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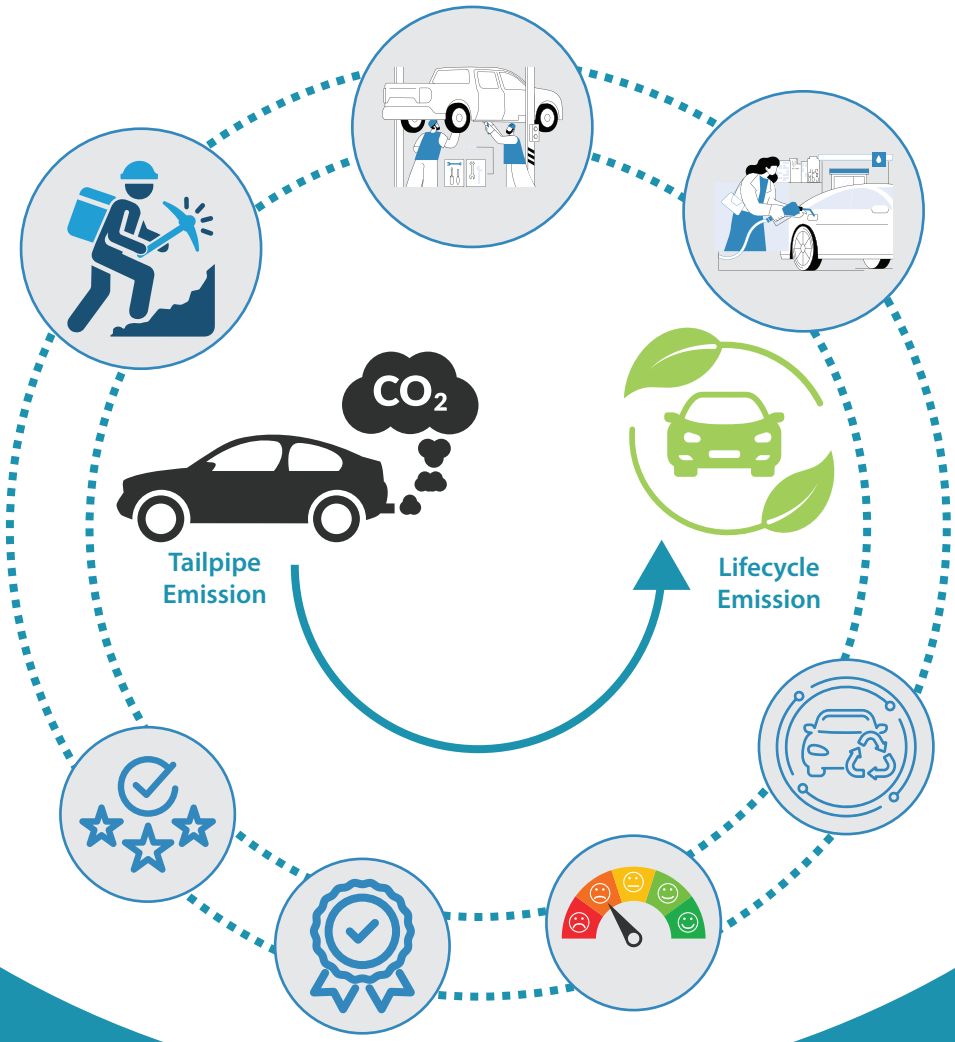

Life Cycle Assessment Based Rating Framework for Four-Wheeler Passenger Vehicles

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Acknowledgement

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It is our pleasure to present the report titled "*Life Cycle Assessment Based Rating Framework for Four-Wheeler Passenger Vehicles*," which develops and demonstrates a transparent, life cycle–based environmental rating framework for passenger vehicles in India. The study integrates comprehensive life cycle assessment with a standardized rating approach to enable comparative evaluation of vehicles across powertrain technologies and support informed decision-making by stakeholders. The Energy and Resources Institute gratefully acknowledges the support and valuable contributions of automotive industry partners, academia, and domain experts throughout the course of this study.

Authors:

Aparna Sajeev, Research Associate, TERI

Debesh Kumar Panda, Consultant, TERI

Rumi Azim, Research Associate, TERI

Souvik Bhattacharjya, Senior Fellow, TERI

Sharif Qamar, Fellow, TERI

Advisor:

I V Rao, Distinguished Fellow, TERI

TERI Publications Team:

Vijay Nipane, Senior Illustrator, TERI

Bhavya Bareja, Assistant Editor, TERI

Sudeep Pawar, Graphic Designer, TERI

Administrative Support:

Liji Joy, Secretary, TERI

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For more information: Project Monitoring Cell- The Energy and Resources Institute, Darbari Seth Block, IHC Complex, Lodhi Road, New Delhi 110 003, India | Tel.: +91 11 2468 2100 or 2468 2111 | Fax: +91 11 2468 2144 or 2468 2145
Email: pmc@teri.res.in | Web: www.teriin.org

Preface

The automotive sector is undergoing a period of rapid transformation driven by climate action, evolving energy systems, regulatory requirements, and changing patterns of mobility demand. As countries seek to decarbonize transport while sustaining economic growth, attention is increasingly shifting from vehicle-level performance indicators (i.e. tailpipe emissions) to system-wide environmental impacts (i.e. life cycle emissions). In this transition, passenger vehicles occupy a critical position due to their scale, longevity, and cumulative contribution to greenhouse gas emissions over time.

Life Cycle Assessment (LCA) has emerged globally as a scientifically robust approach for capturing these impacts across the entire vehicle value chain, from material extraction and manufacturing to energy production, use, and end-of-life management. However, despite growing academic and policy recognition, life cycle information often remains fragmented, methodologically inconsistent, or inaccessible to non-technical stakeholders, like the consumers who constitute the demand side target of any policy framework. In many contexts, including India's, vehicle evaluation and regulatory frameworks continue to rely predominantly on tailpipe emissions and fuel efficiency metrics, which provide only a partial representation of environmental performance.

This report is situated within this gap. It is motivated by the need to translate life cycle–based environmental assessment into a structured, transparent, and interpretable form that can support comparative evaluation of passenger vehicles in the Indian automotive market. Rather than treating LCA as a standalone analytical exercise, the study positions it as the foundation for a rating framework- one that can inform policy design, guide industry decision-making, and enhance consumer understanding of vehicle sustainability beyond operational emissions alone.

The work presented here brings together established LCA principles, international precedents in vehicle rating systems, and India-specific data considerations to develop and demonstrate a life cycle- based environmental rating methodology for four-wheeler passenger vehicles. The emphasis throughout the report is on methodological clarity, transparency of assumptions, and adaptability to future technological and systemic change. By doing so, the study aims to contribute to the broader discourse on sustainable mobility in India and to support the gradual integration of life cycle thinking into vehicle assessment, policy instruments, and market mechanisms.

With optimism and dedication to a sustainable future,

TERI team

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Abbreviations

ABS	Acrylonitrile Butadiene Styrene
ABS-PC	Acrylonitrile Butadiene Styrene–Polycarbonate Blend
AC	Aluminum Casting Alloy
ACEEE	American Council for an Energy-Efficient Economy
ACM	Acrylic Rubber
ADC/ADC12/ALDC12/ALDC	Aluminum Die Casting Alloys
ADH	Aluminum Die-Hardening Alloy
ADR	Australian Design Rules
AEM	Ethylene Acrylic Rubber
Al	Aluminum
AlSi11Cu2 / AlSi9Cu3	Aluminum-Silicon-Copper Alloys
AM50A/AM60B	Magnesium Alloys
ASA	Acrylonitrile Styrene Acrylate
ASA-PC	Acrylonitrile Styrene Acrylate–Polycarbonate Blend
BEE	Bureau of Energy Efficiency
BEVs	Battery Electric Vehicles
BMC	Bulk Molding Compound
BoM	Bill of Materials
BR	Butadiene Rubber
CAFE	Corporate Average Fuel Economy
CBG	Compressed Bio-Gas
CDM	Clean Development Mechanism
CEA	Central Electricity Authority of India
CH_4	Methane
CIIR	Chloro-Isobutylene Isoprene Rubber
CNG	Compressed Natural Gas
CO	Cobalt
CO_2	Carbon Dioxide
CR	Chloroprene Rubber
CSM	Chlorosulfonated Polyethylene
CU	Copper
E10	10% Ethanol Blend
E20	20% Ethanol Blend
ECO	Epichlorohydrin Rubber
EIO-LCA	Economic Input–Output Life Cycle Assessment
EoL	End of Life
EPA	Environmental Protection Agency

EPDM	Ethylene Propylene Diene Monomer Rubber
EPM	Ethylene Propylene Rubber
EU	European Union
EV	Electric Vehicle
EVA	Ethylene Vinyl Acetate
EVOH	Ethylene Vinyl Alcohol Copolymer
FAME	Faster Adoption and Manufacturing of Electric Vehicles
FCEVs	Fuel Cell Electric Vehicles
Fe	Iron
FKM	Fluoroelastomer
FPM	Fluoropolymer Elastomer
FVMQ	Fluorosilicone Rubber
FY	Financial Year
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GLO	Global
GoI	Government of India
GWP	Global Warming Potential
GWP100	Global Warming Potential (100-year time horizon)
HC	Hydrocarbons
HCPP	High-Crystallinity Polypropylene
HDPE	High-Density Polyethylene
H-ECDC	Hyderabad Electric Car Driving Cycle
HEVs	Hybrid Electric Vehicles
HNBR	Hydrogenated Nitrile Butadiene Rubber
HV	High Voltage
HVAC	Heating, Ventilation and Air Conditioning
ICCT	International Council on Clean Transportation
ICE	Internal Combustion Engine
ICEV	Internal Combustion Engine Vehicle
IEA	International Energy Agency
IIR	Isobutylene Isoprene Rubber
IPCC	Intergovernmental Panel on Climate Change
IPCC AR6	Intergovernmental Panel on Climate Change Sixth Assessment Report
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCP-GF30	Liquid Crystal Polymer with 30% Glass Fiber Reinforcement
LCT	Life Cycle Thinking
LDPE	Low-Density Polyethylene
LHV	Lower Heating Value
LFP	Lithium Iron Phosphate
LSR	Liquid Silicone Rubber
Mg	Magnesium

MIDC	Modified Indian Driving Cycle
MoEFCC	Ministry of Environment, Forest and Climate Change
NBR	Nitrile Butadiene Rubber
NCAP	New Car Assessment Program
NEMMP	National Electric Mobility Mission Plan
NMC	Nickel Manganese Cobalt
NOx	Nitrogen Oxides
NR	Natural Rubber
OECD	Organization for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
PA/PA6/PA66	Polyamides
PA-GF	Polyamide with Glass Fiber Reinforcement
PANOX	Oxidized Polyacrylonitrile Fiber
PBT	Polybutylene Terephthalate
PC	Polycarbonate
PE	Polyethylene
PET	Polyethylene Terephthalate
PHEVs	Plug-in Hybrid Electric Vehicles
PLI	Production Linked Incentive
PM	Particulate Matter
PMMA	Polymethyl Methacrylate
POM	Polyoxymethylene
PP	Polypropylene
PPA	Polyphthalamide
PPE	Polyphenylene Ether
PPS	Polyphenylene Sulfide
PUR	Polyurethane
PVB	Polyvinyl Butyral
PVC	Polyvinyl Chloride
R&D	Research and Development
RoW	Rest of World
S355MC	High Strength Structural Steel (355 Mpa yield), Thermomechanically rolled, cold-formable
S45C	Medium Carbon (45%) Structural Steel
SBR	Styrene Butadiene Rubber
SF	Silicone Fluid
SIAM	Society of Indian Automobile Manufacturers
SO_2	Sulphur Dioxide
SPCC	Steel Plate Cold-rolled Commercial quality (Mild)
SPFC	Steel Plate Cold-rolled Commercial quality (High strength)
SPFH	Steel Plate Forming High-Strength(Hot rolled)
SUS	Stainless Steel
SUVs	Sport Utility Vehicles
T&D	Transmission and Distribution

TPA	Terephthalic Acid
TPC	Thermoplastic Copolyester
TPE	Thermoplastic Elastomer
TPEE	Thermoplastic Polyester Elastomer
TPO	Thermoplastic Olefin
TPR	Thermoplastic Rubber
TPS	Thermoplastic Styrenic Elastomer
TPU	Thermoplastic Polyurethane
TPV	Thermoplastic Vulcanizate
TSI	Turbocharged Stratified Injection
TTW	Tank-to-Wheel
UK	United Kingdom
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VMQ	Silicone Rubber (Methyl Vinyl Silicone)
WTT	Well-to-Tank
WTW	Well-to-Wheel
ZAMAK	Zinc-Aluminum-Magnesium Alloy
ZDC2	Zinc Die Casting Alloy
ZEV	Zero Emission Vehicle
ZLEV	Zero and Low Emission Vehicle
Zn	Zinc
ZnAl4Cu1	Zinc-Aluminum-Copper Alloy

Executive Summary

This study develops and demonstrates a **Life Cycle Assessment (LCA)–based environmental rating framework for four- wheeler passenger vehicles tailored to the Indian automotive context**. Unlike existing evaluation systems that focus primarily on tailpipe emissions and fuel efficiency, the proposed framework adopts a full **cradle-to-grave** perspective, capturing greenhouse gas (GHG) emissions from material extraction, manufacturing, energy production, vehicle use, maintenance, and a constrained end-of-life. **Using GWP100 (IPCC AR6) as the assessment metric, life cycle emission results are translated into an interpretable and comparable rating system**. GWP100 (IPCC AR6) is used exclusively because climate change is the most policy-relevant and quantifiable impact of vehicles, and a single, widely accepted metric ensures transparency, comparability, and ease of interpretation across technologies and life-cycle stages.

The importance of an LCA-based rating system is reinforced by global precedents already in place. Europe's Green NCAP integrates life cycle–based clean air, energy efficiency, and GHG performance into its ratings. Belgium's Eco Score accounts for emissions from production, distribution, and vehicle use across multiple vehicle categories. The UK's Green Car Rating and the US Green Book (by ACEEE) help consumers compare environmental performance, with varying degrees of life cycle consideration. These initiatives demonstrate international momentum toward life cycle–based vehicle assessment and highlight the strategic value of establishing an India-specific, LCA aligned rating framework.

For demonstration purposes, the **analysis uses a representative sample of four-wheeler passenger vehicles available in the Indian market as of March 2025**. Vehicle models were selected based on availability of near-complete material composition data to enable robust LCA modelling, with priority given to completeness and transparency of inputs. **The final sample covers approximately 85% of FY 2024–25 passenger vehicle sales nationwide,** ensuring both methodological rigor and market representativeness. **A z-score normalization approach enables unbiased comparison across different powertrains and fuel types, ensuring no technology is advantaged or disadvantaged by default.** Vehicles are assigned star ratings (indicative only; actual ratings require consideration of the full vehicle population) based on the distribution of z-scores, using defined cut-offs in terms of standard deviation from the mean on a scale of 5, which allows for fair emissions' comparison across models.

In this study, the functional unit is defined on a per-vehicle, full lifetime basis. Each passenger four-wheeler is assumed to operate over a total driving distance of **150,000 km**, corresponding to an average annual distance of 10,000 km.

The framework is presented both as a **pooled vehicle rating and as length-segmented vehicle rating,** allowing flexibility for regulators, manufacturers, and consumers. Pooled ratings support absolute performance comparison, while segmented ratings improve consumer relevance within familiar market categories. Methodological consistency is maintained across both formats.

The study also highlights the key role of dynamic rating mechanisms in supporting decarbonization. **As fleet-wide life cycle emissions decrease, the z score–based ratings automatically recalibrate, tightening performance thresholds over time**. Vehicles that qualify as low emitting today may shift to mid-tier categories as technology improves. This adaptive approach prevents stagnation, ensuring that benchmarks reflect technological progress, and keeps incentives aligned with long-term climate objectives.

A structural transition is expected as cleaner powertrains scale, manufacturing efficiency improves, and the electricity grid decarbonizes. Use phase emissions will decline, making material related emissions the dominant lifecycle hotspot. LCA becomes essential for identifying high impact materials and processes, assessing choices such as steel vs. aluminum, virgin materials vs. recycled materials, etc., and avoiding unintended problem shifting. Applied early in design, LCA evolves from a measurement tool into a design influencing mechanism, guiding manufacturers toward lower impact materials and system architectures.

The LCA-based rating framework developed in this study can be applied across multiple policy and incentive arenas, with vehicle ratings directly informing regulatory and financial mechanisms such as **purchase incentives** (tax reductions, lower interest rates, subsidies), **manufacturing incentives** (PLI benefits and expedited approvals), and **consumer incentives** (reduced road tax, toll rebates, and preferential access zones). The framework also enables **carbon credit additionality** by recognizing verified life-cycle emission reductions beyond regulatory baselines achieved through low-carbon, high-impact measures, including material efficiency, cleaner fuels, and low-carbon materials. By shifting the focus from tailpipe emissions to **full life-cycle performance**, the framework supports sustained reductions in fleet-wide emissions and accelerates the transition toward **life-cycle low carbon vehicles.**

To strengthen the framework further, the study identifies several structural challenges and potential solutions:

- **Limited India-specific LCI data** necessitates standardized declarations (EPDs, PCFs), sector-wide reporting and dedicated studies may be required to be considered.
- **Insufficient supplier-level transparency** demands partnerships on emissions disclosure and circular procurement.
- **Constrained end-of-life modelling** underscores the need to formalize recycling, strengthen EPR systems, and build battery recovery infrastructure.

Overall, a life cycle–based, statistically normalized vehicle rating system is technically robust, transparent, and suitable for adoption in India. Such a system provides a **strong foundation for integration into policy instruments, consumer information programs, and long-term voluntary or regulatory sustainability initiatives, including the Automotive Mission Plan 2047 under Viksit Bharat Mission which supports India's decarbonization goals** by establishing lifecycle baselines, guiding material sustainability standards, enabling circularity interventions, strengthening export competitiveness, and informing multi-decadal emission reduction milestones.

Chapter 1: Introduction

1.1 Prelude

The global transportation sector is a significant contributor to greenhouse gas (GHG) emissions, which have been unequivocally identified as the primary driver of climate change (Raugei, 2022). The Intergovernmental Panel on Climate Change (IPCC) states that the transport sector accounts for about 23% of global energy-related carbon dioxide (CO_2) emissions (IPCC, 2022). Road transport accounts for a substantial 69% of total transport GHG emissions, with over 60% of road emissions coming from passenger cars and vans (UN, 2025; IEA, 2025). The high growth in global GHG emissions[1], with significant contribution from the transport sector, has created an urgent need for comprehensive strategies to decarbonize the sector and align it with global climate goals, such as those articulated in the Paris Agreement, which aims to limit global warming to well below 2°C, ideally to 1.5°C, compared to pre-industrial levels (Piasecka, 2025).

The problem is not much different in the context of India. With our nation's rapidly expanding and evolving mobility demand, addressing air quality and climate impacts from the transport sector is central to India's commitments to reduce GDP emissions intensity by 45% relative to 2005 levels by 2030 and to achieve net-zero emissions by 2070 (UNFCCC, 2022). Although transport-related emissions in India remain below the global average, this is largely attributable to low per capita vehicle ownership rather than intrinsic improvements in vehicle or system efficiency (Shet & Moholkar, 2024). Vehicle penetration in India is significantly lower than levels observed in developed economies, with demand remaining highly sensitive to price (MoRTH, 2021).

Even though several policy interventions have been introduced, they largely focus on tailpipe emissions and vehicle-level performance metrics, with limited consideration of emissions occurring across the full vehicle life cycle. For motor vehicles, LCA-based evaluation methodologies are therefore essential to move beyond single-parameter, phase-specific indicators, such as tailpipe emissions and fuel efficiency, towards a more comprehensive assessment of environmental performance. Integrating life-cycle-based measures of environmental 'greenness' into the vehicle evaluation framework can also position sustainability as a component of consumer value, thereby placing it within the domain of competitively driven product improvement (DeCicco & Thomas, 1999). To be effective, LCA-based policy instruments must be readily interpretable by consumers, this can be achieved using green rating systems, like that of Bureau of Energy Efficiency (BEE) energy ratings with which Indian consumers are already familiar. Such an approach would enable consumers to make informed and environmentally responsible choices, while simultaneously supporting policymakers in advancing sustainability objectives.

In this context, the present study develops a green rating system for passenger cars in India that is grounded in LCA. It looks at the life cycle emissions of ICEVs (petrol, diesel, and CNG), BEVs, and strong hybrids in the

[1] Since 2015, the growth in emissions of emerging economies (excluding China) increased by more than 18%, and around 2.5% in the rest of the world (IEA, 2025).

Indian automobile sector, with a specific focus on GHG emissions in order to demonstrate the developed rating framework. The report is structured into 8 chapters as follows:

- Chapter 1 sets the context by examining the evolving transportation sector, the prominence of life cycle thinking in transport sector, and the development of environmental rating mechanisms in transport.
- Chapter 2 reviews existing literature on LCA in the global and Indian automotive sector and outlines the LCA methodologies and environmental rating frameworks applied in transportation worldwide.
- Chapter 3 provides a comprehensive overview of the LCA framework and its application in the transport sector.
- Chapter 4 defines the goal, scope, and methodology of the present study, including the system boundary and powertrain technologies considered.
- Chapter 5 details the development of the life cycle inventory, covering data sources, vehicle material composition, use-phase data, and key assumptions.
- Chapter 6 discusses scaling, rating, and standardization approaches for comparative environmental assessment and presents the vehicle environmental rating framework proposed in this study.
- Chapter 7 applies the LCA methodology to a representative sample of four-wheeler passenger vehicles in the Indian automotive market and demonstrates the implementation of the developed rating framework.
- Chapter 8 discusses the applicability of the LCA-based rating framework within regulatory and incentive-based policy mechanisms and identifies potential areas for improvement.

1.2 State of the Art: The Global and Indian Automotive Sector

The automotive sector remains one of the most influential drivers of economic activity and energy demand. In 2023, worldwide vehicle sales continued to reflect strong geographic concentration, with passenger vehicle sales reaching 78.9 million units, led by China with a one-third share and the United States with almost one-fifth of global sales. Commercial vehicle sales added another 13.2 million units, again dominated by China and the US, while two-wheelers accounted for 65.8 million units, concentrated in India and China (SIAM, 2023). With the growth in the automotive market, transport-related emissions have become a major global challenge. The sector is responsible for approximately 12 gigatonnes of CO_2-equivalent emissions each year, accounting for about 25% of total human-induced emissions (Bieker *et al.*, 2021). Within this, road transport contributes nearly 75% of the sector's emissions, with passenger cars being the primary source (Ika *et al.*, 2023).

India's automotive sector is particularly important in the global landscape. The country is the world's largest two-wheeler market, the largest three-wheeler manufacturer, the third-largest passenger vehicle market, and the top 4 manufacturers of passenger vehicles (GoI, 2025). In the fiscal year 2023–24, India recorded a high growth in domestic sales of approximately 18 million two-wheelers and 4.2 million cars and vans (SIAM, 2023). This demand is further expected to rise substantially given the rapid increase in the urban population, which is expected to approach 600 million by 2030 (MoEFCC, 2022). India's automotive sector is experiencing significant growth, with increasing demand for personal mobility. The passenger vehicle

demand is expected to increase more than threefold from 2019–20 to 2050–51 (TERI, 2024). While the national average of car ownership is modest at 24 cars per 1000 population in 2023, it can exceed 100 cars per 1000 in major cities like Delhi (Abdul-Manan *et al.*, 2022; CEEW, 2025).

Besides high growth in transport demand, a structural technological shift is unfolding in the global transport market. Global electric vehicle sales rose from less than 1 million in 2016 to nearly 19 million in 2024 (NITI Aayog, 2025). Electric cars surpassed 10 million annual sales in 2022, lifting their global market share to 14%, more than ten times higher than in 2017 (IEA, 2023). According to the IEA 2023 report, plug-in electric vehicles accounted for more than 15% of new light-duty vehicle sales in 2021, positioning China as the global leader in electric vehicle production and sales. In Japan, next-generation vehicles- including Hybrid Electric Vehicles (HEVs), Plug-in Hybrid Electric Vehicles (PHEVs), Battery Electric Vehicles (BEVs), and Fuel Cell Electric Vehicles (FCEVs) represented more than 39% of new passenger car registrations in 2019 and 2020 (Ika *et al.*, 2023). To accelerate fleet electrification, European regulators have set up a zero and low-emission vehicle (ZLEV) sales target of 35% by 2030 (Mock, 2019). In many states of the US such as California, zero-emission vehicle (ZEV) regulations have been implemented, together accounting for approximately 32% of new car sales nationwide, which are expected to increase the shares of BEVs, PHEVs, and FCEVs (Bieker *et al.*, 2021). In Brazil, flex-fuel vehicles operating on hydrous ethanol and gasoline-ethanol blends accounted for 92% of passenger car sales in 2020; this ethanol is produced mainly from domestic sugarcane. (Mera & Bieker, 2023).

BEVs and HEVs are gradually increasing their market presence in India (Shet & Moholkar, 2025). Despite the prevalence of fossil fuel vehicles, in FY 2023–24, BEVs captured a 2% market share of car sales and hybrid sales represented 0.4% of car sales (Anup *et al.*, 2025). However, the effectiveness of BEVs in India's fleet decarbonization trajectory is strongly dependent on the decarbonization of the electricity generation mix and improvements in the electricity production efficiency of coal-based thermal power plants across the country (Shet & Moholkar, 2025).The fuel preferences in the passenger car market are also shifting, petrol remains dominant at 67% of new sales in FY 2019–20 (Bieker *et al.*, 2021), but compressed natural gas (CNG) and compressed biogas (CBG) vehicles have surged in popularity, exceeding 1 million units sold in FY 2023–24 due to their cost-effectiveness (SIAM, 2023). Gas-powered vehicle sales rose 54% YoY to comprise 10.5% of the total passenger vehicle sales (SIAM, 2023).

1.3 Transition Towards Low-Carbon Mobility

The global automotive sector is undergoing a significant transition as countries seek to align transport systems with international climate commitments. Achieving the Paris Agreement objective of limiting global warming to 1.5°C requires transport-related greenhouse gas emissions to decline by nearly 80% by 2050 (Bieker *et al.*, 2021). This transition is primarily and traditionally identified as shifting away from fossil fuel-dependent ICEVs to alternative powertrains such as HEVs, PHEVs, BEVs, and FCEVs (Bieker, 2021; Raugei, 2022). Many governments are actively promoting this shift through a combination of policy instruments, including fleet average CO_2 emission standards, incentives for electric powertrains, and investments in decarbonizing electricity grids and renewable fuel production (Bieker, 2021). Legislators in regions like Europe and the UK have already set ambitious targets to effectively phase out the sales of new ICEVs in the coming decades (Raugei, 2022).

India is actively participating in this global transition, recognizing the immense potential of electric mobility to reduce its environmental footprint. The Government of India has articulated ambitious goals, aiming to electrify 30% of the nation's vehicle fleet by 2030, with specific targets of up to 30% for private cars, 70% for commercial vehicles, and 80% for two and three-wheelers (Shet and Moholkar, 2025; NITI Aayog). Key initiatives include the National Electric Mobility Mission Plan (NEMMP) 2020, the FAME Scheme (Phases I & II), the Prime Minister e-Drive Programme (2024–2026), and Production Linked Incentive (PLI) schemes, all aimed at accelerating EV adoption and domestic manufacturing. Concurrently, India promotes alternative fuels to reduce oil dependence and emissions, advancing its ethanol blending target to 20% by 2025–26 and achieving the E10 target ahead of schedule in June 2022 (SIAM, 2023).

Additional steps include the promotion of biodiesel, flex-fuel vehicles, increased natural gas use (targeting 15% share in the energy mix by 2030), and green hydrogen through the 2023 National Green Hydrogen Mission (NGHM) (UNFCC, 2022). Methanol blending has also been introduced to reduce fuel import costs and emissions (Upadhyayula *et al.*, 2019). Corporate Average Fuel Economy (CAFE) norms for various vehicle classes have further driven fuel efficiency and has contributed to a 2.65 $MtCO_2$ reduction in 2018–19 according to MoEFCC (2021).

The transition strategy in India is multi-faceted, however, EVs are considered instrumental in this journey. In the four-wheeler segment, BEVs are considered the most promising option for decarbonization due to its "zero tailpipe emissions" (Raugei, 2022). Even with India's current electricity mix, BEVs can achieve 19%–34% lower life cycle GHG emissions than average new gasoline cars, a benefit projected to increase to 30%–56% for BEVs registered in 2030 (Bieker, 2021). Biofuels offer small but meaningful reductions, especially in India where residue-based feedstocks avoid land-use concerns (IEA, 2023). Hybridization, particularly strong hybrid electric vehicles, is also seen as a transitional solution, offering credible reductions in transport-related GHG emissions and potentially making HEVs competitive with BEVs in terms of fuel cycle GHG emissions (Abdul-Manan *et al.*, 2022; Shet and Moholkar, 2025).

However, before betting on any set, there is a need for assessing the effectiveness of the vehicle-fuel technology chosen for the decarbonization push holistically by determining the full life-cycle impact. An exclusive focus on tailpipe emissions ignores substantial pre-use phase CO_2 sources, including fuel production, electricity generation, and vehicle manufacturing. Thus, it can lead to a phenomenon known as 'burden shifting,' where environmental impacts are merely transferred from the operational phase to other life cycle stages, such as manufacturing or upstream energy production (OECD, 2023; Raugei, 2022). Thus, this approach becomes insufficient for India's decarbonization goals. For instance, while BEVs produce zero tailpipe emissions, their overall environmental impact is intrinsically linked to the carbon intensity of the electricity used for charging and the emissions generated during their manufacturing, particularly battery production (Shet and Moholkar, 2025; Bieker, 2021). Most studies on the Indian transport sector have historically focused on direct CO_2 emissions at the vehicle tailpipe; however, it is increasingly critical to consider the upstream energy and emission impacts of fuel production and electricity generation, especially as alternative energy sources like electricity begin to displace conventional petroleum-based fuels (OECD, 2023).

1.4 Advancing Sustainable Transport through Life Cycle Assessment

A comprehensive approach, such as LCA, systematically quantifies the environmental burdens associated with a product or service from its 'cradle to grave' (OECD, 2023). The LCA framework for a vehicle encompasses emissions across all stages: from the extraction of raw materials, through the processing and manufacturing of the vehicle, its transportation to the consumer, its use, the production of the fuel/energy required for its operation, the infrastructure created for it, and finally, its disposal or recovery after its useful life (Shet and Moholkar, 2025; OECD, 2023). LCA is crucial for policymakers to identify which powertrain and fuel technologies are most effective in shrinking the carbon footprint of cars, thereby facilitating evidence-based policy recommendations (Bieker, 2021; Raugei, 2022).

The shift towards low-carbon mobility necessitates a paradigm shift in how environmental impacts are assessed, moving from traditional tailpipe emission measurements to a comprehensive Life Cycle Thinking (LCT) approach. LCT provides this broader lens by evaluating the environmental implications of a vehicle from the extraction of raw materials to end-of-life treatment. LCA operationalizes this concept by quantifying emissions associated with a product or service across its entire lifespan. This approach is fundamental to the principles of the circular economy, which encourages material efficiency, reuse, and recycling instead of the conventional linear model of production and disposal. Fuel in-use methodologies are good indicators of air quality rankings but would rank a fuel-cell hydrogen vehicle on top along with the electric vehicles which does not reflect the carbon footprint of the overall fuel pathways and side effect pollutants. Therefore, comprehensive life cycle-based environmental-rating methodology is vital, including various stages of the life cycle.

A cradle-to-grave LCA reveals that while the use phase dominates emissions for ICEVs, the manufacturing phase, particularly for batteries, is more significant for BEVs (Bieker, 2021; Piasecka, 2025). Therefore, understanding the full spectrum of emissions from 'well-to-wheel' (fuel/energy production and consumption) to the 'vehicle cycle' (manufacturing, maintenance, and recycling) is essential for accurate environmental accounting (Bieker, 2021; Yadav *et al.*, 2024). This holistic perspective allows for consistent comparison of various powertrain options, including ICEVs, HEVs, PHEVs, BEVs, and FCEVs, across different fuel types and power sources (Bieker, 2021; Raugei, 2022). It also enables policymakers to formulate strategies that address emissions across the entire supply chain and life cycle, rather than inadvertently shifting environmental burdens from one stage to another (OECD, 2023; Raugei, 2022). For India, this is particularly important as the country's electricity grid remains heavily coal-based operating at very low efficiency, which narrows the climate advantage of BEVs relative to efficient ICE or hybrid technologies.

A holistic life cycle approach prevents policy missteps and greenwashing caused by overlooking impacts embedded in manufacturing and energy supply chains. LCA also provides a standardized and scientifically robust methodology to evaluate environmental impacts. It follows the internationally recognized ISO 14040 and 14044 standards, which ensure transparency and methodological consistency. Globally, LCA has become central to vehicle rating systems, sustainability reporting, and regulatory design. Programmes such as Green NCAP, the European Commission's Product Environmental Footprint, and corporate net-zero commitments rely on full life cycle metrics rather than tailpipe-only indicators. Most vehicle LCAs prioritize GWP, expressed as CO_2-equivalent emissions, because of its direct connection to national and international climate targets and its relevance to policy.

1.5 Aiding Sustainable Consumer Decisions through LCA-based Rating Frameworks

The LCA in the automotive space of 4-wheeler passenger cars can be integrated with a rating mechanism to make it available to the consumers to influence their choices. The integration of "greenness" as an aspect of competition had started as early as 1999 with campaigns for California Low Emission Vehicles. Fuel Efficiency based ratings have also been around for quite some time (DeCicco & Thomas, 1999). Historically, variety of approached for environmental ratings/labelings have been followed- from simple hazard warnings, disclosure requirements, meeting requirements of some set environmental standards, certification programmes, so on and so forth. Today, we have more evolved LCA based mechanism around the world (DeCicco & Thomas, 1999). Some of these are simple assessments while others have been integrated with rating mechanisms. Few popular ones are explored in the following Table 1-

Table 1: LCA-based environmental impact assessments and rating systems across the globe

Rating System	Region	Scope & System Boundary	Life Cycle Phases Considered	Emissions	Application
Eco Score	Belgium	• Light-duty vehicles • Heavy-duty vehicles • Two-wheelers	• Production • Distribution • Use phase	GHG, CO, HC, NOx, PM, SO_2	• Consumer information • Policy support
TOPTEN	Europe	• Vehicles • Appliances	• Production • Use Phase • End-of-life	GHG, NOx, SOx, PM	• Consumer guidance • Benchmarking tool to promote energy-efficient and low-emission products
Australian Design Rules (ADR)	Australia	Regulatory standards for vehicle registration in Australia	• Production • Use Phase	GHG, HC, CO, NOx, PM, Fuel consumption	• Regulatory compliance mechanism to ensure minimum safety and environmental performance
Green Book (ACEEE)	USA	Vehicles	• Use phase (primary) • Production (limited) • End-of-life (limited)	GHG, HC, CO, NOx, PM	• Consumer information • Policy support for fleet programmes and incentives • Assisting automakers to market greener products

Table 1: LCA-based environmental impact assessments and rating systems across the globe

Rating System	Region	Scope & System Boundary	Life Cycle Phases Considered	Emissions	Application
Green Car Rating	UK	Vehicles	• Use phase (primary) • Production (limited) • End-of-life (limited)	GHG and evaporate emissions; HC, CO, NOx, PM	• Consumer decision-support tool
Green New Car Assessment Programme (NCAP)	Europe	Vehicles	• Considers full lifecycle • Indicators- » Clean Air » Energy Efficiency » GHG Emissions	GHG (incl. CH_4), NOx; primary energy demand; land-use impacts of biofuels	• Technology benchmarking • Policy analysis • Encouraging sustainable vehicle design • Sustainable Brand Positioning

Taken together, these vehicle rating and regulatory frameworks demonstrate a graduated integration of LCA- from predominantly use-phase and tailpipe-focused approaches (Eco Score, ADR, Green Book, UK Green Car Rating) to more explicit, system-wide lifecycle frameworks (TOPTEN and, most comprehensively, Green NCAP). Early and consumer-facing schemes primarily operationalise LCA concepts by translating operational emissions, fuel consumption, and limited production or end-of-life indicators into accessible scores that support consumer choice, market differentiation, and awareness of cleaner technologies. Regulatory instruments such as ADR embed partial LCA thinking indirectly, by enforcing design, manufacturing, and in-use emission standards to ensure minimum environmental performance rather than full lifecycle optimisation. In contrast, TOPTEN and Green NCAP extend LCA more formally into method development by incorporating multiple life cycle stages, broader pollutant sets, energy demand, and- critically in Green NCAP- upstream energy systems, battery production, infrastructure, and end-of-life pathways using both foreground and background data. Across all systems, LCA has thus been adapted pragmatically: simplified where the objective is consumer guidance and product benchmarking, and expanded where the goal is technology benchmarking, policy analysis, and incentivising sustainable vehicle design.

Chapter 2: Review of Literature

2.1 Evolution of Life Cycle Assessment in Automotive Sector

LCA is a systematic methodology employed to analyse the material and energy flows of a commodity to 'estimate' the environmental burdens associated with a product or service across its entire lifespan (OECD, 2023; Green NCAP). For the automotive industry, this means estimating the energy consumption and GHG emissions from vehicle manufacturing, material acquisition, energy production for vehicle use, and ultimately, recycling or disposal (OECD, 2023). The word 'estimate' is of extreme importance since it is nearly impossible to quantify the complete and multidimensional impact a commodity might have, across all its life cycle phases, on the environment.

Figure 1 shows the development of life cycle assessment in transportation over time through distinct phases. The early phase (pre-2000s) introduced LCA as a foundational concept, featuring basic evaluations of vehicle manufacturing and operational use. The middle phase (2000–2015) emphasized standardization alongside comparative analyses of conventional fuels and emerging alternative vehicles. The mature phase (2015–present) incorporated region-specific datasets (e.g., India, China, EU), methodological advancements (real-world usage, WTW sensitivity), heightened policy relevance of LCAs beyond tailpipe emissions, and green rating systems grounded in comprehensive LCA.

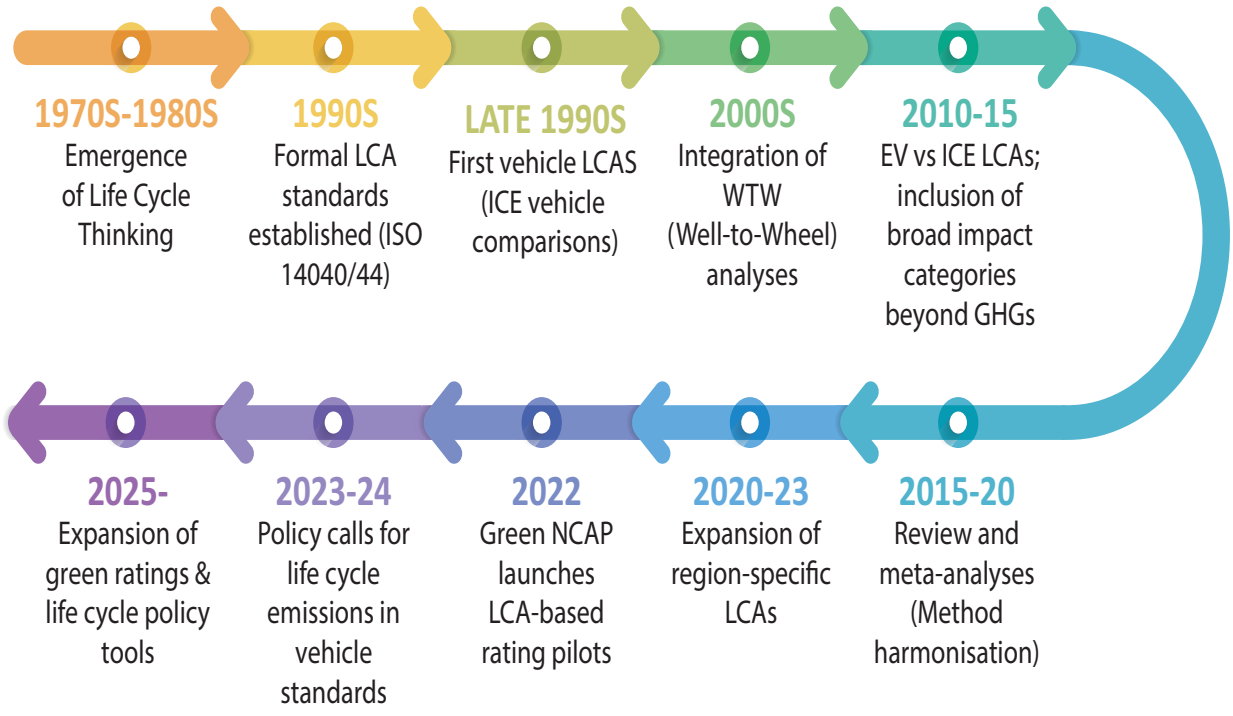

Figure 1: Evolution of LCA in the automotive sector

Source: TERI

2.2 Global Studies on Vehicle LCA

There is a significant regional variation in LCA studies worldwide arising from differences in energy infrastructure, fuel composition, manufacturing processes, vehicle and driving characteristics, LCA methodological boundaries, and policy environments. Manufacturing location substantially affects life cycle emissions. For instance, one study reports the carbon intensity of NMC622 battery production as 69 CO_2eq/kWh in China, versus 54 CO_2eq/kWh in Europe (Bieker, 2021). In China, the Tesla Model 3 produced more GHG emissions at 41.66 tonnes than the Toyota Corolla (38.6 tonnes), contrasting with the UK findings (Wang, 2023). The total GHG emissions were 55% less for Tesla Model 3 and 75% less for Toyota Corolla in the UK compared to those in China (Wang, 2023).

Across numerous global studies, BEVs consistently demonstrate lower life cycle GHG emissions compared to conventional gasoline and diesel ICEVs. This benefit, however, is highly dependent on the carbon intensity of the electricity mix used for charging (Bieker, 2021; Mera & Bieker, 2023). When we look at the production phase of the vehicle, one of the key findings across multiple studies is that BEVs generally have higher production-stage GHG emissions than ICEVs, primarily due to battery manufacturing (Buberger *et al.*, 2022; Stasinopoulos *et al.*, 2016). Battery production can contribute a significant portion (10–40%) of the production-stage emissions, influenced by the degree of electrification (Stasinopoulos *et al.*, 2016). For instance, a Tesla Model 3 Standard Plus BEV has production emissions approximately 49% higher than a conventional gasoline Volkswagen Passat 2.0 TSI (Buberger *et al.*, 2022). This difference is largely attributed to the energy-intensive processes and materials (e.g., rare metals) required for battery cells (Bieker, 2021; Stasinopoulos *et al.*, 2016).

Emissions from manufacturing are also significantly influenced by design decisions, such as the weight of a vehicle. For BEVs, a 10% increase in weight can result in a higher GHG impact, with almost half of this increase (4.26%) due to the use of additional materials during manufacturing (Naranjo *et al.,* 2025). Australian ICEVs have a larger carbon footprint partly because they include a higher percentage of heavy, fossil-fuelled passenger vehicles compared to the European market (Smit & Kennedy, 2022). However, lightweight materials can have much higher embedded impacts than the materials they replace, like iron and steel, because their production processes are more energy-intensive (Hill *et al.*, 2020).

The operational phase is where BEVs offer substantial GHG emission reductions over ICEVs. While ICEVs emit GHGs directly from tailpipes, BEVs produce zero tailpipe emissions, shifting emissions upstream to electricity generation (Gan *et al.*, 2023; Stasinopoulos *et al.*, 2016). The environmental benefits of BEVs in this phase are profoundly influenced by the electricity generation mix. In regions with a high share of renewable or nuclear energy sources, BEVs exhibit significantly lower use-stage emissions (Stasinopoulos *et al.*, 2016). Conversely, in areas with a coal-dominant electricity mix, the life-cycle emissions of BEVs can be comparable to, or even greater than, those of ICEVs (Gan *et al.*, 2023; Stasinopoulos *et al.*, 2016). Studies from Australia, with its coal-intensive electricity mix, have shown that BEVs and conventional vehicles can have similar life cycle GHG emissions (Stasinopoulos *et al.*, 2016). Similarly, Poland's coal-intensive electricity grid (660 g CO_2/kWh) causes a long-range BEV to emit 64 tonnes of CO_2, twice that of a comparable petrol vehicle (Bieker, 2021). On the other hand, in Norway, with its nearly carbon-free electricity grid, the lifetime emissions of a city-sized BEV are over 70% lower than those of a comparable gasoline car (Puricelli *et al.*, 2022). Similarly, in countries like France and Sweden, which rely heavily on renewable and nuclear energy, operational emissions are minimized (Hill *et al.*, 2020).

The end-of-life (EoL) phase's contribution to overall GHG emissions is generally small for conventional vehicles, but it becomes more complex for EVs due to battery recycling (Stasinopoulos *et al.*, 2016). While some studies note that EoL emissions are higher for EVs due to battery toxicity, advanced recycling technologies are critical for mitigating these impacts, reducing resource depletion and global warming potential (Buberger *et al.*, 2022; Piasecka, 2025). Proper battery recycling can significantly reduce the total life-cycle CO_2-equivalent emissions of BEVs, though the efficiency of such processes is still evolving (Buberger *et al.*, 2022).

Figure 2 summarizes regional perspectives on comparative automotive LCA-

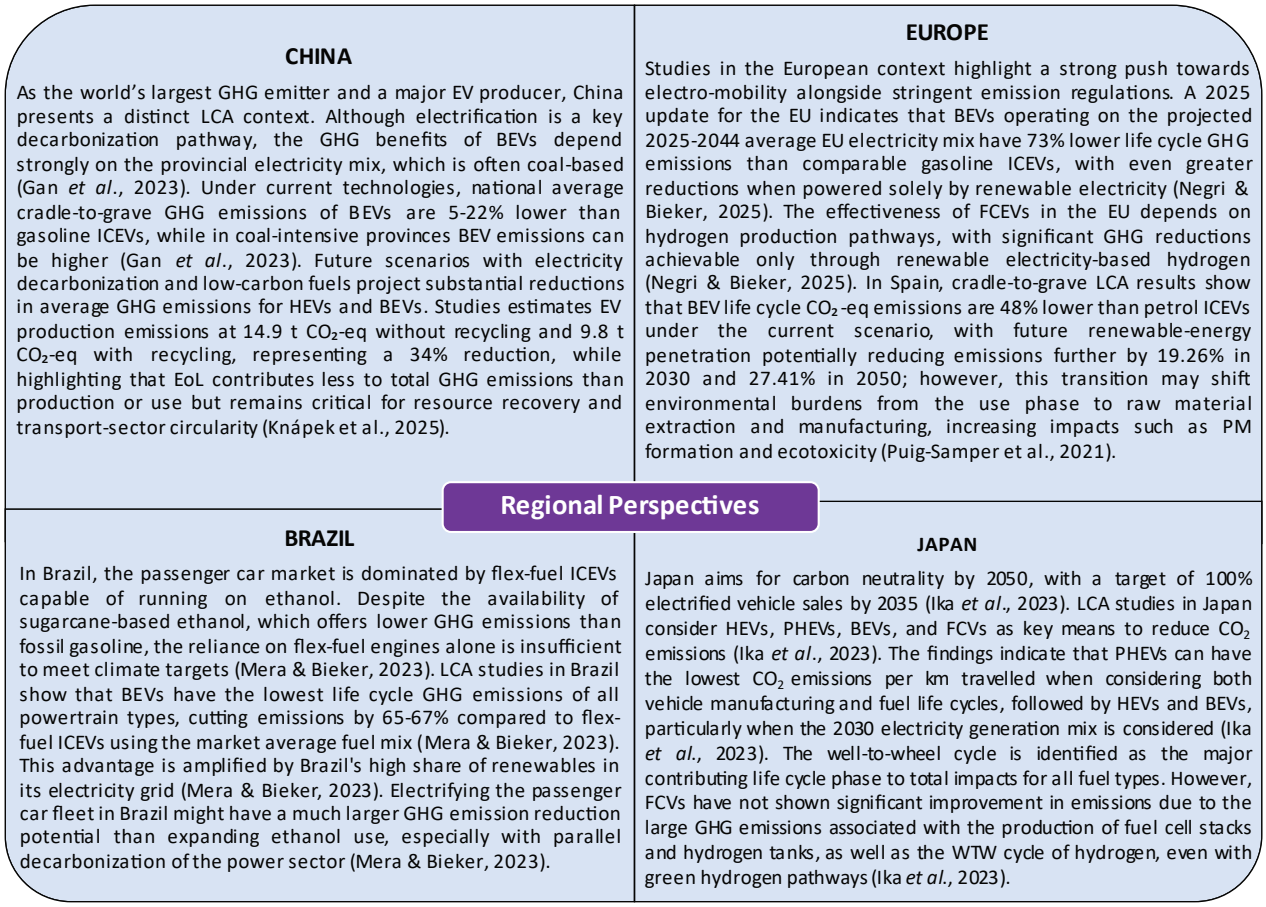

Figure 2: Regional perspectives on comparative automotive LCA

2.3 Automotive LCAs in the Indian Context

Indian LCA studies of passenger cars consistently show that BEVs generally offer the greatest potential for GHG emission reductions as compared to conventional ICEVs and HEVs. However, this advantage is highly contingent on the electricity generation mix, emission factor taken for electricity, number of battery replacements considered, running kilometres considered, models against which the comparison is done,

consideration of charging and on-road efficiency losses, etc. In addition to this, several LCA studies done on the Indian vehicles also treat the end-of-life phase as how a formal set up for the same might look like, giving large credit on contrary to the informal recycling and disposal methods prevailing in the country.

Patil *et al.* (2016) and Gupta *et al.* (2016) conducted well-to-wheel (WTW) and tank-to-wheel (TTW) analyses to show that TTW dominates energy use (75–84%) in gasoline, diesel, and CNG vehicles. Electricity's WTT efficiency is only 20%, due to coal dependence and high transmission and distribution (T&D) losses. Gupta *et al.* (2016) employed component-level simulations using the Indian Drive Cycle to demonstrate that hybrids suit India's frequent stop-and-go traffic, recovering 19–23% of braking energy through regeneration; split hybrids like the Toyota Prius gain 38–45% efficiency in urban areas (versus 15% on highways). Patil *et al.* (2016) concluded that diesel split hybrids are optimal, reducing energy use by 35% compared to gasoline vehicles. Shet and Moholkar (2025) confirm that mild hybrids, such as Maruti Suzuki's system, match BEVs' lifecycle GHG emissions under the current grid.

In addition, Shet and Moholkar (2025) highlight thermal power plant efficiency as a key sensitivity factor. India's reliance on sub-critical coal plants (operating at 27–30% efficiency) hinders BEV performance, with vehicle-cycle emissions 52–63% higher than ICEVs (45% for compact SUVs). Their model shows that without critical technology (>40% efficiency), BEVs struggle to offset the 'carbon debt' from battery production. Gopinathan (2020) supports this conclusion using probabilistic Monte Carlo analysis and explores second-life batteries-reusing degraded EV units for grid storage can amortize manufacturing emissions, potentially reducing BEV lifecycle emissions by up to 60%.

Another critical aspect highlighted by Anup *et al.* (2025) is that significant variations in reported GHG emissions across Indian LCA studies are primarily driven by differences in assumptions regarding grid carbon intensity, test versus real-world energy use, and fuel types. These three factors alone can account for nearly 75% of the variation in life-cycle emission estimates. Additionally, assumptions on vehicle lifetime varies, with some studies using a total travel distance of 1,60,000 km (Shet and Moholkar, 2025) or 2,00,000 km over 16 years (Abdul-Manan *et al.*, 2022). Therefore, a harmonized approach, including dynamic grid carbon intensity values, real-world energy consumption adjustments, and refined assumptions about biofuel blending, is crucial for robust policymaking (Anup *et al.*, 2025).

Differences in life cycle GHG emissions can also arise from methodological differences. For instance, Boruah *et al.* (2025) critically question the application of MIDC in LCA studies. By creating the 'Hyderabad Electric Car Driving Cycle' (H-ECDC), they illustrated that MIDC does not accurately reflect Indian traffic conditions. Their research revealed that the actual energy consumption for electric vehicles is about 0.144 kWh/km, which is nearly 70% higher than the manufacturer's claim of 0.085 kWh/km based on MIDC. As a result, while MIDC-based calculations estimate indirect emissions at 125 gCO_2/km, real-world figures show emissions could reach 213 gCO_2/km in regions with fossil fuel-heavy grids like Telangana. This gap indicates that current policy incentives might be based on a significant underestimation of the carbon footprint of EVs in operation.

Lastly, the environmental impacts and energy mix varies significantly across regions within India. For example, BEVs in the north-eastern region show a notable benefit due to a power sector relying more on natural gas and hydroelectricity (Abdul-Manan *et al.*, 2022). Peshin *et al.* (2022) offer the most extensive geographical analysis, evaluating at the state level. Their research questions the national aggregate perspective. In states

with a high reliance on coal, such as Jharkhand, Chhattisgarh, Bihar, and Goa, four-wheeler BEVs produce more life cycle GHG emissions than traditional gasoline vehicles, making BEV adoption less favourable for climate change under the existing grid conditions.

2.4. Studies on Emission Profiles of Various Fuels and Powertrains

Provided below is a summary of study results and conclusions on the emission profiles of various fuels and powertrains (See Figure 3) –

- **ICEV Petrol and Diesel:** The use-phase is the dominant contributor to life cycle greenhouse gas emissions in the case of ICEV petrol and diesel due to direct tailpipe emissions of CO_2 (Hawkins *et al.*, 2013; Bicer & Dincer, 2017). Substantial upstream emissions also arise from crude oil extraction, refining, and fuel transportation, i.e., WTT emissions (Edwards *et al.*, 2014). Manufacturing emissions are relatively lower compared to electrified vehicles due to the absence of high-energy battery systems (Heywood, 2018). These technologies typically have lower energy efficiency, around 20–30% at the engine level, leading to higher cumulative emissions over the vehicle's lifetime.
- **ICEV CNG:** Natural gas has a lower carbon-to-hydrogen ratio than petrol and diesel, resulting in lower CO_2 emissions per unit of energy during combustion, and typically reduced tailpipe CO_2 emissions compared to conventional ICEVs (IEA, 2021; Verma *et al.*, 2016). However, upstream emissions from natural gas extraction, processing, compression, and distribution, particularly methane leakage, can significantly impact overall life cycle emissions (Alvarez *et al.*, 2018).
- **BEVs:** While operational emissions are zero at the tailpipe, BEVs shift emissions to upstream stages of the life cycle. Electricity generation for charging and battery manufacturing are dominant emission sources, especially in regions with carbon-intensive electricity grids (Hawkins *et al.*, 2013; Ellingsen *et al.*, 2016). Battery production is energy and material-intensive, involving critical materials that contribute significantly to manufacturing-phase emissions (Dunn *et al.*, 2015). Consequently, BEVs generally have higher production-phase emissions than ICEVs but lower operational emissions, with overall life-cycle performance heavily dependent on factors like vehicle lifetime, driving distance, and the decarbonization of the electricity grid (Bauer *et al.*, 2015).
- **HEVs:** From a life cycle perspective, HEVs occupy an intermediate position between ICEVs and BEVs. They incur higher manufacturing emissions than ICEVs due to the inclusion of battery and electric components, but substantially lower operational emissions over the vehicle lifetime (Hawkins *et al.*, 2013). Their environmental performance is less sensitive to the electricity grid's composition than BEVs, making them relevant in regions where grid decarbonization is ongoing.

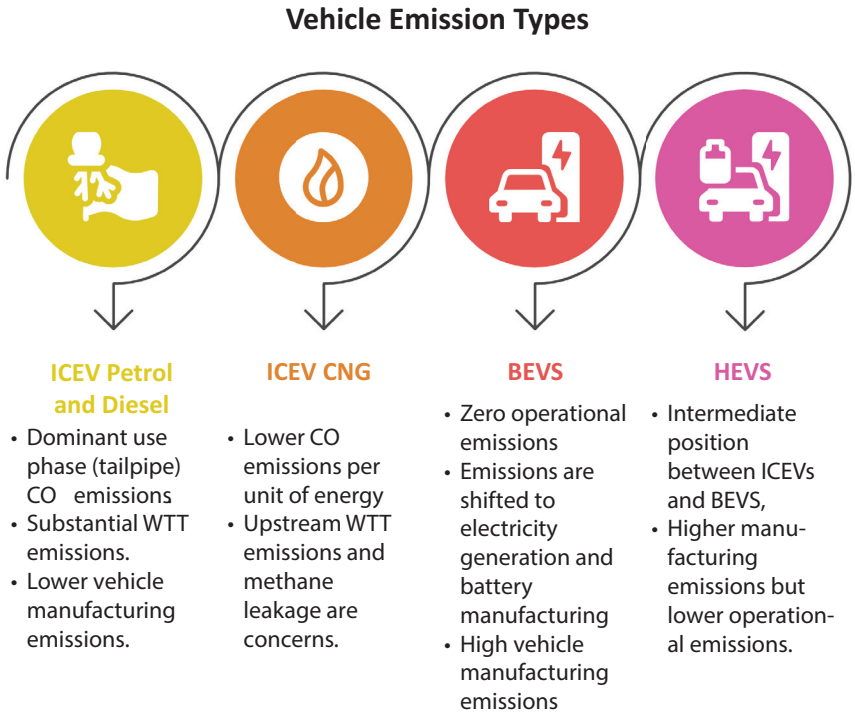

Figure 3: Summary of study results and conclusions on the emission profiles of various fuels and powertrains

2.5 Key Factors Influencing LCA Results

The outcomes of automotive LCA are highly sensitive to various parameters and assumptions as explained in detail in the above sections. Following is a summary of the key factors that the LCA studies in automotive sector are highly sensitive to:

1. **Electricity Grid Mix:** India's current vehicle policies and emission regulations focus predominantly on tailpipe emissions, misrepresenting the climate impacts of different technologies. As discussed earlier, BEVs appear zero-emission by shifting emissions upstream to the electricity generation system, which in India's coal-heavy grid, creates regulatory gaps that hinder decarbonization efforts. Policies also overlook manufacturing emissions which, combined with India's coal-dependent electricity grid, can substantially erode operational emission advantages of electric vehicles during their use-phase (Shet & Moholkar, 2025).

   Off-peak, overnight charging in India can result in 3–9% greater GHG emissions than daytime charging due to variations in the grid mix (Abdul-Manan *et al.*, 2022). Regions with cleaner power sectors, such as India's north-eastern states (due to natural gas and hydroelectricity), show a marked benefit for BEVs (Abdul-Manan *et al.*, 2022). Improving the operating efficiency of existing thermal power plants, which dominate India's electricity generation, can also decrease the indirect emissions of electric vehicles (Shet and Moholkar, 2025).

2. **Battery Raw Material and Manufacturing Emissions:** The raw material required for vehicle battery have high emission embedded in it due to the associated mining, processing, and transportation involved in acquiring these minerals and rare earth elements. Battery manufacturing is also an energy-intensive process (Yadav *et al.*, 2024). However, modern production techniques can reduce GHG emissions in battery manufacturing plants, for example, by about two-thirds in Chinese plants using the US techniques (Buberger *et al.*, 2022). But the need for battery replacement during a BEV's lifetime can adversely affect its life cycle GHG emissions. BEVs are environmentally advantageous only for no or one-time battery replacement over a typical travel distance of 1,60,000 km (Shet and Moholkar, 2025). The influence of battery capacity on production emissions is also noted, as PHEVs with smaller batteries generally emit less GHGs during production (Buberger *et al.*, 2022).

   The exact carbon intensity of manufacturing various vehicle components (e.g., steel, aluminium, plastics) and, critically, batteries within India are often estimated or derived from international benchmarks (Buberger *et al.*, 2022; Stasinopoulos *et al.*, 2016).

3. **Vehicle Lifetime and Usage Patterns:** The assumed total distance a vehicle travels over its lifetime significantly impacts its overall life cycle emissions (Bieker, 2021). Studies consider various lifetime mileages and adjust them for different regions and vehicle segments (Bieker, 2021; Raugei, 2022). Longer vehicle lifetimes can allow the lower operational emissions of EVs (with a clean grid) to offset their initial higher production emissions in case of no battery replacement.

4. **Real-world Driving Conditions vs Test Cycles:** LCA findings are influenced by whether studies rely on official test values or real-world fuel and electricity consumption data. Real-world usage often shows higher fuel consumption or lower fuel efficiency than test values, which can lead to life cycle GHG emissions being more than double the official tailpipe CO_2 values for ICEVs (Bieker, 2021). Incorporating real-world factors into LCA is crucial for accurate assessments. Many LCAs still rely on standardized test cycles, which may not accurately reflect real-world driving conditions, traffic congestion, and ambient temperatures unique to different Indian regions (Abdul-Manan *et al.*, 2022). More empirical data from Indian driving conditions, considering diverse terrains and climate zones, are essential for realistic use-phase emission calculations.

5. **End-of-Life Management and Circularity:** The EoL phase, especially for BEV batteries, is critical. While BEVs show the highest demand for energy in their life cycle (excluding fuel/energy cycles), recycling their plastics, materials, and components can significantly reduce negative environmental impacts, including greenhouse gas emissions, compared to landfilling (Piasecka, 2025). The implementation of advanced recycling technologies is key to mitigating resource depletion and cumulative energy demand (Piasecka, 2025).

   Comprehensive data on vehicle dismantling, material recovery rates, and the energy/emissions associated with recycling processes are largely nascent in India. While some studies acknowledge the importance of battery recycling (Buberger *et al.*, 2022; Piasecka, 2025), detailed lifecycle inventories for Indian recycling operations are scarce. This includes both the environmental credits from recycled materials and the burdens of the recycling process itself.

6. **Biofuels and Alternative Fuels:** The use of biofuels (e.g., ethanol in Brazil) can offer significant GHG reductions compared to fossil fuels, but their effectiveness and emissions depend on sustainable production and market penetration (Mera & Bieker, 2023).

7. **Methodological Considerations in Vehicle LCA:** A significant challenge in comparing vehicle LCA studies lies in the inconsistencies of adopted methodologies, functional units, system boundaries, and assumptions. Ika *et al.* (2023) employed Economic Input-Output LCA (EIO-LCA) to assess the environmental performance of the passenger car fleet in Japan and finds that PHEVs have the lowest CO_2 emissions per km travelled, followed by HEVs and then BEVs. Xiong *et al.* (2021) in China applied hybrid LCA integrating process and environmentally extended input-output LCA to evaluate electric vehicles' carbon footprint in China and found that BEVs with lithium iron phosphate batteries had 8.26% lower sales-weighted life cycle CO_2 emissions than those using nickel-manganese-cobalt batteries. Smit and Kennedy (2022) used probabilistic LCA and found that, despite high input variability, the chance of a BEV emitting more greenhouse gases than an ICE vehicle was low. An ICCT report (2024) employed dynamic modelling, showing that a static electricity mix overestimates life cycle emissions of EU-sold BEVs by 58% compared to scenarios incorporating projected grid changes.

   This significant variance suggests that while numerous studies exist, their comparability and collective utility for national policymaking are limited. Raugei (2022) emphasizes the need for harmonization to enable a consistent 'apples-to-apples' comparison of GHG emission results. This involves standardizing the functional unit, assuming a common total vehicle mileage, and setting consistent system boundaries. A standardized LCA framework, tailored to Indian specificities yet aligned with international best practices, is critically absent.

The identified gaps and variabilities represent critical blind spots that can undermine India's efforts to achieve its ambitious climate goals and ensure sustainable development. With India's push for domestic manufacturing (e.g., under 'Make in India' initiatives), primary data on the energy consumption and emissions profiles of Indian automotive and battery production facilities are essential. India's unique resource base and import dependencies warrant specific investigations into these upstream stages. As a major developing economy, India's decarbonization efforts are globally significant. By developing robust, India-specific LCA methodologies, India can contribute valuable insights to the global discourse on sustainable mobility. This can facilitate international collaborations, knowledge sharing, and the adoption of best practices, positioning India as a leader in sustainable transportation research and implementation.

Chapter 3: Life Cycle Assessment Framework and Standards

3.1 Life Cycle Assessment Framework

LCA has emerged as a leading tool for driving sustainability decisions in the fields of research, industry, and policy decisions. It is a powerful and robust tool for quantifying the various environmental impacts of a product or service throughout its life cycle. Based on the systematic life cycle (cradle to gate/grave/cradle) approaches, it aids stakeholders in comprehending the true impacts of any given product or service. It reduces the risk of problem shifting (from one life cycle phase to another) and helps stakeholders in locating the visible difference between an environmentally sustainable product and a less sustainable alternative.

According to International Organization for Standardization (ISO) 14040/44 standards, LCA should be carried out in four key phases as presented in Figure 4- goal and scope definition phase, life cycle inventory analysis phase, life cycle impact assessment phase, and interpretation phase **(ISO, 2006a)**.

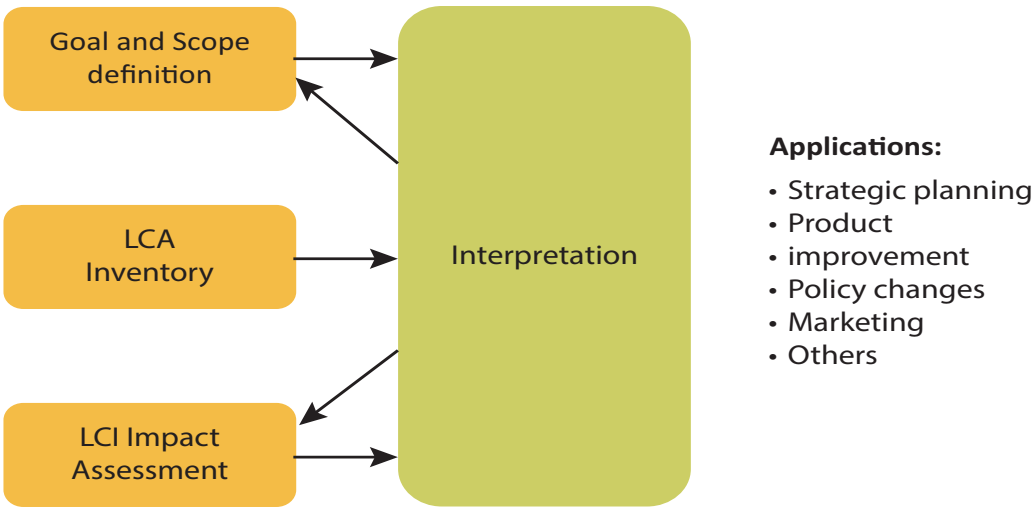

Figure 4: LCA framework- ISO 14040/14044

1. Goal and Scope Definition

LCA begins with a clear articulation of its goal and scope, which together establish the foundation of the entire study. The goal definition explains the purpose of conducting the LCA, identifies the intended application of the results, specifies the target audience, and clarifies the product, system, or service being assessed. Closely linked to this, the scope definition determines the breadth and depth of the analysis. It involves specifying the functional unit against which all inputs and outputs are normalized, delineating the system boundaries, and identifying relevant data requirements. The functional unit defines the reference

basis for comparing environmental impacts, and the system boundary clearly specifies included and excluded processes, activities, life cycle stages, and geographical regions (ISO, 2006a). Additionally, this phase sets expectations for data quality, selects appropriate life cycle impact assessment methods, and defines assumptions and limitations.

2. Life Cycle Inventory Analysis

Once the system boundaries are established, the study proceeds to life cycle inventory analysis. This phase involves the systematic collection and quantification of all material and energy flows entering and leaving each unit process within the defined product system. Inputs may include raw materials, fuels, and electricity, while outputs typically consist of products, co-products, wastes, and emissions to air, water, and soil (Heijungs & Suh, 2002). These flows are compiled and standardized with respect to the functional unit. The inventory results for the overall product system is then obtained by aggregating the contributions of all individual unit processes. Both primary data (from actual measurements) and secondary data (from established life cycle inventory databases like Ecoinvent) are utilized to provide emission factors and process data. Emission factors, typically expressed in kg CO_2-equivalent per unit of activity, serve as the quantitative link between activity data and greenhouse gas emissions.

3. Life Cycle Impact Assessment

The life cycle impact assessment translates the inventory data into potential environmental impacts. In this phase, the quantified environmental loads identified in the LCI are assigned to selected impact categories, such as climate change or resource depletion. These loads are then converted into impact indicators using characterization factors, which express the relative contribution of each emission or resource use to a given impact category. Further refinement of results may be carried out through normalization and weighting, depending on the objectives of the study. However, LCA do not reflect impact at a particular location or point in time.

4. Interpretation

The final phase of an LCA is life cycle interpretation, in which the results from the inventory and impact assessment phases are analysed in an integrated manner. This stage focuses on identifying environmentally significant issues, evaluating the robustness of results, and examining the influence of assumptions and data choices. Based on this evaluation, conclusions are drawn and recommendations are formulated in line with the original goal and scope of the study. If two products are compared with similar resource composition and one of it has higher consumption of each resource, then an interpretation based on the life cycle inventory can be conclusive. However, in case of studies where the resource composition and consumption are complex, impact assessment and result interpretation becomes necessary.

Reporting of findings is also undertaken in this phase, ensuring that results are communicated clearly and appropriately for their intended use, such as product development, strategic decision-making, or public policy formulation.

3.2 Phases of Automotive Life Cycle Assessment

In case of application of life cycle thinking in the automotive sector, the process generally encompasses two main cycles in the creation of life cycle inventory (See Figure 5): the vehicle cycle and the fuel/energy cycle

under a single system boundary, which together constitute a "cradle-to-grave" analysis (Anup et al., 2025; Bieker, 2021; Shet and Moholkar, 2025).

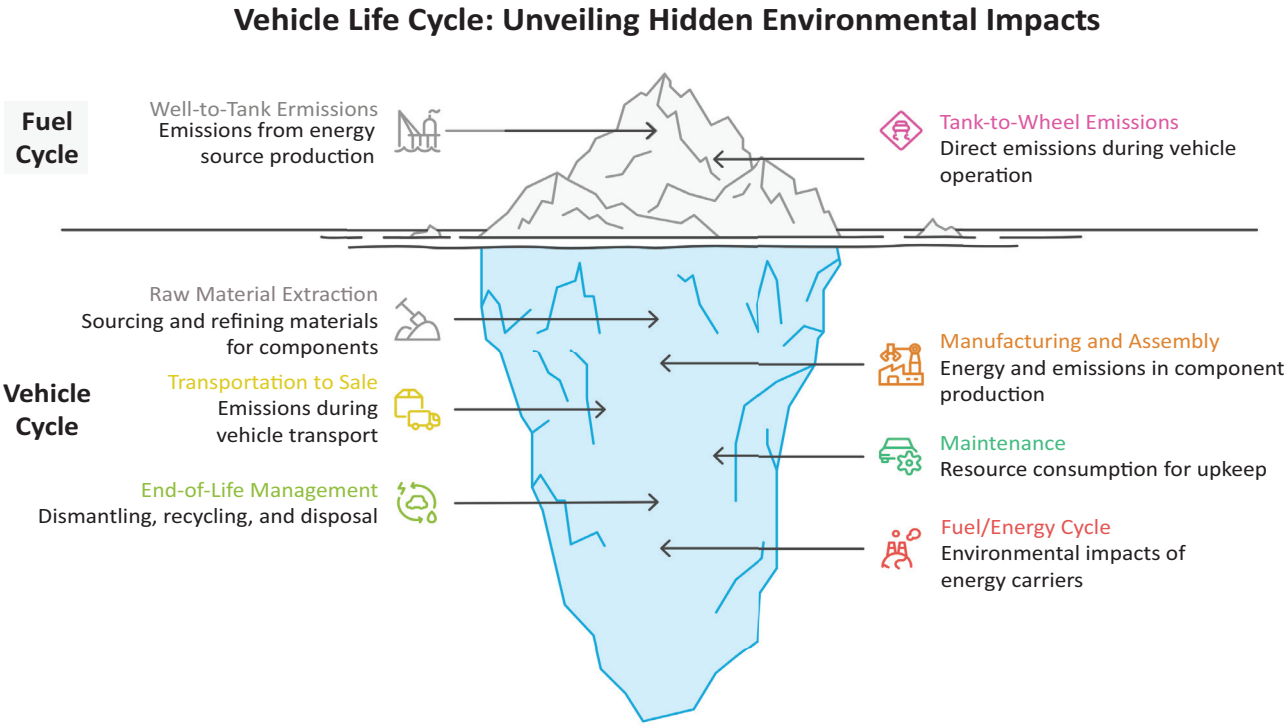

Figure 5: Phases of automotive life cycle assessment

1. Vehicle Cycle

The vehicle cycle covers all processes related to the physical vehicle itself, from its inception to its retirement:

- **Raw Material Extraction and Processing**: This stage accounts for the environmental impacts of sourcing, mining, and refining raw materials required for vehicle components, including metals, plastics, and specific minerals for batteries.
- **Manufacturing and Assembly**: This phase includes the energy and emissions involved in manufacturing individual components (e.g., chassis, body, engine) and assembling the final vehicle. For electric vehicles, the manufacturing of the battery and, for FCEVs, the hydrogen system (tank and fuel cell) are significant contributors to production emissions (Bieker, 2021). Production emissions can contribute approximately 10% to an ICEV's total life cycle GHG emissions and up to 40% for a BEV (Buberger *et al.*, 2022).
- **Transportation to Point of Sale**: Emissions generated during the transport of the manufactured vehicle from the production facility to the point of sale are included (OECD, 2023).
- **Maintenance**: Emissions and resource consumption associated with vehicle maintenance and the production of replacement parts over its operational lifetime are considered (Bieker, 2021).

- **End-of-Life Management**: This final stage involves the dismantling, recycling, and disposal of vehicle components. Recycling can significantly reduce a vehicle's CO_2-equivalent emission footprint, especially for BEVs when proper battery recycling is included (Buberger *et al.*, 2022). The adoption of advanced recycling technologies is crucial for mitigating impacts such as resource depletion, global warming potential, and cumulative energy demand (Piasecka, 2025). However, inconsistencies in reporting end-of-life boundaries and associated emission credits across studies have sometimes led to their exclusion from harmonization efforts (Raugei, 2022).

2. Fuel/Energy Cycle

The fuel/energy cycle assesses the environmental impacts associated with the production and consumption of energy carriers used during vehicle operation:

- **Well-to-Tank**: This stage accounts for emissions from the extraction, processing, and transportation of energy sources (e.g., crude oil, natural gas, electricity generation, hydrogen production) to the vehicle's "tank" or battery (Bieker, 2021; Shet and Moholkar, 2025).
- **Tank-to-Wheel**: These are the direct emissions generated during vehicle operation. While ICEVs emit GHGs from their tailpipes, BEVs have zero tailpipe emissions, effectively shifting these emissions upstream to the electricity generation process (Bieker, 2021).

Chapter 4: Goal, Scope, and Methodology of the Study

4.1 Goal and Scope of the Study

This study adheres to the globally recognized ISO 14040 and 14044 standards for LCA, ensuring a systematic, transparent, and scientifically rigorous environmental assessment. The assessment quantifies CO_2-equivalent emissions over the entire vehicle lifetime, including both, vehicle and fuel cycle.

4.1.1 Goal of the Study

This section presents the key objectives of the present study, which were briefly introduced in the preceding chapter while establishing the overall context of the research. The key objectives are:

1. To undertake a comprehensive review of the literature to assess the current state of the Indian and global automotive sectors, with particular emphasis on the extent to which LCA approaches have been adopted in the evaluation of in-use vehicles as well as in the environmental marketing and communication of vehicle performance.
2. To examine existing environmental rating and labelling mechanisms implemented internationally within the automotive sector, with the objective of understanding their scope, methodological foundations, and relevance for vehicle environmental performance assessment.
3. To develop a standardized emission rating framework for four-wheeler passenger vehicles based on life-cycle greenhouse gas emissions, which constitutes the primary objective of this study. The proposed framework aims to provide an objective and transparent basis for comparing environmental performance across vehicle models and powertrain technologies by translating complex life-cycle emission data into clear and accessible ratings. The framework establishes defined performance benchmarks and rating tiers that reflect overall climate impact rather than tailpipe emissions alone.
4. To formulate a base methodological approach and conduct a comprehensive life cycle assessment of greenhouse gas emissions for a representative sample of four-wheeler passenger cars across multiple powertrain and fuel technologies in the Indian automobile market. This assessment is undertaken to demonstrate the application and functionality of the proposed vehicle emission rating framework.
5. To examine the applicability of the LCA-based rating framework within the policy arena by identifying key drivers that encourage policymakers, OEMs, and consumers to adopt and promote low-emission vehicles.

Target Audience of the Study

The core purpose of this study is to provide evidence-based insights for:

- Governmental and policy-oriented stakeholders to support decision-making related to sustainable transport planning.
- Academia for scientific analysis and policy evaluation, and industry stakeholders to guide product development and sustainability planning.

- Consumers, it aims to enhance awareness and inform purchasing decisions based on genuine life cycle environmental performance.

4.1.2 Scope of the Study

The scope of the study is detailed below-

Product System and Function Considered

The study conducts the assessment of the environmental performance of a selected sample of 4-wheeler passenger vehicles across several fuel and powertrain types- ICEVs running on petrol and diesel; CNG; BEVs; and HEVs- to demonstrate the 4-wheeler passenger vehicle rating framework that has been developed in the following chapters. These powertrains exhibit fundamental differences in their energy carriers, propulsion mechanisms, drivetrain architectures, and emission generation pathways, which significantly influence their life-cycle environmental performance.

The functional differences across various powertrain types are as follows:

- **ICEV Petrol and ICEV Diesel:** ICEVs rely solely on the combustion of liquid fossil fuels (petrol or diesel) to generate mechanical work through a thermodynamic engine cycle. They use a conventional drivetrain comprising an engine, transmission, driveshaft, and differential.
- **ICEV CNG:** CNG vehicles are a variation of internal combustion technology, using methane-rich natural gas as the primary fuel. They operate on spark-ignition engines like petrol ICEVs but require specialized components like reinforced fuel tanks and high-pressure fuel storage systems.
- **BEVs:** BEVs are exclusively propelled by electric motors powered by onboard rechargeable batteries, typically lithium-ion. They lack an internal combustion engine, producing zero tailpipe emissions during operation.
- **HEVs:** HEVs integrate both an internal combustion engine and an electric propulsion system, featuring a fuel tank, electric motor, power electronics, and a relatively small battery. They do not require external charging infrastructure, as batteries are charged internally through regenerative braking and engine operation. The primary functional principle of HEVs is to enhance vehicle efficiency through regenerative braking, engine load optimization, and limited electric-only operation, particularly in low-speed and stop-and-go driving conditions (Ehsani et al., 2018). Compared to conventional ICEVs, HEVs achieve lower fuel consumption and reduced tailpipe emissions due to improved energy management strategies (Samaras & Meisterling, 2008).

Geographical Scope

This assessment focusses on 4-wheeer passenger vehicles currently available in the Indian automotive cars to develop an LCA-based green rating framework applicable in the physical and political boundary of India.

Functional Unit and Lifespan

In this study, the functional unit is defined on a per-vehicle, full-lifetime basis. Each passenger four-wheeler is assumed to operate over a total driving distance of 150,000 km, corresponding to an average annual distance of 10,000 km. This lifetime assumption is consistent with typical original equipment manufacturer (OEM) warranty and design life considerations. All greenhouse gas emissions are therefore quantified and reported per vehicle over its assumed lifetime and expressed in terms of kilograms of CO_2 equivalent (kg CO_2-eq).

System Boundary Setting

The life cycle considered in this study is defined using a cradle-to-grave framework. However, the modelling of the EoL phase is constrained by the predominantly informal and poorly documented vehicle dismantling and recycling practices prevalent in the Indian context. Recycling provides significant avoided emission benefits compared to primary material production (Modaresi *et al.*, 2014; Ciacci *et al.*, 2010). While several studies adopt formalised EoL management systems as a core scenario, such assumptions risk misrepresenting ground realities. To maintain methodological realism, the present LCA incorporates only the major recycled material flows explicitly reported in the vehicle's bill of materials (BoM). No additional EoL treatment processes or recovery pathways are assumed. As the formalisation and traceability of vehicle EoL systems improve, this phase can be progressively modelled with greater certainty. Consequently, the current analysis comprehensively evaluates the manufacturing and use phases, with limited consideration of recycled material inputs as documented in the BoM.

Figure 6 presents the system boundary of our study, encompassing upstream (cradle-to-gate), core manufacturing (gate-to-gate), and downstream (gate-to-grave) life cycle stages. Processes are clearly classified as either within or outside the system boundary to ensure transparency and reproducibility.

1. Upstream Processes (Cradle-to-Gate)

The upstream phase includes all processes associated with the acquisition of raw materials and the production of components required for 4-wheeler passenger vehicle manufacturing. Specifically, the following processes are included within the system boundary:

- Mining and extraction of primary raw materials used in vehicle components and sub-systems.
- Processing and production of raw materials.
- Manufacturing emissions from energy consumption associated with parts and components for passenger vehicle assembly.
- Transportation of raw materials and components between extraction sites, material processing facilities, and manufacturing units.

The following processes are excluded from the upstream system boundary:

- Production of packaging materials used for raw materials and components.
- Infrastructure construction and maintenance, including buildings and industrial facilities.
- Capital goods, such as machinery and equipment used in material extraction and component production.

2. Core Manufacturing Processes (Gate-to-Gate)

The core manufacturing phase represents activities carried out within the vehicle manufacturing facility, from the receipt of components to the completion of the final vehicle. The following processes are included:

- Manufacturing and processing operations involved in producing vehicle sub-assemblies.
- Final assembly of the passenger car, including integration of all major systems.
- Direct energy consumption (electricity and fuel) used during manufacturing and assembly operations within the plant.

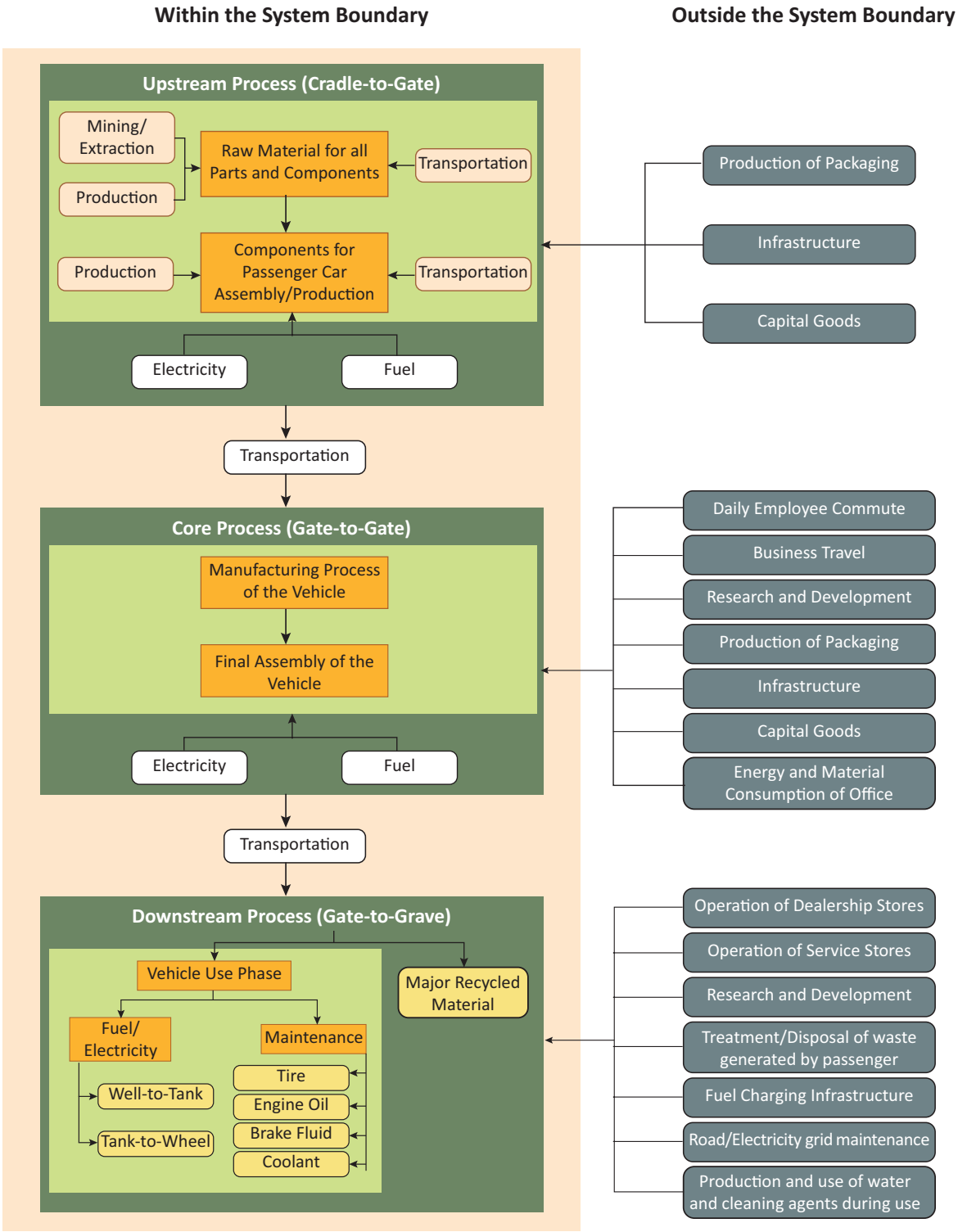

Figure 6: System boundary of the study

The following processes are excluded from the core manufacturing boundary:

- Daily employee commuting and business travel.
- Research and development (R&D) activities.
- Energy and material consumption of administrative and office buildings.
- Production of packaging materials.
- Infrastructure and capital goods, including factory buildings, production lines, and machinery.

3. Downstream Processes (Gate-to-Grave)

The downstream phase covers the use and end-of-life stages of the passenger car. The following processes are included within the system boundary:

- Vehicle use phase, including energy consumption in the form of fuel or electricity.
- Routine maintenance activities, including the production and use of consumables such as:
  - » Tires
  - » Engine oil
  - » Brake fluid
  - » Coolant
- Constrained inclusion of End-of-life- focus on major recycled materials explicitly mentioned in BoM.

The following processes are excluded from the downstream system boundary:

- Operation of dealership and service centres.
- Road infrastructure and electricity grid construction and maintenance.
- Fuel production and charging infrastructure.
- Treatment and disposal of waste generated by passengers during vehicle use.
- Research and development activities.
- Production and use of water and cleaning agents during the use phase.

Excluding capital goods and infrastructure aligns with standard comparative LCA practices, as these processes have minimal impact on relative results (Frischknecht *et al.*, 2007). Upstream material production and component manufacturing are well-documented major contributors to vehicle life-cycle emissions (Kim *et al.*, 2016; Mayyas *et al.*, 2012). Use-phase emissions dominate for ICEVs, whereas the electricity generation mix determines BEV operational emissions (Hawkins *et al.*, 2013; IEA, 2022).

Assessment Parameter and Method

Global Warming Potential (GWP) was selected as the sole impact assessment parameter, as it is the only environmental indicator included in the adopted rating framework. Accordingly, the IPCC 2021 GWP 100-year characterization method available in SimaPro was applied to quantify greenhouse gas emissions, with results expressed in terms of kg CO_2-equivalent.

The IPCC 2021 GWP 100 refers to the 100-year Global Warming Potential characterization factors published by the Intergovernmental Panel on Climate Change (IPCC) in its Sixth Assessment Report (AR6). This method quantifies the climate change impact of greenhouse gas emissions by expressing them as carbon dioxide equivalents (CO_2-eq) over a 100-year time horizon, enabling consistent comparison of different gases based on their relative radiative forcing effects.

4.2 Overall Methodological Framework of the Study

The overall methodological structure of this paper is provided in the following Figure 7:

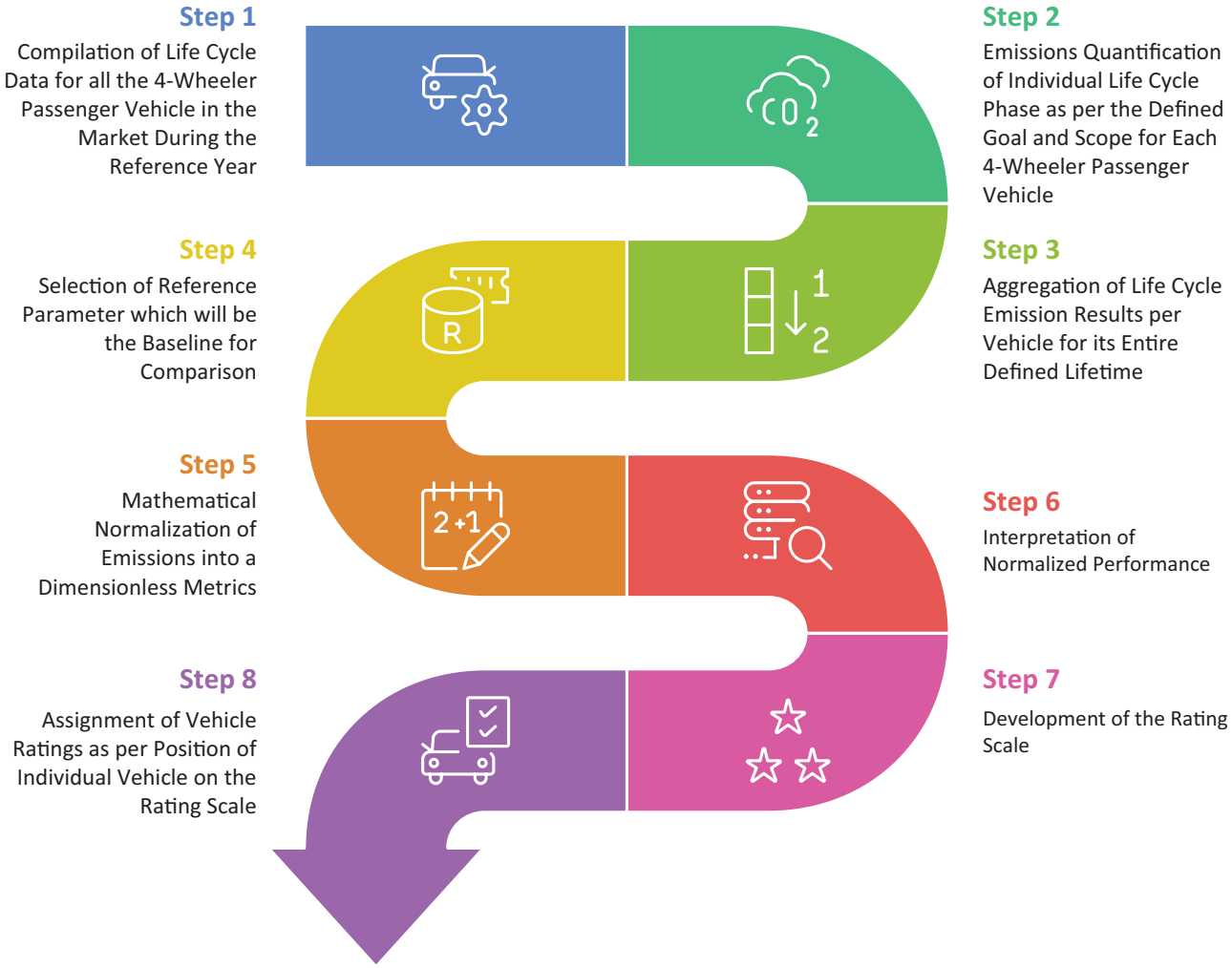

Figure 7: Broad methodological structure of the study

- **Step 1- Data Compilation and Classification**: For each vehicle, a verified BoM and all relevant life cycle inputs are compiled for the selected reference year. This includes data related to material production, manufacturing and assembly, transportation and logistics, fuel or electricity consumption, maintenance, and end-of-life treatment. All data are harmonized to maintain consistency in geographic, temporal, and technological assumptions.
- **Step 2- Life Cycle Emissions Quantification:** A comprehensive cradle-to-grave life cycle assessment is conducted for each vehicle by integrating emissions from material extraction and processing, manufacturing, logistics, well-to-tank processes, vehicle operation, maintenance, and recycling. The outcome of this step is the total life cycle GHG emissions, expressed as kg CO_2-equivalent per vehicle over its lifetime.
- **Step 3- Aggregation of Life Cycle Emission Results:** The emission contributions from individual life cycle stages are aggregated to obtain a single life cycle GHG value for each vehicle. This aggregation ensures that upstream, use-phase, and end-of-life emissions are consistently represented in the final performance indicator, avoiding overemphasis on any single stage.
- **Step 4- Definition of Reference Parameter**: A reference parameter is defined to serve as the baseline for comparative evaluation. This reference represents the central tendency or benchmark against which individual vehicle performances are assessed, providing the necessary context for scaling and normalization.
- **Step 5- Mathematical Normalization of Emissions:** The aggregated life cycle GHG emissions are mathematically transformed into a dimensionless metric by normalizing each vehicle's emissions relative to the reference parameter. This step removes differences in magnitude and enables direct comparison across vehicles with varying technologies, sizes, and energy pathways.
- **Step 6- Interpretation of Normalized Performance:** The normalized scores are interpreted to understand relative differences in life cycle performance among vehicles. This step bridges quantitative results and qualitative meaning, ensuring that the transformed values reflect meaningful distinctions in environmental performance.
- **Step 7- Development of the Rating Scale:** Based on the distribution of normalized scores, a structured rating scale is developed to classify vehicles into performance categories. The scale is designed to ensure transparency, comparability, and robustness across the vehicle fleet.
- **Step 8- Assignment of Vehicle Ratings**: Each vehicle is assigned a final rating according to its normalized score and position on the rating scale. The resulting rating represents the vehicle's relative life cycle GHG performance within the defined system boundary and reference context.

The life cycle stages, system boundary, and methodological framework adopted in this study have been discussed earlier in this chapter. The subsequent chapters present the detailed life cycle inventory, key assumptions, and the development of the rating mechanism, including the formulation of the reference parameter, rating scale, and associated categorization criteria.

Chapter 5: Life Cycle Inventory and Study Assumptions

5.1 Material Composition and Emission Factors

The Vehicle material composition data was sourced from A2MAC1, a specialized automotive benchmarking platform that provides one of the industry's most comprehensive teardown data and material composition information across hundreds of vehicle models, including 4-wheeler passenger vehicles.

The detailed BoM of 59 vehicles have been obtained and modelled using the A2MAC1 database. It had material composition of various systems of a 4-wheeler including the interior system, seating system, comfort & heating, ventilation, and air conditioning (HVAC) system, electrical system, electronic & control system, infotainment system, safety system, steering system, suspension system, braking system, powertrain system, transmission system, fuel system, exhaust & after-treatment system, wheels & tires system, fluids & consumables, accessories & miscellaneous system.

During the material sorting of vehicle BoM, certain components lacked complete material composition data or were absent for specific variants. To ensure consistency and completeness of the analysis, a structured mapping and assumption-based approach was adopted. For missing material details of components, mapping was done using functionally identical or symmetric components within the same vehicle. This ensured that material inventories remained internally consistent. In cases where component material composition was entirely absent from a vehicle's BoM, equivalent components were assumed using reference vehicles with similar kerb weights or from the same component manufacturer.

To address missing fuel variants, CNG systems were selectively added or removed using closely comparable vehicles as references. Where petrol variants were unavailable, CNG systems were removed from existing CNG vehicle BoMs to obtain the corresponding petrol configuration. Conversely, in cases where CNG variants were absent, complete CNG systems were retrofitted using reference vehicles of similar kerb weight and segment. Factory-fitted CNG variants are typically developed from petrol counterparts through the integration of modular and well-defined CNG sub-systems. As these sub-systems are largely additive in nature and do not fundamentally alter the base vehicle architecture, this approach ensured consistent representation of fuel-specific components while preserving overall vehicle mass balance and system integrity. The brief of mapping of components and systems are provided in Annexure 2.

The material composition of most components was explicitly reported along with measured weights. However, for a subset of parts, the material composition was grouped under the category "other several components," where material types were specified but individual material weights were not provided. To address this, the BoM was cleaned and systematically reorganized for each vehicle into two broad categories- mono-materials and composite materials. This classification separates components with explicitly stated material weights from those comprising multiple materials reported without explicit weight allocation. The composite materials were further disaggregated by allocating 60% of the total composite mass to the

primary material and 40% to the secondary material, unless specified otherwise. This allocation approach was adopted based on consultations with the data providers and applied consistently across the dataset.

Following the consolidation and sorting of the BoM, a total of 93 material and system categories were considered in the assessment of emissions associated with the material composition of passenger four-wheeler vehicles. Emission factors corresponding to each material, or to an appropriate proxy material where direct data were unavailable, were assigned accordingly. Most of these emission factors were sourced from the Ecoinvent database, while the remaining values were derived from peer-reviewed literature. Detailed source information for each emission factor is provided in Table 2 below.

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
1	ABS/ ABS-PC	Exact	GLO	4.652505835	Ecoinvent	market for acrylonitrile-butadiene-styrene copolymer - Global - acrylonitrile-butadiene-styrene copolymer | ecoQuery	
2	AC / ADH / AlSi11Cu2 / AlSi9Cu3 / AM50A / AM60B	Exact	GLO	6.348500445	Ecoinvent	market for aluminium, cast alloy - Global - aluminium, cast alloy | ecoQuery	The grouped non-ferrous casting alloys primarily consist of aluminium–silicon casting grades. Aluminium cast alloy was selected as a representative material proxy. The presence of minor magnesium casting alloys may result in underestimation
3	AC Refrigerant	Exact	RoW	20.2870653	Ecoinvent	refrigerant R134a production - Rest-of-World - tetrafluoroethane, R134a | ecoQuery	
4	AdBlue	Proxy	RoW	0.561619119	Ecoinvent	(market for urea - Rest-of-World - urea | ecoQuery), (https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/14635/impact_assessment)	32.5% urea + 67.5% de-ionized H_2O
5	ADC /ADC12 / ALDC / ALDC12	Proxy	RoW	0.804	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/4517/impact_assessment	
6	AEM/ ACM	Proxy	GLO	3.168238952	Ecoinvent	market for synthetic rubber - Global - synthetic rubber | ecoQuery	Synthetic Rubber

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
7	Air Tires	Exact	RoW	0.076760705	Ecoinvent	compressed air production, 600 kPa gauge, >30kW, best generation - Rest-of-World - compressed air, 600 kPa gauge | ecoQuery	
8	Al (Aluminium)	Exact	GLO	18.64966926	Ecoinvent	aluminium ingot, primary, to aluminium, cast alloy market - Global - aluminium, cast alloy | ecoQuery	
9	ALLOY	Proxy	GLO	6.348500445	Ecoinvent	market for aluminium, cast alloy - Global - aluminium, cast alloy | ecoQuery	The grouped non-ferrous casting alloys primarily consist of aluminium–silicon casting grades. Aluminium cast alloy was selected as a representative material proxy. The presence of minor magnesium casting alloys may result in underestimation
10	ASA / ASA-PC	Proxy	GLO	4.329078853	Ecoinvent	market for styrene-acrylonitrile copolymer - Global - styrene-acrylonitrile copolymer | ecoQuery	
11	Bituminous	Proxy	GLO	0.872	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/424/impact_assessment	

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
12	BMC	Proxy	GLO	3.91821696	Ecoinvent	market for glass fibre reinforced plastic, polyester resin, hand lay-up - Global - glass fibre reinforced plastic, polyester resin, hand lay-up | ecoQuery	Glass Fiber Reinforced Polymer taken as proxy
13	BR	Exact	GLO	4.08203721	Ecoinvent	market for polybutadiene - Global - polybutadiene | ecoQuery	
14	Brake Fluid	Proxy	GLO	1.119075651	Ecoinvent	market for solvent, organic - Global - solvent, organic | ecoQuery	
15	Brass	Exact	RoW	5.817459217	Ecoinvent	market for brass - Rest-of-World - brass | ecoQuery	
16	Bronze	Exact	GLO	7.122581312	Ecoinvent	market for bronze - Global - bronze | ecoQuery	
17	Cable System/ HV Cable Bracket System	Proxy	GLO	6.046397753	Ecoinvent	market for cable, unspecified - Global - cable, unspecified | ecoQuery	
18	Cardboard	Exact	RoW	1.318592083	Ecoinvent	market for corrugated board box - Rest-of-World - corrugated board box | ecoQuery	
19	Carpet	Proxy	RoW, GLO	4.54244366	Ecoinvent	market for polyester resin, unsaturated - Rest-of-World - polyester resin, unsaturated | ecoQuery, market for polyethylene terephthalate, granulate, amorphous - Global - polyethylene terephthalate, granulate, amorphous | ecoQuery	Polyester (60%), PE (40%)

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
20	Carpets + Sound Dampening/ Sound Dampening	Proxy	RoW	5.1182	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/8759/documentation; polyethylene terephthalate, granulate, amorphous, recycled to generic market for PET, granulate, amorphous - Rest-of-World - polyethylene terephthalate, granulate, amorphous | ecoQuery	
21	Cellulose	Exact	RoW	0.334735037	Ecoinvent	market for cellulose fibre - Rest-of-World - cellulose fibre | ecoQuery	
22	CIIR/ CSM	Proxy	RoW	2.84	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/8994/impact_assessment	
23	Co (Cobalt)	Exact	GLO	49.31651684	Ecoinvent	market for cobalt - Global - cobalt | ecoQuery	
24	Coolant	Exact	RoW	1.376020035	Ecoinvent	(market for ethylene glycol - Rest-of-World - ethylene glycol | ecoQuery) ,(https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/14635/impact_assessment)	50% ethylene glycol+ 50% deionized H_2O
25	Cooling System	Proxy	GLO	5.786	Ecoinvent	Mixed Dataset	Combined- Aluminium cast alloy: 43.5% PP: 19.5% Steel: 10.9% Synthetic rubber: 7.6% Coolant: 8.7% Motor: 5.4% Electronics: 4.3%

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
26	CR/ IIR	Exact	GLO	6.1429	Ecoinvent	market for polychloroprene - Global - polychloroprene | ecoQuery	
27	Cu (Copper)	Exact	GLO	6.749650438	Ecoinvent	market for copper, cathode - Global - copper, cathode | ecoQuery	
28	ECO	Exact	RoW	3.9	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/5469/documentation	
29	Electric Power Control Unit/ Electronic Unit Control/ Power Electronic Combined Module System/ Junction Box/ Power Inverter Module	Proxy	GLO	41.80845281	Ecoinvent	market for inverter, for electric passenger car - Global - inverter, for electric passenger car | ecoQuery	Power inverter and power electronic module proxy dataset used
30	Electronic Components	Exact	GLO	31.7	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/5610/impact_assessment	
31	Engine Oil	Proxy	RoW	1.719522912	Ecoinvent	market for lubricating oil - Rest-of-World - lubricating oil | ecoQuery	
32	EPDM	Proxy	GLO	3.168238952	Ecoinvent	market for synthetic rubber - Global - synthetic rubber | ecoQuery	Synthetic Rubber

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
33	EVA	Exact	RoW	3.384796371	Ecoinvent	market for ethylene vinyl acetate copolymer - Rest-of-World - ethylene vinyl acetate copolymer | ecoQuery	
34	EVOH	Proxy	RoW	3.384796371	Ecoinvent	market for ethylene vinyl acetate copolymer - Rest-of-World - ethylene vinyl acetate copolymer | ecoQuery	EVA-shared ethylene–vinyl acetate chemical lineage and comparable polymerization route
35	Fabrics	Proxy	RoW	3.620362282	Ecoinvent	market for polyester resin, unsaturated - Rest-of-World - polyester resin, unsaturated | ecoQuery, https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/16859/impact_assessment	Polyester (60%), Recycled PET (40%)
36	Fasteners	Proxy	GLO	2.037335228	Ecoinvent	market for steel, low-alloyed - Global - steel, low-alloyed | ecoQuery	Steel, low alloyed
37	Fe (Iron)	Exact	GLO	1.834688479	Ecoinvent	market for cast iron - Global - cast iron | ecoQuery	
38	Felt	Proxy	GLO	3.75240377	Ecoinvent	market for polyethylene terephthalate, granulate, amorphous - Global - polyethylene terephthalate, granulate, amorphous | ecoQuery	
39	FKM/ FPM/ EPM/ FVMQ	Proxy	GLO	3.49	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/18749/documentation	Silicone Product
40	Gearbox Oil	Proxy	RoW	1.719522912	Ecoinvent	market for lubricating oil - Rest-of-World - lubricating oil | ecoQuery	

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
41	Glass	Exact	RoW	1.0614	Ecoinvent	flat glass production, uncoated - Rest-of-World - flat glass, uncoated | ecoQuery	
42	Glass Fibre	Exact	GLO	2.495447172	Ecoinvent	market for glass fibre - Global - glass fibre | ecoQuery	
43	Glued Sound Insulation	Proxy	GLO, RoW	4.5100	Ecoinvent	Mixed dataset	Synthetic Rubber (67.7%), PET Felt (20.8%), Aluminium Foil (8.3%) & Bitumen adhesive (3.13%)
44	LCP-GF30	Proxy	RoW	9.376721275	Ecoinvent	market for nylon 6 - Rest-of-World - nylon 6 | ecoQuery	PA
45	Lead	Exact	GLO	1.531262237	Ecoinvent	market for lead - Global - lead | ecoQuery	
46	Lead-Acid Battery	Exact	GLO	2.902209112	Ecoinvent	market for battery, lead acid, rechargeable, stationary - Global - battery, lead acid, rechargeable, stationary | ecoQuery	
47	Leather	Exact	GLO	22	Secondary Literature[2]	https://link.springer.com/article/10.1007/s43621-025-00798-6	Emission factor per kg of finished bovine leather based on 56 global LCAs (IPCC GWP100; cradle-to-tannery gate; economic allocation).
48	LFP Battery	Exact	GLO	15.2106267	Ecoinvent	market for battery, Li-ion, LFP, rechargeable - Global - battery, Li-ion, LFP, rechargeable | ecoQuery	

[2] (Brugnoli et al., 2025)

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
49	Magnet	Exact	GLO	31.44107818	Ecoinvent	market for permanent magnet, for electric motor - Global - permanent magnet, for electric motor | ecoQuery	
50	Magnetite	Exact	GLO	1.996454733	Ecoinvent	market for magnetite - Global - magnetite | ecoQuery	
51	Mg (Magnesium)	Exact	GLO	24.82953565	Ecoinvent	market for magnesium - Global - magnesium | ecoQuery	
52	Motors	Exact	GLO	8.853418036	Ecoinvent	market for electric motor, electric passenger car - Global - electric motor, electric passenger car | ecoQuery	
53	Natural Fibres	Proxy	GLO	1.952739396	Ecoinvent	market for fibre, jute - Global - fibre, jute | ecoQuery	Jute
54	NBR/HNBR	Proxy	GLO	3.168238952	Ecoinvent	market for synthetic rubber - Global - synthetic rubber | ecoQuery	Synthetic Rubber
55	NMC Battery	Exact	GLO	15.83793507	Ecoinvent	market for battery cell, Li-ion, NMC811 - Global - battery cell, Li-ion, NMC811 | ecoQuery	
56	NR	Exact	GLO	2.5220	Ecoinvent	market for seal, natural rubber based - Global - seal, natural rubber based | ecoQuery	
57	Other Elastomers	Proxy	GLO	3.168238952	Ecoinvent	market for synthetic rubber - Global - synthetic rubber | ecoQuery	Synthetic Rubber
58	Other Plastics	Proxy		3.049225634	Ecoinvent	market for polypropylene, granulate - Global - polypropylene, granulate | ecoQuery	PP

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
59	PA / PA6 / PA66/ PPA	Exact	RoW	9.376721275	Ecoinvent	market for nylon 6 - Rest-of-World - nylon 6 | ecoQuery	Nylon
60	PA-GF	Exact	GLO	8.913010883	Ecoinvent	market for glass fibre reinforced plastic, polyamide, injection moulded - Global - glass fibre reinforced plastic, polyamide, injection moulded | ecoQuery	
61	PANOX	Proxy	US	8.47	USLCI	USLCI	PAN
62	Paper	Exact	GLO	2.532445271	Ecoinvent	market for printed paper - Global - printed paper | ecoQuery	
63	PBT	Proxy	GLO	3.75240377	Ecoinvent	market for polyethylene terephthalate, granulate, amorphous - Global - polyethylene terephthalate, granulate, amorphous | ecoQuery	PET
64	PC	Exact	RoW	6.157874369	Ecoinvent	market for polycarbonate - Rest-of-World - polycarbonate | ecoQuery	
65	PE / HDPE / LDPE/ HCPP	Exact	GLO	2.847960957	Ecoinvent	polyethylene production, high density, granulate - Rest-of-World - polyethylene, high density, granulate | ecoQuery	
66	PET	Exact	RoW	3.75240377	Ecoinvent	market for polyethylene terephthalate, granulate, amorphous - Global - polyethylene terephthalate, granulate, amorphous | ecoQuery	

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
67	Plug In System	Proxy	GLO	300	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/1415/impact_assessment	Printed wiring board production, surface mounted
68	PMMA	Exact	RoW	7.7039346	Ecoinvent	market for polymethyl methacrylate - Rest-of-World - polymethyl methacrylate | ecoQuery	
69	Polyester	Exact	RoW	5.069136919	Ecoinvent	market for polyester resin, unsaturated - Rest-of-World - polyester resin, unsaturated | ecoQuery	
70	POM	Proxy	RoW	9.376721275	Ecoinvent	market for nylon 6 - Rest-of-World - nylon 6 | ecoQuery	Nylon
71	PP	Exact	GLO	3.049225634	Ecoinvent	market for polypropylene, granulate - Global - polypropylene, granulate | ecoQuery	
72	PPE	Proxy	GLO	6.15	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/27784/documentation	Polycarbonate
73	PPS	Exact	GLO	7.285167221	Ecoinvent	market for polyphenylene sulfide - Global - polyphenylene sulfide | ecoQuery	
74	PUR	Exact	GLO	6.441725137	Ecoinvent	polyurethane production, flexible foam, TDI-based, high density - Rest-of-World - polyurethane, flexible foam | ecoQuery	

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
75	PVC/ PVB	Exact	RoW	2.616004445	Ecoinvent	polyvinyl chloride production, suspension polymerisation - Rest-of-World - polyvinyl chloride, suspension polymerised | ecoQuery	
76	Recycled Fibres	Exact	RoW	1.4472	Ecoinvent	market for polyethylene terephthalate, granulate, amorphous, recycled - Rest-of-World - polyethylene terephthalate, granulate, amorphous, recycled | ecoQuery	
77	S45C/ S355MC/ SPFC	Proxy	GLO	2.037335228	Ecoinvent	market for steel, low-alloyed - Global - steel, low-alloyed | ecoQuery	Steel, low alloyed
78	SBR	Proxy	GLO	3.168238952	Ecoinvent	market for synthetic rubber - Global - synthetic rubber | ecoQuery	Synthetic Rubber
79	Silicone / VMQ / LSR / SF	Exact/ Proxy	RoW	3.527280884	Ecoinvent	market for silicone product - Rest-of-World - silicone product | ecoQuery	Silicone
80	SPCC/ SPFH	Proxy	GLO	1.864320827	Ecoinvent	market for steel, unalloyed - Global - steel, unalloyed | ecoQuery	Steel, un-alloyed
81	Steel	Exact	IN	1.9225	Ecoinvent	steel production, converter, low-alloyed - India - steel, low-alloyed | ecoQuery	
82	SUS / Stainless Steel	Exact	GLO	5.215643585	Ecoinvent	market for steel, chromium steel 18/8, hot rolled - Global - steel, chromium steel 18/8, hot rolled | ecoQuery	

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
83	Synthetic Fibres	Exact	GLO	6.2044	Ecoinvent	market for textile, nonwoven polyester - Global - textile, nonwoven polyester | ecoQuery	
84	Tires			2.66	Ecoinvent/ British Tire Manufacturers Association	Modelled on Simapro using Ecoinvent Dataset	Elastomers (42%), Carbon Black and Silica (28%), Steel (12%), Oils (6%), Textile (5%), Zinc Oxide (1%), Sulphur (1%), Other Ingredients (5%)
85	TPA	Proxy	RoW	9.376721275	Ecoinvent	market for nylon 6 - Rest-of-World - nylon 6 | ecoQuery	PA
86	TPC / TPE / TPEE / TPO / TPV / TPS / TPR / TPU	Proxy	GLO	3.168238952	Ecoinvent	market for synthetic rubber - Global - synthetic rubber | ecoQuery	Synthetic Rubber
87	Transfer Case Oil	Proxy	RoW	1.719522912	Ecoinvent	market for lubricating oil - Rest-of-World - lubricating oil | ecoQuery	Lubricating Oil
88	Unidentified Material	Proxy		2.3993	An average of all the materials considered for analysis has been taken as emission factor as there was no material code provided for these items (The share unidentified material is around 1-7% of the total material weight for each vehicle.		
89	Window Washing Fluid	Exact	GLO	3.901770475	Ecoinvent	market for soap - Global - soap | ecoQuery	
90	Wire Harness	Proxy	GLO	5.50955664	Ecoinvent	refer copper and PVC source	copper 70% + PVC 30%

Table 2: List of materials considered in LCA of 4-wheeler passenger cars and their emission factors along with sources

S. No	Materials	Match type	Region	IPCC 2021 GWP 100 (In Kg CO2-eq. per Kg)	Database		Remarks
91	Wood	Exact	IN	0.134446703	Ecoinvent	market for waste wood, untreated - India - waste wood, untreated | ecoQuery	
92	ZAMAK / ZDC2 / ZnAl4Cu1	Proxy	GLO	2.990741465	Ecoinvent	market for zinc - Global - zinc | ecoQuery	Zinc Alloy
93	Zn (Zinc)	Exact	GLO	2.990741465	Ecoinvent	market for zinc - Global - zinc | ecoQuery	

**GLO (Global): Represents an average emission profile aggregated across global production and supply chains, without distinguishing a specific geographic region.*

**RoW (Rest of World): Represents an average emission profile for all regions excluding those explicitly modelled in ecoinvent, used when country- or region-specific data are unavailable.*

**Please refer to the Abbreviation sheet provided in the beginning of the report to know the full forms of materials mentioned*

5.2 Use Phase Data

The use phase of passenger four-wheeler vehicles comprises two primary sources of emissions:

- Emissions associated with fuel or electricity consumption during vehicle operation
- Emissions arising from vehicle maintenance activities.

The emission factors applied for both the production of fuel or electricity (WTT) and the combustion or use phase (TTW) are presented in Table 3 below.

Table 3: Fuel/ energy emission factors

	Fuel/ Energy	Emission Factor	Unit		Source	Remarks
WTT Emission Factor	Petrol (E20)	0.781	KgCO2 eq. /L	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/20637	Standard fuel density specifications were used for petrol and diesel emission factor unit conversions. Ethanol WTT emission factors were sourced from literature for calculating E20 petrol WTT emission factors. CNG emission factors were calculated on a mass basis using density of CNG, 5% CBG blending with CNG (no emissions for CBG Fraction)
	Diesel	0.993	KgCO2 eq./L	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/20687	
	CNG	0.785	KgCO2 eq./ Kg	Ecoinvent	https://ecoquery.ecoinvent.org/3.11/cutoff/dataset/28627	
TTW Emission Factor	Petrol (E20)	2.127	KgCO2 eq. /L	Smart Feight Centre	India_Default_GHG_Emission_Values_V1_SFC_INDIA_latest.pdf	Ethanol TTW emission factors were sourced from literature for calculating E20 petrol TTW emission factors. 5% CBG blending with CNG (no emissions for CBG Fraction)
	Diesel	2.675	KgCO2 eq. /L			
	CNG	2.712	KgCO2 eq. / Kg			

Table 3: Fuel/ energy emission factors

	Fuel/ Energy	Emission Factor	Unit		Source	Remarks
Grid Emission Factor	Electricity (Adjusted)	0.91	$KgCO_2$ eq./ kWh	CEA; Shet and Moholkar (2025)	https://cea.nic.in/wp-content/uploads/baseline/2025/12/User_Guide_V_21.0.pdf https://cea.nic.in/wp-content/uploads/general/2025/Updated_GR_2025_merged_new.pdf	Grid EF: 0.71 kg CO_2/ kWh (CEA); 17.63% T&D losses (CEA); CH_4 and N_2O emission factors adopted from Shet and Moholkar (2025) and proportionally scaled to match the grid CO_2 emission factor; CO_2-eq. calculated using IPCC GWP values (CH_4 = 29.8; N_2O = 273)

The WTT emission factors for petrol and diesel were sourced from the Ecoinvent database. Average density values of 747.5 kg/m³ for petrol and 827.5 kg/m³ for diesel, as specified in IS 2796:2017, were applied to calculate the final mass-based emission factors. A 20% ethanol blend (E20) was considered to reflect recent developments in the Indian automotive fuel market. The WTT emission factor for ethanol was taken as 28 g CO_2 eq./MJ (Agarwal et al., 2025). The ethanol life cycle followed a cradle-to-gate boundary and included sugarcane cultivation, transport to the mill, ethanol production from molasses, and distribution to bulk terminals by road tankers. Emissions from agricultural activities and industrial processing were identified as the dominant contributors to the overall carbon footprint. Using a lower heating value (LHV) of 21.1 MJ/L, the ethanol WTT emission factor was calculated as 0.59 kg CO_2 eq./L. For the TTW stage, an emission factor of 1.708 kg CO_2 eq./L was applied, based on SFC India greenhouse gas emission factors. With the adoption of higher flex-fuel blends, whose effective tailpipe CO_2 emissions are comparatively lower due to biogenic carbon neutrality (subject to feedstock pathways), the overall use-phase fuel emission factors for ICEVs are expected to decline significantly.

For CNG, emission factors were derived from the Ecoinvent market dataset for "natural gas, high pressure" specific to the Indian context. A standard density of 0.735 kg/m³ was used to calculate emissions on a mass basis. The final compression step required to reach vehicle storage pressure was not included in this dataset. In addition, a 5% blending of Compressed Biogas (CBG) with CNG was assumed. Emissions from the CBG fraction were treated as zero, as CBG is produced from biogenic waste streams and its combustion-related emissions are considered climate-neutral. As a result, only the fossil CNG fraction contributes to both WTT and TTW greenhouse gas emissions.

India's grid electricity emission factor was derived using plant-level operational data for all grid-connected power stations following the UNFCCC/CDM methodology reported by the Central Electricity Authority (CEA, 2025). Annual CO_2 emissions were estimated from fuel consumption, calorific values, and fuel-specific emission factors and normalised by total net electricity supplied to the grid. This resulted in a weighted average grid emission factor of 0.71 kg CO_2/kWh. To estimate CO_2-equivalent emissions, CH_4 and N_2O emission factors from Shet and Moholkar (2025) were proportionally adjusted to match this value, yielding 1.15 g/kWh for CH_4 and 16.72 mg/kWh for N_2O. Using IPCC GWP values of 29.8 for CH_4 and 273 for N_2O, the grid emission factor was calculated as 0.748 kg CO_2-eq/kWh. After accounting for 17.63% transmission losses, the final emission factor was 0.91 kg CO_2-eq/kWh.

5.3 Other Auxiliary Data and Assumptions

1. OEM Manufacturing and Logistics Emissions

OEM manufacturing emissions refer to the direct emissions generated at vehicle manufacturing and assembly facilities, excluding emissions from upstream material and components production. These emissions include emissions from on-site fuel combustion, thermal processes and the use of purchased electricity. Compared to emissions from raw material and component supply chains, OEM manufacturing emissions are relatively small.

Direct OEM operational emissions amount to 5.09 Mt CO_2, which is approximately 20% of raw material-related emissions in the Indian vehicle manufacturing sector (Arora et al., 2025). Since upstream material-level emissions as well as system-level emissions such as batteries, are modelled in our study, component-level manufacturing emissions are not included separately.

For Logistics emissions, an industry average value has been taken using the sustainability report of various brands that were available.

2. Maintenance Emissions

Maintenance emissions are considered as part of the use-phase emissions and account for emissions associated with the replacement of consumables and components that undergo wear and tear during a vehicle's lifetime. Maintenance assumptions are based on manufacturer user manuals and standard service schedules.

Tire replacement is assumed to occur every 50,000 km or five years, whichever comes first. Over a vehicle lifetime of 150,000 km or 15 years, this results in three complete replacements of all four tires. The spare tire, if present, is excluded from maintenance emissions, as it is already included in raw material emissions of the vehicle. For internal combustion engine vehicles, engine oil replacement is assumed every 10,000 km or one year (15 changes). Coolant replacement is assumed to occur six times, while brake fluid replacement is assumed seven times over the lifetime, in line with typical manufacturer service recommendations. For battery BEVs, the current study with vehicle lifetime of 1,50,000 km, assumes no battery replacements; however, under real-world usage conditions, accounting for such a replacement would increase BEV emissions due to the additional material and manufacturing impacts associated with lithium-ion battery production.

3. Adjustment Factors for Real-World Vehicle Operation

Fuel and electricity consumption values often underestimate actual energy use under real-world driving conditions. To better represent in-use vehicle performance, adjustment factors are applied to account for differences between test-cycle values and real-world operation.

For internal combustion engine vehicles (gasoline, diesel, and CNG), real-world fuel consumption is assumed to be 34% higher than MIDC values, consistent with findings from the literature and observed discrepancies between laboratory and on-road performance in other regions, such as NEDC-based assessments (Bieker, 2021). Accordingly, an adjustment factor of 1.34 is applied to the total lifetime fuel consumption of ICE vehicles.

For BEVs, real-world electricity consumption is adjusted using two considerations. The real-world driving range is assumed to be approximately 30% lower than MIDC-certified values and charging losses of 15% are included to account for inefficiencies during electricity transfer from the grid to the vehicle battery (Bieker, 2021). Combining these effects, a net adjustment factor of 1.64 is applied to BEV electricity consumption over the lifetime.

5.4 Data Quality Declaration

Material composition data for the vehicle manufacturing phase were obtained from A2Mac1, a recognized teardown-based database. Overall data quality is assessed as good, although detailed material grade information was not available for all components. Approximately 20–30% of the material mass was reported as aggregated "*composite materials*". These entries were disaggregated using the corresponding material codes provided, applying a 60:40 mass allocation between the first and second listed materials in accordance with data provider recommendations.

Material production emission factors were primarily sourced from the ecoinvent database, using global or rest-of-world datasets where India-specific data were unavailable. India-specific datasets were used wherever available, though their coverage remains limited. Fuel and energy emission factors were derived from official government publications and secondary literature considered reliable.

Maintenance emissions were modelled using assumed consumable replacement schedules based on manufacturer brochure information, without explicit modelling of real-world variability. OEM manufacturing and logistics emissions were estimated using secondary literature and industry-average values from selected automotive sustainability reports due to the absence of primary data.

Overall, the data used in this study are considered fit for purpose for comparative life cycle assessment and rating development. The primary limitations are transparently acknowledged.

Chapter 6: Environmental Rating Mechanism for 4-Wheeler Passenger Cars

6.1 Scales, Ratings, and Standardization in Comparative Environmental Assessment

Rating systems are widely employed across disciplines to translate complex quantitative information into interpretable comparative indicators. In environmental assessment, particularly in the transport sector, such systems play a crucial role in benchmarking products with heterogeneous technologies, performance characteristics, and life cycle profiles. The intent of green rating in any product category is to better inform the decisions of environmentally conscious consumers along with helping the government to form environmentally supportive policy environment for such green products to thrive. For motor vehicles, LCA based methodology of rating is important in order to move beyond the currently popular tailpipe- based approach.

Green rating information can influence consumer choices and might influence technological development towards green future. Surveys suggest that consumers would buy green product if quality and affordability were maintained (EPA, 1993a). However, for green ratings to become credible aspect of marketing, a holistic approach is required. This necessitates an explicit attention to scale theory, standardization methods, and the statistical meaning of comparative scores (DeCicco & Thomas, 1999).

Brown and Daniel (1990) emphasize that ratings are not intrinsic properties of objects but relational measures whose meaning arises only through comparison within a defined reference set. They demonstrate that unscaled or improperly scaled values confound true differences in the attribute being measured with artefacts arising from scale origin, dispersion, or contextual effects. Although their work originates in psychometric and perceptual assessment, the underlying principles of scaling apply equally to any domain in which entities are evaluated relative to peers, including environmental performance assessment.

Performance rating systems may be broadly categorized as criterion-referenced, content-referenced, or norm-referenced. Criterion-referenced systems evaluate performance against fixed thresholds, while content-referenced systems assess attainment across predefined objectives. Norm-referenced systems, in contrast, interpret performance relative to a population distribution, positioning each entity with respect to the mean and variability of a reference group (Whati et al., 2009). Norm-referenced approaches are particularly appropriate when the objective is comparative benchmarking and longitudinal monitoring rather than compliance with static standards.

In dynamic systems such as the passenger vehicle market- where technological progress, regulatory norms, and energy systems evolve continuously- fixed thresholds risk rapid obsolescence. Norm-referenced interpretation allows ratings to remain sensitive to market-wide improvement while preserving comparability across vehicle categories and technologies. As Whati et al. (2009) demonstrate in the context of performance assessment, such systems enable intuitive categorization of outcomes (e.g., below average, average, above average) while retaining a statistically grounded basis for interpretation.

6.2 Z-Score Standardization: Conceptual Basis and Function

Literature consistently cautions against the uncritical use of raw means, medians, or ranks for comparative evaluation. Median-based rankings provide only ordinal information and do not capture the magnitude of differences between entities. Mean values, while commonly used, assume uniform scale intervals and fail to account for differences in dispersion across datasets. Brown and Daniel (1990) show that such approaches can obscure real differences or exaggerate apparent ones when distributions vary in spread or central tendency.

Research on rating scale equivalence further highlights the limitations of direct numerical comparison across heterogeneous scales or distributions. Colman *et al.* (1997) demonstrate that naïve proportional transformations or unstandardised comparisons embed implicit assumptions about psychological or statistical equivalence that are rarely justified empirically. These concerns are directly relevant to environmental datasets, where emission values may differ substantially across vehicle technologies and where distributional skewness is common.

Z-score standardisation is a statistical scaling method that transforms raw values into unitless scores representing their deviation from the mean of a reference distribution in standard deviation units. By construction, z-scores remove both origin effects (differences in means) and interval effects (differences in dispersion), thereby enabling interval-scale comparability across datasets (Brown & Daniel, 1990). Importantly, z-scores preserve the relative structure of the original distribution while allowing meaningful interpretation of distance from the average.

The conceptual strength of z-scores lies in their relational interpretation. A z-score does not claim absolute superiority or adequacy; rather, it indicates relative standing within a defined population. This aligns with the foundational principle articulated by Brown and Daniel (1990) that scale values derive meaning only through comparison. In applied contexts, z-scores provide a transparent mechanism for benchmarking heterogeneous entities without imposing arbitrary thresholds.

6.3 Cross-Disciplinary Precedent for Z-Score–Based Rating

The use of z-scores as comparative indicators is well established across multiple fields. In educational and public health research, z-scores are routinely employed to develop norm-referenced performance ratings that translate raw scores into interpretable categories while maintaining statistical validity (Whati *et al.*, 2009). These studies demonstrate how z-score distributions can be mapped onto simplified rating scales without loss of analytical rigor.

In financial and risk assessment literature, z-scores are widely used to express relative stability or distance to failure, precisely because they integrate both central tendency and variability into a single comparative metric (Li *et al.*, 2017). Although the substantive interpretation differs, the methodological rationale is analogous: z-scores enable comparison across heterogeneous entities using a common statistical reference frame.

Furthermore, research on rating scale comparability confirms that standardisation via z-scores is among the most defensible approaches for aligning data derived from different scales or distributions, if interpretation remains norm-referenced rather than absolute (Colman *et al.*, 1997).

In life cycle–based environmental assessment of passenger vehicles, emission intensities and lifetime impacts vary widely across fuel types, vehicle sizes, and usage assumptions. Absolute emission values, while scientifically robust, are difficult to interpret for comparative decision-making. A z-score–based framework embeds each vehicle's environmental performance within its relevant market distribution, enabling fair comparison across peer groups while remaining neutral to technology type.

Consistent with scaling theory, such a framework does not assert fixed environmental acceptability but communicates relative environmental standing. As the vehicle market evolves and cleaner technologies become prevalent, recalculation of distribution parameters allows the rating system to adapt dynamically, preserving its relevance without altering its underlying statistical logic.

Among the scaling methods discussed in the literature, z-score standardisation represents a balance between methodological rigor and practical applicability. It offers greater robustness than simple averaging or ranking, while avoiding the complexity and data requirements of more elaborate regression-based scaling techniques that are primarily designed for subjective observer data (Brown & Daniel, 1990). When the objective is comparative environmental benchmarking using objective life-cycle indicators, z-scores provide a transparent, statistically grounded, and widely accepted basis for rating development.

6.4 Proposed Vehicle Rating Mechanism

The following sub-sections details out the proposed z-score based vehicle rating framework on a 5-star scale: -

6.4.1 Assessment Metric

The system focuses on Global Warming Potential (GWP) as the primary impact category, expressed in kilograms of CO_2-equivalent (kg CO_2-eq) emissions. GWP represents the aggregated climate change impact of all greenhouse gases emitted throughout the vehicle's life cycle, considering the emissions embedded in material extraction, manufacturing, use, and end-of-life stages. This indicator measure can be expressed per kilometre driven and in absolute lifetime terms. In our assessment, we are considering Kg CO2-eq. emission per vehicle over its lifetime.

6.4.2 Proposed Methodology: Z-Score–Based Rating System

The proposed rating mechanism is founded on a z-score- based statistical approach, which allows vehicles to be evaluated relative to the overall market average. The z-score converts raw LCA results into unitless, standardized values, thereby becoming well-suited for environmental benchmarking as it:

- **Standardizes data** across diverse units and scales,
- **Reflects real-time market performance**, and
- **Automatically adjusts benchmarks** as cleaner technologies emerge.

Unlike static threshold-based systems that quickly become outdated, the z-score approach ensures that the baseline evolves with market progress, keeping the rating system dynamic, equitable, and technologically neutral.

Each vehicle's LCA-derived emission value is compared against the mean and standard deviation of emissions across all vehicles in the total population.

6.4.3 Understanding the Z-Score

The z-score (standard score) represents how far and in what direction a particular data point lies from the mean of the dataset, expressed in standard deviations (σ).

It is calculated as:

$$z = \frac{x_i - \mu}{\sigma}$$

where:

- $\mathbf{x_i}$ = vehicle's LCA result for a specific indicator. In our analysis, this is the lifetime GHG emission of the vehicle measured in Kg. CO2-eq.
- **μ** = mean value of that indicator for all vehicles in the population, i.e., mean GHG emission of the 4-wheeler passenger vehicles in the Indian Automotive Market
- **σ** = standard deviation of the indicator, i.e., standard deviation of GHG emission of the 4-wheeler passenger vehicles in the Indian Automotive Market

Interpretation:

- ***Negative z-score (z < 0):*** *Indicates lower-than-average emissions; better environmental performance*
- ***Positive z-score (z > 0):*** *Indicates higher-than-average emissions; poorer environmental performance*

This statistical normalization allows for fair comparison across models and technologies and serves as the foundation for assigning star ratings.

6.4.4 Rating Scale for 4-Wheeler Passenger Cars

Vehicles are assigned star ratings based on the distribution of z-scores, using defined cut-offs in terms of standard deviation from the mean on a scale of 5. The range and ratings are given in the table 4 below-

Table 4: Star rating scale for 4-wheeler passenger vehicles

Star Rating	Performance Description	Z-Score Range
★★★★★	Top performers – significantly better than mean	z ≤ -1 SD
★★★★	Above average – moderately better than mean	-1 < z ≤ -0.5 SD
★★★	Average performers – close to mean	-0.5 < z ≤ +0.5 SD
★★	Below average – moderately worse than mean	+0.5 < z ≤ +1 SD
★	Poor performers – significantly worse than mean	z > +1 SD

6.5 Dynamic Baseline and Continuous Updating

The strength of the z-score methodology lies in its dynamic adaptability:

- The mean (μ) and standard deviation (σ) are recalculated automatically whenever new vehicles or updated LCA datasets are added.
- This ensures that ratings remain current and reflective of technological advancements, thereby encouraging continuous innovation and improvement in vehicle design.
- For instance, a vehicle rated ★★★★ today may shift to ★★★ in the next assessment cycle if cleaner and more efficient vehicles enter the market- thereby maintaining competitive pressure toward sustainability.

Chapter 7: Demonstration of the Environmental Rating Mechanism

This chapter demonstrates the application of the proposed life cycle–based environmental rating framework to a representative set of four-wheeler passenger cars available in the Indian market. The objective of this demonstration is to illustrate how life cycle GHG emission results can be systematically translated into a transparent, statistically robust, and consumer-facing rating mechanism. The ratings presented in this exercise are illustrative in nature, as definitive vehicle ratings can only be established after assessing the entire set of vehicles available in the market.

For the purpose of demonstration, a sample of the 4-wheeler passenger cars in the Indian automotive market has been taken keeping in mind two factor-

- 4-wheeler passenger cars that are available in the Indian Automotive Market as of March 2025 have been considered.
- Vehicles for which the material composition data quality was satisfactory has been taken with priority consideration to be able to conduct proper LCA.
- A representative sample of models covering ~85% of FY 24-25 sales have been used.

7.1 Overview of Dataset

The demonstration uses total life cycle GHG emissions (expressed in kg CO_2-eq per vehicle over its assumed lifetime, i.e., 1,50,000 kilometer) derived from the cradle-to-grave LCA described in earlier chapters. Table 5 presents the total life cycle emissions for each vehicle, disaggregated by major life cycle phases, including vehicle production, use phase (fuel or electricity consumption and maintenance), and end-of-life management. This phase-wise breakdown is provided to contextualize the emission profiles and to establish the credibility of the life cycle results feeding into the rating framework.

These analysis results are standardized and converted into relative performance ratings in the following sections, rather than in interpreting absolute emission magnitudes.

Table 5: Life cycle emission assessment of a sample of 59 4-wheeler passenger vehicles in India

Brand Name	Vehicle Name	Material Emissions (in kg CO_2 eq.)	Use Phase Emissions (in kg CO_2 eq. over lifetime)	OEM Manufacturing and Logistics Emissions (in kg CO_2 eq.)	Total Emissions (in kg CO_2 eq.)
BYD	eMax EV	15835.62	31488.08	3513.12	50836.82
Citroen	C3 Petrol	3856.99	29861.37	1117.40	34835.76
Honda	Elevate Petrol	5506.10	38604.54	1447.22	45557.86
Hyundai	Exter CNG	3993.81	26231.16	1144.76	31369.74
Hyundai	Exter Petrol	3887.00	30423.28	1123.40	35433.69
Hyundai	Verna Petrol	6118.54	28769.64	1569.71	36457.89
Hyundai	Creta Petrol	4805.74	32186.17	1307.15	38299.05
Hyundai	Creta EV	13267.89	23477.86	2999.58	39745.32
Hyundai	Grand i10 Petrol	3753.56	28542.75	1096.71	33393.02
Hyundai	i20 Petrol	4357.04	29558.75	1217.41	35133.20
Hyundai	Creta Diesel	5080.22	34281.03	1362.04	40723.30
Jeep	Meridian Diesel	8383.14	49977.87	2022.63	60383.64
Kia	Sonet Kappa Petrol	4462.71	32532.26	1238.54	38233.52
Kia	Carens Petrol	6308.98	35814.65	1607.80	43731.42
Kia	Seltos Petrol	6949.07	33107.50	1735.81	41792.38
Kia	Seltos Diesel	5223.79	37173.81	1390.76	43788.36
Mahindra	XUV 3XO Petrol	7398.11	29556.16	1825.62	38779.89
Mahindra	Scorpio-N Diesel	9395.05	48485.76	2225.01	60105.82
Mahindra	XUV400 EV	12190.70	20167.21	2784.14	35142.05
Mahindra	XUV700 Petrol	8573.89	37155.41	2060.78	47790.08
Mahindra	BE 6 EV	16931.19	27022.52	3732.24	47685.96
MG	Windsor EV	11002.42	26680.99	2546.48	40229.90
MG	Comet EV	5438.30	17413.63	1433.66	24285.60
MG	Astor Petrol	6659.64	39915.24	1677.93	48252.81
MG	ZS EV	13036.54	25377.04	2953.31	41366.89
MG	MG Gloster Diesel	11098.28	60181.53	2565.66	73845.47
MSIL	Celerio CNG	3458.40	20695.97	1037.68	25192.05
MSIL	Celerio Petrol	3128.11	23438.72	971.62	27538.46
MSIL	Grand Vitara Hybrid	6631.08	21315.05	1672.22	29618.35
MSIL	Fronx Petrol	4398.17	25864.64	1225.63	31488.45

Table 5: Life cycle emission assessment of a sample of 59 4-wheeler passenger vehicles in India

Brand Name	Vehicle Name	Material Emissions (in kg CO_2 eq.)	Use Phase Emissions (in kg CO_2 eq. over lifetime)	OEM Manufacturing and Logistics Emissions (in kg CO_2 eq.)	Total Emissions (in kg CO_2 eq.)
MSIL	WagonR CNG	3235.06	20945.45	993.01	25173.51
MSIL	Alto CNG	2283.95	21316.48	802.79	24403.23
MSIL	Swift Dzire CNG	4348.04	21158.38	1215.61	26722.03
MSIL	WagonR Petrol	2759.39	24306.80	897.88	27964.07
MSIL	Swift Dzire Petrol	4301.24	23929.99	1206.25	29437.48
MSIL	Baleno Petrol	3733.41	26497.32	1092.68	31323.40
MSIL	S-Presso Petrol	2827.11	23889.23	911.42	27627.76
MSIL	Baleno CNG	3895.51	23307.82	1125.10	28328.43
MSIL	Alto Petrol	2034.93	23745.88	752.99	26533.79
MSIL	Fronx CNG	4734.60	24983.52	1292.92	31011.05
MSIL	S-Presso CNG	3149.97	21757.90	975.99	25883.87
Nissan	Magnite Petrol	3753.05	29738.20	1096.61	34587.86
Nissan	Magnite CNG	3931.16	29653.31	1132.23	34716.71
Renault	Kwid Petrol	2689.31	25679.00	883.86	29252.17
Skoda	Slavia Petrol	5512.50	31598.80	1448.50	38559.80
Skoda	Kylaq Petrol	5030.55	31077.27	1352.11	37459.93
Skoda	Kushaq Petrol	5557.88	32744.46	1457.58	39759.91
Tata	Altroz CNG	5181.29	23751.29	1382.26	30314.84
Tata	Altroz Petrol	4834.54	30559.78	1312.91	36707.22
Tata	Punch Petrol	5103.49	29439.09	1366.70	35909.28
Tata	Punch CNG	5450.25	26387.48	1436.05	33273.77
Tata	Punch EV	10332.80	18524.40	2412.56	31269.76
Tata	Harrier Diesel	7482.34	44186.77	1842.47	53511.58
Tata	Nexon EV	11819.25	21432.04	2709.85	35961.13
Tata	Curvv EV	13610.01	20916.28	3068.00	37594.29
Tata	Tiago Petrol	3661.39	24817.50	1078.28	29557.17
Tata	Tiago CNG	3839.51	26833.98	1113.90	31787.38
Toyota	Innova Hycross Hybrid	8666.27	26865.55	2079.25	37611.07
Volkswagon	Taigun Petrol	4890.42	31141.35	1324.08	37355.85

7.2 Scenario 1: Pooled Market Rating

The core of the proposed framework is a pooled rating of all 4-wheeler passenger cars, wherein vehicles are assessed collectively against the overall market population mean, without segmentation by size, weight, or technology. This pooled approach is critical for reaping the full analytical benefit of LCA.

From an environmental perspective, climate impacts are absolute in nature: one ton of CO_2-equivalent emitted has the same effect on the atmosphere regardless of whether it is associated with a small entry-level vehicle or a large premium car. A pooled rating framework therefore deliberately moves away from implicit value judgements that prioritize vehicle class, luxury, or consumer positioning, and instead foregrounds total life-cycle environmental burden as the primary basis for comparison.

By aggregating all vehicles into a single reference population, the pooled rating transparently captures the emissions that are embedded in material extraction and vehicle manufacturing, which scale strongly with vehicle size, complexity, and material intensity along with the use phase emissions. This approach ensures that larger, heavier, and more resource-intensive vehicles are not structurally insulated from scrutiny, and that improvements in environmental performance are evaluated in relation to the entire market rather than within narrowly defined peer groups.

For this combined category, z-scores were calculated using a mean lifetime emission value and standard deviation as follows:

$$1)\quad \text{Mean} = \mu = \frac{\Sigma x_i}{n}$$

$$= \frac{\text{Sum of life cycle emissions of each vehicle}}{\textit{Number of Vehicles}}$$

$$= 36712.71 \text{ Kg CO2-eq.}$$

$$2)\quad \text{Standard Deviation} = \sigma = \sqrt{\frac{\Sigma(x_i-\mu)^2}{n}}$$

$$= \sqrt{\frac{\Sigma(\textit{Life cycle emission of each vehicle} - \textit{Mean Emission})^2}{\textit{Number of Vehicles}}}$$

$$= 9625.29 \text{ Kg CO2-eq.}$$

Each vehicle's total life cycle emission was standardized relative to this distribution, producing a dimensionless z-score that captures its deviation from the market average as given in Table 6. Vehicles with negative z-scores demonstrate better-than-average environmental performance, while those with positive z-scores perform worse than the average.

These standardized scores were subsequently mapped onto the proposed rating scale. This combined rating table demonstrates how the framework enables direct, absolute comparison across diverse powertrain technologies and vehicle types using a single, transparent metric. In this analysis we see that vehicles with less resource consumption, both in terms of material composition as well as use phase efficiency, perform generally better than other vehicles in the sample.

Table 6: Z-score and pooled market star rating

Brand Name	Vehicle Names	Fuel Type	Z-score	Star Ratings
BYD	eMax EV	EV	1.47	★
Citroen	C3 Petrol	ICEV-Petrol	-0.20	★★★
Honda	Elevate Petrol	ICEV-Petrol	0.92	★★
Hyundai	Exter CNG	ICEV-CNG	-0.56	★★★★
Hyundai	Exter Petrol	ICEV-Petrol	-0.13	★★★
Hyundai	Verna Petrol	ICEV-Petrol	-0.03	★★★
Hyundai	Creta Petrol	ICEV-Petrol	0.16	★★★
Hyundai	Creta EV	EV	0.32	★★★
Hyundai	Grand i10 Petrol	ICEV-Petrol	-0.34	★★★
Hyundai	i20 Petrol	ICEV-Petrol	-0.16	★★★
Hyundai	Creta Diesel	ICEV-Diesel	0.42	★★★
Jeep	Meridian Diesel	ICEV-Diesel	2.46	★
Kia	Sonet Kappa Petrol	ICEV-Petrol	0.16	★★★
Kia	Carens Petrol	ICEV-Petrol	0.73	★★
Kia	Seltos Petrol	ICEV-Petrol	0.53	★★
Kia	Seltos Diesel	ICEV-Diesel	0.74	★★
Mahindra	XUV 3XO Petrol	ICEV-Petrol	0.21	★★★
Mahindra	Scorpio-N Diesel	ICEV-Diesel	2.43	★
Mahindra	XUV400 EV	EV	-0.16	★★★
Mahindra	XUV700 Petrol	ICEV-Petrol	1.15	★
Mahindra	BE 6 EV	EV	1.14	★
MG	Windsor EV	EV	0.37	★★★
MG	Comet EV	EV	-1.29	★★★★★
MG	Astor Petrol	ICEV-Petrol	1.20	★
MG	ZS EV	EV	0.48	★★★
MG	MG Gloster Diesel	ICEV-Diesel	3.86	★

Table 6: Z-score and pooled market star rating

Brand Name	Vehicle Names	Fuel Type	Z-score	Star Ratings
MSIL	Celerio CNG	ICEV-CNG	-1.20	★★★★★
MSIL	Celerio Petrol	ICEV-Petrol	-0.95	★★★★
MSIL	Grand Vitara Hybrid	ICEV-Petrol Hybrid	-0.74	★★★★
MSIL	Fronx Petrol	ICEV-Petrol	-0.54	★★★★
MSIL	WagonR CNG	ICEV-CNG	-1.20	★★★★★
MSIL	Alto CNG	ICEV-CNG	-1.28	★★★★★
MSIL	Swift Dzire CNG	ICEV-CNG	-1.04	★★★★★
MSIL	WagonR Petrol	ICEV-Petrol	-0.91	★★★★
MSIL	Swift Dzire Petrol	ICEV-Petrol	-0.76	★★★★
MSIL	Baleno Petrol	ICEV-Petrol	-0.56	★★★★
MSIL	S-Presso Petrol	ICEV-Petrol	-0.94	★★★★
MSIL	Baleno CNG	ICEV-CNG	-0.87	★★★★
MSIL	Alto Petrol	ICEV-Petrol	-1.06	★★★★★
MSIL	Fronx CNG	ICEV-CNG	-0.59	★★★★
MSIL	S-Presso CNG	ICEV-CNG	-1.13	★★★★★
Nissan	Magnite Petrol	ICEV-Petrol	-0.22	★★★
Nissan	Magnite CNG	ICEV-CNG	-0.21	★★★
Renault	Kwid Petrol	ICEV-Petrol	-0.78	★★★★
Skoda	Slavia Petrol	ICEV-Petrol	0.19	★★★
Skoda	Kylaq Petrol	ICEV-Petrol	0.08	★★★
Skoda	Kushaq Petrol	ICEV-Petrol	0.32	★★★
Tata	Altroz CNG	ICEV-CNG	-0.66	★★★★
Tata	Altroz Petrol	ICEV-Petrol	0.00	★★★
Tata	Punch Petrol	ICEV-Petrol	-0.08	★★★
Tata	Punch CNG	ICEV-CNG	-0.36	★★★
Tata	Punch EV	EV	-1.04	★★★★★
Tata	Harrier Diesel	ICEV-Diesel	1.75	★
Tata	Nexon EV	EV	-0.08	★★★
Tata	Curvv EV	EV	0.09	★★★
Tata	Tiago Petrol	ICEV-Petrol	-0.74	★★★★
Tata	Tiago CNG	ICEV-CNG	-0.51	★★★★
Toyota	Innova Hycross Hybrid	ICEV-Petrol Hybrid	0.09	★★★
Volkswagon	Taigun Petrol	ICEV-Petrol	0.07	★★★

Figure 8 below is a graphical representation of the rating-

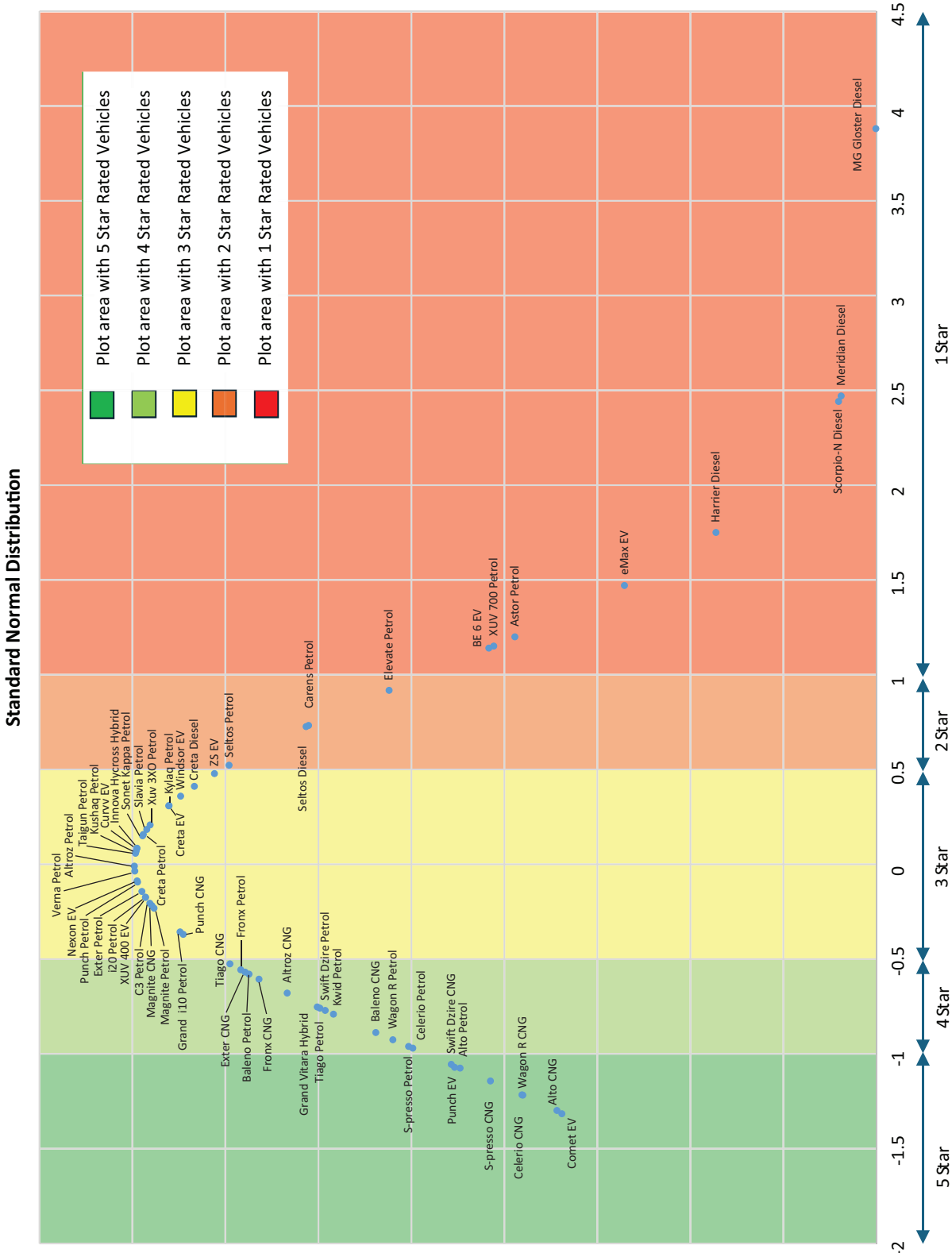

Figure 8: Z-score and pooled market star rating

7.3 Scenario 2: Length-Segmented Ratings for Consumer Interpretation

In addition to the pooled rating, the framework also incorporates length-based categorization, distinguishing between vehicles below and above four meters. This categorization is intended to serve a complementary, behavioural objective.

The sub-4-metre and above-4-metre distinction is deliberately aligned with the prevailing Goods and Service Tax classification structure in India for 4-wheeler passenger vehicles. This alignment enhances policy coherence and ensures that the rating framework remains intuitive and accessible to consumers. Length-based categorization enables consumers to compare vehicles within the segment they are realistically considering for purchase. It helps to Identify "best-in-segment" options that minimize environmental impact without forcing cross-segment trade-offs. From a behavioural standpoint, this approach recognizes that purchasing decisions are often constrained by price bands, tax structures, and perceived utility. Segment-level ratings therefore nudge towards cleaner choices within existing decision boundaries while still being anchored in life cycle impacts.

7.3.1 Segment 1: Sub-4 Meter

For vehicles below 4 meters, z-scores were calculated using mean and standard deviation as follows-

1) $$\text{Mean} = \mu = \frac{\sum x_i}{n}$$

$$= \frac{\text{Sum of life cycle emissions of each vehicle in sub-4 meter category}}{\textit{Number of Vehicles in Sub-4 Meter Category}}$$

$$= 31067.77 \text{ Kg CO2-eq.}$$

2) $$\text{Standard Deviation} = \sigma = \sqrt{\frac{\sum(x_i-\mu)^2}{n}}$$

$$= \sqrt{\frac{\sum(\textit{Life cycle emission of each vehicle in sub-4 meter category} - \textit{Mean Emission})^2}{\textit{Number of Vehicles} \text{ in sub-4 meter category}}}$$

$$= 4309.71 \text{ Kg CO2-eq.}$$

This group exhibits lower absolute emissions and narrower distribution, reflecting relatively homogeneous vehicle designs and power requirements. Within this category, even moderate deviations from the mean can result in meaningful differences in rating outcomes, allowing consumers to distinguish between comparatively efficient and inefficient models within the same size class. The star ratings are presented in the following table 7-

Table 7: Z-score and segmented star rating in sub-4-meter category

Brand Name	Vehicle Names	Fuel Type	Total Emissions	Z-score	Star Ratings
Citroen	C3 Petrol	ICEV-Petrol	34835.75956	0.87	★★
Hyundai	Exter CNG	ICEV-CNG	31369.74009	0.07	★★★
Hyundai	Exter Petrol	ICEV-Petrol	35433.68636	1.01	★
Hyundai	Grand i10 Petrol	ICEV-Petrol	33393.02112	0.54	★★
Hyundai	i20 Petrol	ICEV-Petrol	35133.20464	0.94	★★
Kia	Sonet Kappa Petrol	ICEV-Petrol	38233.51593	1.66	★
Mahindra	XUV 3XO Petrol	ICEV-Petrol	38779.89132	1.79	★
MG	Comet EV	EV	24285.59756	-1.57	★★★★★
MSIL	Celerio CNG	ICEV-CNG	25192.04618	-1.36	★★★★★
MSIL	Celerio Petrol	ICEV-Petrol	27538.45557	-0.82	★★★★
MSIL	Fronx Petrol	ICEV-Petrol	31488.44528	0.10	★★★
MSIL	WagonR CNG	ICEV-CNG	25173.51273	-1.37	★★★★★
MSIL	Alto CNG	ICEV-CNG	24403.22523	-1.55	★★★★★
MSIL	Swift Dzire CNG	ICEV-CNG	26722.02891	-1.01	★★★★★
MSIL	WagonR Petrol	ICEV-Petrol	27964.06658	-0.72	★★★★
MSIL	Swift Dzire Petrol	ICEV-Petrol	29437.47551	-0.38	★★★
MSIL	Baleno Petrol	ICEV-Petrol	31323.40231	0.06	★★★
MSIL	S-Presso Petrol	ICEV-Petrol	27627.76016	-0.80	★★★★
MSIL	Baleno CNG	ICEV-CNG	28328.43288	-0.64	★★★★
MSIL	Alto Petrol	ICEV-Petrol	26533.78969	-1.05	★★★★★
MSIL	Fronx CNG	ICEV-CNG	31011.04555	-0.01	★★★
MSIL	S-Presso CNG	ICEV-CNG	25883.86509	-1.20	★★★★★
Nissan	Magnite Petrol	ICEV-Petrol	34587.85726	0.82	★★
Nissan	Magnite CNG	ICEV-CNG	34716.70565	0.85	★★
Renault	Kwid Petrol	ICEV-Petrol	29252.17468	-0.42	★★★
Skoda	Kylaq Petrol	ICEV-Petrol	37459.93325	1.48	★
Tata	Altroz CNG	ICEV-CNG	30314.84226	-0.17	★★★
Tata	Altroz Petrol	ICEV-Petrol	36707.2237	1.31	★
Tata	Punch Petrol	ICEV-Petrol	35909.2771	1.12	★
Tata	Punch CNG	ICEV-CNG	33273.77444	0.51	★★
Tata	Punch EV	EV	26684.81523	-1.02	★★★★★
Tata	Nexon EV	EV	35961.13322	1.14	★
Tata	Tiago Petrol	ICEV-Petrol	29557.17243	-0.35	★★★
Tata	Tiago CNG	ICEV-CNG	31787.38219	0.17	★★★

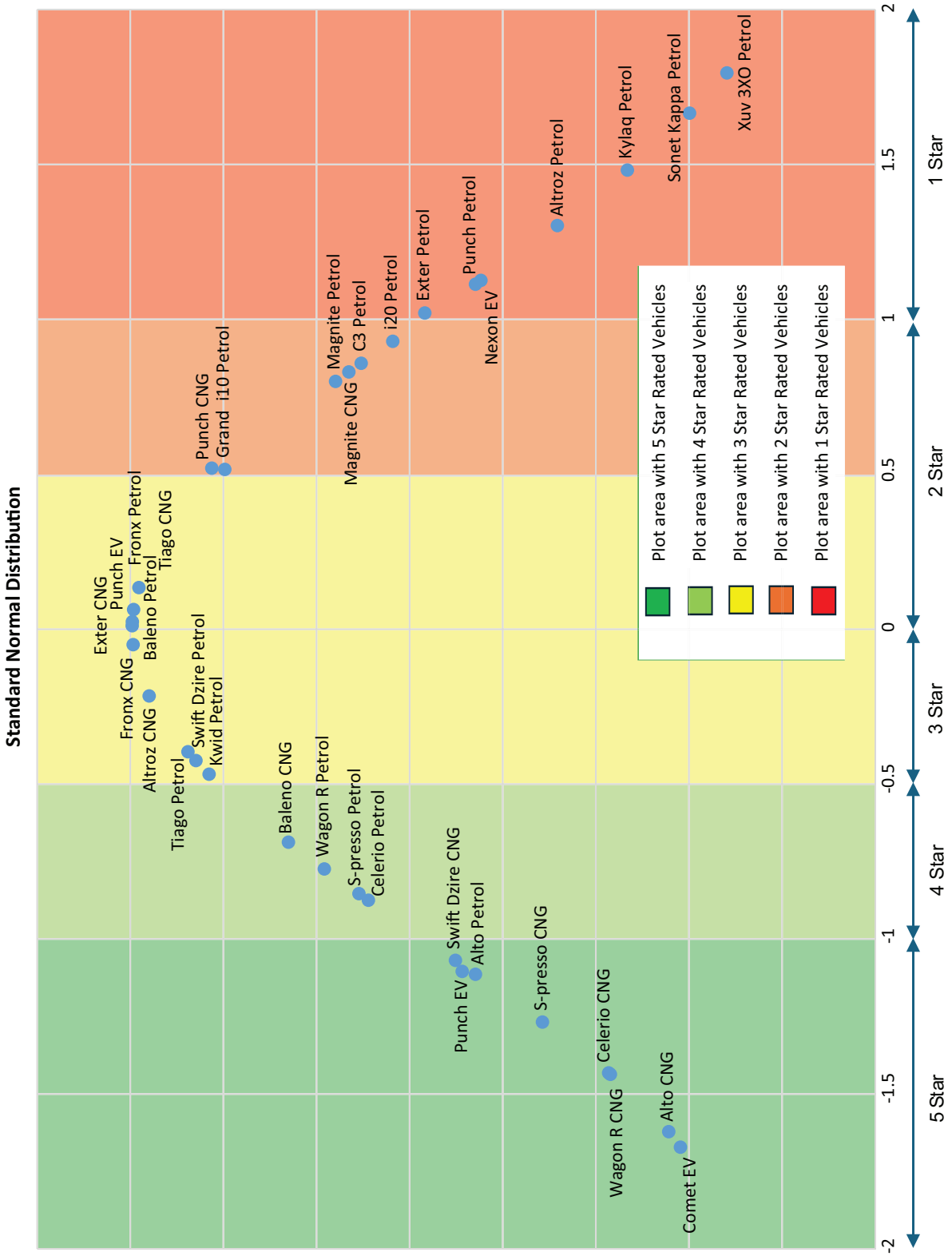

Figure 9: Z-score and segmented star rating in sub-4-meter category

7.3.2 Segment 2: Greater than or Equal to 4- Meter

For vehicles above 4 metres, the reference distribution is characterized by mean and standard deviation as follows-

3) Mean $= \mu = \frac{\Sigma x_i}{n}$

$$= \frac{\text{Sum of life cycle emissions of each vehicle in greater than or equal to 4 meter category}}{\textit{Number of Vehicles in greater than or equal to 4 Meter Category}}$$

$$= 44389.83 \text{ Kg CO2-eq.}$$

4) Standard Deviation $= \sigma = \sqrt{\frac{\Sigma(x_i - \mu)^2}{n}}$

$$= \sqrt{\frac{\Sigma(\textit{Life cycle emission of each vehicle in} \text{ greater than or equal to 4 meter category} - \textit{Mean Emission})^2}{\textit{Number of Vehicles} \text{ greater than or equal to 4 meter category}}}$$

$$= 9582.26 \text{ Kg CO2-eq.}$$

This indicates both higher average emissions and greater variability. The resulting ratings highlight the widespread life cycle performance within larger vehicles, demonstrating that size alone does not determine environmental performance and that substantial differentiation is possible even within this segment. Table 8 and Figure 10 below provide the star rating for this category-

Table 8: Z-score and segmented star rating in greater than or equal to 4-meter category

Brand Name	Vehicle Names	Fuel Type	Z-score	Star Ratings
BYD	eMAX EV	EV	0.67	★★
Honda	Elevate Petrol	ICEV-Petrol	0.12	★★★
Hyundai	Verna Petrol	ICEV-Petrol	-0.83	★★★★
Hyundai	Creta Petrol	ICEV-Petrol	-0.64	★★★★
Hyundai	Creta EV	EV	-0.48	★★★
Hyundai	Creta Diesel	ICEV-Diesel	-0.38	★★★
Jeep	Meridian Diesel	ICEV-Diesel	1.67	★
Kia	Carens Petrol	ICEV-Petrol	-0.07	★★★
Kia	Seltos Petrol	ICEV-Petrol	-0.27	★★★
Kia	Seltos Diesel	ICEV-Diesel	-0.06	★★★

Table 8: Z-score and segmented star rating in greater than or equal to 4-meter category

Brand Name	Vehicle Names	Fuel Type	Z-score	Star Ratings
Mahindra	Scorpio-N Diesel	ICEV-Diesel	1.64	★
Mahindra	XUV 700 Petrol	ICEV-Petrol	0.35	★★★
Mahindra	XUV 400 EV	EV	-0.97	★★★★
Mahindra	BE 6 EV	EV	0.34	★★★
MG	Windsor EV	EV	-0.43	★★★
MG	Astor Petrol	ICEV-Petrol	0.40	★★★
MG	ZS EV	EV	-0.32	★★★
MG	Gloster Diesel	ICEV-Diesel	3.07	★
MSIL	Grand Vitara Hybrid	ICEV-Petrol Hybrid	-1.54	★★★★★
Skoda	Slavia Petrol	ICEV-Petrol	-0.61	★★★★
Skoda	Kushaq Petrol	ICEV-Petrol	-0.48	★★★
Tata	Harrier Diesel	ICEV-Diesel	0.95	★★
Tata	Curvv EV	EV	-0.71	★★★★
Toyota	Innova Hycross Hybrid	ICEV-Petrol Hybrid	-0.71	★★★★
Volkswagen	Taigun Petrol	ICEV-Petrol	-0.73	★★★★

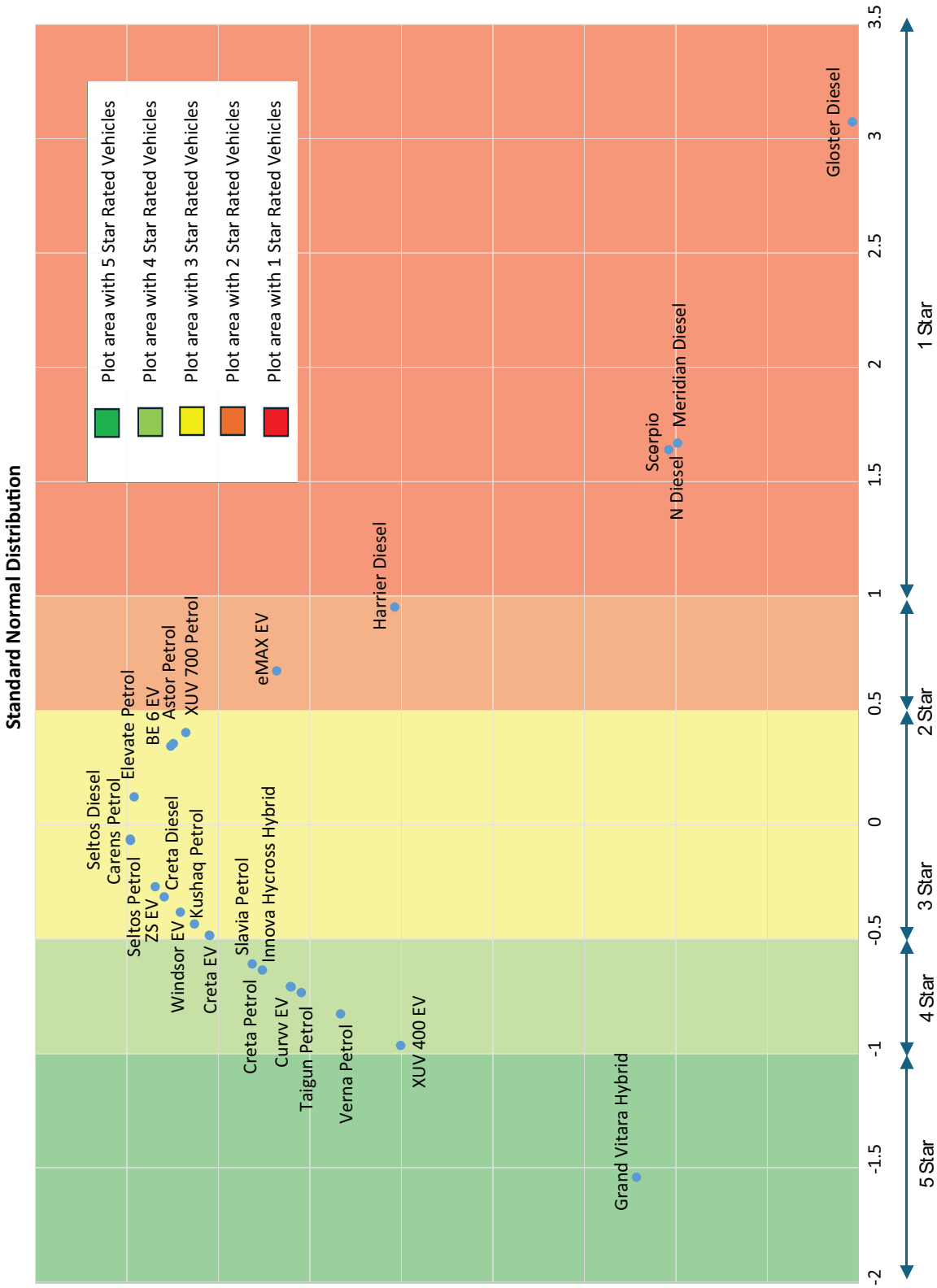

Figure 10: Z-score and segmented star rating in greater than or equal to 4 meter category

Chapter 8: Conclusion

This study set out to develop and demonstrate a life cycle assessment based environmental rating framework for four-wheeler passenger cars in the Indian automotive context. In contrast to prevailing vehicle evaluation approaches that rely predominantly on tailpipe emissions or fuel efficiency indicators, the framework proposed in this study adopts a cradle-to-grave perspective, thereby capturing GHG emissions arising across vehicle manufacturing, energy production, use, maintenance, and constrained end-of-life considerations.

Using Global Warming Potential (GWP100, IPCC AR6) as the sole assessment parameter, the study translates comprehensive life cycle emission results into an interpretable and comparable rating structure. The application of z-score normalization enables objective comparison across heterogeneous vehicle technologies, fuel types, and emission magnitudes without privileging or penalizing any specific powertrain category a priori.

By presenting ratings both as a pooled assessment and as a length-segmented classification, the framework demonstrates flexibility in addressing diverse stakeholder needs. While pooled ratings align with the principle of absolute environmental performance, segmented ratings improve interpretability for consumers operating within familiar market categories. Importantly, the framework remains methodologically consistent across both representations.

Identified Areas of Opportunities and Applications

- **Feasibility of Life Cycle Based Emission Framework & Declarations**

Overall, the study establishes that a life cycle- based, statistically normalized rating mechanism is technically feasible, transparent, and adaptable for application in India. It provides a credible foundation for integrating life cycle thinking into vehicle evaluation systems, consumer information tools, and future voluntary or regulatory sustainability initiatives such as Automotive Mission Plan 2047. It can support India's shift toward a sustainable, globally competitive automotive ecosystem under Viksit Bharat by:

  - » Establishing life-cycle emission baselines
  - » Guiding sustainability and circularity policies
  - » Enhancing export competitiveness
  - » Supporting long-term emission targets (2030–2047)

- **Role of Dynamic Rating Mechanisms in Decarbonization Policy**

With a dynamic framework & rating methodology, reductions in the fleet-wide mean life cycle emission intensity result in an automatic tightening of the performance distribution. This dynamic recalibration ensures that performance bands evolve in accordance with technological progress: vehicles classified as less emitting under current baselines may only correspond to mid-tier performance as sectoral emission intensities decline. Such an adaptive rating mechanism aligns with long-term decarbonization pathways by preventing threshold stagnation, ensuring that policy incentives remain forward-looking rather than tied to static benchmarks.

- **Shifting Material Driven Emission Burdens**

As low emission powertrains scale, manufacturing energy efficiency improves, and the electricity grid decarbonizes, fleet average use phase emissions will steadily decline. The transition to greener energy sources such as flex fuels and Bio-CNG will further strengthen these reductions across vehicle operations. As a result, material related emissions- from raw material extraction and processing to component manufacturing and endoflife treatment- will constitute an increasing share of total life cycle impacts. This will elevate the importance of material efficiency, lowcarbon supply chains and alternatives such as bio-based or Post-Consumer Recycled (PCR) materials, recycling infrastructure, and circular economy strategies. LCA enables deeper insight into which materials drive the largest burdens in GHG emissions, energy use, or resource depletion, allowing manufacturers to evaluate material substitutions to understand how environmental impacts shift. This helps prevent the issue of "problem shifting" from one phase to another.

- **LCA Rating based Incentives to Reduce Emissions**

There is a reasonable expectation that stronger incentives for low emission vehicles- such as supportive policies, subsidies, and regulatory pressure- combined with increasingly climate aware consumer preferences, will encourage manufacturers to accelerate the shift toward more sustainable vehicle designs. Based on the assigned life cycle emission rating, incentives can be structured across three key stakeholder groups (See Figure 11).

a. **Purchase Incentives**: Vehicles proving lower life cycle emissions may qualify for financial benefits at the point of sale, such as reduced registration taxes, direct purchase subsidies reduced interest rates from banks, lower GST or VAT rates, and access to preferential financing options. These measures directly influence consumer choice by lowering the upfront cost of environmentally superior vehicles.

b. **Manufacturing Incentives**: OEMs producing vehicles with low life cycle carbon footprints may become eligible for manufacturing-side incentives, including production-linked incentive (PLI) benefits, enhanced carbon credit multipliers, and accelerated type approval or certification pathways. Such incentives encourage manufacturers to invest in cleaner materials, efficient production processes, and low-emission vehicle architectures.

c. **Consumer-Use Incentives**: Additional benefits may be extended to consumers owning low life cycle emission vehicles, including reduced annual road taxes, preferential access to designated low-emission zones in urban areas, lower toll charges, and parking incentives or exemptions. These measures reinforce the value of low-emission vehicles beyond the purchase stage and promote their sustained use.

Using the LCA-based rating framework, **carbon credit additionality** can be extended to OEMs for achieving verified life-cycle emission reductions beyond regulatory baselines through low-technology, high-impact interventions, including low-carbon or recycled materials, material-efficient lightweighting, energy-optimized manufacturing, and the use of greener fuels (e.g., flex fuels, Bio-CNG). Additionality is the principle that carbon credits are granted only for emissions reductions beyond business-as-usual, enabling OEMs to monetize verified LCA-based incremental improvements.

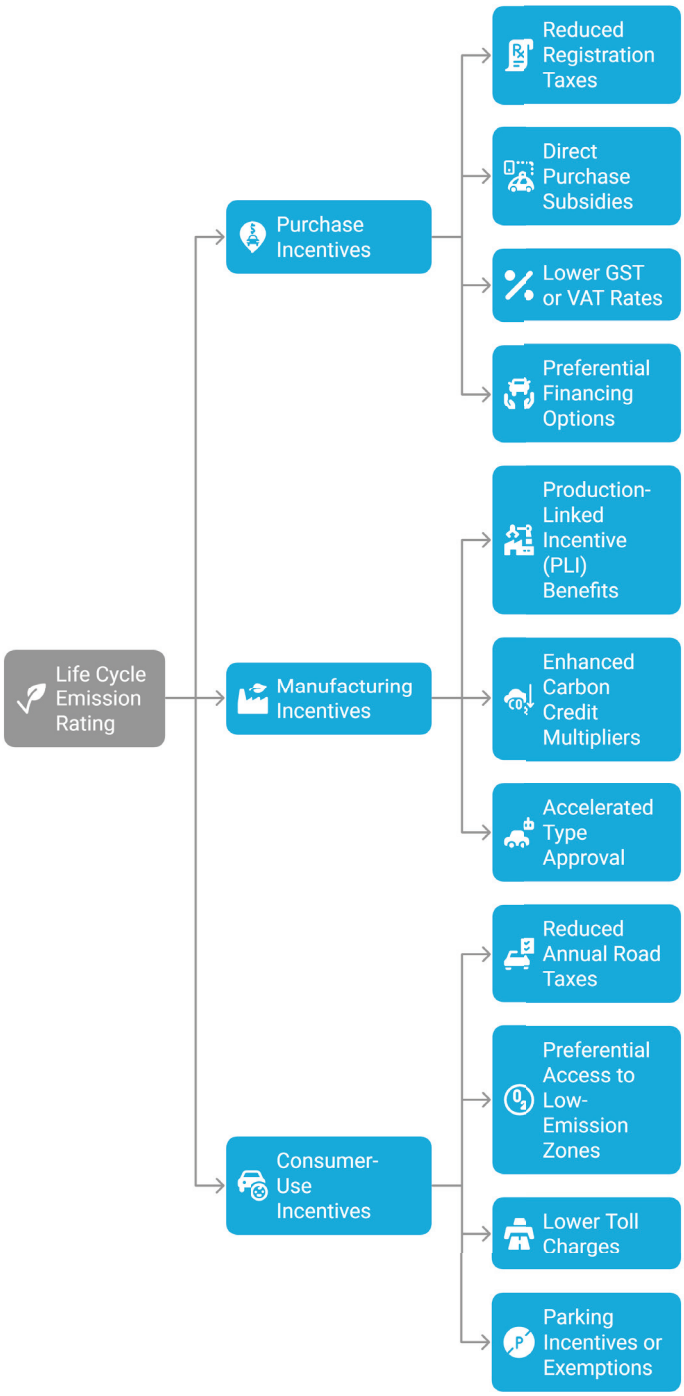

Figure 11: LCA rating based incentive design to reduce emissions

Additional credits may arise from:

- Reducing embodied carbon in high-impact materials and components (e.g., steel, aluminum, plastics, batteries)
- Transitioning to lower-carbon supply chains, including renewable energy and recycled feedstocks.
- Optimizing design and manufacturing processes to reduce material and energy intensity
- Adopting cleaner fuels across manufacturing, logistics, and auxiliary operations

By linking LCA-verified improvements to carbon credit provisions or multipliers, policy mechanisms can:

- Improve financial viability of low-cost, scalable decarbonization measures
- Broaden OEM participation beyond advanced or disruptive technologies
- Drive ecosystem-wide emission reductions across materials, suppliers, and logistics
- Reward life cycle cleaner vehicles, rather than tailpipe performance alone
- Such an approach supports a robust carbon market by ensuring credits represent real, measurable, and additional life-cycle emission reductions, while enabling OEMs to capture value from incremental yet impactful sustainability actions.

Limitations and Challenges

Several pathways exist to strengthen and extend the proposed framework. However, there are few limitations and challenges that need to be overcome, such as:

- **Lack of India-specific LCI data** for vehicle materials and energy use can be addressed through standardized emission declarations and wider adoption of LCA-based reporting (e.g., EPDs, PCFs) across the automotive value chain.
- **Restricted understanding of upstream supplier-level emissions:** Greater visibility can be enabled through proactive supplier partnerships on emission declarations, integration of circular procurement practices, and co-developed pathways for shared emissions reduction.
- **Reliance on secondary data for manufacturing and logistics:** Can be improved through primary data collection via OEM–supplier partnerships, periodic industry surveys, and digital MRV (Monitoring, Reporting, Verification) systems
- **Narrow focus on climate impacts** limits the framework; future expansion to additional categories (e.g., resource depletion, particulate matter) and hybrid rating approaches combining absolute thresholds with relative rankings could improve robustness.
- **Relative nature of the rating system** meaning performance is benchmarked against the assessed fleet rather than external climate targets; however, progressive market-wide emission reductions are expected to tighten benchmarks over time.
- **Constrained end-of-life modelling**, reflecting informal recycling practices in India, limits accounting of future circularity benefits; strengthening formal recycling systems, EPR mechanisms, and battery recovery infrastructure is essential.

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Annexures

Annexure 1: Specifications of the Selected Vehicles

Table A 1: Specifications of the selected vehicle

Brand Name	Vehicle Name	Fuel Type	Kerb Weight	Engine Capacity	Length (mm)	Representative Fuel Efficiency (km/l for Petrol and Diesel ICEVs, km/kg for ICEV-CNG, and range for EVs)
BYD	eMax	EV	1941.373		4710	530
Citroen	C3	ICEV-Petrol	978	1.2	3981	19.8
Honda	Elevate	ICEV-Petrol	1243	1.5	4312	15.31
Hyundai	Exter	ICEV-CNG	1050	1.2	3815	27.1
Hyundai	Exter	ICEV-Petrol	976.109	1.2	3815	19.4
Hyundai	Verna	ICEV-Petrol	1242	1.5	4535	20.6
Hyundai	Creta	ICEV-Petrol	1254.203	1.6	4300	18.4
Hyundai	Creta	EV	1576.261		4340	510
Hyundai	Grand i10	ICEV-Petrol	938.08	1.2	3765	20.7
Hyundai	i20	ICEV-Petrol	1062.35	1	3995	20.02
Hyundai	Creta	ICEV-Diesel	1315.997	1.5	4300	21.8
Jeep	Meridian	ICEV-Diesel	1834	2	4769	14.9
Kia	Sonet Kappa	ICEV-Petrol	1139	1	3995	18.2
Kia	Carens	ICEV-Petrol	1404	1.4	4540	16.5
Kia	Seltos	ICEV-Petrol	1396.721	1.5	4365	17.9
Kia	Seltos	ICEV-Diesel	1306.163	1.5	4315	20.08
Mahindra	XUV 3XO	ICEV-Petrol	1422.072	1.2	3990	20.1
Mahindra	Scorpio-N	ICEV-Diesel	2126	2.2	4662	15.42
Mahindra	XUV400	EV	1580.496	2	4200	456
Mahindra	XUV700	ICEV-Petrol	1719.641	2	4695	16
Mahindra	BE 6	EV	2145.609		4371	683
MG	Windsor	EV	1554		4295	332
MG	Comet	EV	821		2974	230
MG	Astor	ICEV-Petrol	1364	1.4	4323	14.82
MG	ZS	EV	1652.221		4323	461
MG	MG Gloster	ICEV-Diesel	2484.669	2	4985	12.4
MSIL	Celerio	ICEV-CNG	906	1	3695	34.43
MSIL	Celerio	ICEV-Petrol	812.186	1	3695	25.24

Table A 1: Specifications of the selected vehicle

Brand Name	Vehicle Name	Fuel Type	Kerb Weight	Engine Capacity	Length (mm)	Representative Fuel Efficiency (km/l for Petrol and Diesel ICEVs, km/kg for ICEV-CNG, and range for EVs)
MSIL	Grand Vitara	ICEV-Petrol Hybrid	1299	1.5	4345	27.97
MSIL	Fronx	ICEV-Petrol	984.637	1	3995	22.89
MSIL	WagonR	ICEV-CNG	914	1	3655	34.05
MSIL	Alto	ICEV-CNG	823.7455911	1	3445	33.4
MSIL	Swift Dzire	ICEV-CNG	1001.236	1.2	3860	33.73
MSIL	WagonR	ICEV-Petrol	827	1	3655	24.35
MSIL	Swift Dzire	ICEV-Petrol	920	1.2	3860	24.8
MSIL	Baleno	ICEV-Petrol	949.873	1.2	3990	22.35
MSIL	S-Presso	ICEV-Petrol	757.049	1	3565	24.76
MSIL	Baleno	ICEV-CNG	1020	1.2	3990	30.61
MSIL	Alto	ICEV-Petrol	746.3478804	1	3445	24.9
MSIL	Fronx	ICEV-CNG	1076.095	1	3995	28.51
MSIL	S-Presso	ICEV-CNG	843.222	1	3565	32.73
Nissan	Magnite	ICEV-Petrol	1022.919	1	3994	19.9
Nissan	Magnite	ICEV-CNG	1094.749		3994	24
Renault	Kwid	ICEV-Petrol	736.981	1	3730	23
Skoda	Slavia	ICEV-Petrol	1249	1	4541	18.73
Skoda	Kylaq	ICEV-Petrol	1221.589	1	3995	19.05
Skoda	Kushaq	ICEV-Petrol	1274.034	1	4225	18.09
Tata	Altroz	ICEV-CNG	1181	1.2	3990	30
Tata	Altroz	ICEV-Petrol	1079.926	1.2	3990	19.33
Tata	Punch	ICEV-Petrol	1041	1.2	3827	20.09
Tata	Punch	ICEV-CNG	1142.074	1.2	3827	26.99
Tata	Punch	EV	1349		3857	421
Tata	Harrier	ICEV-Diesel	1801	2	4605	16.9
Tata	Nexon	EV	1544.451		3995	489
Tata	Curvv	EV	1718.862		4308	502
Tata	Tiago	ICEV-Petrol	992.612	1	3746	23.84
Tata	Tiago	ICEV-CNG	1064.442		3746	26.49
Toyota	Innova Hycross	ICEV-Petrol Hybrid	1700.931	2	4755	22.16
Volkswagon	Taigun	ICEV-Petrol	1260	1.5	4221	19.01

Annexure 2: Addressing Data Gaps and Inconsistencies in Bill of Materials

The table below lists vehicles where incomplete component material data were supplemented using functionally identical or symmetric components within the same vehicle.

Table A 2: Summary of vehicles with assumed component material mapping

Component Category	Mapping Assumption	Vehicle Models Applied
Seats	Passenger seat mapped to front driver seat	Hyundai Grand i10 nios & i20, Hyundai Creta (P), Hyundai Venue (D), Kia Seltos (D), MSIL Brezza (Petrol & CNG), MSIL Baleno (Petrol & CNG), S-Presso (Petrol & CNG), MG Gloster(D), Renault Kwid(P), Skoda Kushaq(P), Tata Tiago (Petrol & CNG)
Doors (Front)	Front passenger door mapped to driver door	Hyundai Grand i10 nios, Hyundai Creta (P), Hyundai Venue (D), Nissan Magnite(Petrol and CNG), Renault Kwid(P), Skoda Kushaq(P), Tata Tiago (Petrol & CNG)
Doors (Rear)	Rear right door mapped to rear left door	Hyundai Grand i10 nios & i20, Hyundai Creta (P), Hyundai Venue (D), Kia Seltos (D), S-Presso (Petrol & CNG), MG Gloster(D), Renault Kwid (P), Skoda Kushaq(P), Tata Tiago (Petrol & CNG), Nissan Magnite (Petrol and CNG)
Seats (Rear – Individual)	Rear right seat mapped to rear left seat	MG Gloster(D)

In cases where component material composition was entirely absent from a vehicle's Bill of Materials, equivalent components were assumed using reference vehicles with similar kerb weights or from the same component manufacturer.

- For the i20, the steering column and headline filler (interior trim components) were mapped using data from the Grand i10 Nios, supplied by Antolin.
- Steering column assemblies for the Creta (petrol variant) and S-Presso were mapped using steering column data from the Grand i10, supplied by Mando, based on supplier commonality.
- In the case of the MG Gloster, several components including the headline filler, curtain airbags, front bumper, vacuum brake booster system, and front passenger door panel were mapped using corresponding components from the MG Windsor, reflecting shared manufacturer design.
- Due to the absence of detailed material breakdowns for shock absorbers across some models (Grand i10 & i20, Creta, S-Presso, Kushaq and Tiago), a uniform material composition assumption was applied. Shock absorbers were assumed to consist predominantly of steel and elastomers in a mass ratio of 60:40.

The table below presents vehicles where missing fuel variants were addressed through CNG system addition or removal based on functionally comparable reference vehicles-

Table A 3: Fuel-variant mapping and CNG system assumption

Model Name	Conversion Type	CNG System Action
MSIL Celerio	CNG to Petrol	CNG system removed
Tata Altroz	CNG to Petrol	CNG system removed
Hyundai Exter	CNG to Petrol	CNG system removed
MSIL WagonR	CNG to Petrol	CNG system removed
MSIL Alto	CNG to Petrol	Petrol variant was mapped with reference to the weight distribution between Celerio Petrol and CNG models
Tata Punch	Petrol to CNG	CNG system added
Nissan Magnite	Petrol to CNG	CNG system added from Swift Dzire (approx. 72 kg)
Tata Tiago	Petrol to CNG	CNG system added from Swift Dzire (approx. 72 kg)
MSIL Baleno	Petrol to CNG	CNG system added from Swift Dzire (approx. 72 kg)
MSIL Fronx	Petrol to CNG	CNG system added from Tata Altroz (approx. 92 kg)
MSIL S-Presso	Petrol to CNG	CNG system added from Celerio (approx. 87 kg)