



A Review of Global Road Transportation and Climate Change: Mitigation Strategies and Adaptation Challenges in Developing Countries

Sani Abubakar Sadiq, Hari Imrana, Abdulaziz Ahmed
Department of Geography,
Federal University of Education, Zaria Kaduna State

ABSTRACT

Road transportation is a significant and rapidly growing contributor to Global Greenhouse Gas (GHG) emissions, exacerbating climate change. This impact is particularly pronounced in developing countries, where burgeoning populations, urbanization, and increasing motorization rates are driving a rapid expansion of road networks and vehicle fleets. Simultaneously, these nations are highly vulnerable to the adverse effects of climate change, including extreme weather events, sea-level rise, and changing precipitation patterns, which directly threaten road infrastructure and mobility. This paper provides a comprehensive review of the complex interplay between global road transportation and climate change, with a specific focus on the unique challenges and opportunities present in developing countries. It examines various mitigation strategies aimed at reducing emissions from the road transport sector and explores the critical need for adaptation measures to enhance the resilience of road infrastructure against climate impacts. Furthermore, it discusses the prevalent barriers to implementing these strategies and highlights potential solutions, including innovative financing mechanisms and integrated policy frameworks.

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INTRODUCTION

Climate change represents one of the most pressing global challenges of the 21st century, with far-reaching environmental, social, and economic consequences. The Intergovernmental Panel on Climate Change (IPCC) unequivocally states that human activities, primarily the burning of fossil fuels, are the dominant cause of observed warming (IPCC, 2023). Among these activities, the transportation sector plays a pivotal role, accounting for a substantial portion of global energy-related greenhouse gas (GHG) emissions (International Energy Agency [IEA], 2024). Within this sector, road transportation is the largest contributor, driven by an ever-increasing demand for passenger and freight movement worldwide.

The situation is particularly critical in developing countries. While historically contributing less to cumulative GHG emissions,

these nations are experiencing rapid economic growth, urbanization, and a corresponding surge in vehicle ownership and road infrastructure development (United Nations Environment Programme [UNEP], 2024). This growth trajectory, if unchecked, threatens to lock in high-carbon development pathways, making it challenging to meet global climate targets. Moreover, developing countries often possess less resilient infrastructure and limited financial and technical capacities, rendering them exceptionally vulnerable to the impacts of climate change on their road networks (World Bank, 2021). Extreme weather events such as floods, droughts, heatwaves, and rising sea levels pose significant threats, leading to infrastructure damage, disruptions in supply chains, and adverse socio-economic consequences.

This paper aims to synthesize the current understanding of the relationship between

Corresponding author: Sani Abubakar Sadiq

✉ abusadiqsan@gmail.com

Department of Geography, Federal University of Education, Zaria Kaduna State.

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global road transportation and climate change, with a particular emphasis on the context of developing countries. It will delve into both mitigation strategies, designed to reduce the climate footprint of road transport, and adaptation challenges, focusing on building resilience into road infrastructure and operations.

The Impact of Road Transportation on Climate Change

Road transport contributes to climate change primarily through the emission of greenhouse gases, predominantly carbon dioxide (CO₂), from the combustion of fossil fuels (gasoline, diesel) (IEA, 2024). Other GHGs, such as methane (CH₄) and nitrous oxide (N₂O), are also emitted, albeit in smaller quantities. The key factors driving increasing emissions from road transport include:

1. Growing Vehicle Fleets: Rapid motorization, especially in developing countries, leads to a significant increase in the number of vehicles on the road (UNEP, 2024). The desire for private vehicle ownership, often fueled by rising incomes and inadequate public transport, contributes to this trend.
2. Increased Vehicle Kilometers Traveled (VKT): Urban sprawl, longer commute distances, and the expansion of freight logistics contribute to a rise in the total distance traveled by vehicles.
3. Dominance of Internal Combustion Engine (ICE) Vehicles: Despite advancements in vehicle efficiency, ICE vehicles still dominate the global fleet, heavily reliant on fossil fuels (IEA, 2024).
4. Congestion: Traffic congestion leads to inefficient fuel consumption and higher emissions due to prolonged idling and stop-and-go driving (World Health Organization [WHO], 2023).
5. Fuel Quality: In some developing countries, lower fuel quality standards can result in higher emissions of pollutants and GHGs.

6. Infrastructure Development: The construction and maintenance of road infrastructure also involve energy-intensive processes, leading to embodied carbon emissions.

The implications of these emissions are profound, contributing to global warming, which in turn manifests as more frequent and intense extreme weather events, sea-level rise, and disruptions to natural ecosystems, all of which feedback to impact the transportation sector itself (IPCC, 2023).

Mitigation Strategies in Road Transportation

Mitigation strategies in the road transport sector aim to reduce GHG emissions by decreasing fuel consumption, shifting to cleaner energy sources, and optimizing transport demand. For developing countries, these strategies often offer co-benefits such as improved air quality, reduced traffic congestion, and enhanced energy security (WHO, 2023). Key mitigation approaches include:

Technological Advancements and Vehicle Efficiency:

1. Promotion of Electric Vehicles (EVs) and Hybrid Electric Vehicles (HEVs): This involves incentives for EV adoption (subsidies, tax breaks, charging infrastructure development) and stricter fuel economy standards for ICE vehicles (Smith & Chen, 2025; UNEP, 2024). The effectiveness of EVs is highly dependent on the decarbonization of the electricity grid.
2. Improved Fuel Efficiency for Conventional Vehicles: Implementing stricter emissions standards, promoting eco-driving practices, and encouraging regular vehicle maintenance.
3. Development and Use of Alternative Fuels: Exploring and scaling up sustainable biofuels, hydrogen, and other low-carbon energy sources for transportation, while ensuring their environmental and social sustainability.



Urban Planning and Infrastructure Design:

1. Transit-Oriented Development (TOD) and Compact City Planning: Designing urban areas to integrate residential, commercial, and recreational spaces with efficient public transport networks reduces the need for private vehicle travel and encourages walking and cycling (Lättman & Otsuka, 2024; UNEP, 2024).
2. Investment in Public and Mass Transit Systems: Expanding and improving the quality, accessibility, and affordability of public transport (buses, trains, metro systems) can encourage modal shifts away from private cars (Asian Development Bank [ADB], 2023).
3. Development of Non-Motorized Transport (NMT) Infrastructure: Creating safe and convenient infrastructure for walking and cycling (e.g., sidewalks, bike lanes) can promote active mobility for short distances (WHO, 2023).

Demand-Side Management and Behavioral Changes:

1. Pricing Mechanisms: Implementing congestion charges, road pricing, and carbon taxes on fuel can disincentivize private vehicle use and encourage more sustainable modes (IEA, 2024).
2. Ride-sharing and Car-pooling Initiatives: Promoting shared mobility options to reduce the number of vehicles on the road.
3. Freight Logistics Optimization: Improving the efficiency of freight movement through better routing, consolidation, and modal shifts (e.g., from road to rail or inland waterways).
4. Public Awareness Campaigns: Educating the public on the benefits of sustainable transport choices and encouraging behavioral shifts.

Policy and Regulatory Frameworks:

1. National and Sub-national GHG Reduction Targets: Setting ambitious and legally binding targets for emissions reduction in the transport sector (Bongardt et al., 2014).
2. Integrated Transport and Land-Use Planning: Ensuring coherence between urban development plans and transport infrastructure investments to promote sustainable mobility patterns (UNEP, 2024).
3. Supportive Fiscal Policies: Utilizing subsidies, tax incentives, and levies to promote cleaner vehicles and fuels, and disincentivize high-carbon transport options.

Adaptation Challenges in Developing Countries

While mitigation addresses the root causes of climate change, adaptation focuses on minimizing its inevitable impacts. Road transport infrastructure in developing countries faces significant adaptation challenges due to:

Extreme Weather Events:

1. Increased Frequency and Intensity of Flooding: Roads are vulnerable to inundation, erosion, and damage from heavy rainfall and riverine or coastal flooding, leading to closures and disrupted connectivity (Mohsen & Abdul-Ghani, 2025; World Bank, 2021). This is particularly critical in urban areas with inadequate drainage.
2. Heatwaves: Extreme heat can cause asphalt to degrade, railway tracks to buckle, and affect vehicle performance and safety.
3. Droughts and Wildfires: Droughts can lead to soil instability and increased risk of wildfires, which can damage road infrastructure and impair visibility.
4. Strong Winds and Storms: These can cause direct damage to road structures, bring down trees, and lead to debris on roads.

Sea-Level Rise and Coastal Erosion:

For developing countries with extensive coastal road networks, rising sea levels and increased storm surges threaten to inundate, erode, and salinize vital infrastructure, displacing communities and disrupting trade (IPCC, 2023; UN-OHRLS, 2020).

Permafrost Thaw:

In regions with permafrost (e.g., some high-altitude or northern developing countries), rising temperatures can cause thawing, leading to ground instability, settlement of roads, and damage to foundations.

Limited Financial and Technical Capacity:

1. Insufficient Funding: Developing countries often struggle with limited domestic budgets for infrastructure development and maintenance, making it challenging to allocate resources for climate-resilient designs and upgrades (ADB, 2023; United Nations Development Programme [UNDP], 2025).
2. Lack of Data and Assessment Tools: Insufficient data on climate risks, vulnerability assessments, and cost-benefit analyses for adaptation measures hinder effective planning.
3. Technical Expertise Gaps: A shortage of skilled personnel in climate-resilient infrastructure design, construction, and maintenance can impede implementation (UNDP, 2025).
4. Institutional Weaknesses: Fragmented governance structures, lack of coordination among relevant agencies, and weak regulatory frameworks can impede integrated adaptation planning.

Existing Vulnerable Infrastructure:

Much of the existing road infrastructure in developing countries was not designed with future climate change impacts in mind, making it inherently vulnerable. Retrofitting existing infrastructure can be prohibitively expensive.

Socio-Economic Impacts:

Disruption to road networks due to climate events disproportionately affects vulnerable populations, hindering access to essential services (healthcare, education), markets, and livelihoods (WHO, 2023).

Strategies for Adaptation and Building Resilience

To address the adaptation challenges, developing countries need to implement a range of strategies to build climate resilience into their road transport systems:

Climate-Resilient Design and Construction:

1. Elevating Roadways: Raising road levels in flood-prone areas (World Bank, 2021).
2. Improved Drainage Systems: Designing and implementing robust drainage infrastructure to manage increased precipitation and prevent flooding.
3. Using Climate-Resistant Materials: Employing materials that can withstand higher temperatures, increased moisture, or erosion (PIARC, 2016).
4. Flexible Pavement Designs: Designing pavements that can better accommodate ground movement due to permafrost thaw or extreme heat.
5. Bio-engineering Solutions: Utilizing natural systems like mangroves or vegetation to protect coastal roads from erosion and storm surges (OECD, 2024).

Other Key Strategies:

1. Vulnerability and Risk Assessments: Conducting systematic assessments to identify critical infrastructure at risk, quantify potential impacts, and prioritize adaptation interventions. This requires robust data collection and modeling capabilities (World Bank, 2021).
2. Early Warning Systems and Emergency Response: Developing and implementing effective early warning systems for extreme weather events and establishing rapid response

mechanisms to minimize disruptions and facilitate recovery.

Integrated Planning and Policy:

1. Mainstreaming Climate Change into Transport Planning: Integrating climate change considerations into all stages of road infrastructure planning, design, construction, operation, and maintenance (UNDP, 2025).
2. Cross-Sectoral Collaboration: Fostering collaboration between transport authorities, urban planners, disaster management agencies, and environmental ministries.
3. Developing National Adaptation Plans (NAPs) for Transport: Creating specific action plans with clear targets and indicators for climate resilience in the transport sector.
4. Capacity Building and Knowledge Transfer: Investing in training and education for engineers, planners, and policymakers on climate-resilient infrastructure practices. Facilitating knowledge exchange with developed countries and international organizations (UNDP, 2025).

Innovative Financing Mechanisms:

1. Leveraging Climate Finance: Accessing international climate funds (e.g., Green Climate Fund, Adaptation Fund) and multilateral development bank financing for climate-resilient transport projects (ADB, 2023; World Bank, 2023).
2. Public-Private Partnerships (PPPs): Exploring partnerships with the private sector to mobilize resources and expertise for resilient infrastructure development.
3. Green Bonds and Climate Bonds: Issuing financial instruments specifically designed to fund climate-friendly projects.
4. National Climate Funds: Establishing dedicated domestic funds for climate

action, supported by national budgets and innovative revenue streams.

5. Cost-Benefit Analysis: Demonstrating the long-term economic benefits of investing in climate resilience, as the costs of inaction often far outweigh the costs of adaptation.

Case Studies and Lessons Learned (Examples from developing countries)

While a comprehensive list is beyond the scope of this review, several developing countries are implementing promising strategies:

1. Ethiopia: The government has been integrating climate resilience into its road sector development program, focusing on improved drainage, erosion control, and community-based adaptation measures for rural roads (Ministry of Planning and Development, 2023).
2. Bangladesh: Faced with severe flood risks, Bangladesh is investing in elevating road embankments, constructing flood-resistant bridges, and improving early warning systems for road users (Local Government Engineering Department [LGED], 2022).
3. Small Island Developing States (SIDS): Many SIDS are prioritizing coastal road protection measures, including seawalls, mangroves, and nature-based solutions, to combat sea-level rise and storm surges (UN-OHRLS, 2020).
4. India (e.g., Bangalore): Case studies have shown how GIS-based approaches can be used to evaluate the impact of floods on road networks and to design mitigation and adaptation policies, such as increasing public transport road networks and restricting private vehicle access in certain areas (Sharma & Kumar, 2019).

These examples, while diverse, highlight the importance of:

1. Context-specific solutions: Adaptation and mitigation strategies must be tailored to the specific climatic, geographical, and socio-economic conditions of each country or region.
2. Integrated approaches: Combining mitigation and adaptation measures often leads to more effective and sustainable outcomes.
3. Multi-stakeholder engagement: Successful implementation requires collaboration among government agencies, local communities, the private sector, and international partners.

Barriers and Opportunities for Developing Countries

Despite the clear imperative, developing countries face significant barriers in addressing road transport's climate impact:

1. Financial Constraints: The high upfront costs of investing in low-carbon technologies and climate-resilient infrastructure remain a major hurdle (ADB, 2023).
2. Technological Gaps: Access to and adoption of advanced low-carbon transport technologies can be limited.
3. Lack of Data and Planning Capacity: Insufficient data on emissions, climate vulnerabilities, and the effectiveness of different interventions hinders informed decision-making.
4. Institutional Weaknesses and Governance Challenges: Corruption, lack of coordination, and inadequate regulatory frameworks can impede effective policy implementation (UNDP, 2025).
5. Prioritization of Economic Growth: In many developing countries, immediate economic development and poverty alleviation often take precedence over long-term climate considerations.
6. Informal Transport Sector: The large informal transport sector in many developing cities presents unique

challenges for regulation and emissions control.

However, significant opportunities also exist:

1. "Leapfrogging" Technologies: Developing countries have the potential to bypass outdated, high-carbon technologies and directly adopt cleaner alternatives (e.g., widespread EV adoption, renewable energy for public transport) (UNEP, 2024).
2. Green Growth Pathways: Integrating sustainable transport into national development plans can foster green growth, creating jobs and improving quality of life.
3. International Support: Increasing availability of climate finance, technical assistance, and capacity-building programs from international donors and organizations (ADB, 2023; UNDP, 2025).
4. Urbanization as an Opportunity: Planned urbanization can create opportunities for designing sustainable, transit-oriented cities from the outset, rather than retrofitting existing car-dependent urban areas (UNEP, 2024).
5. Co-benefits: Mitigation and adaptation measures often yield significant co-benefits, such as improved air quality, reduced traffic congestion, enhanced public health, and energy security, which can strengthen the case for investment (WHO, 2023).

CONCLUSION AND RECOMMENDATIONS

Global road transportation undeniably plays a dual role in the climate change crisis: as a major emitter of GHGs and as a sector highly vulnerable to climate impacts. For developing countries, this dynamic is particularly challenging, given their rapid growth and inherent vulnerabilities. Addressing this complex issue requires a holistic and integrated approach that simultaneously pursues ambitious mitigation strategies and robust adaptation measures.



Key recommendations for developing countries include:

1. Prioritize Sustainable Urban Mobility: Invest heavily in integrated public transport systems, non-motorized transport infrastructure, and compact urban planning to reduce reliance on private vehicles (UNEP, 2024).
2. Accelerate the Transition to Low-Carbon Vehicles: Implement policies and incentives for the adoption of electric vehicles, and promote the development of renewable energy sources to power them (UNEP, 2024).
3. Integrate Climate Resilience into all Transport Planning: Mandate climate risk and vulnerability assessments for all new and existing road infrastructure projects, and incorporate climate-resilient design standards (World Bank, 2021).
4. Strengthen Institutional and Technical Capacities: Invest in training, knowledge transfer, and institutional reforms to enhance the ability of government agencies and local communities to plan, implement, and manage climate-resilient transport systems (UNDP, 2025).
5. Leverage Innovative Financing: Actively seek and effectively utilize international climate finance, explore public-private partnerships, and develop domestic funding mechanisms to bridge the investment gap for sustainable and resilient transport (ADB, 2023; World Bank, 2023).
6. Foster Regional and International Collaboration: Share best practices, technologies, and lessons learned through regional and global partnerships.
7. Embrace Data-Driven Decision Making: Invest in data collection, modeling, and monitoring systems to inform policy development, track progress, and evaluate the effectiveness of interventions.

By embracing these strategies, developing countries can transform their road transportation sectors from being a source of climate vulnerability into a pathway for sustainable development, enhanced resilience, and a cleaner, more prosperous future. The transition will require strong political will, innovative policy design, sustained financial commitment, and concerted collaboration among all stakeholders.

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Corresponding author: Sani Abubakar Sadiq

✉ abusadiqsan@gmail.com

Department of Geography, Federal University of Education, Zaria Kaduna State.

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