



International Journal of Technology, Health and Sustainability

The Growing Shadow on Indian Skies: A Comprehensive Review of Road Vehicular Pollution

Gaurav Meena^{1*}, Shobhit Kumar²

^{1,2} Department of Civil Engineering, National Institute of Technology Kurukshetra, Kurukshetra, India.

*Corresponding author

(Received: 16.11.2025; Accepted: 26.11.2025)

Web link: <https://ijths.com/volume-1-issue-2-october-december/>

Abstract

This research paper comprehensively reviews and analyses the status, environmental and health impacts, and trends of vehicular emissions in India. It aims to synthesise data on pollutant sources, their consequences, and evaluate the efficacy of existing policy frameworks in mitigating the growing environmental burden from the road transport sector. The study is based on a systematic review of secondary data from government reports (e.g., CPCB, MoRTH), international agencies (e.g., IEA, EDGAR), and scientific literature. Data on vehicular population, fuel consumption, and emission factors were compiled and analysed using statistical and comparative methods to identify trends and project future scenarios for key pollutants like CO₂, CO, NO_x, and PM. India's road transport sector is a rapidly growing source of air pollution and greenhouse gases, contributing approximately 10.6% of the nation's GHG emissions in 2024. The analysis reveals a dramatic projected increase in CO₂ emissions, from 208 million tonnes in 2005 to a forecasted 1,212 million tonnes by 2035. Key findings highlight that while two-wheelers dominate the vehicle fleet, heavy commercial vehicles (≈2% of the fleet) contribute disproportionately to NO_x and particulate matter emissions. Pollutants from vehicular exhaust are linked to severe respiratory and cardiovascular health issues and cause widespread environmental damage, including acid rain, smog, and ecosystem degradation. The article concludes that despite policy interventions like the Bharat Stage (BS-VI) emission standards and electric vehicle promotion, the rapid growth in vehicle numbers and fuel consumption continues to outpace mitigation efforts. A multi-pronged strategy involving stricter emission norms, an accelerated transition to electric and cleaner fuels, and enhanced public transport infrastructure is critical for achieving sustainable mobility and improving air quality in India.

Keywords: Vehicular emissions; Air pollution; Road transport; Environmental impact; Bharat stage norms; Climate policy

INTRODUCTION

With rapid urbanisation, industrial growth, and a rising population, vehicular emissions have emerged as one of the most significant contributors to environmental pollution (Deswal and Verma, 2016; Desai, 2018; CEEW, 2024; Saharan and Deswal, 2023). The ever-increasing number of vehicles on roads, coupled with dependence on fossil fuels such as petrol and diesel, has led to a sharp rise in the release of harmful gases and particulates into the atmosphere (Kumari and Deswal, 2017). These emissions include carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), hydrocarbons, volatile organic compounds (VOCs), sulphur dioxide (SO₂), and suspended particulate matter (SPM), all of

which pose serious risks to human health, ecosystems, and global climate.

Vehicular emissions not only deteriorate air quality but also contribute to environmental phenomena such as acid rain, smog formation, the greenhouse effect, and global warming (Deswal and Chandna, 2010; Kumar *et al.*, 2022; IEA, 2023). Studies have shown that road transport alone accounts for a significant share of energy-related CO₂ emissions worldwide, and this share is expected to rise in the absence of effective mitigation measures (IEA, 2023). In developing countries such as India, poorly maintained vehicles, outdated engine technologies, and severe traffic congestion further aggravate the problem (Ramachandra and Kashyap, 2009; Desai, 2018).

Table 1: GHG Emissions in various sector (in Mt CO₂eq/yr) (Source: Crippa *et al.*, 2025).

Sector	1990	1995	2000	2005	2010	2015	2020	2024
Transportation	66.91	81.58	98.97	119.66	199.65	265.45	275.91	354.23
Power industry	217.15	348.09	462.93	566.49	795.51	1088.10	1101.48	1532.63
Industrial combustion and processes	151.26	159.25	196.59	237.68	399.04	523.37	524.85	699.38
Agriculture	570.98	608.33	627.13	659.88	708.67	723.77	772.65	805.63
Fuel Exploitation	89.55	100.45	111.98	140.01	145.64	154.70	172.12	225.26
Buildings	123.19	145.06	152.84	170.15	198.07	208.09	223.45	256.26

The environmental and health impacts of vehicular emissions are far-reaching. They lead to respiratory illnesses, cardiovascular problems, and premature deaths in humans, while also damaging flora, fauna, soil, and water resources (WHO, 2023). According to the World Health Organisation, millions of premature deaths annually are linked to air pollution, a large portion of which arises from transport-related sources (WHO, 2023). Economically, vehicular pollution imposes heavy burdens through increased healthcare costs, reduced labour productivity, and long-term environmental degradation.

Given these alarming consequences, it becomes essential to study vehicular emissions in detail, understand their sources and effects, and explore effective mitigation strategies. Promoting cleaner fuels, adopting energy-efficient vehicle technologies, strengthening emission standards, and shifting towards sustainable modes of transport are crucial to reducing the environmental burden of road transport and ensuring a healthier, more sustainable future for both people and the planet (Kumar *et al.*, 2022; IEA, 2023; CEEW, 2024).

MATERIALS AND METHODS

This paper is based entirely on secondary data and literature review to analyse vehicular emissions and their environmental impacts. Relevant information was collected from government reports, scientific journals, websites of national and international agencies' databases, such as the Central Pollution Control Board (CPCB), Ministry of Road Transport and Highways (MoRTH), The Energy and Resources Institute (TERI), the International Energy Agency (IEA), and the Emissions Database for Global Atmospheric Research. (EDGAR) of the European Commission's Joint Research Centre (JRC). Data regarding vehicular population, fuel consumption, and emission factors were compiled from these sources to estimate pollutant levels of CO₂, CO, NO_x, SO₂, and particulate matter. Statistical and comparative analyses were performed using Microsoft Excel to identify trends and variations in emission levels over time. Graphs, charts, and tables were prepared to visually represent the relationship of vehicular growth. The environmental effects were interpreted based on existing scientific studies highlighting impacts on air quality, vegetation, and human health.

AIR POLLUTION DUE TO ROAD TRANSPORTATION IN INDIA

India is the World's 3rd largest emitter of GHGs, with a total share of 7.8% (Statista, 2025). Rapid urbanisation and economic development have significantly increased the

number of motor vehicles in India, leading to severe impacts on human health, economic well-being, and the environment. Most Indian cities face high traffic congestion, which has become a major source of urban air pollution (Kishore and Deswal, 2017). In 2023 alone, over 22.7 million new vehicles (including electric, petrol, and diesel) were registered nationwide (PIB, 2023). India is the fourth-largest country in the automotive sector (WPR, 2025). As of recent estimates, India's vehicle fleet includes roughly on the order of 260 million two-wheelers and 50 million cars. This corresponds to about 185 two-wheelers and 34 cars per 1,000 people (Waghmare, 2025). The transport sector contributes 14% of energy-related direct (Kumar *et al.*, 2022) CO₂ emissions and is one of the fastest-growing emissions sectors in the country, along with industry (CT 2020; IEA, 2023) (Table 1). The primary pollutants include Carbon Dioxide (CO₂), Carbon Monoxide (CO), Hydrocarbons (HC), Nitrogen Oxides (NO_x), Sulphur Dioxide (SO₂), Suspended Particulate Matter (SPM), and Respirable Suspended Particulate Matter (RSPM). Among these, according to the International Energy Agency (IEA, 2023), CO₂ accounts for nearly 92% of vehicular emissions, followed by hydrocarbons, while particulate matter contributes only about 3–5% (Desai, 2018). The dominance of PM₁₀ and the resuspension of road dust further worsen air quality.

The transportation sector's share of total GHG emissions in India has grown steadily from approximately 6.4 % in 1990 to around 10.6% in 2024 (Table 1), highlighting its rising contribution to national emissions (Crippa *et al.*, 2025). While the power industry remains the largest emitter, accounting for over 45% of total emissions in 2024, the transport sector's emissions have increased more sharply in relative terms than most other sectors. This escalation corresponds with India's rapid vehicle fleet expansion, has reached over 22.7 million new registrations in 2023 (PIB, 2023). The growing transport emission share underscores a significant shift in India's carbon profile: road transport alone is now responsible for nearly 90–92% of total transport emissions (Kumar *et al.*, 2022), and vehicular sources contribute substantially to urban air pollution, accounting for 20–35% of particulate matter in major Indian cities (CEEW, 2024).

TYPES OF EMISSIONS FROM ROAD TRANSPORT AND THEIR IMPACT ON THE ENVIRONMENT AND HUMAN HEALTH

Vehicular emissions consist of several harmful pollutants, including particulate matter (PM), carbon monoxide (CO), oxides of nitrogen (NO_x), sulphur oxides (SO_x), carbon

Table 2: Major Pollutants emissions from vehicle
(Source: Desai, 2018).

Pollutants	Sources
Particulate Matter (PM)	Dust, pollen, sea salt and combustion such as domestic cooking, forest fire, garbage burning, vehicles, ships and railways
Carbon Monoxide (CO)	Incomplete combustion of fossil fuels
Oxides of Nitrogen (NO _x)	Diesel engines operated at high temperatures
Sulphur Oxides (SO _x)	Oxidation of Sulphur during combustion of fuel
Carbon Dioxide (CO ₂)	Oxidization of carbon during combustion of fuel
Lead Emissions	Vehicle exhaust

dioxide (CO₂), and lead compounds (Table 2). These emissions primarily result from incomplete fuel combustion, high-temperature engine operations, and the oxidation of carbon and sulphur during fuel burning. Such pollutants contribute to air quality deterioration, climate change, and various health disorders, including respiratory and cardiovascular diseases. The cumulative impact of these emissions poses a significant threat to environmental sustainability and public health (Desai, 2018).

Types of Emissions

Desai (2018) outlined the different types of pollutants emitted by vehicles and classified them on the basis of their chemical composition and their sources as follows:

Particulate matter

Particulate matter (PM) can exist in solid, liquid, or gaseous form and is broadly classified as either primary or secondary in nature. Primary particulate matter is directly released from emission sources, whereas secondary particulate matter forms through chemical reactions between precursor gases in the atmosphere (Deswal and Deswal, 2017). PM occurs across a wide range of sizes, typically from 0.005 microns up to 500 microns. Based on aerodynamic diameter, it is categorised into PM₁₀, PM_{2.5}, and Respirable Suspended Particulate Matter (RSPM). Particles with diameters of 10 microns or less are termed PM₁₀, while those below 2.5 microns are designated as PM_{2.5}. The fraction of particulate matter smaller than 10 microns is generally referred to as RSPM. More recently, ultrafine particles of less than 0.1 micron (PM_{0.1}) have also been included in industrial ambient air quality assessments due to their increasing significance. Common sources of PM emissions include natural processes such as dust storms, pollen dispersion, and sea spray, as well as anthropogenic activities like domestic fuel combustion, forest fires, open waste burning, and emissions from vehicles, railways, and shipping.

Carbon monoxide (CO)

Carbon monoxide (CO) is primarily generated due to the incomplete combustion of fossil fuels. The level of CO emissions is strongly influenced by the air–fuel ratio during

engine operation, with richer mixtures (lower air–fuel ratios) leading to higher CO output. In India, gasoline-powered vehicles are the dominant source of CO emissions, while diesel engines contribute relatively little. The application of catalytic converters is highly effective in mitigating this pollutant, as they can reduce CO emissions by up to 90% through its conversion into less harmful compounds.

Hydrocarbons (HC)

Hydrocarbon (HC) emissions from vehicles primarily arise from unburned fuel or the incomplete combustion of fuel within the engine. In gasoline-powered vehicles without catalytic converters, approximately 55% of HC emissions originate from the engine exhaust. An additional 20–22% is released due to fuel evaporation from components such as fuel lines, the carburettor, and the fuel tank, while around 13–25% is attributed to engine blow-by. In comparison, diesel engines generally emit significantly lower levels of hydrocarbons than petrol engines. The incorporation of catalytic converters effectively mitigates HC emissions by oxidizing hydrocarbons into carbon dioxide and water. Furthermore, minimizing the ingress of engine oil into the combustion chamber can also contribute to reducing HC levels.

Oxides of nitrogen (NO_x)

Nitrogen oxides (NO_x) are primarily generated during fuel combustion when atmospheric nitrogen reacts with oxygen at elevated temperatures. Within exhaust gases, nitrogen combines with oxygen to form nitric oxide (NO), which is subsequently oxidised to nitrogen dioxide (NO₂). Diesel engines, operating at higher combustion temperatures, are a major source of NO_x emissions. On average, diesel cars release about 116.9 g/km of NO_x, compared to only 3.3 g/km from gasoline-powered vehicles. Since motor vehicles contribute nearly 60–70% of the total NO_x present in ambient air, controlling emissions is critical. One effective approach is lowering the in-cylinder combustion temperature, thereby reducing NO_x formation. In India, advancements in diesel engine design have played a significant role in decreasing NO_x levels in the atmosphere.

Sulphur oxides (SO_x)

Sulphur dioxide (SO₂) is primarily emitted through the oxidation of sulphur present in fuels during combustion. Gasoline-powered vehicles release negligible quantities of sulphur compounds compared to diesel-fuelled vehicles, as diesel in India typically contains 0.05–5% sulphur by weight. Consequently, diesel vehicles are major contributors to ambient sulphur oxide (SO_x) emissions, accounting for approximately 2–6% of total SO_x in urban air. In the atmosphere, sulphur dioxide undergoes further oxidation and hydration to form sulphuric acid:



These acidic products precipitate as acid rain, leading to the acidification of soils and aquatic bodies, degradation of vegetation, corrosion of buildings and monuments, and adverse impacts on human respiratory health. However, the introduction of low-sulphur fuels and stringent emission

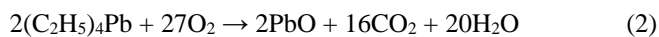
standards in India has resulted in a noticeable decline in ambient SO₂ concentrations across several urban centres, reflecting the effectiveness of recent regulatory interventions.

Carbon dioxide (CO₂)

During fuel combustion, the carbon content present in the fuel is primarily oxidised to form carbon dioxide (CO₂). However, incomplete combustion often results in the release of carbon monoxide (CO) and hydrocarbons (HC). Since CO₂ emissions are directly linked to the quantity of fuel consumed, older vehicles and heavy-duty categories such as trucks, buses, and goods carriers tend to generate higher levels of CO₂ compared to lighter vehicles. Carbon dioxide is recognised as the most significant greenhouse gas (GHG), and in India, vehicular emissions account for approximately 14% of the nation's total CO₂ emissions from all sources (Kumar *et al.*, 2022).

Lead emissions

Vehicle exhaust is recognised as a significant source of lead contamination in the environment. To enhance the octane rating of petrol to "super grade" quality, tetraethyl lead was historically added as an anti-knock agent. During engine combustion, it undergoes the reaction:



This process results in the release of fine lead particulates, which are dispersed and deposited along roadways, especially downwind of highways. Elevated concentrations of lead from automotive emissions have raised considerable environmental and health concerns. Consequently, the transition to unleaded gasoline has been implemented globally as a key measure to mitigate lead pollution from road transport.

Impacts of Vehicular Emissions on The Environment

Bolaji and Adejuyigbe (2006) reviewed the effects of vehicular emissions on the natural environment and highlighted their contribution to air quality deterioration as:

Vehicular emissions exert profound and multifaceted impacts on both human health and the environment. The pollutants released from vehicles contribute to a wide spectrum of adverse health outcomes, ranging from mild respiratory irritation to severe, life-threatening conditions. Exposure to vehicle-emitted pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂), and suspended particulate matter (SPM) has been strongly linked to respiratory and cardiovascular diseases, increased morbidity and mortality rates, and impaired pulmonary function. In acute exposure cases, carbon monoxide poisoning can be fatal, while chronic exposure to fine particulate matter and sulphur dioxide is associated with long-term respiratory disorders, reduced lung capacity, and cancer risks. Additionally, these pollutants contribute to environmental degradation by reducing air quality, impairing visibility, and damaging ecosystems, thereby posing a serious threat to public health and ecological balance.

Effects on agriculture

Optimal plant growth depends on the balanced availability of essential factors such as light, heat, moisture, nutrients, and suitable soil conditions. Any imbalance among these parameters induces physiological stress, which can manifest as stunted growth, chlorosis, or foliar damage. Environmental pollution introduces an additional layer of abiotic stress that can overwhelm the plant's natural defence and repair mechanisms, potentially leading to tissue injury or mortality. Plants readily absorb gaseous pollutants through their leaves, as gas exchange is a primary physiological process for photosynthesis and respiration. Structurally, a leaf comprises the epidermis, mesophyll, and vascular veins responsible for nutrient and water transport. Pollutant gases and fine particulates penetrate the leaf via stomata into the mesophyll's intercellular spaces, where they can disrupt cellular function and biochemical processes (Posthumus, 1983). Common symptoms of pollution-induced foliar injury include necrosis and bleaching along leaf margins, glazing and silvering of surfaces (particularly on the undersides), chlorosis resulting from chlorophyll degradation, and flecking or stippling on the upper leaf surfaces—each reflecting specific physiological and biochemical disturbances within the plant.

Effects on the ecosystem

Vehicular emissions exert significant detrimental effects on both flora and fauna, disrupting ecological balance and biodiversity. Pollutants such as carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO₂), hydrocarbons, and particulate matter (PM) contribute to air, soil, and water contamination, thereby impairing the physiological and reproductive functions of living organisms. In plants, these emissions interfere with photosynthesis and respiration by damaging chloroplasts, reducing chlorophyll content, and obstructing stomatal function, leading to chlorosis, necrosis, and inhibited growth. Deposition of heavy metals like lead, cadmium, and zinc from vehicle exhausts contaminates soil and accumulates in plant tissues, subsequently entering food chains and affecting herbivores and higher trophic levels. Among fauna, prolonged exposure to vehicular pollutants can cause respiratory distress, cardiovascular disorders, weakened immune response, and behavioural changes. Wildlife inhabiting urban or roadside ecosystems experiences habitat degradation and reduced food availability due to vegetation loss. Overall, vehicular emissions impose compounded toxic stress on terrestrial and aquatic ecosystems, threatening species diversity, ecosystem productivity, and long-term ecological sustainability.

Greenhouse effect

Vehicle emissions significantly contribute to the accumulation of greenhouse gases (GHGs) in the atmosphere, exacerbating the greenhouse effect—a natural process in which certain gases, such as carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), trap heat within the Earth's atmosphere, maintaining surface temperatures necessary for life. However, excessive emissions from on-road vehicles, primarily CO₂ from fuel combustion, intensify this effect, leading to global warming and associated climatic changes. These emissions not only alter temperature patterns

Table 3: Health Impacts of Different Vehicular Air Pollutants (Source: (CPCB), 2010).

Pollutants	Effect on Human Health
Suspended Particulate Matter (SPM) and Respirable Particulate Matter (RPM)	Fine particulate matter may be toxic in itself or may carry toxic (including carcinogenic) trace substance, and can alter the immune system. Fine particulates penetrate deep into the respiratory system irritating lung tissue and causing long-term disorders.
Carbon Monoxide (CO)	Affects the cardio vascular system, exacerbating cardiovascular disease symptoms, particularly angina; may also particularly affect foetuses, sick, anaemic and young children, affects nervous system impairing physical coordination, vision and judgments, creating nausea and headaches, reducing productivity and increasing personal discomfort.
Oxides of Nitrogen (NO _x)	Increased susceptibility to infections, pulmonary diseases, impairment of lung function and eye, nose and throat irritations.
Sulphur Oxides (SO _x)	Affect lung function adversely.
Carbon Dioxide (CO ₂)	High concentrations of CO ₂ can cause headaches, dizziness, respiratory distress, and impaired cognitive function in humans due to reduced oxygen availability.
Lead Emissions	Impairs liver and kidney, causes brain damage in children resulting in lower I.Q., hyperactivity and reduced ability to concentrate.

but also contribute to air pollution, which can harm human health, reduce air quality, and disrupt ecological balance. Furthermore, the increase in atmospheric GHGs can lead to extreme weather events, melting of polar ice, sea-level rise, and loss of biodiversity, highlighting the urgent need to regulate vehicular emissions and adopt sustainable transportation strategies to mitigate the adverse environmental impacts of the enhanced greenhouse effect.

Ozone Depletion

Vehicular emissions significantly contribute to the depletion of the stratospheric ozone layer, primarily through the release of nitrogen oxides (NO and NO₂) and volatile organic compounds (VOCs) during fuel combustion. Nitrogen oxides act as catalysts in ozone-destroying reactions, following the cycle:



This cycle effectively converts ozone (O₃) into molecular oxygen (O₂), reducing the ozone concentration in the stratosphere. The depletion of ozone allows increased penetration of harmful ultraviolet (UV-B) radiation, which can lead to higher incidences of skin cancer, cataracts, and immunosuppression in humans, as well as adversely affecting terrestrial and aquatic ecosystems. Additionally, ozone layer thinning exacerbates photochemical smog formation near the ground, further contributing to environmental and public health hazards. Hence, vehicular emissions, beyond contributing to local air pollution, play a critical role in global atmospheric chemical disturbances with far-reaching biological consequences.

As mentioned in the table (Table 3), vehicular air pollutants have significant adverse impacts on human health, affecting multiple organ systems and contributing to both acute and chronic illnesses. Particulate matter (PM), particularly fine and respirable particles, can penetrate deep into the respiratory tract, irritating lung tissues and causing long-term respiratory and cardiovascular disorders. Carbon monoxide (CO) interferes with oxygen transport in the blood, aggravating cardiovascular diseases and impairing the

nervous system, especially among vulnerable groups such as children and individuals with pre-existing conditions. Oxides of nitrogen (NO_x) increase susceptibility to respiratory infections, pulmonary diseases, and throat and eye irritations, while sulphur oxides (SO_x) adversely affect lung function and contribute to respiratory distress. Carbon dioxide (CO₂), though not directly toxic, can cause dizziness, headaches, and cognitive impairment at elevated concentrations due to reduced oxygen availability. Lead emissions are particularly harmful, causing neurological damage, reduced cognitive ability, and behavioural problems in children. Collectively, these pollutants not only impair human health but also diminish overall productivity and quality of life (CPCB, 2010).

TRENDS AND ANALYSIS OF VEHICULAR EMISSIONS IN INDIA

According to the International Energy Agency (IEA, 2023), India's growing mobility demand and rapid motorisation have significantly increased road transport-related energy consumption and CO₂ emissions over the past two decades. In 2021, road transport accounted for 14% of India's total energy use—lower than the global average of 20% and other emerging economies such as Indonesia (30%) and Mexico (38%)—primarily due to the high proportion of traditional biomass in the national energy mix. The road transport sector dominates both transport-related energy demand (92%) and CO₂ emissions (94%), with oil products like gasoline and diesel fulfilling 95% of its energy needs, making it the largest and fastest-growing oil-consuming segment (44% of national final oil consumption in 2021). Since 2000, road transport energy demand and emissions have tripled, driven largely by freight trucks (38%) and passenger cars (25%), while two- and three-wheelers, despite comprising 80% of the total vehicle stock, contribute only 20% of fuel use and emissions. Overall, road transport emissions accounted for 12% of India's fossil fuel-related CO₂ output in 2021, with per-capita emissions rising 2.5 times since 2000 yet remaining 50–75% lower than those of comparable economies such as Brazil, China, Indonesia, and Mexico.

Table 4 provides that different vehicle types and fuel combinations contribute to distinct profiles of major air

Table 4: Vehicle types and pollutants for emissions for common engines and fuel combinations
(Source: DieselNet, 2025).

Vehicle Type	Fuel and Ignition Type	Major Pollutants
2-Wheelers	Petrol; Spark-Ignition (SI)	CO, HC, NO _x , PM (low), CO ₂
3-Wheelers (SI)	Petrol / CNG; SI	CO, HC, NO _x , CO ₂
3-Wheelers (CI)	Diesel; Compression-Ignition (CI)	CO, HC, NO _x , PM, CO ₂
Passenger Cars	Petrol; SI	CO ₂ , CO, HC, NO _x , PM (low)
Passenger Cars	Diesel; CI	CO ₂ , NO _x , PM (high), SO ₂
Trucks & Buses	Diesel; CI	CO ₂ , NO _x , PM (high), SO ₂
CNG Vehicles	CNG; SI	CO ₂ (low), NO _x (low), minimal PM
Electric Vehicles	Battery + Motor	Zero tailpipe (life-cycle depends on grid)

pollutants, with notable variations in emission intensity and composition. For example, spark-ignition two-wheelers primarily emit carbon monoxide (CO), hydrocarbons (HC), nitrogen oxides (NO_x), and low particulate matter (PM), alongside carbon dioxide (CO₂). Compression-ignition diesel vehicles, such as certain three-wheelers, trucks, and buses, tend to release higher levels of NO_x, PM, and sulphur dioxide (SO₂), posing substantial health and environmental challenges. In contrast, CNG vehicles exhibit lower emissions of CO, NO_x, and PM, while electric vehicles offer practical zero tailpipe emissions, though their overall lifecycle emissions depend on the electricity grid's energy mix. (DieselNet, 2025).

According to Status of the vehicular pollution control programme in India Report (CPCB, 2010), the graphical representation (Fig. 1) clearly projects the Total CO₂ emissions from a "Well to exhaust" perspective on Indian roads from 2005 to 2035, illustrating a dramatic and accelerating increase in the transport sector's carbon footprint. In the base year of 2005, emissions stood at 208 million tonnes of CO₂. This figure saw a moderate rise to 256 million tonnes by 2008, representing a 23.08% increase over

the three-year period. The pace of growth accelerated significantly over the next seven years, with emissions climbing to 391 million tonnes in 2015, marking a substantial 52.73% increase from the 2008 level. The subsequent decade, encompassing the first major projection, indicates an even more worrying trend, with emissions expected to nearly double, reaching 721 million tonnes in 2025—an enormous 84.40% leap from the 2015 figure. The most substantial projected rise occurs in the final decade shown, as the total CO₂ emissions are forecasted to reach an alarming 1212 million tonnes by 2035. This segment of the forecast alone shows a 68.10% increase over the 2025 figure, highlighting a critical failure point in current sustainability efforts. Overall, the data points to a massive long-term challenge: the projected 2035 emission level of 1212 million tonnes represents an overwhelming 482.69% (nearly a five-fold) increase compared to the 2005 base year.

The "well to exhaust" metric is crucial here as it considers the entire lifecycle of the fuel, from its extraction or production (the "well") to its final use and release of gases (the "exhaust"), providing a comprehensive view of the total carbon footprint. The steep trajectory after 2015 strongly suggests that without major policy interventions, such as the aggressive adoption of electric vehicles, improvements in fuel efficiency standards, or a substantial shift toward public and non-motorised transport, the country's transportation sector will become a vastly larger contributor to global carbon emissions. The data serves as a stark warning and a critical reference point for policymakers planning sustainable transportation and climate mitigation strategies for India.

State-wise CO₂ Emissions in India

According to Mohan *et al.* (2025), the graphical representation (Fig. 2) provides a comparative analysis of state-wise CO₂ emissions in India for the year 2023 and the projected scenario for 2050, with a particular emphasis on vehicular contributions. The data indicates that states with higher population density and rapid urbanisation are expected to experience a sharp escalation in emission levels.

Uttar Pradesh emerges as the highest contributor, with emissions rising from 37 million tonnes in 2023 to a projected 124 million tonnes in 2050, marking an unprecedented increase. Maharashtra follows, with emissions increasing from 38 to 50 million tonnes, while Gujarat is projected to rise from 27 to 41 million tonnes. West Bengal, Madhya Pradesh, and Rajasthan also demonstrate significant growth trajectories, with emissions expected to range between 35 and 46 million tonnes by 2050. In the southern region, Karnataka, Tamil Nadu, and Telangana are forecasted to exhibit consistent growth, largely attributable to increasing vehicle ownership, infrastructural expansion, and economic development. Conversely, smaller states and Union Territories such as Goa, Mizoram, Sikkim, and the Andaman and Nicobar Islands are expected to remain negligible contributors due to their comparatively low vehicular density and limited industrial activity.

According to a report by the Centre for Study of Science, Technology and Policy (CSTEP, 2025), heavy commercial vehicles, though representing only ≈ 2% of the vehicle fleet,

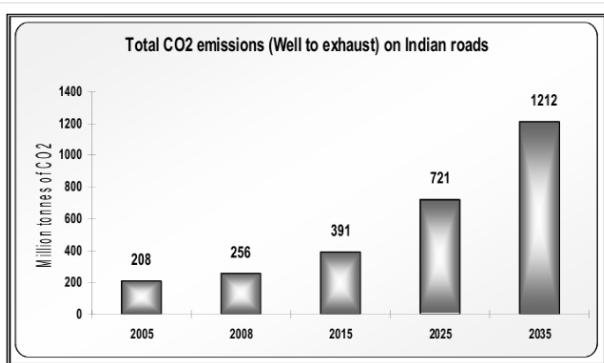


Fig. 1: CO₂ emissions on Indian roads (2005-2035).

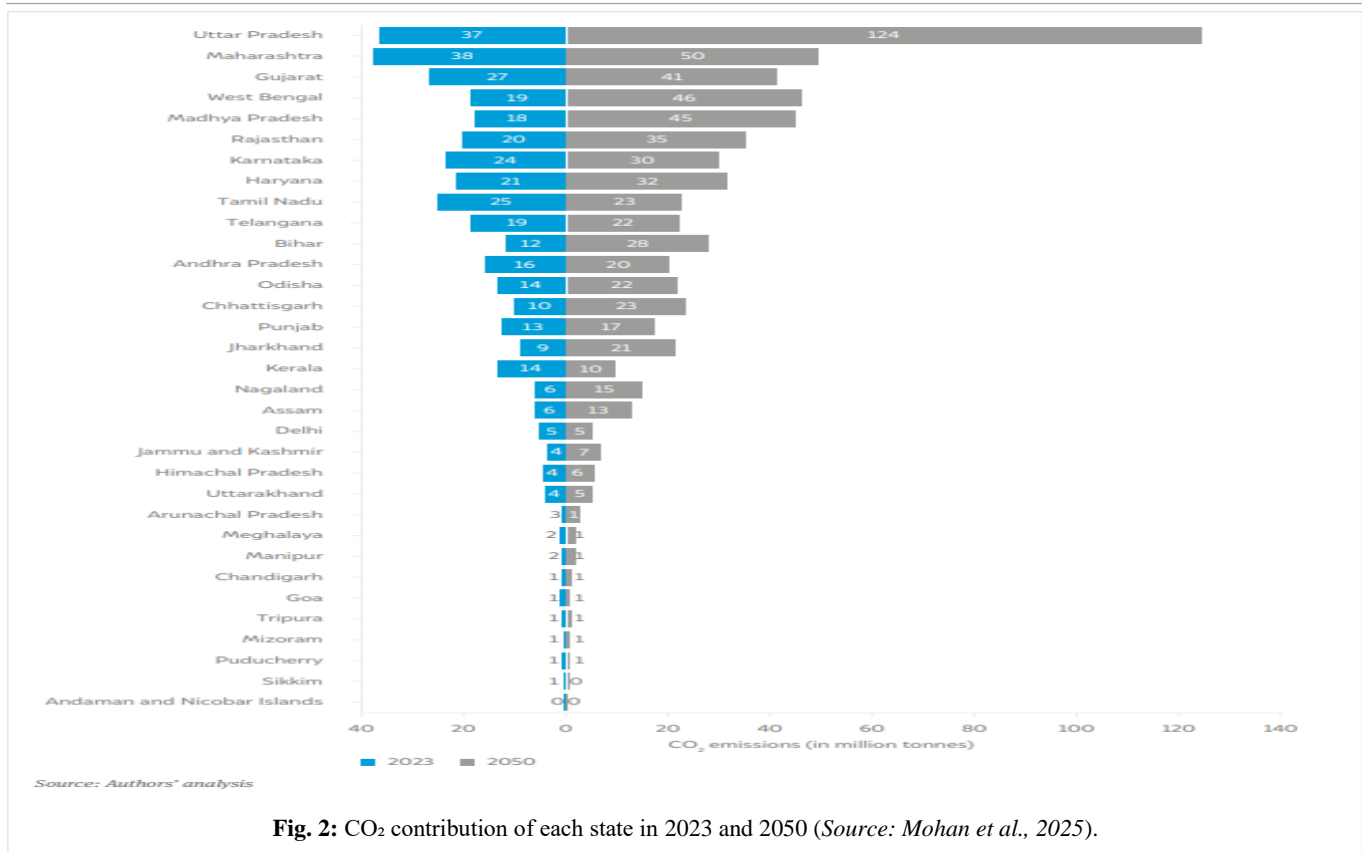


Fig. 2: CO₂ contribution of each state in 2023 and 2050 (Source: Mohan et al., 2025).

contribute nearly 70% of vehicular pollution emissions in India, especially in terms of NO_x, particulate matter, and other exhaust gases. The Transport sector’s emissions profile also includes that road transportation in 2019 was responsible for over 40% of total NO_x emissions (≈ 3.3 million tonnes) and around 7% of combustion-related PM_{2.5} emissions. As of 2018, India had over 300 million registered vehicles, up from roughly 128 million in 2010; the growth has been especially large in two- and four-wheelers, reflecting increasing motorisation and the rising environmental burden from non-industrial sources.

On the policy side, India has implemented Bharat Stage VI (BS-VI) emission standards (effective for all new vehicles after March 2020) to reduce tailpipe emissions. Furthermore,

policy proposals are underway to convert a substantial portion of heavy-duty long-haul trucks from diesel to liquefied natural gas (LNG) over the next 5-7 years, which the government estimates could lower emissions from the heavy vehicle segment markedly.

Emissions from Different Fuel Types in India

The two major fuels used by the transport sector are petrol and diesel. These fuels are carbon-intensive as they contain 80-85% of carbon by weight. On combustion, these fuels release GHGs along with other pollutants, thus contributing to the GHG effect. (IEA-AMF, 2025).

According to Singh et al. (2021), based on data from Table 5 of their emissions inventory for India’s road transport sector:

Table 5: Emissions from on-road vehicles with percentage share of fuel type (2001-2020) (Source: Singh et al., 2021).

Pollutant	Total Emission	Fuel Type Contribution	Vehicle Type / Fleet Share	Age-wise Contribution
CO ₂	274 Mt (265–292)	Diesel 61%, Petrol 37%, CNG 2%	Freight (HDV + LDV) 38% (104 Mt), Private 2W & cars 36% (97.5 Mt), Public transport 15% (41.3 Mt), IPT 11% (31.2 Mt)	Till 2000: 1%, post-2000: 4%, post-2005: 16%, post-2010: 32%, post-2015: 47%
CO	4.463 Mt (3.253–6.676)	Petrol 76%, Diesel 23%, CNG 1%	Private 2W & cars 71% (3.159 Mt)	Till 2000: 9%, post-2000: 7%, post-2005: 13%, post-2010: 31%, post-2015: 40%
PM	0.164 Mt (0.119–0.250)	Petrol highest (103 Gg), Diesel, CNG	Gasoline 2W is dominant due to the fleet size	Till 2000: 4%, post-2000: 12%, post-2005: 21%, post-2010: 28%, post-2015: 36%
NO _x	2.378 Mt (2.191–3.045)	Petrol 57%, Diesel 42%, CNG 1%	Gasoline is dominant due to the fleet size	Till 2000: 3%, post-2000: 8%, post-2005: 21%, post-2010: 38%, post-2015: 31%

Carbon Dioxide (CO₂): Singh *et al.*, (2021) estimated that total CO₂ emissions from on-road vehicles were estimated at 274 Mt (265–292 Mt). Diesel-fuelled freight vehicles (HDV and LDV) were the largest contributors, accounting for 38% (104 Mt), followed by private transport (2W and cars) with 36% (97.5 Mt), public transport at 15% (41.3 Mt), and inter-para transit (IPT) vehicles at 11% (31.2 Mt). Fuel-wise, diesel vehicles contributed 61%, gasoline 37%, and CNG 2%. Age-wise analysis showed post-2015 vehicles (0–5 years old) were responsible for 47% of total CO₂ emissions, while vehicles registered till 2000, post-2000, post-2005, and post-2010 contributed 1%, 4%, 16%, and 32%, respectively (Table 5). Emission control policies have primarily targeted air pollutants, with CO₂ reductions as a co-benefit.

Carbon Monoxide (CO): Total CO emissions were estimated at 4.463 Mt (3.253–6.676 Mt). Gasoline vehicles dominated with 76%, diesel 23%, and CNG 1% (Table 5). Private 2W and cars emitted 71% (3.159 Mt) of the total CO. Post-2015 vehicles contributed 40% (1.789 Mt), followed by post-2010 31%, post-2005 13%, post-2000 7%, and till-2000 vehicles 9%.

Particulate Matter (PM): PM emissions were estimated at 0.164 Mt (0.119–0.250 Mt), with gasoline vehicles contributing the highest share (0.103 Mt) due to their large fleet size despite lower emission factors compared to diesel. Post-2015 vehicles contributed 36%, post-2010 28%, post-2005 21%, post-2000 12%, and till-2000 vehicles 4% (Table 5). Implementation of BS-IV norms in post-2015 vehicles has helped reduce PM emissions.

Nitrogen Oxides (NO_x): NO_x emissions totalled 2.378 Mt (2.191–3.045 Mt), with 57% from gasoline, 42% from diesel, and 1% from CNG vehicles (Table 5). Despite higher NO_x emission factors for diesel vehicles, the larger number of gasoline vehicles resulted in their dominant contribution. Age-wise shares were post-2015 31%, post-2010 38%, post-2005 21%, post-2000 8%, and till-2000 3%.

According to the International Energy Agency (IEA, 2023), the analysis of road transport CO₂ emissions from 2000 to 2021 (Fig. 3) reveals a pronounced and concerning upward trajectory, indicative of rising global fuel consumption in the sector. Total emissions escalated by approximately 232% over the two decades, growing from an estimated 83 Mt CO₂ in 2000 to around 276 Mt CO₂ by 2021. This growth was consistently strong, with emissions increasing by about 106% in the 2000-2010 period (~83 Mt to ~171 Mt), and a further 61% between 2010 and 2021. While Freight Trucks and Light Duty Vehicles remained the largest absolute contributors, their emission growth rates highlight significant challenges: Freight Truck emissions rose by approximately 155% (from ~40 Mt to ~102 Mt), and Light Duty Vehicles saw a 538% increase (from ~13 Mt to ~83 Mt). The most dramatic expansion, however, was recorded in the 2/3 Wheelers category, which experienced a 358% surge in emissions (from ~12 Mt to ~55 Mt), pointing to rapid motorisation in key regional markets. Emissions from Buses also doubled, showing a 105% increase (from ~17 Mt to ~35 Mt). The data collectively indicate that efforts to curb CO₂ from road transport are being substantially outpaced by the underlying growth in vehicle activity and fuel consumption across all segments.

POLICY FRAMEWORK

Policies to Promote Electric Vehicles

Road transport electrification is a crucial strategy for India to mitigate CO₂ emissions, enhance air quality, and promote sustainable economic growth. The government initiated the National Mission for Electric Mobility in 2011, followed by the National Electric Mobility Mission Plan (NEMMP) 2020, (NEMP, 2025), which aimed to boost electric vehicle (EV) adoption through demand incentives, local manufacturing, charging infrastructure, and R&D support. Although the NEMMP targeted 6–7 million EV sales by 2020, less than half a million units were sold due to high costs (MoRTH,

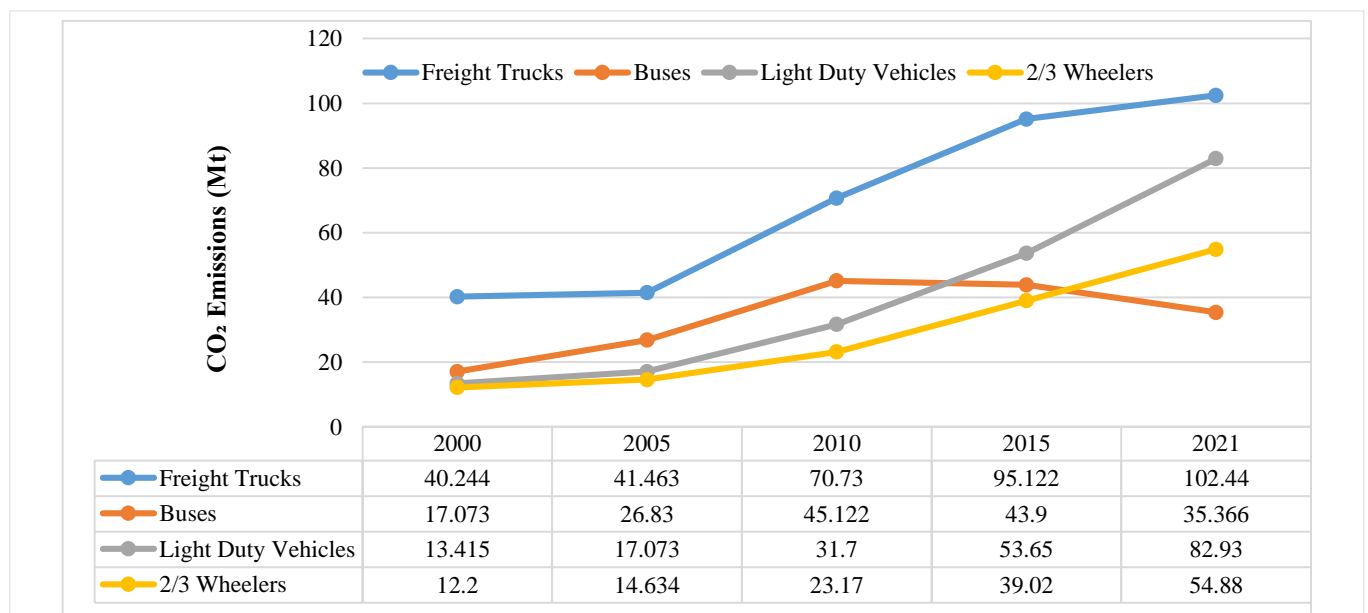


Fig. 3: CO₂ Emissions in Transportation Sector as per Vehicle type.

2025), limited infrastructure, and technological challenges. Renewed momentum came with the 2019 National Mission on Transformative Mobility and Battery Storage, focusing on domestic production of EVs and batteries. Furthermore, India's commitment to the global EV30@30 initiative reflects its goal of achieving a 30% EV sales share by 2030 (CEM, 2022). Despite challenges such as cost barriers, inadequate charging networks, and safety concerns, India's EV market continues to expand steadily, positioning the nation toward a cleaner and more sustainable transport future.

Policies to Reduce Air Pollutant Emissions

In 2000, India introduced the Bharat Stage (BS) Emission Standards modelled on the EU norms. The BS-IV standards were implemented in 2017, and in April 2020 – establishing a precedent of global relevance – India successfully leapfrogged to the implementation of BS-VI. These largely parallel Euro-6/VI norms. The BS standards regulate tailpipe emissions, including PM, SO_x and NO_x as well as carbon monoxide, hydrocarbons and methane. Developed for all vehicle categories, they are applied to vehicles manufactured after April 2020 (ICCT, 2016). Transitioning from BS-IV to BS-VI standards required significant changes for vehicle manufacturers. For example, BS-VI requires diesel vehicles to contain advanced emission control technologies (after-treatment solutions for NO_x and PM) that increase upfront costs. As a result, the market share of diesel-powered passenger cars dropped from 30% in 2019 to 18% in 2020. There has also been a shift from diesel to gasoline engine vehicles in the light commercial vehicle (LCV) fleet (ICCT, 2021). Manufacturers of two-wheelers were for the first time required to introduce a fuel injection system to meet the BS-VI standards. Expectedly, the BS VII norms will introduce stricter controls on the emissions from both petrol and diesel vehicles. A key feature in these new norms will be the 'On Board Monitoring' (OBM) that will monitor the tailpipe emissions in real time. This system will have to be installed in cars, and along with the engine and exhaust gases, this system will monitor the emissions of Nitrogen oxides, Ammonia, and Particulate matter. Moreover, there will be additional rules for particulate emissions from brakes and microplastic emissions from tyres, which will be applicable to EVs as well.

Odd-even rule policy

The Odd-Even vehicle policy was introduced by the Government of Delhi as a short-term traffic management and air pollution control measure (CPCB, 2016). Under this scheme, vehicles with license plates ending in odd and even numbers are allowed to operate on alternate days, thereby reducing traffic volume and tailpipe emissions (TERI, 2017). The policy aimed to lower concentrations of major pollutants such as PM_{2.5}, CO, and NO_x, which are primarily emitted from vehicles (CPCB, 2019). Studies reported a temporary decline in air pollution levels and improved traffic flow during its implementation, though long-term effectiveness remained limited due to exemptions and enforcement challenges (Milne, 2016). Despite its short duration, the policy raised public awareness about vehicular pollution and the need for sustainable mobility strategies.

CONCLUSION AND DISCUSSIONS

Vehicular emissions in India have emerged as a major contributor to air pollution, releasing significant amounts of CO₂, CO, NO_x, SO₂, and particulate matter, which adversely affect air quality, human health, and ecosystems. The rapid growth of urban transport, reliance on diesel-fuelled vehicles, and inadequate emission control measures have intensified environmental degradation, leading to phenomena such as smog formation, acid rain, and ozone depletion. Policy interventions, including the implementation of Bharat Stage emission standards, promotion of electric vehicles, and initiatives like the Odd-Even scheme, have shown potential in reducing pollutant loads, though challenges such as infrastructure limitations, high vehicle density, and public awareness remain. The transition towards cleaner fuels, the adoption of electric mobility, and stricter enforcement of vehicular emission norms are essential to mitigate the environmental impact of road transport. Overall, a combination of technological innovation, policy support, and public participation is critical to achieving sustainable urban mobility and improving air quality in India.

Acknowledgement

The study is part of the author's undergraduate project. The author is thankful to Prof. S. Deswal, Department of Civil Engineering, National Institute of Technology, Kurukshetra, for his unwavering guidance, support and mentorship throughout the project.

Grant Support Details

The present study did not receive any financial support.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/ or submission, and redundancy, have been completely observed by the authors.

REFERENCES

- 1) Bolaji, B.O. and Adejuyigbe, S.B. (2006) 'Vehicle emissions and their effects on the natural environment - a review', *Journal of the Ghana Institution of Engineers*, 4(1), pp. 35-41.
- 2) CEEW (2024) *Vehicular emissions in India: an overview of sources and mitigation strategies*. Council on Energy, Environment and Water. Available at: <https://www.ceew.in/gfc/quick-reads/explains/vehicular-emissions-in-india> (Accessed: 15 Oct. 2025).
- 3) CEM (2022) *EV30@30 campaign*. The Clean Energy Ministerial. Available at: <https://www.cleanenergyministerial.org/initiatives-campaigns/ev3030-campaign/> (Accessed: 15 October 2025).
- 4) CPCB (2010) *Status of the vehicular pollution control programme in India. Programme Objective Series PROBES/136/2010*. Central Pollution Control Board, New Delhi. Available at: <https://www.transportpolicy.net/wp-content/uploads/2021/08/status-of-the-vehicular-pollution.pdf> (Accessed: 27 September 2025).
- 5) CPCB (2016) *Report on ambient air quality data during odd and even period, 15th to 30th April, 2016*. Central Pollution Control Board, New Delhi. Available at: <https://cpcb.nic.in/displaypdf.php?id=T0REX0VVRU5fc2NoZW11Xz-IucGRm> (Accessed: 27 September 2025).
- 6) CPCB (2019) *National ambient air quality status & trends*. Central Pollution Control Board, New Delhi. Available at:

- https://cpceb.nic.in/upload/NAAQs_2019.pdf (Accessed: 27 September 2025).
- 7) Crippa, M., Guizzardi, D., Pagani, F. *et al.* (2025) *GHG emissions of all world countries*. JRC/IEA 2025 Report, Luxembourg. <https://data.europa.eu/doi/10.2760/9816914> (Accessed: 27 September 2025).
 - 8) CSTEP (2025) *Heavy duty, high impact: mitigating heavy commercial vehicle emissions in India*, The Center for Study of Science, Technology and Policy (CSTEP). Bengaluru. Available at: https://cstep.in/wp-content/uploads/2025/09/Heavy-duty-high-impact_Mitigating-heavy-commercial-vehicle-emissions-in-India-1.pdf (Accessed: 15 Oct. 2025).
 - 9) CT (2020) *Climate transparency report: comparing G20 climate action and responses to the COVID-19 crisis*. Climate Transparency. Available at: <https://www.climate-transparency.org/wp-content/uploads/2020/11/Climate-Transparency-Report-2020.pdf> (Accessed: 14 October 2025).
 - 10) Desai, A.A., (2018) 'A review on assessment of air pollution due to vehicular emission in traffic area'. *International Journal of Computational Engineering Research*, 8(2), pp. 356–360. <https://doi.org/10.14741/ijcet/v.8.2.27>
 - 11) Deswal, S. and Chandna, P. (2010) 'Effects of meteorological conditions on concentration of air pollutants in Delhi', *International Journal of Environment and Pollution*, 42(1-3), pp. 58-67.
 - 12) Deswal, S. and Deswal, A. (2017) *A Basic Course in Environmental Studies*. 3rd ed. New Delhi: Dhanpat Rai & Co. (P) Ltd.
 - 13) Deswal, S. and Verma, V. (2016) 'Annual and seasonal variations in air quality index of the national capital region, India', *International Journal of Environmental and Ecological Engineering*, 10(10), pp. 1000-1005.
 - 14) DieselNet (2025) *Emission standards - India: 2- and 3-wheel vehicles*. DieselNet. Available at: <https://dieselnet.com/standards/in/2wheel.php> (Accessed 27 September 2025).
 - 15) ICCT (2021) *Fuel consumption from new passenger cars in India: manufacturers' performance in fiscal year 2020–21*. International Council on Clean Transportation. Available at: <https://theicct.org/publication/fuel-consumption-from-new-passenger-cars-in-india-manufacturers-performance-in-fiscal-year-2020-21/> (Accessed: 28 October 2025)
 - 16) ICCT (2016) *India bharaat stage VI emission standards: policy update*. International Council on Clean Transportation. Available at: <https://theicct.org/sites/default/files/publications/India%20BS%20VI%20Policy%20Update%20vF.pdf> (Accessed: 28 October 2025)
 - 17) IEA (2023). *Transitioning India's road transport sector: realising climate and air quality benefits*. The International Energy Agency. Available at: <https://www.iea.org/reports/transitioning-indias-road-transport-sector> (Accessed 26 September 2025).
 - 18) IEA-AMF (2025) *Fuel information: diesel and gasoline*. the International Energy Agency-Advanced Motor Fuel. Available at: https://www.iea-amf.org/content/fuel_information/diesel_gasoline (Accessed: 15 October 2025).
 - 19) Kishore, N. and Deswal, S. (2017) 'Analysis of air pollution in Indian cities—a literature review', *Int. J. Emerg. Technol.*, 8(1), pp. 191-195.
 - 20) Kumar, M., Shao, Z., Braun, C. and Bandivadekar, A. (2022) 'Decarbonising India's road transport: a meta-analysis of road transport emissions models', *International Council on Clean Transportation (ICCT)*. Available at: https://theicct.org/wp-content/uploads/2022/05/Meta-study-India-transport_final.pdf (Accessed 27 Sept. 2025).
 - 21) Kumari, J. and Deswal, S. (2017) 'Assessment of air pollution tolerance index of selected plants unveil to traffic roads of Noida, Uttar Pradesh', *International Journal on Emerging Technologies*, 8(1), pp. 179-184.
 - 22) Milne, E. (2016) 'Note from the editor in chief. *Environmental Development*, 18, pp. 1.
 - 23) Mohan, D.S., Elango, S., Mallya, H., Jain, H. and Jha, A. (2025) *What is fuelling India's road transport sector? Projecting district-level energy demand*. The Council on Energy, Environment and Water (CEEW), New Delhi. Available at: <https://www.ceew.in/sites/default/files/how-will-fuel-demand-grow-with-changing-fuel-mix-in-different-vehicle-segments.pdf> (Accessed 8 October 2025).
 - 24) MoRTH (2025) *Vahan dashboard*. The Ministry of Road Transport and Highways, Government of India. Available at: <https://analytics.parivahan.gov.in/analytics/publicdashboard/vahan?lang=en> (Accessed 8 October 2025).
 - 25) NEMMP (2025) *The status of implementation of the national electric mobility mission plan*. The National Electric Mobility Mission Plan. Available at: <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2102783>. (Accessed: 27 September 2025).
 - 26) PIB (2023) *Total 2,27,17,562 vehicles registered during 2023 including electric, petrol and diesel vehicles*. Press Information Bureau, Delhi. Available at: <https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1987802> (Accessed 14 October 2025).
 - 27) Posthumus, A.C. (1983) 'Higher plants as indicators and accumulators of gaseous air pollution', *Environmental Monitoring and Assessment*, 3, pp. 263–272. <https://doi.org/10.1007/BF00396220>
 - 28) Ramachandra, T.V. and Kashyap, S. (2009) 'Emissions from India's transport sector: statewise synthesis'. *Atmospheric Environment*, 43(34), pp. 5510–5517. Available at: <https://doi.org/10.1016/j.atmosenv.2009.07.015>.
 - 29) Saharan, S. and Deswal, S. (2024) 'Air quality mapping and urban planning for sustainable urban ecology: a case study of Chandigarh, India', *Ecological Questions*, 35(2), pp. 107-116.
 - 30) Singh, N., Mishra, T. and Banerjee, R. (2021) 'Emissions inventory for road transport in India in 2020: framework and post facto policy impact assessment', *Research Square*. Available at: <https://doi.org/10.21203/rs.3.rs-297185/v1> (Accessed: 26 September 2025).
 - 31) Statista (2025) *Worldwide annual carbon dioxide emissions by select country*. Statista. Available at: <https://www.statista.com/statistics/500524/worldwide-annual-carbon-dioxide-emissions-by-select-country/> (Accessed 8 October 2025)
 - 32) TERI (2017) *Step up the controls beyond odd-even scheme: TERI*. The Energy and Resources Institute, New Delhi. Available at: https://www.teriin.org/sites/default/files/pressrelease/TERI_odd-even_pressrelease.pdf (Accessed: 25 October 2025)
 - 33) Waghmare, A. (2025) *Vehicle ownership in India*. Data For India. Available at: <https://www.dataforindia.com/vehicle-ownership/> (Accessed 8 October 2025)
 - 34) WHO (2023) *Ambient air pollution: health impacts*. The World Health Organization. Available at: [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health) (Accessed 27 Sept. 2025).
 - 35) WPR (2025) *Car production by country 2025*. World Population Review. Available at: <https://worldpopulationreview.com/country-rankings/car-production-by-country> (Accessed 14 October 2025).