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Article

Climate-resilient transportation policies for India: Strategies and challenges

Krishna Murthy Inumula[1,*], Anupama Tadamarla[2]

[1] Symbiosis Institute of International Business, Symbiosis International (Deemed University), Pune 412115, India
[2] ICFAI Business School, Pune 411028, India
[*] **Corresponding author:** Krishna Murthy Inumula, dr.krishna@siib.ac.in

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Abstract: The transportation sector in India, which is a vital engine for economic growth, is progressively facing challenges related to climate change. Increased temperature, extreme weather conditions, and rising seas threaten physical infrastructure, service delivery, and the economy. This research examines efforts towards improving the climate resilience of India's transport sector through policy interventions. Strategies encompass broadening the focus to cover the integration of sustainability, innovative technology deployment, and adaptive infrastructure planning. Multi-sectoral measures are proposed to guarantee longevity, equity and environmental protection. National transport infrastructure will be secured, people will be enabled to move sustainably, and India will take its position in the world economy as a climate-resilient country. Long-term resource management and promoting inclusive governance are critical to agri-transportation systems that can withstand the changing climate.

Keywords: transportation; climate resilience; India; infrastructure; sustainable development; Policy Framework

1. Introduction

India's rising transportation sector, an economic development engine, is rapidly becoming susceptible to the vagaries of climate change. On the rise in temperature, extreme weather events and a rise in sea level over the year constitute a danger to the infrastructure, cause service interruptions, and have high economic costs. Transporting goods, on which about 6% of India's GDP is dependent, incurs various pains, such as flooding, heat waves, and cyclones, which spoil the roads, railways, and ports' transport system. Coastal cities such as Mumbai and Chennai, with transportation hubs on the coast, are in danger from rising sea levels, threatening the functional status of these economic hubs. Urban transport systems found in the cities, especially in metropolitan cities, are prone to the effects of the urban heat island restricting such levees, which raises the costs of maintaining them. The dispatch and transportation of goods are not only affected by such climatic challenges that disrupt the urban normal but also interfere with the movement of raw materials required for productive undertakings. Hence, climate change concerns call for the immediate deployment of appropriate policy measures and structural changes to protect and sustain the economic activities of the transport sector.

The impacts of global warming are severe and pose a significant challenge to India's transportation structure, which is essential for the country's economy. The transport system of bridges, tunnels, overpasses, highways, railroads, and airports has a long life and works under changes in temperature and humidity. Therefore, it is highly susceptible (Picketts et al., 2015). Extreme city events may directly affect

transportation systems (2022). The key stressors range from heavy rainfall to extreme heat, coastal inundation, and wildfires, affecting essential facilities (2021). Adverse economic impacts arise from physical destruction, loss of normal operations, and aggravation of the social system, which is distressed by extreme climate events (Dundon et al., 2016). About the sector, high temperatures and increased or decreased winds and rain may impact how airports function, making the distance on take-off longer and the angle of climbing sharply less; therefore, there will be supposed delays, longer flights and increased fares affecting travel and tourism (Paraschi, 2023). Transport resilience needed to support economic development objectives will require adaptation measures and proactive planning strategies like nature-based solutions (NbSs), risk-assessment strategies, long-term strategies, and climate change policies (Blackwood et al., 2022; Paraschi, 2023).

In light of floods, extreme heat, and other climate-related challenges, authorities are designing and constructing climate-smart infrastructure and embracing green modes of transportation. This entails the application of sophisticated materials and designs, the use of safe technologies, and the enhancement of predictive capabilities. Transport infrastructures are threatened with disruption and economic losses due to rising climatic temperatures and increasing sea levels. Policymakers need to incorporate adaptive strategies, improve structures, and encourage green options to increase productivity without compromising the sustainability of transportation networks three-fold. Implementing these strategies involves several actors, including the state, the private sector, and communities. Working together can meet short-term objectives while achieving a more holistic long-term sustainability vision. Further, financing the research and development of climate-proof technologies and materials, for instance, can generate novel ideas to strengthen transport infrastructure's ability to cope with environmental changes.

This study examines the possible strategic measures that could provide heightened climate adaptation to India's transport sector through policy. It identifies the existing gaps and reviews best international practices that have worked. Then, it suggests policy recommendations that are specifically meant for India's first suggestions that have come to try and create solutions. The study structure is set in such a way that it will offer an in-depth look into impacts associated with climate change on Indian transport, anchor the framework for crucial policies, sell cases of success stories in climate resilience, reveal in real terms what it means when programs like this are being implemented, and give recommendations. The conclusion will summarize and consolidate the essential findings and present implications; it underscores the importance of planning in the long run, efficiency in using resources, and governance inclusivity in living a resilient transport network. Proposed policies and strategies are implemented to enhance India's claims as climate-resilient even as the nation works on the insured properties, sustainable mobility, and becoming a benchmark to other nations in climate-resilient development.

2. Literature review

In India, natural calamities such as floods, cyclones, and heatwaves are common and wreak havoc on transport infrastructure, such as roads, railways, and ports. The 2015 Chennai floods exposed many weaknesses, especially in the road and rail transport, which experienced tremendous disturbances. Transportation networks along the coasts, especially the ports and airports of Mumbai and Chennai, are increasingly at risk of being underwater due to global warming. As a result, the efficiency of these modes of transport is under threat. Metropolitan transportation, which comprises metro rail and roading activities, is at more risk of failure due to heat waves, which causes damage to the facilities and increases the cost of their repair. Extreme weather conditions also disturb and influence supply chain operations, especially the distribution of goods and services, which is essential in facilitating production processes.

Natural calamities are common in India, destroying much of the infrastructure and impacting millions of people. Such hazards include floods, cyclones and heat waves (Benny and Sujatha, 2010; Parida et al., 2020). Adding to the country's problem, geo-climatic conditions render the country vulnerable to floods, cyclones, droughts, landslides and even earthquakes (P et al., 2021). Natural disasters significantly impact the transport systems, including roads and railways, and in some cases, facilities that are considered necessary. For instance, the coastal states regularly experience periodic cyclones and flooding, which tend to cause damage to road and bank walls (Sahoo et al., 2021). In addition to the damage to physical structures, there is the destruction of services, foods, people's means of survival, health, water, and hygiene (Patel et al., 2019). The intermediate and the most disadvantaged groups and developing countries have even more severe and drawn-out repercussions (Somasundaram et al., 2004). In order to minimize the impacts of disasters on people and the economy, more attention is being focused on climate adaptation infrastructure and management of disasters using geospatial technologies as well as adaptable strategies (P et al., 2021; Parida et al., 2020; Roy et al., 2023). Policy measures such as Early Warning Systems and Cyclone Rehabilitation Centers, among others, are critical in mitigating community vulnerability (Patel et al., 2019; Thattai et al., 2017).

Urban transport, especially metro rail and roadways, is becoming more and more subject to the adverse effects of heat waves, leading to wear and tear of the materials, increased costs of maintenance, and health risks to the passengers (Chester and Fraser, 2016; Costa et al., 2023; Fu et al., 2024). This problem is compounded by climate change, given the increased frequency and severity of heat waves (Costa et al., 2023; Fu et al., 2024). Although public transportation is viewed as a way to save on energy and reduce emissions, it is still of great concern since its utilization during extreme heat presents some health risks to the users, thus calling for a cycle of policy planning for transit that incorporates climate change challenges, both envisaged and in existence (Chester and Fraser, 2016). Solutions to optimize urban resilience include, among others, urban limits of development and or greening, installation of heatwave early warning systems, and or community projects that are participatory (Fu et al., 2024), optimal design of the transit system (Chester and

Fraser, 2016), and 'cool retrofitting toolkits' and thermal solutions in construction (Boland and Hatvani-Kovacs, 2015).

In India, extreme weather patterns cause tremendous interruptions to supply chains, paralyzing critical sectors of the economy, such as the chemical sector and the distribution of food supplies. These risks further aggravate risks associated with supply chains, such as problem factors emanating from the changes in demand and supply orders (Hebbar and Khan, 2019, 2021), resulting in an increase in the raw materials stock, variation in sales and the bullwhip effect which calls for adjustments in ordering as well as transportation and cycle time management. This is not just confined to the national fronts, as it had been noted with instances in the past where trade had been cut off (Bowen, 2002) as well as with the logistical movements of supply chains that were affected by the coronavirus pandemic (Kansal and Kumar, 2021). In this regard, companies should be equipped with more sophisticated risk management approaches in order to contain these impacts, such as formulation of the system dynamics models (Bala et al., 2019), including hurdles in the logistics and transportation networks in the decisions about facility location (Singh et al., 2011), embracing of green logistics (Manzini et al., 2014) and customs and clearance logistics enhancement (Bekauri and Chechelashvili, 2022). All these strategies should help businesses in India cope with the negative impact of climate change and disruption of business activities due to extreme weather patterns and help ensure the supply of critical products and services in the form of goods and raw materials.

India's transport sector, which consumes 18% of the country's overall energy and is estimated to demand 200 Mtoe yearly by 2030 (Bakre et al., 2020), suffers from climate change impacts, leading to costs in billions of dollars. On the one hand, this sector plays a significant role in India's status as the third-largest CO2 emitter in the world after China and the USA (Jain and Rankavat, 2023); on the other hand, this sector also has visual impacts on the transportation systems in the megalopolis areas causing economic damage (Pregnolato et al., 2019). The government policies aimed at mitigating Greenhouse gas emissions (Bakre et al., 2020) and the measures towards electric mobility are commendable. However, the intricate complexities of vulnerabilities and the differences in the criticality of transport system networks make it necessary for sophisticated analytical methods for climate risk assessment and adaptation (Pregnolato et al., 2019).

3. Policy Framework for climate-resilient transportation

3.1. Integrating climate risk assessment

Integrating climate risk assessment within policy and planning frameworks in India is crucial for developing appropriate interventions to combat climate change. This entails carrying out vulnerability mapping to identify areas, sectors and communities most susceptible to climatic changes. Some of these sectors include agriculture, water resources, energy, and infrastructure, which are known to be critical and, therefore, subject to specific assessments. Climate-proofing development plans ensure that national and state-level strategies embrace risk elements. Improved early warning systems strengthen forecasting and information relaying. Capacity building improves the skills required to carry out the assessments

and make effective use of the assessments. Mainstreaming adaptation involves extending climate actions to policies that are already in place. Financial risk assessment Appraises the economic consequences and designs strategies for reducing those risks. Stakeholder engagement is the participation of various other groups in assessment and planning work, including individuals and communities. Risk assessments are regularly updated in light of changing climate information and socio-economic conditions. Mechanisms of cross-sectoral coordination provide the means for various government departments to work on climate change risk management in an integrated manner. These approaches would, in turn, enable India to create efficient climate policies that are resistant to various shocks.

Action: Integrate climate risk assessment into the transport planning and infrastructure development processes.

Implementation: Carry out the GIS mapping of climate-vulnerable areas and develop appropriate responses.

Example: India has indeed gained immense ground regarding infrastructure on climate risk assessment for all sectors and at all levels of governance. The National Disaster Management Authority has developed such a holistic risk assessment framework model about the climate in India, and many states have also put in place what is known as SAPCC, similar to state adaptation programmes on climate change at state rates. The government has ordered climate risk and vulnerability assessments for projects in major sectors. At the same time, the ICAR, or the Indian Council of Agricultural Research, has done extensive evaluations under all possible zone categories for different evaluations related to agro-climatic zones. This is an example of incorporating some significant acts by developing a Coastal Vulnerability Index. Different areas already constructed are applied for urban climate resilience planning, and work has started with this in the financial sector. Similarly improved and implemented, climate risk assessments are extended for various fields.

3.2. Promoting sustainable modes of transport

India is working on providing sustainable solutions to urbanization, pollution, and climate change challenges. Government agencies are implementing various initiatives to encourage the use of public transport, electric vehicles, or even non-motorized means of transit. Examples include expanding the metro and bus rapid transit systems and increasing shared mobility’s last-mile connection to the end-users. The National Electric Mobility Mission Plan promotes the use of electric vehicles, and the Smart Cities Mission promotes the installation of integrated transport systems. In addition, bicycle-sharing schemes and walking facilities are being introduced. These actions mitigate carbon emissions, contribute to cleaning the air, and improve the urban transport system and the standard of living. Despite these levels of awareness, there are challenges to realizing sustainable transport, including weak physical structures, restricted funding, and behavioural change towards commuting.

Action: Allocate financial resources to public transit systems, non-motorized means of transportation, and electric cars.

Implementation: Introduce incentives for using EVs and develop the urban transportation infrastructure to minimize the usage of transportation systems that rely on fossil fuels.

Example: India is initiating various measures in sustainable transportation, such as the creation of the Delhi Metro, the National Electric Mobility Mission Plan 2020, the Green Urban Transport Scheme, the Smart Cities Mission, the National Urban Transport Policy, the FAME India Scheme, Bus Rapid Transit System, Dedicated Freight Corridors and a lot more. They will reduce traffic choking, air pollution, and carbon emissions, provide excellent public transport efficiency, and promote electric and hybrid vehicles. The integration of sustainable transportation solutions within urban planning would put added stress on creating urban public transport systems and non-motorized transport options. It would indicate India's commitment to better and greener transportation networks.

3.3. Upgrading infrastructure to climate-resilient standards

India is making bold moves to upgrade its infrastructure to a climate-resilient status. This is because there is an urgent need to address the growing concerns and threats climate change poses. This entails modernizing the old buildings and putting up new structures with designs that resist extreme weather variances, rising ocean levels and a number of other climate-related perils. The main areas of concern are developing transport systems, improving water systems management, and reshaping urbanization to build more resilient cities. The government is implementing climate-smart technologies such as climate-resistant roads, climate-smart agriculture, and green buildings. At the same time, India is trying to build a green infrastructure by using natural resources in addition to design and engineering. These impacts are aimed not only at safeguarding people and physical assets from the adverse effects of the climate but also towards enhancing sustainable development across the economy and supporting growth while minimizing environmental risks.

Action: Review and modify the existing building standards and construction methods to withstand harsh weather conditions.

Implementation: Construct flood-resistant road networks, deploy heat-resistant rail systems, and design coastal areas to withstand storms.

Example: India has made significant developments in the infrastructure sector as a climate-resilient infrastructure, primarily through implementing Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) programs. The programme's primary focus is on making rural areas adaptive to climate with various kinds of natural resources, including water conservation and flood management, with a particular focus on activities related to afforestation, soil conservation, and sustainable agriculture. Not only does it raise the economic conditions of a region, but it also ensures the emergence and maintenance of long-term climate resilience. India's goal of improving urban infrastructure is shown by the Smart Cities Mission, along with avenues for coastal protection and climate-resilient energy systems. What has further shown its commitment to responding to real climate-related challenges is the internationalization of comprehensive measures taken by the Indian government

to address climate adaptation into their development strategy, benefiting the country's rural and urban dovetails.

3.4. Adopting nature-based solutions

The use of Nature-Based Solutions (NBS) in climate-resilient transportation policies in India is particularly beneficial as it addresses climate change mitigation and adaptation strategies in a sustainable manner. There are several ways in which NBS can be incorporated into the transportation system; for example, through urban green infrastructure, bioengineering methods against eroded slopes, restoration of wetlands and the conservation of mangroves. Such approaches tend to increase the ability of transportation systems to withstand climate-related impacts while enhancing carbon sinks and protecting ecosystems. Using permeable pavements and bioswales and planting trees in strategic places within the cities are some ways to curb stormwater runoff and lessen the heat emitted by the cities. Furthermore, constructs such as an animal overpass or noise barrier walls can help alleviate the adverse effects caused by the transportation network on the environment. To achieve the successful embedding of NBS within India's transportation policy, there is a need for a structure with a baseline policy, guidelines for integration, funding strategy, private sector engagement, and a framework for impact assessment. Such a policy would also strengthen cross-cutting inter-departmental collaboration and capacity enhancement of the stakeholders regarding implementing climate change and sustainable development policies in the country.

Action: Rely on natural systems such as mangroves, wetlands, and urban green spaces to create defence lines for transportation facilities against the impact of climate change.

Implementation: Re-rehabilitate and plant mangroves around the coastal highways and ports and install rain-suitable gardens in the urban transportation centres.

Example: Nature-based solutions (NBS) in Indian contexts are more impactful in sustainable transport, primarily by building green corridors covering road and rail tracks. These initiatives, which entail widespread native tree plantation and a wide range of bioengineering approaches to shade stabilization, wetland restoration-adjacent infrastructure, widespread impermeable pavements, constructing green flyovers and wildlife corridors, reforesting coastal roadsides with mangroves or urban green spaces in proximities to transport hubs, represent effective initiatives for climate resiliency. These collective NBS tactics significantly upgrade the transportation infrastructure in India in terms of increased durability on climate change exposure.

3.5. Leveraging smart technologies

India's active adoption of intelligent technologies is making India's transportation system climate resilient. The country is also employing intelligent transportation systems (ITS) to control traffic and minimize emissions while moving vehicles to ensure traffic is flowing optimally. Especially in municipal and metropolitan urban areas, intelligent traffic management systems such as adaptive

signal control and real-time road traffic monitoring have been introduced to foster mobility. In addition, India is developing physical electric vehicle (EV) infrastructure and provisioning advanced charging equipment and battery swapping facilities to enhance the use of clean energy vehicles. Moreover, the management and mitigation of extreme weather incidents on transport networks in the country have made the government research the potential of artificial intelligence and big data technology. In addition, smart sensor technologies and the Internet of Things (IoT) are being adopted in the roads, bridges and railways for proactive infrastructural upkeep and to strengthen structures to withstand climatic changes. Such developments are significant in the Indian context, which focuses on developing a transport system that can withstand the adversities of climate change.

Action: Implement IoT sensors, artificial intelligence, and big data analytics to forecast equipment failure and quick response to disasters accurately.

Implementation: Set up flood warning systems for roads and heat monitoring systems for railway tracks.

Example: India's incorporation of intelligent technologies to build a climate-resilient transport system fuses several vital initiatives. These practices consist of intelligent traffic management systems that use bright traffic lights and sensors to achieve emission savings and improve trafficking while considering an increase in transit. Increasing infrastructure and the potency of electric public transportation for low-carbon emissions and having GIS-based data applications increase the efficiency in track areas. High-quality, weather-resilient infrastructure using state-of-the-art materials provides resilience against extreme climate conditions. Integrating real-time air and road conditions and infrastructure health monitoring can be achieved with IoT instrumentation throughout the setup. Urban ICT deployments need to leverage technologies for transport policy to support these case frames for goals including, but not later limited to, smart parking to ease traffic congestion. Multimodal transportation applications foster modulating congestion and fostering eco-friendly travel options. Thus, increasing greenway connectivity in bicycle projects will create green corridors in cities and encourage the transportation of non-motorized and electric vehicles. It is, however, a cluster action plan to make the transportation system more efficient, sustainable, and adaptable to climate change challenges in India.

3.6. Institutional and policy reforms

India has initiated drastic institutional and policy-based reforms to strengthen the climate resilience of its transport systems. The National Action Plan on Climate Change (NAPCC) and the National Transport Policy Framework have played significant roles. Among critical reforms, the setting up of climate change cells within transport ministries and departments responsible for integrating climate concerns in the infrastructure planning and development processes is notable. Other than that, through its agencies, the government has rolled out policies encouraging the use of electric vehicles and sustainable urban mobility. Moreover, India has also put stringent vehicular and fuel emission standards in line with global good practices. Inter-ministerial structures have been created to address issues that cut

across climate-resistant transport systems to assist in implementation. These reforms are intended to develop a more solid, sustainable, and flexible transport system that will cope with the effects of climate change while minimizing the impact of carbon emissions on this sector.

Action: Enhance inter-agency collaboration and participation of private sector and community actors.

Implementation: Develop a National Climate Resilient Transport Authority for policy formulation and implementation.

Example: India has established several institutional and policy reforms to make climate-resilient in its transport systems. Among these are the National Action Plan on Climate Change (2008), which is meant for sustainable transportation, and the National Electric Mobility Mission Plan 2020 (2013), which encourages electric and hybrid vehicles—about safer, faster, and healthier transportation within the urban framework. Green Urban Mobility Scheme (2019) and Faster Adoption and Manufacturing of Hybrid and Electric Vehicles (FAME) similarly help the causes of green urban transport and electric vehicle adoption. The Smart Cities Mission (2015) and the newly updated National Urban Transport Policy (2014) are promising as they discuss multi-modal integrated transport systems. Key actions include the Dedicated Freight Corridors that are expected to switch freight from road to rail; guidelines for urban transport infrastructure about climate change adaptation; the Green Highways Policy (2015) for eco-friendly national highways and National Rail Plan (2019) for increasing the modal share of railways in freight transport. In sum, India has focused on climate resilience in developing transport systems.

4. Case studies

These case studies display integrated, sustainable, and resilient examples of urban mass transportation in India. The provision of renewable energy necessitates solar power for public transit and programs on the roofs of metro stations (**Table 1**), as well as energy solutions to keep a continuous energy supply for a wide variety of applications. Green infrastructure is based on green building concepts in transportation facilities (**Table 2**), rainwater harvesting, water recycling facilities, and climate-friendly materials for heat protection. Metro, bus, and non-motorized transport (**Table 3**) will be better integrated through smart ticketing; this connects the metro with electric feeders and intelligent technology that virtually eliminates the tension of transfers. Resilient design elevates those facilities imperative in thwarting flooding, abetting traffic flow by drains handling and processing increased precipitation, and conducting climate-risk assessments as a regular feature. Laudable among the energy-saving features would be regeneration brake systems in the case of metro trains, energy-efficient lighting and cooling, and fine-tuning of train schedules.

Table 1. Kochi metro's solar initiative: A case study.

Background	**Being an urban transportation system, Kochi metro in Kerala, India, has installed solar panels on station and depot rooftops to promote sustainable urban transportation and enhance the urban habitat in the area. Nearly 25% of its electricity is produced from solar panels, which set an example for sustainable practices in public infrastructure.**
Implementation	1) Rooftop Solar Installations: Solar panels mounted on the roofs of stations and depots to optimize space without needing extra land. 2) Power Generation Capacity: The installed capacity of several megawatts is an integral part of the energy consumption of the metro. 3) Phased Implementation: Step-wise increase to enable the system's active efficiency.
Outcomes and Benefits	1) Lessening of Carbon Footprint: Less use of grid electricity is the main reason for operational carbon emissions. 2) Operational Expense: Operational expenditure reduction and long-run economic gains compensate for the start-up costs. 3) Energy Self-Reliance: Greater dependability on power in the event of fluctuations and power cuts. 4) Environmentalism as a Priority: At the same time, improving urban transport makes all environmental approaches possible. 5) Interrelationship with Environmental Strategies: Rainwater harvesting and vertical gardens are enhanced to provide broader environmental advantages.
Challenges and Solutions	1) High Start-Up Costs: High start-up capital costs moderated by phased implementation and support from the government. 2) Maintenance: Difficulties arising from weather-based output performance are minimally managed by regular maintenance and staff training.
Future Prospects	1) Plans for Further Development: More solar energy capacity and the use of green energy in new metro levels. 2) Technological Improvements: Regular improvements in solar technology in order to increase efficiency and energy production.
Conclusion	Kochi metro has taken the commendable step of promoting the use of renewable energy in urban transport, and as a result, there has been environmental enhancement with lesser operational costs. This project can be considered an example for other cities and transport systems looking to incorporate green energy on a vast scale.

Table 2. Case study: Flood-resilient roads in Odisha.

Background	**Due to the intense monsoon rains and cyclone activities, Odisha has experienced much damage, especially in the transportation system. The rural road improvement project sought to solve this by embracing flood-resilient road construction methods, such as elevating the road and ensuring the drainage systems are efficient.**
Problem	1) Accelerated Decline: Frequent destruction of the roads due to floods. 2) Blockade of Roads: Intermissions that occur regularly because of monsoon seasons. 3) Expenditures: High amounts spent on fixing and maintaining the road. 4) Economic Effects: Inactive economic activities and emergency response systems are caused by unconnected roads.
Solution	1) Elevated Road Design: Construction of higher elevated roads to combat flooding effects in the region. 2) Improved Drainage Systems: More side and cross-drainage systems to allow for quick escape of water. 3) Water-Resistant Materials: Employs long-lasting and waterproof bituminous mixes. 4) Reinforced Embankments: These have been fortified with geotextiles and plants to control soil erosion. 5) Upgraded Bridges and culverts: Reconstruction with an increased capacity for hydraulic flow.
Implementation	Phased execution takes into consideration the most vulnerable to flooding roads first. Local contractors were educated in resilient techniques and took quality control seriously.
Results	1) Enhanced Longevity of Roads: A notable increase in resilience against damage during flooding has occurred. 2) Cut down Maintenance Expenditures: There was a 30% cost reduction in the annual expense. 3) Better Accessibility: Road closures during the rainy season have decreased by 60%. 4) Boosted Economic Activities: Transport facilities improved for agricultural produce and business. 5) Emergency Management: Use of roads has improved, resulting in rapid deployment of disaster response teams.
Challenges	1) Expense: More initial costs for resilient designs. 2) Limited Knowledge: Lack of personnel skilled in applying flood-resilient structures. 3) Balancing Development with the Environment: Carrying out development with concern for the environment.
Lessons Learned	1) Even though they were more expensive to build at the beginning, the routine rebuilding of roads that proved to be resilient became cheaper in the long run with little maintenance. 2) The provision of training for local contractors and engineers ensured that the project was able to deliver as anticipated. 3) Better results were achieved when the road construction was integrated with managing floods in the area. 4) New technologies were added to the practice, and patient monitoring rehabilitated the practice.
Conclusion	The road construction in Odisha incorporates flood mechanisms that further help fight the adverse effects of floods on the infrastructure. The undertaking strengthened the geometry of transportation, improved economic activities, enhanced disaster readiness, and provided a model that can be applied to other regions with flooding risks.

Table 3. Case study: Mumbai's coastal road project.

Background	**Mumbai Coastal Road Project refers to an approximately 29.2 km long freeway being constructed on the western seashore of Mumbai, starting from Marine Lines in Southern Mumbai and going up to Kandivali in the north. It is intended to improve connectivity, decrease the overall travelling time, and enhance the coastal areas in the city from flooding and rising sea levels. The project cost was estimated at ₹12721 crores ($1.7 billion), and it boasts the use of modern technology for construction and is expected to be finished in 2023.**
Objectives	1) Mitigate Traffic Congestion: Enhancing traffic flow along the crucial western axis of Mumbai. 2) Minimize Travel Time: Anticipated to Reduce travel time in South Mumbai and North Mumbai to 70%. 3) Develop Connectivity to the Suburbs: Improved connections to the periphery. 4) Resilience to Flooding: Make flood-prone regions more secure.
Key Features	1) Additional Details: The first lane shift zone is expected to be constructed approximately 300 m down the road from the vicinity of the Ayosh Hwy Junction on the eastern side of the construction vertical. 8 Lane Highway 4 lanes in each direction. 2) Underwater Tube Tunnels: Overcome engineering problems such as falling bridges using underwater passageways. 3) Enhance connectivity: Interchanges and entry and exit ways and points are installed. 4) Land reclamation: Develop more land from the Arabian Sea for construction activities.
Challenges	1) Ecological: Effects around the oceanic ecosystems, drainage of mangroves and tide disruptions. 2) Societal: Disruption and possible relocation of fishing populations. 3) Political: Intervening litigations and lack of environmental clearance. 4) Practical: Challenges in erecting tunnels beneath the water and dredging the land. 5) Economic: Exorbitant costs and risk of cost overrun.
Impacts	Advantages include: Minimizing travelling time, Improved connectivity, Development of new urban spaces, and Improved flood defences. Disadvantageous aspects: Pollution, displacement of communities and alteration in the coastline of Mumbai.
Conclusion	The Coastal Road project in Mumbai is a case that exemplifies the challenges faced during the construction of urban infrastructure on a large scale as it seeks to enhance connectivity and resilience against flooding but with severe environmental and social issues. This case illustrates the need for strategic planning, social inclusion and environmental protection in contemporary urbanism.

5. Challenges to implementation

5.1. Financial constraints

Enhancing the current system and installing new technology that is more advanced in the Indian scenario proves to be cost-prohibitive. Due to its enormous expanse and varying topography, there is a need for massive capital injection in the rehabilitation of ageing infrastructure in the transport, energy, and telecommunication sectors, among others. The cost of such revolutionary new technologies as 5G network infrastructure, smart electricity grids and intelligent transportation systems is intensive. Such costs involve the hardware and software systems and the recruitment and retraining of personnel to run the high-tech systems. Furthermore, the incumbent design of the current facilities would have to be altered, adding even further to the overall investment. Although the payoffs from such improvements are apparent in the long run, the initial costs are, in most instances, too high for many areas and local governments to bear, resulting in imbalanced development and technological equality in the country.

5.2. Policy gaps

India's transportation policies have exhibited inertia in factors related to climate change adaptation in transportation planning about climate change unaffected measures. This is even though the geographic location of this nation makes it very prone to the effects of climate change. A range of risks that climate change poses to

transportation systems has been recognized, but unfortunately, actions taken tend to be more rhetorical than concrete policy measures. Many such policies also emphasize addressing pressing concerns, such as constructing new facilities and fast-tracking economic growth, rather than understanding the importance of the measures, such as strengthening the infrastructures against the effects of climate change in the future. This exposed the essential transport infrastructures to risk brought by severe weather changes, increasing ocean levels and climate change effects. Besides, transportation planning is further complicated by the system's absence of climate risk evaluation and mitigation processes. It has also been observed that there are no clear policies or specific requirements on how to include Climate Resilient Designs in the engineering structures in infrastructure development projects. An absence of this component in most transport policies hampers the timely exposition of adaptive actions across transport systems. It may have implications for increased costs and risks in the coming days.

5.3. Public awareness

The country's potential to leverage and adopt sustainable practices for its citizens is restricted to a great extent by the level of awareness of the users and stakeholders. This knowledge gap is experienced in several areas, such as energy use, waste, and resource management. Many people, including businesses, do not understand how their activities affect the environment and the benefits of going green and other sustainable options. In most cases, comprehension deficiency results in a massive attack against any change; hence, there is no change from unsustainable habits. Moreover, apprehension increases with remoteness, especially in the availability of information in the hinterlands. It is essential to implement educational programs and awareness campaigns to overcome such barriers and develop a culture of sustainability. In practice, however, these measures are often incomplete and poorly executed, leading to slow growth in implementing green habits in the nation. Such ignorance must be dealt with if India is to promote and enhance its sustainability levels and help with environmental efforts at the global scale.

5.4. Interdepartmental coordination

India's policy implementation structure has many agencies and departments that cut across each other. Most of these agencies, however, work in silos, which creates many troubles for the realization of national policies and programs. Central, state and local levels often engage in similar activities without sufficient coordination of efforts, resulting in redundancies, wastage of resources and inconsistencies. Rarely does anybody make a genuine attempt at integrating the work of one such agency as there is diffused accountability. Often, due to the absence of direction in working together towards a single purpose, policy implementation is said to be incoherent as various agencies would embark on different and sometimes counterproductive activities. The problem with such structural arrangements is that they do not promote accessible communication between or among the agencies, nor do they promote working together on complex problems like poverty, environmental management or economic growth. It emerges that the culprits in this case and the factors that drain

the efficacy of implementing policies are the divisions between agencies. The result is that the siltation in the delivery of the government policies adversely compromises the positive influence of the policies and slows down the accomplishment of the devolvement agenda in India.

6. Recommendations

6.1. Increase public and private investment

There has been an immense improvement regarding issuing green bonds and establishing public-private partnerships (PPPs) to fund climate change adaptive projects in India. To begin with, green bonds are becoming popular in the nation as they are defined as fixed-income financial instruments responsible for raising money for climate and environmental projects. For instance, the state and private actors in India have raised green bonds for purposes such as developing renewable energy, developing transportation systems and constructing energy-efficient buildings. At the same time, public-private partnerships have become crucial tools for financing climate-resilient infrastructure projects by tapping into the private sector's resources and skills. In such arrangements, the public and the private sectors share the risk, allowing the execution of enormous climate change adaptation and mitigation strategies. Consequently, by using the green bond market and PPP, the country has built a comprehensive system for enhancing climate change resilient infrastructure development financing and promoting economic growth while effectively combating the risks of climate change.

6.2. Capacity building

By doing this, India should design systematic endeavours that focus on climate science fundamentals, urban impacts, risk analysis and forecasting and means of implementation. Custom-made programs targeting each group must be given that deter policymakers on climate governance and policy, infrastructure engineers on resilient infrastructure designs and urban planners on sustainable urbanization. The training should include case studies, workshops, and fieldwork and promote cross-discipline teamwork. In this regard, climate modelling and data analysis will be a great asset in the decision-making process. Importance should also be given to developing means for integrating communities and addressing their social issues. The availability of continuing education, website-based materials, and cooperation with other educational institutions will greatly help specialists become acquainted with the latest advancements in climate science and technology. Such an initiative will allow India's urban development agents to implement appropriate climate adaptation interventions.

6.3. Community engagement

The engagement of the local populace in devising and executing plans is essential in promoting inclusiveness and nurturing ownership of development initiatives. For example, by mobilizing local people, policymakers can acquire relevant information, comprehend the context in which they operate, including the

needs and challenges to be met, and appropriately design their responses. This approach is aimed at improving the relevance and efficiency of the initiatives and enables the communities to become active participants in the sociopolitical process. In part because of this, if local stakeholders are engaged in processes from the beginning, there exists a greater tendency for them to buy, implement and maintain the outcomes of the process stemming from the project, hence more long-term achievement. Also, including community members ensures a system of checks and balances over the government, which builds citizens' confidence in the authorities. As a result, the system of governance becomes much more responsive and participatory. By ensuring that the baselines of such strategies incorporate people's participation, the development strategies that will be put in place will be more viable, just and sustainable, capturing the wishes and needs of the country's population.

6.4. International collaboration

India has been particularly attentive to international cooperation and funding mechanisms in its fight against climate change and has been dominantly focused on the GCF. The Green Climate Fund (GCF), formed under the United Nations Framework Convention on Climate Change (UNFCCC), is of great importance as it offers opportunities for the nation to obtain financial and non-financial assistance from external sources. Thanks to its involvement with GCF, India has conceived and used climate initiatives in several sectors, such as renewable energy, food security, and urban infrastructure development. This assistance is not limited to finance only; it helps in knowledge sharing and building as well. Their positive responses to the available global systems signal that India is serious about the climate change challenge and wishes to strike a balance between development and climate change mitigation worldwide. The nation's participation in the GCF and other similar initiatives has allowed the country to enhance its climate change mitigation and adaptation activities, thereby making a substantial contribution to preparing and implementing the Paris Climate Agreement.

7. Conclusion

To sum up, introducing climate-resilient policies in India's transportation systems is essential for sustainable development. If these policies are given precedence, India can simultaneously combat environmental degradation and enhance its economy. Such policies can cut greenhouse gas emissions, improve air quality and make the transport systems more efficient. Furthermore, it can encourage employment in greener technologies for the country's people and elevate its status as the best in planning for urban centres' development. With climate change becoming a serious problem, it is not a luxury but a necessity for the climatic conditions that investment in the transport system becomes environment-friendly or economically sustainable for both the market and the ecosystem. This ensures sustainable and efficient transportation systems and enables the country to achieve its overall objectives of development and bettering the people's living standards.

By employing a paradigm that is both multi-faceted and technologically enhanced, India has the potential to protect its infrastructure, promote mobility

without compromising the ecosystem, and become a champion of climate-resilient growth among countries around the world. In striving to create a safe, flexible and efficient transportation system in unpredictable climate development, the primary efforts have to be focused on long-term strategies, resource management, and, most of all, people's participation in decision-making processes. Long-term planning focuses on integrating climate change impact and adaptation strategies over all phases of projects, including assessing the vulnerability of climate-sensitive projects, especially those that enhance flexibility and redundancy of systems, and implementing informatics, including climate and new technologies in plans. Resource optimization is about strengthening and developing networks and structures that can withstand the effects of climate change and new materials, control systems and energy use, infrastructure to support different systems rather than one, and new materials for continued system repair and restoration. Inclusive governance means the variety of perspectives is respected and considered in decision processes, working with residents to appreciate the needs and limitations of the area, supporting the private sector, developing transport solutions, and ensuring that transport provision is fair within all population categories. Transport networks can be enhanced to cope with the challenges of climate change and still ensure mobility and accessibility for the coming generations by paying attention to these issues.

The paper discusses in detail the impacts of climate change on India's transport sector, besides recommending approaches to strengthening climate resilience. Policy frameworks were covered, case studies were elaborated, challenges were identified, and policy recommendations were detailed. The contribution of this work was that it foregrounded the climate-resilient transport policy in India on the most requirements for risk assessment, more sustainable modes of transport, upgrade of infrastructure, and reforms in institutions.

However, the study has many limitations, such as a lack of robust quantitative data regarding the economic aspects of the suggested resiliency measures, little debate on the regional heterogeneity in climate risks, and not thorough findings on exploring innovative financing mechanisms. The perspective brings long-term planning, resource optimization, and inclusive forms of governance to build a transportation system that will resiliently serve future transport needs. It further suggests research efforts on integrating climate considerations into transport planning and advocates more involvement of the private sector and cooperation from abroad to stimulate innovation and investment in responsive infrastructures.

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