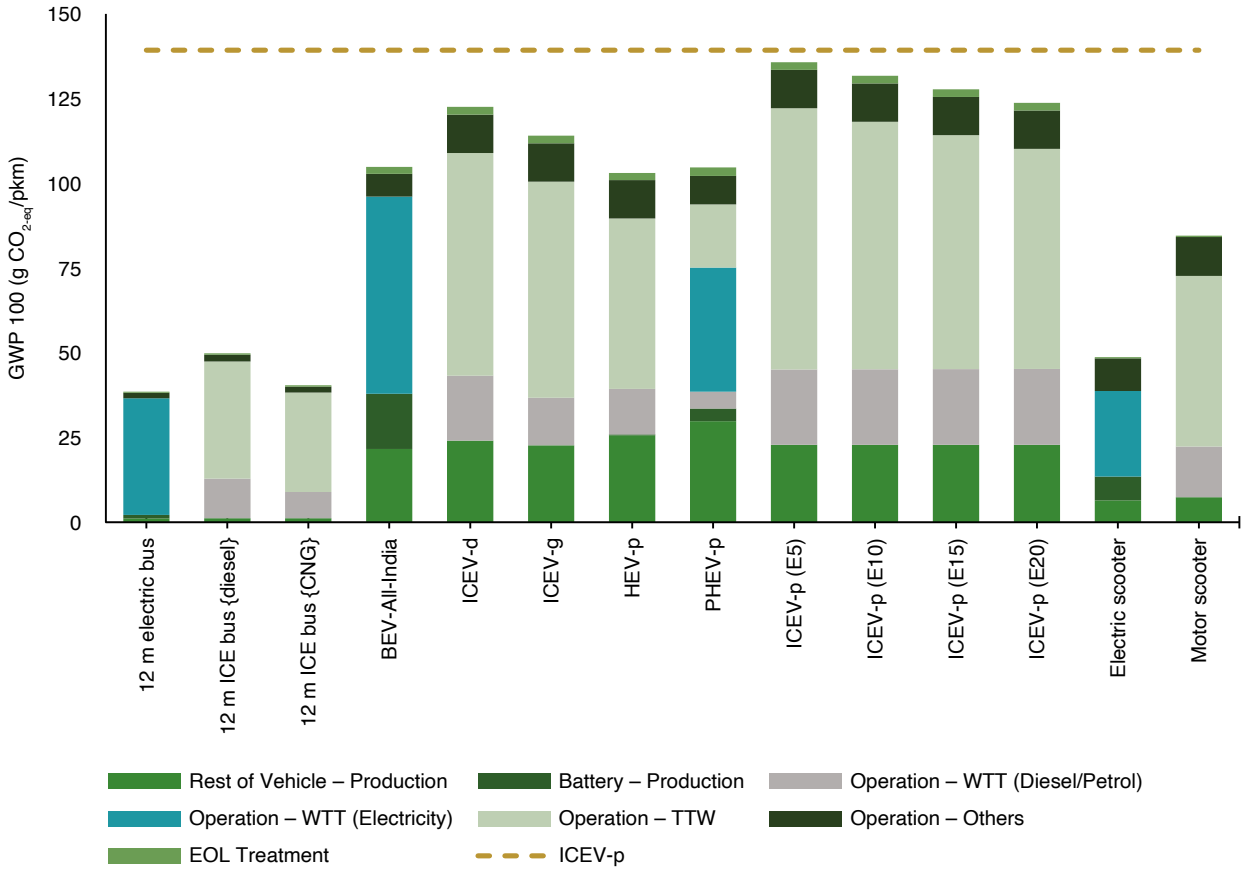
Given India's current electricity generation mix, with an average GWP of 901 g CO_2-eq/kWh (see Figure 1), the decarbonization of passenger transportation should be combined with the decarbonization of the electricity sector. As shown in Figure 2, focusing on electrifying and expanding bus transit systems offers greater potential for reducing GHG emissions per passenger traveling. This finding is similar to the findings of other studies on mitigating GHG emissions from urban passenger transport (Milovanoff et al. 2021; McCollum and Yang 2009). Currently, electric and CNG buses are the best options for the Indian context, with electric buses potentially being the better long-term choice, provided that the electricity mix is decarbonized.

In general, mass transportation systems offer more equitable mobility benefits for densely populated urban areas in India and align with the avoid-shift-improve paradigm for sustainable urban planning and transport (IEA 2020; Papadakis et al. 2024). Buses transport more passengers per kilometer, use fewer critical minerals and urban space, and emit less GHG emissions per passenger kilometer than do cars. Compared with dispersed private cars, municipal bus fleets are centralized and easier to upgrade for electrification, facilitating a quicker transition to electric buses and increased ridership. Urban bus networks also provide essential transportation to lower-income populations without car access, contributing to a just transition (Venter et al. 2018). While passenger cars still warrant decarbonization efforts, prioritizing bus electrification and transit-oriented city development provides superior emission cuts, as shown in Figure 2

and echoed in Milovanoff et al. (2021). In addition, such prioritization can reduce traffic congestion and increase equitable access for the efforts invested while creating a virtuous cycle for further sustainable mobility transition in India.

While our LCA results suggest that passenger buses, especially electric buses, offer greater emission reduction potential per passenger, private vehicles are likely to play a significant role in the transport sector. Even as cities decarbonize, private cars may still appeal to wealthy and affluent passengers, who value the convenience and flexibility of personal mobility. Additionally, growing middle classes in developing Indian regions may continue driving private vehicle adoption, posing challenges for transit-focused emission strategies. Therefore, policymakers need to pursue a balanced approach that integrates private EVs, shared mobility, and public transit enhancements. This approach can help address emissions across all passenger transport modes, recognizing the persistent relevance of private vehicles, even in the decarbonized future. In that context, India should also focus on decarbonizing the electricity and energy sector, including expanding renewable energy capacity, utilizing low-carbon fuels, and implementing carbon capture technologies at conventional power plants to reduce the life-cycle GHG emissions of EVs and alternative low-carbon passenger vehicles (Wang et al. 2022). Likewise, improving grid stability and implementing policies and incentives to accelerate the transition to clean energy sources are important considerations for holistic decarbonization efforts.

Figure 2. Global warming potential (GWP) of the vehicle types considered, reported to the person × kilometer functional unit.[1]

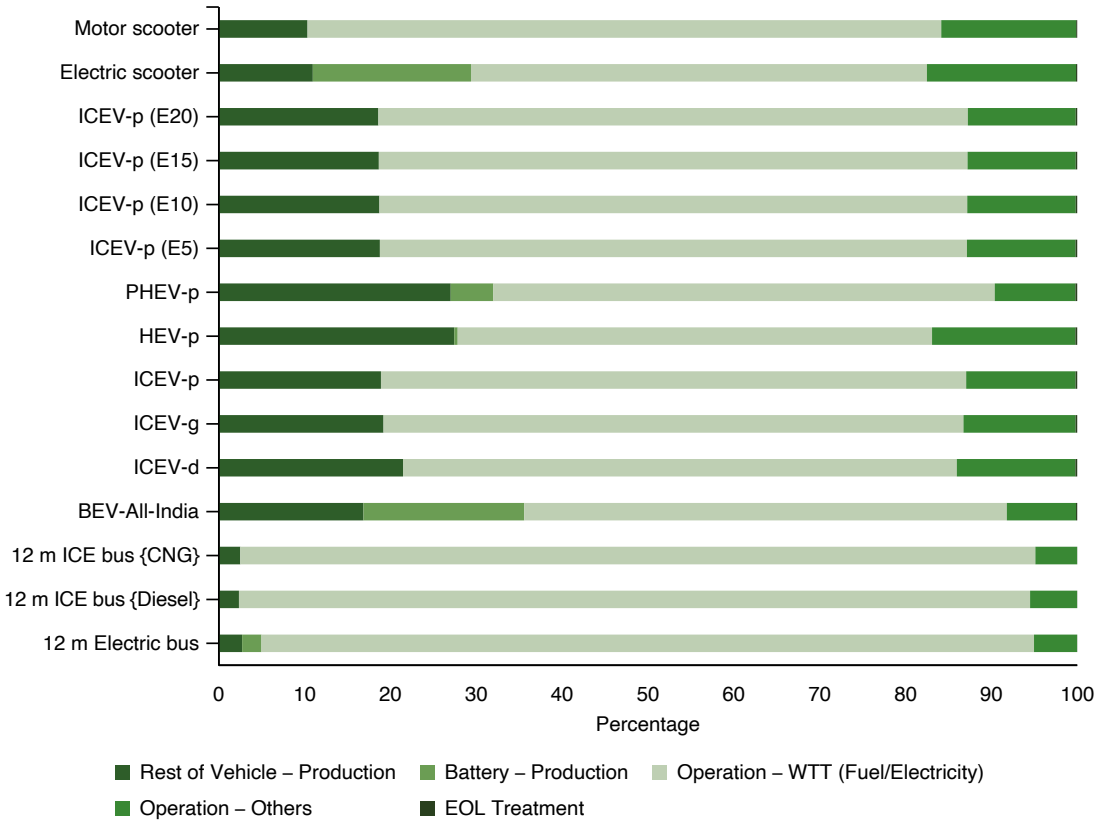


Source: Authors' analysis.

Cumulative Energy Demand (CED)

The CED indicator measures the total energy consumption throughout a product's life cycle, including direct (fuel and electricity use) and indirect (embodied energy, production, and transportation) energy inputs at each of the following stages: raw material extraction, manufacturing, use, and EOL disposal. Figure 3 shows the CED and contribution analysis for each life cycle phase of the assessed vehicle types. The vehicle operation phase accounts for most of the energy consumed. This includes energy/fuel demand for propulsion (operation-WTT in Figure 3) and vehicle maintenance and road construction and maintenance (operations in Figure 3). The operation-WTT phase consumes more than 90% of the energy for bus technologies, 53% to 59% for electric cars, 64% to 68% for conventional cars, and 53% to 75% for scooters. This finding confirms the critical importance of the operation phase in the life cycle of passenger vehicles and underscores the need for energy-efficient powertrains to reduce direct energy demand and, consequently, GWP across all vehicle technologies.

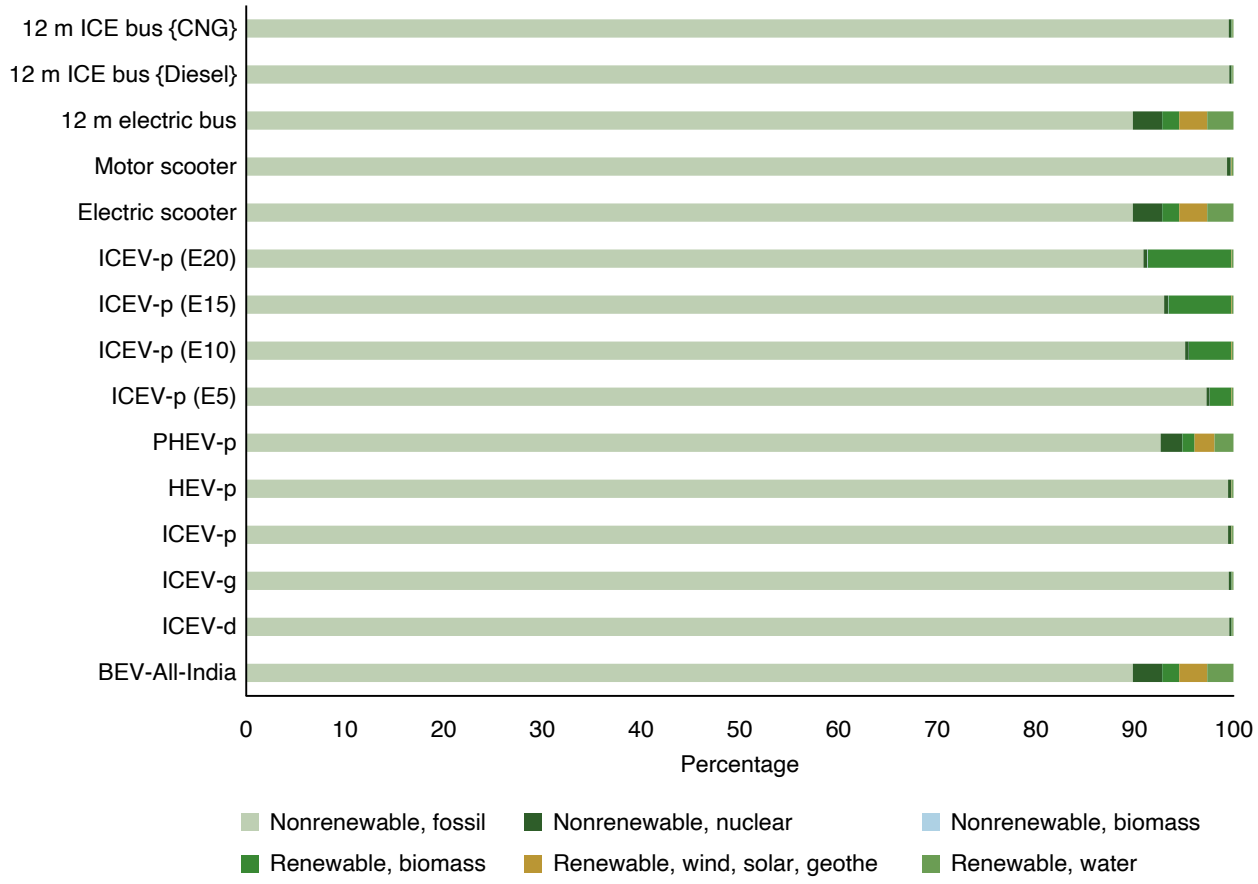
Figure 3. Cumulative energy demand (CED) – contribution analysis across all vehicle types assessed.[2]



Source: Authors' analysis.

A detailed contribution analysis of the vehicle operation-WTT phase, as shown in Figure 4, reveals that nonrenewable fossil fuels constitute more than 90% of the energy used during the operation phase across all vehicle types. This dominant dependence on fossil fuels presents a significant barrier to achieving further emission reduction sacross the vehicles assessed and highlights the urgent need for a transition toward more sustainable energy sources for passenger vehicles in India. In addition, the findings underscore the importance of energy-efficient powertrains and the critical role of the energy source in decarbonizing transportation.

Figure 4. Cumulative energy demand (CED) – contribution analysis of the operation-well to tank (WTT) of the vehicles assessed.



Source: Authors' analysis.

Conclusions and the Way Forward

The comprehensive LCA of passenger vehicles operating in India has provided valuable insights into the environmental performance and key sustainability challenges facing the transportation sector. The findings clearly demonstrate the dominance of the operation phase in contributing to overall GHG emissions and CED across all vehicle types.

The analysis reveals the significant climate benefits of electric and CNG buses over private passenger cars. With the potential for 70%-72% reductions in life-cycle GHG emissions per passenger-kilometer, these mass public transit options have emerged as the preferred near-term solutions to decarbonizing the passenger transport sector in India. This situation is attributable primarily to the inherent efficiency of mass transit systems and the lower carbon intensity of their operation. In contrast, despite advancements in powertrain technologies, passenger cars and two-wheelers continue to impose a substantial environmental burden per passenger traveling. This situation underscores the need for targeted policy support to accelerate the adoption of electric (including low-carbon powertrains) and CNG buses through measures such as purchase subsidies, favorable taxation, and investment in refueling/charging infrastructure.

The detailed contribution analysis further reveals the Achilles' heel of India's passenger transport system – its overwhelming reliance on nonrenewable fossil fuels, which account for more than 90% of the energy consumption during the operation phase. This heavy dependence on carbon-intensive energy sources presents a formidable barrier to achieving significant emission reductions and aligning the transportation sector with the country's net-zero aspirations. Given India's current (2022) grid emission factor of ~901 g CO_2-eq/kWh, policymakers must prioritize the decarbonization of the power sector in parallel with the decarbonization of the transportation sector. This can involve accelerating the deployment of renewable energy, improving grid efficiency, and implementing carbon pricing mechanisms. Simultaneously, the promotion of alternative fuels, such as biofuels blended with petrol, and stricter fuel efficiency standards can help diversify the energy mix and reduce the overall reliance on conventional petroleum-based fuels (Stančin et al. 2020; Nouni et al. 2021).

Beyond vehicle technology, the dominance of the operational stage in contributing to life-cycle impacts points to the need for policies that enhance the overall efficiency and utilization of passenger transport systems. This can include measures to improve public transit service quality, integrate multimodal networks, and manage private vehicle usage through congestion pricing or restricted access zones. Complementary urban planning and infrastructure policies, such as transit-oriented development, walkable neighborhoods, and safe cycling networks, are also essential. These strategies can help reduce overall passenger travel demand and shift mobility patterns toward more sustainable modes (IEA 2020; Papadakis et al. 2024).

The realization of this vision requires collaborative efforts among various stakeholders, including government agencies, automobile manufacturers, energy suppliers, urban planners, and civil society organizations. Only through a coordinated, multifaceted approach can India effectively address the dominance of nonrenewable fossil

fuels in the transportation sector and transition toward a more sustainable and low-carbon mobility future. Thus, the insights gained from this study provide robust insights for policymakers, urban planners, and industry leaders in terms of developing targeted strategies and implementing evidence-based interventions. By prioritizing public transportation, accelerating the electrification of vehicle fleets, and decarbonizing the energy sector, India can position itself as a global leader in sustainable mobility, setting an example for other developing nations to follow.

Appendix

Table A1. Key vehicle parameters for LCA modeling.

Parameter	Motor scooter	Electric scooter	Bus AC – ICE -12 m	Bus – AC-ICE -12m	Bus – AC-CNG -12m	Coach bus – AC-ICE 12 m	Private car – ICEV-p	Private car – ICEV-d	Private car – ICEV-g	Private car – HEV-p	Private car – PHEV-p	Private car – BEV
Sample vehicles	Hero Splendor	Ola Electric Scooter	Tata Starbus Ultra	Tata Starbus Electric			Tata Nexon	Tata Nexon	Toyota Hyryder	Toyota Hyryder	Kia Niro	Tata Nexon - EV
Vehicle weight (kg)	99.00	83.30	9,950.00	10,800.00	9,950.00	9,950.00	1,255.00	1,305.00	1,245.00	1,295.00	1,610.00	1,400.00
Battery capacity (kWh)	–	3.70	–	324.00	–	–	–	–	–	0.80	11.50	40.00
Battery technology (LIB)	–	NMC111	–	NMC111	–	–	–	–	–	NMC111	NMC111	NMC111
Battery specific energy (Wh/kg)	–	143	–	–	–	–	–	–	–	143	143	143
Battery lifetime mileage (km)	–	–	–	–	–	–	–	–	–	–	–	160,000.00
Vehicle lifetime mileage (km)	65,000.00	65,000.00	840,000.00	840,000.00	840,000.00	1,470,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00	200,000.00
Approximate battery replacement during vehicle life	–	–	–	–	–	–	–	–	–	–	–	0.25
Electricity consumption (kWh/km)	–	0.028	–	1.3	–	–	–	–	–	–	0.129	0.129
Average fuel consumption (L/km)	0.02	–	0.468	–	–	0.468	0.058	0.0423	–	0.036	0.036	–
Average fuel consumption (m^3/km)	–	–	–	–	0.4926	–	–	–	0.0525	–	–	–
Average # of passengers in vehicles per kilometer*	1	1	34	34	34	25	2	2	2	2	2	2
PHEV utility factor*	–	–	–	–	–	–	–	–	–	–	0.63*	–

Endnotes

[1] Here, scooters refer to two-wheelers; BEV-All India refers to a battery EV charged with average electricity mix for India; ICEV-d refers to diesel-powered internal combustion engine vehicle (ICEV); ICEV-g refers to gas-powered ICEV; ICEV-p refers to petrol-powered ICEV; HEV-p refers to petrol hybrid EV; PHEV-p refers to petrol plug-in hybrid EV; ICEV-p (E5), ICEV-p (E10), ICEV-p (E15) and ICEV-p (E20) refer to petrol ethanol blend-powered ICEV; and E5 to E20 denote the percentage of ethanol blended with petrol.

[2] Here, WTT denotes well to tank.

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Notes

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About the Project

This project, with its focus on India's clean energy policies in the transportation sector and its mapping of India's advancements in hydrogen and carbon capture, utilization, and storage (CCUS), has practical implications. This study provides policymakers and authorities with an outlook on India's crude oil demand from the transportation sector under different scenarios, thereby guiding future policy decisions and industry strategies.



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