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# Exploring Adaptation Strategies to Mitigate Climate Threats to Transportation Infrastructure in Nigeria: Lagos City, as a Case Study

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**Abstract:** This study aims to explore innovative adaptation strategies that can effectively mitigate the climate threats faced by transportation infrastructure in Lagos, Nigeria. The study highlights the urgent need for innovative approaches to address the challenges posed by climate change to transportation systems. By analyzing the current vulnerabilities and potential impacts of climate change on transportation infrastructure, the authors identify and propose four current challenges facing transportation infrastructure as a result of climate change. These threats include the impact of rising sea levels on coastal roads and bridges, the vulnerability of inland transportation systems to extreme weather events such as floods and heavy rainfall, the potential disruption of transportation networks as storms become more frequent and intense, and the implications of temperature changes on road surfaces and their structural integrity. The study also identified and proposed ten potential adaptation measures that can enhance the resilience of transportation systems in Lagos, Nigeria. The adaptive measures ranged from increasing the resilience of road networks through the implementation of proper drainage systems and slope stabilization measures to forming partnerships with private sector companies to promote sustainable practices and the development of green transportation initiatives. To facilitate these adaptive measures, the authors used them to develop various policy frameworks for transportation resilience in Lagos, Nigeria. These policy frameworks aimed to provide guidelines and regulations for the implementation of adaptive measures, ensuring their effective integration into the transportation system. The authors emphasized the importance of stakeholder engagement and public participation in decision-making processes to foster a sense of ownership and collective responsibility towards building resilient transportation systems. By adapting to these measures, Lagos, Nigeria, can enhance its ability to withstand and recover from transportation disruptions caused by various hazards, such as extreme weather events, infrastructure failures, or security threats.

**Keywords:** resilient infrastructure; green transportation solutions; smart technology integration; climate threat; climate change; transportation infrastructure

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## 1. Introduction

The existence of transportation infrastructure in both developed and developing nations, regardless of size or location, has numerous beneficial impacts on economic prosperity, urban growth, tourism, and equity. It has substantially reduced prices and successfully bolstered levels of investment [1], commerce [2], and output [3]. According to Rozenberg and Fay [4], low- and middle-income countries will need to dedicate a portion of their gross domestic product (GDP) each year, ranging from 0.5% to 3.3%, which translates to an estimated sum of US$157 billion to US$1 trillion, for the purpose of developing new transportation infrastructure by 2030. According to Roberts et al. [3], it is recommended that an annual allocation of 1.1% to 2.1% of GDP is required to maintain and develop existing and future transportation infrastructure. Santamaria-Ariza et al. [5] highlighted that in countries with well-developed transportation networks, such as European nations, the expenses related to upkeep and repairs are more significant than the cost of new investments. Neglecting routine maintenance not only results in below-average performance but also increases overall expenses by 50% [4], making the problem worse.

Transportation networks cover extensive geographical regions, rendering each infrastructure asset vulnerable to a range of forces, such as floods, earthquakes, tsunamis, landslides, storms, wildfires, and excessive temperatures. The convergence of this peril, along with the inherent vulnerability of transportation infrastructure, has already led to substantial monetary damages. Koks et al. [6] found that surface and river floods contribute to over 73% of the global estimated annual damages (EADs) caused by direct natural hazard damage to road and railway systems. The projected damages can range from US$3.1 to US$22 billion. The researchers have also computed that EADs can represent around 0.5% to 1% of a nation's GDP on a yearly basis. This quantity is almost equal to the financial resources designated for the progress and maintenance of the national transportation system [5]. Natural hazards not only result in the destruction of physical assets but also hinder the functioning of infrastructure services, leading to significant repercussions for enterprises, government and non-government organizations, and individuals. According to research by Hallegatte et al. [7], the World Bank estimates that the yearly impact of transport infrastructure disruption in low- and middle-income countries on the capacity utilization rates of enterprises is $107 billion. The repercussions resulted in monetary losses and the delay of supply and deliveries. The analysis neglected to consider the long-term ramifications, such as reduced global competitiveness, that highlight the substantial costs linked to malfunctioning infrastructure networks.

The management of transportation infrastructure systems is anticipated to face increased difficulties as a result of the escalating frequency and severity of extreme weather events linked to global warming, which is caused by human activities such as the emission of carbon dioxide and other greenhouse gases [8]. The World Meteorological Organization (WMO) has provided an insight into the increasing influence of weather-related disasters from 1970 to 2019 [9]. The World Meteorological Organization (WMO) has recorded a substantial escalation in economic losses, multiplying by a factor of seven from the 1970s to the 2010s. Based on the data, the mean daily losses throughout the duration of ten years from 2010 to 2019 amounted to US$383 million. This represents a sevenfold increase compared to the losses incurred from 1970 to 1979, which amounted to a total of US$49 million. Multiple studies have demonstrated the immediate and indirect impacts that natural disasters have on global transportation systems, which has sparked interest among scholars and governments worldwide. As a result, significant resources, such as knowledge, time, and money, have been dedicated to improving the ability to withstand and manage risks in existing and future transportation infrastructure systems.

The objective of engineers, policymakers, and operators of transportation infrastructure is to construct and uphold systems that possess the qualities of sustainability and resilience [10]. Various approaches and strategies have been devised to integrate these two concepts, with some complementing and others conflicting with one another [11]. While certain individuals perceive resilience and sustainability as mutually supportive objectives, others view them as separate and perhaps conflicting in terms of design [12]. While the systematic application of these concepts has been observed in the construction of buildings [13], it is challenging to optimize the performance of large-scale transportation infrastructure systems and assets using the same principles [14]. An essential initial stage in integrating the two ideas into a cohesive framework and worldwide measurements is to enhance the climate-resilient efficiency of transportation assets such as bridges while considering the environmental impacts produced by factors like overall carbon emissions during the lifespan, in addition to prices.

The transportation sector is accountable for over 70% of global greenhouse gas (GHG) emissions. The primary cause of this is predominantly attributed to the establishment and maintenance of transportation infrastructure [15]. In order to evaluate the environmental effects, different greenhouse gases are measured in terms of their carbon dioxide ($CO_2$) equivalents [16]. According to the ASCE Report Card History [17], an estimated $125 billion is needed to repair the 36% of bridges in the United States that are in need of restoration, as stated by Lehman [18]. According to Wardhana and Hadipriono [19], hydraulic phenomena, such as floods and scour, account for around 53% of bridge failures. The present value of this figure is anticipated to increase as a result of the worsening environmental circumstances. The importance of infrastructure in meeting sustainable development goals, such as achieving emission targets by 2030 and reaching net zero emissions by 2050, cannot be overstated. The cited figures are replicated worldwide using GDP, as noted by the European Commission [20] and Mitoulis et al. [11]. The 2020 Medicane Ianos, which hit Greece and impacted a considerable region of the country, exemplifies a recent occurrence of a flash flood that caused severe destruction to bridges and transportation networks. Three additional bridges sustained substantial damage, while five bridges were completely or partially obliterated [21].

Khanna et al. [22] and the Ecochain Mobius platform provide a comprehensive description of the 15 environmental impact categories in life cycle assessments (LCAs). They discovered that these categories encompass resource depletion, climate change, and human health implications. Furthermore, their research emphasizes the significance of taking into account all environmental effects when conducting life cycle assessments (LCAs) in order to effectively evaluate the sustainability of products and processes. Implementing eco-friendly approaches in machining processes can result in substantial reductions in carbon emissions and energy consumption. The case study emphasized the significance of taking into account the complete life cycle of a product when evaluating sustainability criteria. In the field of building, it has been discovered that environmental harm is typically measured using the Global Warming Potential (GWP). This metric is used to assess the extent of climate change resulting from the emission of greenhouse gases. By integrating sustainable practices into machining operations, organizations can simultaneously decrease their environmental impact and enhance their overall efficiency and competitiveness in the market.

Mitoulis et al. [23] discovered that integrating sustainability and climate resilience measures into decision-making processes for the recovery of transport infrastructure assets can result in outcomes that are both more robust and environmentally benign. Achilleos et al. [24] discovered that incorporating steel fiber-reinforced concrete mixes in pavement construction is an environmentally friendly approach to address the effects of climate change on transportation infrastructure. The study conducted by McKenna et al. [25] revealed that the inclusion of end-of-life tire components in concrete production can lead to a substantial decrease in greenhouse gas emissions and energy usage when compared to conventional ways of producing concrete. Sabau et al. [26] discovered that recycled aggregate concrete exhibited markedly reduced carbon emissions in comparison to natural aggregate concrete, particularly when the amount of cement used was decreased. Using recycled resources in concrete production can effectively decrease the environmental impact of construction activities. According to Reza et al. [27], climate change is projected to have substantial adverse effects on the longevity and performance of paved roads, resulting in higher expenses for maintenance and a reduced lifespan. The study utilizes the Em-LCA approach, which offers a complete framework for assessing the sustainability of infrastructure systems in the context of climate change. It emphasizes the significance of including environmental impacts in infrastructure planning and design. According to Wang et al. [28], the establishment of highways in the southwest area of China had a substantial impact on the release of carbon dioxide into the atmosphere. The research emphasized the immediate requirement for sustainable methods in infrastructure development to alleviate the environmental consequences of transportation projects.

Somboonpisan and Limsawasd [29] discovered that including environmental factors in bid evaluations can effectively foster sustainability in highway construction projects. This strategy can result in the development of more robust infrastructure that is more capable of withstanding the difficulties presented by climate change. Nahangi et al. [30] discovered that the bridge's embodied greenhouse gas emissions were considerably greater than previously calculated, emphasizing the need for precise evaluation of environmental effects in infrastructure endeavors. This study highlights the necessity for enhanced techniques in assessing and reducing carbon emissions in construction endeavors to tackle the increasing apprehensions regarding climate change. Dong et al. [31] discovered that bridges that are susceptible to seismic activity face a higher likelihood of being damaged as a result of climate change-related hazards, such as flooding and severe weather events. The study emphasizes the significance of integrating these ever-changing elements into infrastructure planning and design to guarantee long-term durability and adaptability. Dong et al. [32] discovered that the rising occurrence and severity of natural catastrophes caused by climate change present a substantial risk to the long-term viability of highway bridge networks. The study also emphasized the significance of taking proactive steps to improve the resilience of transportation infrastructure in response to these issues.

Mackie et al. [33] discovered that climate change is causing extreme weather events to occur more frequently and with greater severity. This, in turn, is presenting considerable obstacles to the ability of transport infrastructure to withstand and recover from these difficulties. The study also emphasizes the significance of integrating sustainability criteria into the evaluation of bridge performance during seismic events to guarantee its long-term sustainability. Noland and Hanson [34] discovered that the utilization of construction equipment significantly contributes to onsite emissions. In fact, it can constitute up to 20% of the overall emissions of a project when employing conventional equipment. The characteristics of the site have a significant impact on the quantity of these emissions, according to Barandica et al. [35]. When comparing flat sites to hilly ones, the disparity might be as significant as 30-fold. This emphasizes the significance of taking geographical considerations into account when designing and implementing road improvements in order to reduce greenhouse gas emissions.

Somboonpisan and Limsawasd [29] discovered that the utilization of hybrid engines or other environmentally friendly alternatives can effectively lower equipment emissions by as much as 50%. This reduction in emissions ultimately results in a decrease in the overall carbon footprint of building projects. Mackie et al. [33] discovered that transportation usually accounts for approximately 4% or less of average haulage requirements. However, it is anticipated that this proportion will rise as climate change continues to impact infrastructure. The study also emphasized the significance of adopting sustainable practices in transportation to alleviate these effects. Wang et al. [28] discovered that the production of materials is responsible for around 80% of emissions, whereas material transportation and onsite activities contribute only 3% and 10% of total emissions, respectively. The data indicate that directing efforts towards decreasing emissions during the manufacturing phase could have a substantial effect on the total carbon dioxide emissions in highway buildings.

Liu et al. [36] found that steel and cement are responsible for 98% of the carbon emissions generated during the construction of bridges. Nevertheless, these components account for just about 15% of the overall resources utilized. Rock and sand make up 80% of the material, yet they only contribute less than 1% of the total carbon. This suggests that directing efforts towards decreasing carbon emissions, specifically from steel and cement used in bridge construction, could have a substantial influence on the total amount of emissions produced. According to Keolwian et al. [37], bridge projects that utilize low-carbon and high-performance materials can achieve a carbon emission reduction of over 40% compared to conventional options. Although the upfront expenses of incorporating these materials may be greater, the enduring advantages in terms of resilience, upkeep, and ecological impact render them a more sustainable option for forthcoming infrastructure endeavors.

According to Heidari et al. [38], the environmental impact and energy consumption of road surfacing differ based on the specific pavement type utilized. Cement pavement exhibits a reduction in emissions and energy consumption ranging from 12% to 55% when compared to asphalt pavements. According to Santero and Horvath [39], the flexibility of pavement and the decrease in rolling resistance can independently impact emissions throughout the recovery period after a hazard. These impacts can have long-lasting implications for the lifespan of the asset. Nazarnia et al. [40] discovered that the frequency and intensity of flooding occurrences have increased as a consequence of climate change. This has led to the substantial destruction of railway tracks, bridges, and signaling systems. Consequently, there has been a rise in the expenses associated with maintenance, as well as interruptions in the provision of services, and apprehensions over the safety of both passengers and workers. Santamaria-Ariza et al. [5] reviewed the current body of research on the issue to highlight important topics and areas where information is lacking. Their findings offer valuable insights for policymakers and practitioners in the field.

Rattanachot et al. [41] discovered that the adaptation solutions with the highest effectiveness involved the integration of robust design features, intensifying maintenance efforts, and integrating climate change considerations into long-term planning. A study conducted by Arsenio et al. [42] revealed that climate change is expected to exert substantial adverse impacts on Portugal's transportation infrastructure by the year 2030. The study emphasizes the immediate necessity of implementing adaptation measures and making investments in robust infrastructure to minimize these effects and guarantee that the nation's transportation requirements are fulfilled in light of a shifting environment. Mesdaghi et al. [43] discovered that institutional ties have a significant impact on the effectiveness of climate adaptation methods in the transport industry. The study emphasized the significance of collaboration and coordination among many stakeholders to effectively tackle the problems presented by climate change for transport infrastructure. Sanchez and Govindarajulu [44] discovered that the incorporation of blue-green infrastructure into urban planning can greatly enhance the ability of transport systems to withstand the effects of climate change. The case studies of Chennai and Kochi showcased the effectiveness of integrating nature-based solutions, such as green roofs, permeable pavements, and rain gardens, in adapting to flooding, improving water quality, and offering other advantages for urban regions.

Niskanem et al. [45] discovered that the group of individuals and organizations involved in Sweden's transport infrastructure sector, known as the discourse coalition, has changed its focus to prioritize sustainability and resilience. This move is a response to the difficulties presented by climate change. This trend indicates an increasing acknowledgment of the necessity for proactive actions to reduce the effects of climate change on transportation networks. According to Blackwood et al. [46], the inclusion of natural-based solutions, such as green infrastructure and ecosystem restoration, can effectively reduce the impact of climate change on rail infrastructure. According to Markolf et al. [47], transportation networks are becoming more susceptible to the impacts of climate change as a result of more frequent and intense weather events.

Chatzichristaki et al. [48] reported that the flash flood on 22 November 2013, in Rhodes Island, caused significant damage to roads, bridges, and other transportation infrastructure. The study also highlighted the need for improved infrastructure design and maintenance to mitigate the effects of severe weather events in the future. Jones et al. [49] conducted a study that found that climate change-induced extreme weather events have resulted in substantial disruptions to transportation networks worldwide. In 2017, the City of Atlanta observed an increasing frequency of severe weather events, such as hurricanes and heavy rainfall, which have caused significant damage to the city's roads, bridges, and public transportation infrastructure [50]. In 2015, the City of Atlanta conducted a study and concluded that its transportation system is particularly vulnerable to extreme weather events, such as hurricanes and flooding [51]. The study highlights the importance of implementing sustainable transportation options to mitigate these risks and adapt to a dynamic environment. Mehare and Joshi [52] found that urban areas with high population density and extensive paved surfaces are more susceptible to the impacts of the urban heat island (UHI) phenomenon. This is because these regions have less vegetation and absorb more heat. Habermann and Hedel [53] found that severe weather events, such as storms and flooding, have significantly disrupted transportation networks, resulting in economic losses and safety hazards.

Although various studies have been undertaken worldwide on adaptation techniques to reduce the effects of climate change on transportation infrastructure, there has been no systematic analysis of the specific impacts of these measures in Lagos, Nigeria. The majority of articles published in Lagos, Nigeria, about transportation infrastructure primarily examine the effects of climate change on flooding and erosion [54] and the Centre for Research on the Epidemiology of Disasters [55] as shown in Table 1, while neglecting to discuss the implementation of adaptation techniques that can effectively mitigate these effects. This study aims to address the lack of understanding by investigating the efficacy of several adaptation measures in reducing the impact of climate-related risks on transportation infrastructure in Lagos, Nigeria. The second phase of this study will examine and assess the effects of previous climate change on transportation infrastructure, strategies for adapting to climate change-related damages to transportation infrastructure, and the consequences of future climate change on transportation infrastructure in Lagos, Nigeria. This section aims to establish a foundation for proposing a comprehensive framework to adapt Lagos's transportation infrastructure to future climate change scenarios. It will achieve this by developing strategic theories to analyze the impacts of climate change and formulating strategies and policies to assess the effectiveness of different adaptation measures. The ultimate goal is to devise sustainable solutions that enhance Lagos's transportation infrastructure's resilience to climate change. The objective of this study is to provide policymakers and stakeholders with valuable insights into the most efficient strategies for safeguarding transportation infrastructure against the impacts of climate change. This study aims to identify effective adaptation solutions that can be used to guide future planning and investment decisions, with the goal of ensuring the long-term resilience of Lagos's transportation networks. The final phase of this study focuses on providing closing remarks and suggesting future research directions that will enhance Lagos's transportation infrastructure's resilience in the face of climate change-induced challenges. We will present recommendations for policy reforms and investment priorities to facilitate the adoption of these adaptation strategies.

**Table 1.** Climate change impacts on flooding in Nigeria and for Africa as a whole for the years 2011–2020.

| | **Numbers of People Affected** | | **Value of Damages ('000 US$)** | | **Numbers of Deaths** | |
|---|---|---|---|---|---|---|
| **Year** | **Nigeria (% Contribution in Africa)** | **Africa** | **Nigeria (% Contribution in Africa)** | **Africa** | **Nigeria (% Contribution in Africa)** | **Africa** |
| 2011 | 30,915 (2.19) | 1,414,579 | 4500 (0.45) | 1,006,500 | 174 (25.89) | 672 |
| 2012 | 7,000,867 (75.26) | 9,302,672 | 500,000 (49.45) | 1,011,115 | 363 (42.81) | 848 |
| 2013 | 81,506 (3.48) | 2,345,261 | – | 147,024 | 19 (2.59) | 735 |
| 2014 | 10,000 (1.05) | 948,522 | – | 126,000 | 15 (3.02) | 496 |
| 2015 | 100,420 (3.99) | 2,519,490 | 25,000 (5.46) | 458,000 | 53 (6.40) | 828 |
| 2016 | 12,000 (0.88) | 1,369,507 | – | 295,700 | 18 (1.91) | 943 |
| 2017 | 10,500 (0.66) | 1,595,141 | – | 12,000 | 20 (5.67) | 353 |
| 2018 | 1,938,204 | 3,455,250 | 275,000 | 768,100 | 300 | 742 |

**Table 1.** *Cont.*

| | Numbers of People Affected | | Value of Damages ('000 US$) | | Numbers of Deaths | |
|---|---|---|---|---|---|---|
| Year | Nigeria (% Contribution in Africa) | Africa | Nigeria (% Contribution in Africa) | Africa | Nigeria (% Contribution in Africa) | Africa |
| | (56.09) | | (35.80) | | (40.43) | |
| 2019 | 123,640 (2.74) | 4,516,338 | – | 57,100 | 36 (3.94) | 914 |
| 2020 | 193,725 (2.95) | 6,575,132 | 100,000 (22.52) | 444,000 | 189 (14.09) | 1341 |
| **Total** | **9,501,777** (27.91) | **34,041,892** | **904,500** (20.91) | **4,325,539** | **1187** (15.08) | **7872** |

Source: Centre for Research on the Epidemiology of Disasters (2021) [55]. Data on value of damages were not available for Nigeria in some years.

## 2. Impacts of Climate Change on Transportation Infrastructure in Lagos, Nigeria

Climate change is a worldwide occurrence that is having a substantial impact on transportation infrastructure in Lagos, Nigeria. With the rising frequency of extreme weather events, the infrastructure of the country, including roads, bridges, and trains, is increasingly vulnerable to damage and interruption. This presents a significant menace to the effectiveness and security of transportation networks in Nigeria. This section will examine the precise effects of climate change on transportation infrastructure in Nigeria and deliberate on potential approaches for adapting and building resilience. Figure 1 illustrates the process used in this study to evaluate the susceptibility of transportation infrastructure in Lagos, Nigeria, to climate change. It emphasizes the immediate necessity for proactive actions to reduce risks and promote sustainable development. Lagos can enhance its transportation infrastructure to become more resilient to the effects of climate change and effectively contribute to economic growth and social development.

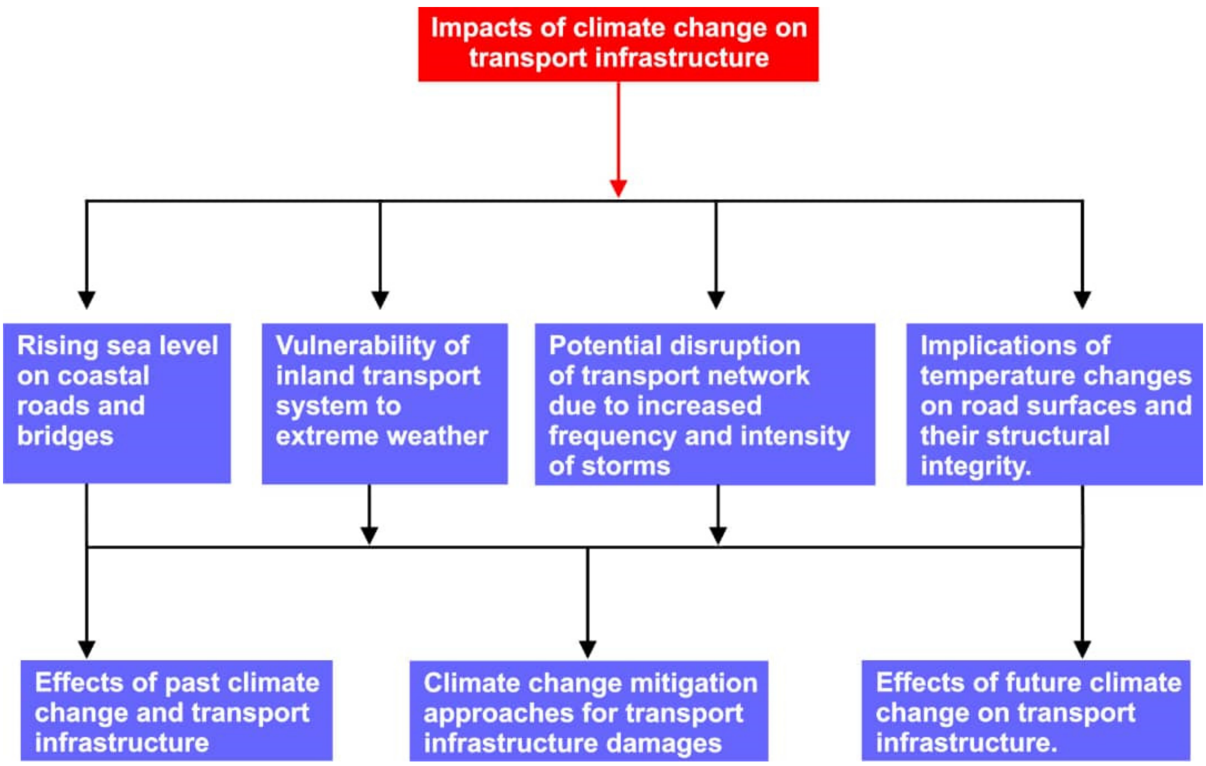


**Figure 1.** Impacts of climate change on transportation infrastructure in Lagos city, Nigeria.

### *2.1. Effects of Past Climate Change on Transportation Infrastructure in Lagos, Nigeria*

The transportation infrastructure in Nigeria, especially in Lagos, a highly populated and economically crucial city, has been greatly affected by climate change. The impact of climate change, specifically the rise in sea levels and subsequent increase in flooding, has resulted in significant harm to transportation infrastructure such as roads, bridges, and other systems [56]. The flooding that occurred in Lagos in 2012 led to the devastation of more than 100 bridges and roadways, resulting in an estimated $1.5 billion in financial losses [57]. Recurrent cyclones in Lagos have caused significant harm to ports and harbors along the coastline, leading to disruptions in maritime transit and commerce operations [58].

Consequently, this has caused interruptions in the transportation of both individuals and products. Furthermore, the occurrence of severe weather events, such as intense precipitation and storms, has worsened these problems, underscoring the immediate necessity for the implementation of adaptation and resilience strategies. Climate change and extreme weather events in Nigeria have resulted in various cases of transportation infrastructure damage. These include the collapse of bridges due to flooding [58], erosion and landslides on roads caused by heavy rainfall [59], and damage to railway tracks due to rising temperatures [59]. Additional examples include the suspension of Lagos's airport operations as a result of extremely high temperatures [59], disruptions in maritime transportation as a result of rising sea levels [60], and the destruction of road infrastructure by hurricanes and storms [61]. The Otedola Bridge in Lagos was closed for repairs in 2012 due to floods, resulting in an estimated cost of $2.3 million [57]. According to the European Commission Joint Research Centre [57], the cost of repairing this erosion exceeded $5 million just in 2018. The erosion of the Lagos coastline has endangered important transportation infrastructure like the Third Mainland Bridge, leading to investments of more than $3 million in precautionary measures [57]. The rise in flooding in coastal areas like Lagos and Port Harcourt has resulted in regular road closures and bridge damage, which has negatively affected the effectiveness of transportation systems [57].

Past climate change in Nigeria has caused both physical damage and economic losses to the country's transportation system. The expenses associated with the restoration and upkeep of deteriorated roadways and bridges have imposed a burden on government resources, redirecting financial allocations that could have been allocated towards alternative development initiatives. Moreover, the interruptions in transportation systems have impeded economic activity and commerce, affecting the livelihoods of numerous individuals who depend on effective transportation networks for their daily necessities.

In order to tackle these difficulties, it is imperative for policymakers in Nigeria to give priority to the design and investment in infrastructure that is robust to climate change. This involves integrating climate change considerations into the planning and implementation of new transportation projects, as well as upgrading existing infrastructure to withstand the future effects of climate change. Furthermore, it is crucial to improve the synchronization among various tiers of government and stakeholders to guarantee a comprehensive strategy for constructing resilient transportation networks that can endure the impacts of climate change in Lagos and other areas.

The effects of previous climate fluctuations on transportation infrastructure in Lagos, Nigeria, have been substantial, since escalating sea levels and heightened flooding have resulted in the degradation of roads, bridges, and other essential infrastructure. The impacts have emphasized the immediate necessity for adaptable strategies and enduring solutions to safeguard against forthcoming climate-related hazards and guarantee the durability of the city's transportation system. As a reaction, researchers are investigating advanced technologies like green infrastructure and smart transportation systems to reduce the effects of climate change on Lagos's transportation infrastructure and improve its overall sustainability. Furthermore, the city is actively seeking collaborations with foreign organizations and climate resilience experts to capitalize on their expertise and best practices in order to formulate sustainable long-term policies for the city's transportation network. These cooperative endeavors seek to not only tackle present difficulties but also equip Lagos for the future ramifications of climate change on its infrastructure. Lagos is collaborating with various organizations and implementing creative strategies to develop a transportation infrastructure that is both robust and efficient, capable of adjusting to the evolving climate circumstances. The city is endeavoring to diminish carbon emissions and enhance the general quality of life for its citizens by integrating green infrastructure and smart technologies.

### *2.2. Climate Threats to Transportation Infrastructure in Lagos, Nigeria*

Lagos's transportation infrastructure is at serious risk from climate change, primarily due to the escalating occurrence of extreme weather events. Flooding, rising sea levels, and hurricanes can all disrupt travel and economic operations. The report categorizes various climatic factors affecting Lagosian transportation infrastructure, such as the consequences of increasing sea levels on coastal roads and bridges, as well as the economic consequences of climate change-related disruptions. It is imperative to tackle these difficulties in order to sustain effective and dependable transportation networks.

#### 2.2.1. The Impact of Rising Sea Levels on Coastal Roads and Bridges

The phenomenon of climate change is resulting in the elevation of sea levels, which is creating significant alterations to the Earth's physical structure. Lagos is currently confronted with a critical issue in relation to this matter. The escalating sea levels in Lagos pose a critical problem for coastal roads and bridges, necessitating urgent attention and inventive remedies. These essential facilities are of utmost importance in linking communities, enabling trade, and stimulating economic development in Lagos. Nevertheless, the increasing sea levels pose a substantial peril to these infrastructures, as they are susceptible to erosion, inundation, and even total devastation. In the absence of immediate action and the implementation of long-term adaptation strategies, Lagos may encounter significant interruptions to its transportation infrastructure and heightened isolation in coastal areas.

Research conducted by engineers revealed that almost 60% of coastal roads and bridges (particularly in Lagos) in Nigeria are presently vulnerable to erosion resulting from elevated sea levels. If the rate of the sea level rise remains unchanged, over 80% of these infrastructure assets could face significant impact in the next ten years [62]. If no adaptive measures are implemented, the proportion of coastal roads and bridges that are vulnerable might rise to 50% by 2030. These findings emphasize the immediate requirement for strategic infrastructure design and investment to minimize possible harm and guarantee the ability of coastal communities to withstand and recover from adverse events.

The menace of escalating sea levels is more imminent than ever, especially in Lagos and other coastal urban centers in Nigeria. The imminent inundation of large urban areas as a result of escalating sea levels is a worrisome fact that cannot be disregarded. The urgency for prompt and efficient actions to alleviate the consequences of climate change has never been more critical, as the future of these susceptible communities teeters on the edge. By 2050, a forecast by Climate Central predicts that around 150 million people living in flood-prone areas could be fully drowned due to the powerful impact of high tides [63]. Lagos, a densely populated city with a population of over 18 million, requires immediate care because of the imminent disaster it and other urban areas at low altitudes are facing. It is of utmost importance to tackle this imminent catastrophe, since Lagos serves not only as a significant economic center but also houses essential infrastructure and a valuable cultural legacy.

Engineering the Future [62] has underscored the need to tackle climate change, as it has the potential to result in a one-meter elevation in ocean levels from 2030 to 2050. This presents a substantial peril to the lives and means of subsistence of millions of individuals and to the economy of Nigeria. The Engineering the Future has stressed the necessity of adopting a comprehensive strategy to alleviate the consequences of increasing sea levels on coastal cities, such as Lagos, which is located in close proximity to sea level. Nevertheless, the federal government's apathy and failure to do anything regarding this matter continue to be discouraging. The lack of protective measures for Lagos and other coastal communities, which also house critical oil industry installations, against the potentially catastrophic effects of an approaching severe ocean surge is worrisome. The absence of tangible measures damages the welfare of susceptible populations and ecosystems and impedes progress towards attaining sustainable development objectives.

Lagos, which serves as Nigeria's main center for business and commerce, is confronted with a significant issue as a result of its distinctive geographical location close to sea level. With the ongoing increase in global sea levels, the need to protect Lagos and its residents from impending destruction becomes even more urgent and crucial. The Lagos State Government has allocated a significant budget of N36 billion to address the persistent ocean surge that is affecting its shoreline. Nevertheless, more measures are necessary to completely alleviate the consequences of this ongoing threat [54]. The proposed project involves the construction of 18 groins (sea breakers) at intervals of 40 m between Goshen Estate and Alpha Beach. The anticipated cost of the project is N2 billion [54]. This project demonstrates a praiseworthy dedication to coastal protection and the safety of the nearby communities. Nevertheless, it is crucial to implement a thorough plan that includes sustainable infrastructure and active involvement from the community in order to effectively tackle the difficulties presented by the increasing sea levels and erosion.

The effects of climate threat on transportation infrastructure in Lagos, Nigeria, are becoming more apparent as sea levels rise and extreme weather events occur more frequently, resulting in damage to roads, bridges, and other essential infrastructure. These threats not only interrupt the movement of goods and people but also provide substantial safety hazards to commuters and homeowners in the area.

To address these difficulties, novel strategies like green infrastructure design, robust building materials, and enhanced monitoring systems are being created to reduce the impact of climate risks on transportation infrastructure in Lagos. By integrating these advanced technologies and tactics into urban planning and development initiatives, stakeholders may enhance their readiness for future climate-related disruptions and guarantee the enduring sustainability of the city's transportation networks.

#### 2.2.2. Implications of Temperature Changes on Road Surfaces and Their Structural Integrity

As Lagos rapidly urbanizes and traffic increases, understanding how temperature fluctuations affect road surfaces and structural integrity is vital. This hinders road maintenance and safety and reduces transportation network efficiency. Nigeria's varied climate, from intense heat to heavy rainfall, exacerbates road surface temperature variations. Due to greater average temperatures and rainfall, southern Nigeria is more vulnerable than the north. Temperature variations can expand and contract road surfaces, generating cracks and potholes that can cause accidents and car damage. Erosion and washouts from severe rainfall in the south (where Lagos, the case in study, is situated) can further weaken roadways. Other difficulties include ice buildup in winter, which can make roads perilous for cars. Extreme heat can soften asphalt and make it more susceptible to wear and tear, speeding up road deterioration. Temperature variations can cause cracks and potholes by expanding and contracting materials. Due to their thermal qualities, road materials may expand or contract at different rates, creating uneven surfaces and driving hazards.

Temperature variations in Nigeria can affect road surfaces and structural integrity, according to a Nigerian Institute of Civil Engineers study [64]. Average temperatures range from 25 °C to 40 °C, and the country has considerable seasonal temperature changes [64]. Thermal stress from high temperature swings can cause road materials to expand and contract quickly. The study also found that common Nigerian road (particularly Lagos metropolis) materials like asphalt and concrete have uneven thermal characteristics. Inconsistent thermal characteristics can worsen thermal stress on road surfaces because different materials react differently to temperature changes. The study found that Nigeria's different climate zones affect road surface thermal characteristics. When developing and building roads and executing maintenance methods, road engineers and policymakers must consider each region's thermal characteristics. Doing so reduces thermal stress on road surfaces and improves Nigeria's road infrastructure's longevity and performance.

This means Nigeria has all climate zones, from hot and desert in the north to moderate and humid in the south. Each climatic zone has unique thermal circumstances, including seasonal temperature, humidity, and rainfall patterns that affect road surface thermal qualities. These different thermal qualities must be considered by road engineers and policymakers when designing, selecting, and maintaining roads. By doing so, they can make Nigeria's road infrastructure adaptable to adverse weather in different regions. Considering road surfaces' thermal qualities can also lower the incidence of temperature-related incidents on slick or damaged roadways. This holistic approach to road infrastructure can make Nigeria's transportation networks safer and more efficient.

Temperature fluctuations can exert a substantial influence on the condition of road surfaces in Lagos, Nigeria, resulting in problems such as fissures, grooves, and degradation of the pavement structure. These impacts can be worsened by factors such as high traffic volume and inadequate maintenance techniques, ultimately weakening the structural integrity of the roads. Given the escalating impact of climate change, it is imperative for infrastructure designers and engineers in Lagos to prioritize inventive measures to alleviate the consequences of temperature fluctuations on road surfaces. This may require the adoption of novel materials or technologies that possess greater resistance to severe temperatures, together with the enhancement of maintenance procedures to guarantee the long-lasting and robust nature of the city's road infrastructure.

## 3. Development of Transport Theories for Strategic Discussion of Climate Change Impacts on Nigeria's Transport Infrastructure with Special Focus on Lagos City

### 3.1. Development of Transport Theories

Transportation theories are essential for comprehending the intricate dynamics of our transportation networks. Given the growing influence of climate change, it is crucial to investigate how these theories can provide insight into the weaknesses and dangers that transportation infrastructure is exposed to. Through the analysis of the relationship between climate change and transportation theories, we can acquire useful knowledge about the possible dangers, strategies for adjustment, and sustainable solutions that are essential for protecting our vital transportation networks in an unpredictable future. Gaining a comprehensive understanding of the possible hazards presented by climate change to transportation infrastructure is essential in order to formulate efficient adaptation solutions. By incorporating climate change factors into transportation theories, we can pinpoint vulnerabilities such as heightened flooding or severe weather events that have the potential to disrupt transportation networks. This information can subsequently be used to guide the creation of sustainable solutions, such as including resilient infrastructure designs or advocating for alternative means of transportation in order to mitigate greenhouse gas emissions. The study proposes five theories that can be utilized to elucidate climate-related risks to transportation infrastructure, as shown in Figure 2:

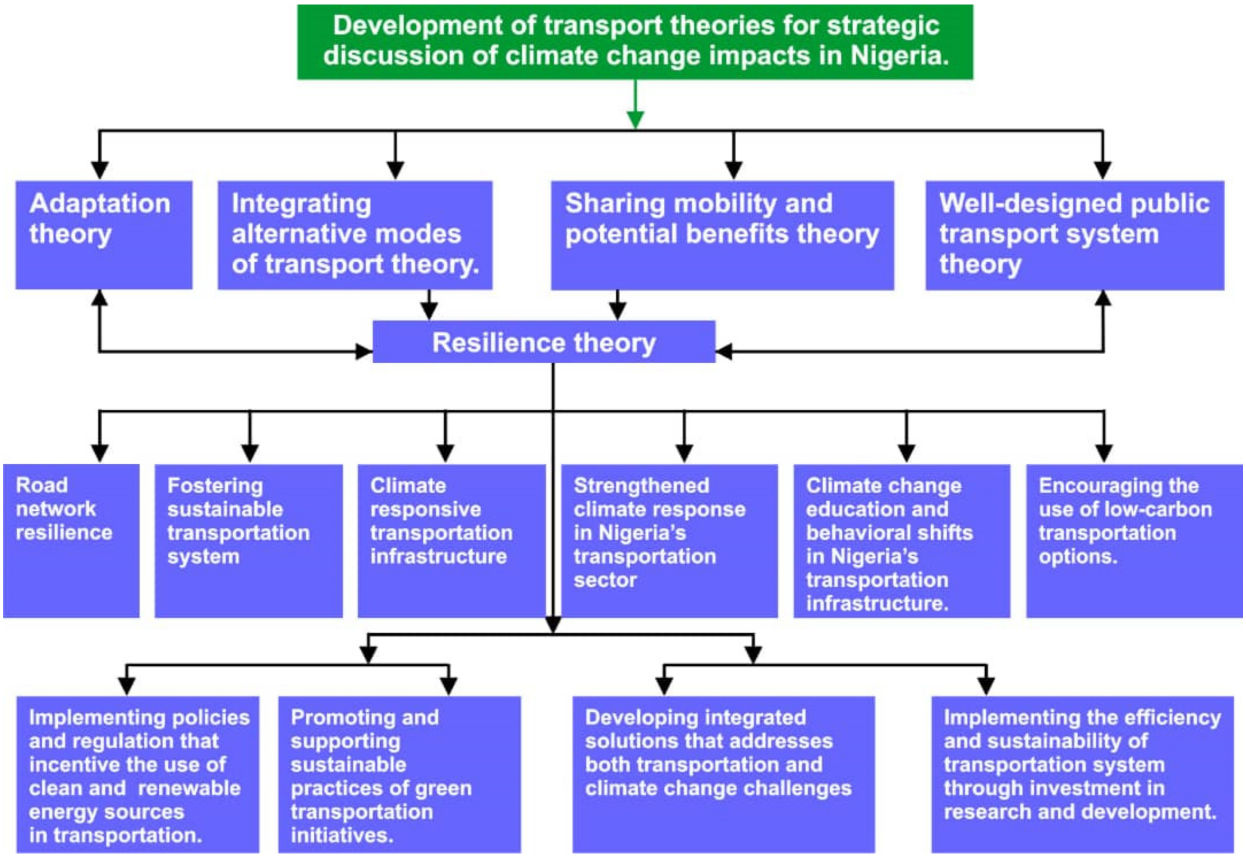


**Figure 2.** Development of transport theories for strategic discussion of climate change impacts on Nigeria's transport infrastructure.

#### 3.1.1. Resilience Theory

According to resilience theory, transportation networks should be built and planned to withstand climatic threats and limit their impact. Climate change projections and adaptable transportation infrastructure are crucial to this notion. Thus, transportation systems can improve their resilience to severe weather and reduce product and people flow disruptions. Climate-related repairs are less frequent and severe with durable infrastructure, saving money over time. The American Society of Civil Engineers (ASCE) estimates that resilient infrastructure saves $4.60 in climate-related damages for every $1 invested [7]. The World Bank [65] estimates that investing $1.8 trillion in resilient infrastructure worldwide over the next decade may yield $4.2 trillion. Resilience theory in transportation design can help adapt to climate change, ensure the ongoing provision of key services, and minimize disruptions to daily life, according to the UNFCCC [20]. Building flood-resistant roadways or installing early warning systems can help communities withstand extreme weather and keep access to important services.

The IPCC [66] estimates that resilience measures can reduce climate-related transportation system damage by 80%. Elevating roads and bridges, increasing drainage, and strengthening coastal defenses can lessen the impact of climate risks on transportation infrastructure using resilience theory. These methods can protect transportation infrastructure from climate-related flooding and storm surges. Transportation networks can be resilient during extreme weather, allowing communities to access essential services and supplies. Resilience theory applies to transportation infrastructure and other areas. Resilience theory stresses adapting and preparing for shocks like climate change. Transportation planning and design incorporate resilience concepts to help communities recover from extreme weather. This technique improves transportation resilience and community sustainability. By employing resilient transportation planning and design, communities can keep vital infrastructure running after severe weather. Raising roads and bridges to lessen flood danger or offering alternative transit can reduce dependency on a single route. Strong transportation infrastructure can help communities adapt to climate change.

#### 3.1.2. Adaptation Theory

According to the principle of adaptation, transportation infrastructure needs to be modified in response to climate change. When undertaking the development and construction of roads, bridges, and other transportation infrastructure, it is imperative to take into account the potential impact of increasing sea levels, intensifying storms, and elevated temperatures. Transportation networks can enhance their ability to endure climate challenges and maintain the continuous movement of products and people by implementing resilient design and adaptive solutions. Adapting transportation infrastructure to climate change can also help decrease greenhouse gas emissions [2] and encourage sustainable transportation [3]. Implementing alternative energy sources [1], such as electric vehicle charging stations, and giving priority to public transportation that does not rely on fossil fuels can be beneficial [4]. By adapting to the impacts of climate change on transportation systems, we can foster a more sustainable and robust future.

#### 3.1.3. Integrating Alternative Modes of Transportation Theory

In order to mitigate climate change and decrease the release of greenhouse gases, this concept emphasizes the integration of alternative modes of transportation, such as public transit and cycling infrastructure. This statement underscores the importance of implementing emergency response techniques and communication networks to reduce the impact of severe weather disasters [5] and safeguard transportation users [6]. Utilizing alternative modes of transportation can effectively decrease the release of greenhouse gases [5], alleviate traffic congestion [7], and improve the quality of urban air. Cycling infrastructure additionally enhances public health [10] and promotes physical exercise [12]. In order to effectively address transportation delays caused by severe weather conditions and safeguard our transportation infrastructure and communities, it is crucial to give priority to the development and implementation of emergency action plans [13] and communication systems [14]. Transportation systems equipped with intelligent technology and data analytics have the capability to optimize the flow of traffic and reduce journey durations. Urban areas can see advantages from increased productivity and expansion. Electric vehicles and public transportation are sustainable mobility alternatives that can significantly reduce greenhouse gas emissions and enhance the environment for future generations.

#### 3.1.4. Shared Mobility and the Potential Benefits Theory

This theory examines the concept of shared mobility and its potential advantages for transportation systems. According to this theory, advocating for carpooling, ride-sharing, and other forms of shared transportation might potentially decrease traffic congestion and energy consumption and improve the efficiency of transportation networks. In order to enhance future transportation systems, transportation theory four emphasizes the integration of emerging technologies such as autonomous cars and smart infrastructure. Autonomous vehicles have the potential to enhance safety [30], eradicate human error [31], and augment road capacity [32]. Implementing advanced infrastructure, such as intelligent traffic control systems [33] and real-time data analysis [35], can enhance traffic flow and provide accurate information to commuters about their trips [35]. Integration can optimize road capacity utilization and mitigate traffic congestion, thereby boosting transportation efficiency. Autonomous vehicles and intelligent infrastructure have the potential to facilitate ride-sharing and on-demand mobility services, fundamentally changing the way we move.

#### 3.1.5. Well-Designed Public Transportation System Theory

The fundamental principle of a meticulously planned public transportation system asserts that it has the capacity to alleviate traffic congestion by efficiently transporting a larger number of individuals compared to private automobiles. Public transportation promotes social equity by ensuring that transportation is inexpensive and accessible to individuals of all income levels and abilities. The text highlights the role of public transportation in adapting to greenhouse gas emissions and fostering sustainability. Promoting the allocation of resources towards efficient and easily accessible public transportation systems might incentivize individuals to opt for other modes of transportation, thereby adapting to the release of carbon emissions associated with private vehicle usage [36]. This theory asserts that the establishment of a well-connected and sustainable public transportation network necessitates the implementation of effective urban planning [42] and the development of appropriate infrastructure [5]. This strategy also emphasizes the importance of incorporating public transportation with cycling and pedestrianism [41]. By creating a smooth and interconnected infrastructure, individuals are more likely to opt for alternative modes of transportation, thereby reducing their carbon footprint. Public transportation enhances accessibility for marginalized communities and mitigates congestion, hence enhancing the overall quality of life.

### *3.2. Unveiling the Resilience Theory: Unmatched Approach for Analyzing Lagos's Climate Threats and Transportation Challenges*

In a time when climate change poses unprecedented hazards and transportation systems become increasingly complex, resilience theory offers a novel way to understand and address Lagos's climate and transportation concerns. This theory examines the complicated interaction between environmental factors and transportation infrastructure from a new perspective. Beyond ordinary analysis, it provides persistent, effective answers. Resilience theory recognizes that climate change has systemic effects. It emphasizes the need for flexible transportation systems that can anticipate and address these complex difficulties.

Which of the transportation theories in Section 3.1—resilience, adaptation, integrating alternative modes of transportation, shared mobility and the potential benefits, and a well-designed public transportation system—is best for studying climate adaptation measures in Lagos's transportation infrastructure? Resilience theory is best for evaluating adaptation solutions in Lagos, Nigeria, because of its unique climatic threats and transportation infrastructure issues.

Lagos's unique climate dangers, such as increased floods and droughts [54], require a full understanding of resilience theory. Adaptive capacity and transportation infrastructure's resilience to climatic shocks are the focus of this strategy. Poor road conditions [67] and insufficient public transportation networks [68] also plague Lagos's transportation infrastructure. These characteristics demonstrate the need for resilience theory to develop appropriate adaptation techniques. Using resilience theory, Lagos's transportation infrastructure's risks can be assessed. Governments can improve infrastructure resilience by addressing specific issues like flooding [69] and extreme weather [54]. Using resilience theory in transportation design could help individuals find creative solutions like green infrastructure or adaptable transportation systems [70]. Resilience theory emphasizes the importance of including several stakeholders and disciplines in decision making to ensure a complete approach to transportation infrastructure resilience. Engineering, urban planning, and climate research experts can help identify vulnerabilities and remedies. This cooperative strategy helps identify and execute innovative strategies to increase transportation networks' resilience to climate shocks and other challenges. It recognizes the need for comprehensive approaches that consider nature and humans. This comprehensive strategy ensures that transportation networks are planned and controlled to reduce environmental impact and meet community needs by addressing natural and human systems. This complete perspective allows for environmentally friendly [59], climate-resilient [71], and long-term resilient transportation solutions.

These factors are essential for transportation project performance in Lagos, making resilience theory the best theory for evaluating adaptation measures given Lagos's climate concerns and transportation infrastructure issues. Resilience theory provides a comprehensive framework for constructing and maintaining transportation networks in Lagos that can adapt to changing climate conditions and support community growth and well-being [72], considering environmental and societal issues. This approach also recognizes the interconnection of infrastructure, social equality, and environmental sustainability, which are essential for a strong Lagosian transportation system.

## 4. Strategic Exploration of Resilience Transportation Theory to Strengthen Nigeria's Transportation Infrastructure: Unveiling Adaptive Approaches for the Future

Resilient transportation offers adaptive ways to improve Nigeria's transportation infrastructure. This notion emphasizes the need to anticipate and prepare for transportation system disruptions like extreme weather or infrastructure failures. Understanding these scenarios can help policymakers and stakeholders design adaptive measures to maintain transportation networks, prevent interruptions, and boost resilience. Establishing a stable and functional transportation infrastructure helps Nigeria overcome unexpected challenges and boost economic growth. Infrastructure maintenance can reduce disruptions in Nigeria. By anticipating problems and minimizing delays to businesses and persons that depend on reliable transportation, this proactive strategy improves the system and lowers costs. Ten potential adaptive scenarios to improve Nigeria's transportation infrastructure resilience are examined in this section. Figure 3 shows how these scenarios ensure the transportation system can function after natural disasters or technology failures. These steps could improve Nigeria's transportation infrastructure, boosting economic growth and social well-being.

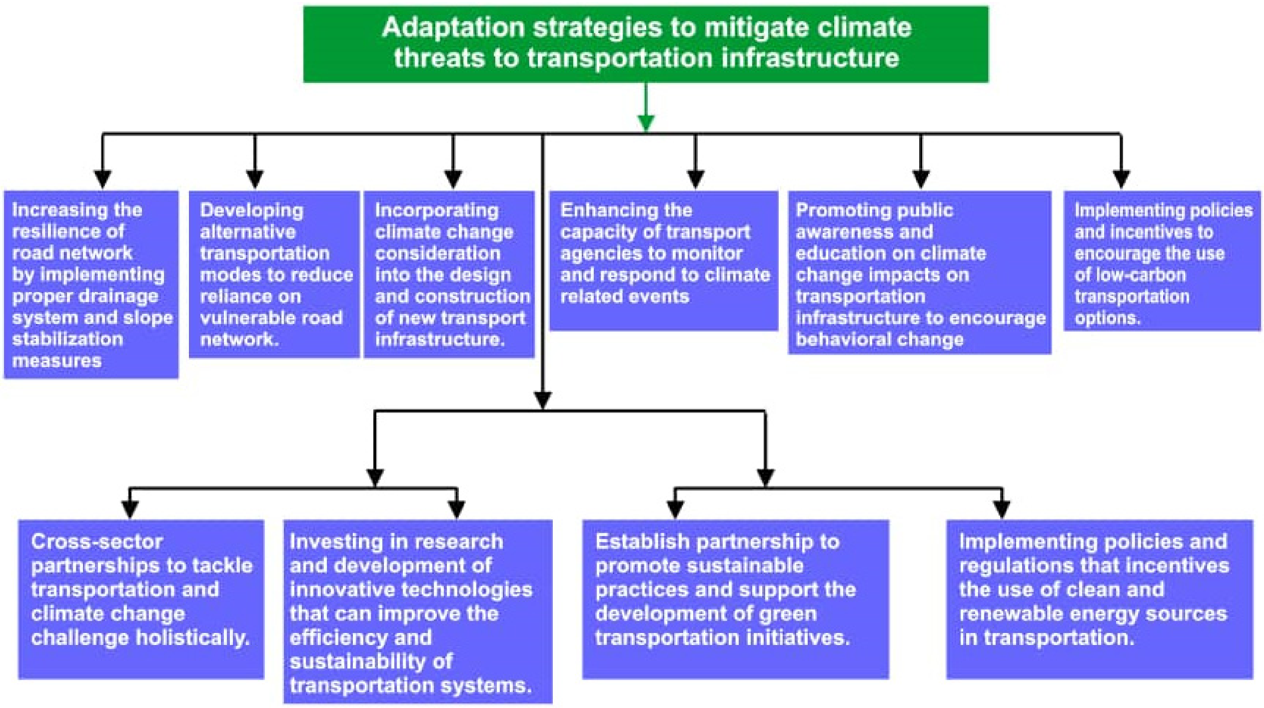


**Figure 3.** Strategic exploring resilience transportation theory to strengthen Nigeria's transportation infrastructure: unveiling adaptive approaches for the future.

### *4.1. Leveraging Resilience Theory for Enhanced Road Network Resilience in Nigeria*

Resilience theory proposes that the implementation of effective drainage systems and slope stabilization measures in Nigeria can enhance the ability of road networks to withstand environmental challenges, such as intense rainfall and landslides. This approach acknowledges the importance of improving the resilience of road networks in order to ensure their functionality and durability [73]. By doing so, road networks are better equipped to withstand and recover from disruptive occurrences. Nigeria can mitigate the economic and social consequences of road damage and disruptions caused by extreme weather occurrences by allocating resources to these initiatives. Enhancing the resilience of road networks can improve transportation efficiency and accessibility, benefiting both urban and rural residents in the country. Durable transportation systems can have a crucial impact on emergency response and disaster management by enabling the prompt transportation of necessary products and services during times of crisis [69]. Bolstering the durability of road networks has the potential to entice investments and stimulate economic expansion by expanding connections and facilitating trade both domestically in Nigeria and with neighboring nations.

### *4.2. Applying Resilience Theory to Foster Sustainable Transportation Systems in Nigeria*

Resilience theory, which is based on ecological systems thinking, provides a new viewpoint on promoting sustainable transportation systems in Nigeria. Resilience theory can aid in the identification of potential vulnerabilities and the development of initiatives to improve the long-term sustainability of the transportation system by analyzing the interconnections and flexibility of its many components. This approach acknowledges that disturbances, such as the effects of climate change or fluctuations in the economy, are unavoidable and highlights the significance of constructing adaptable and resilient transportation systems that can endure and bounce back from shocks while still delivering efficient and accessible services. Resilience theory highlights the importance of collaboration and coordination among various stakeholders, such as government agencies [70], transportation providers [71], and community organizations [74], in order to respond to and recover from disturbances in an efficient manner. By integrating resilience principles into transportation planning and decision-making processes, we may establish a transportation system that is more flexible and robust, capable of withstanding future difficulties and ensuring the uninterrupted flow of people and products.

### *4.3. Harnessing Resilience Theory for Climate-Responsive Transportation Infrastructure in Nigeria*

Resilience theory, a widely utilized framework in the fields of ecology and social sciences, can provide a new and insightful approach to the idea of "Utilizing Resilience Theory for Climate-Responsive Transportation Infrastructure in Nigeria." By utilizing this theory in the context of transportation infrastructure, it enables a comprehensive comprehension of how systems can adjust and flourish in response to the effects of climate change. This approach prioritizes the significance of constructing resilient and adaptable infrastructure [75] that can endure severe weather phenomena, guarantee dependable transportation services [56], and foster sustainable development in Nigeria [72]. Resilience theory acknowledges that climate change is a multifaceted and ever-changing problem that necessitates creative responses. Nigeria should prioritize the incorporation of climate-resilient elements, such as flood-resistant roads, efficient drainage systems, and renewable energy sources, into transportation infrastructure development by applying this approach. Implementing a resilience-focused strategy can bolster the ability of transportation networks to swiftly bounce back from disruptions and mitigate the adverse effects on communities and the economy.

### *4.4. Leveraging Resilience Theory to Strengthen Climate Response in Nigeria's Transportation Sector*

The application of resilience theory can help us understand and improve the climate response in Nigeria's transportation industry. Resilience theory is a paradigm that specifically examines how systems can effectively absorb and adapt to shocks. Resilience theory can assist in identifying strategies and interventions that enhance the sector's ability to adapt and flourish in the presence of climate-related shocks, such as extreme weather events or rising sea levels, by assessing its capacity to endure and recover from these difficulties. This method surpasses conventional adaptation efforts by placing emphasis on incorporating resilience into the infrastructure, operations, and policy of the transportation sector. The statement acknowledges the significance of both adapting to greenhouse gas emissions and adequately preparing for and responding to the consequences of climate change. Nigeria may enhance the long-term viability of its transportation sector in a changing climate by incorporating resilience theory into its decision-making processes. This approach would enable the development of sustainable transportation systems that not only help mitigate climate change but also secure the sector's continued success. When building and implementing transportation projects, it is important to take into account elements such as severe weather events, rising sea levels, and shifting patterns of precipitation. Nigeria may strengthen the resilience of its transportation sector to climate change impacts by taking measures such as constructing flood-resistant infrastructure [60] and adopting adaptive management practices [74]. This will ultimately result in a transportation infrastructure that is more resilient and enduring, capable of operating efficiently despite the challenges posed by a shifting environment.

### *4.5. Leveraging Resilience Theory for Climate Change Education and Behavioral Shifts in Nigeria's Transportation Infrastructure*

The application of resilience theory, a generally utilized framework in ecological systems, can help in comprehending and tackling the obstacles related to climate change education and behavioral changes in Nigeria's transportation infrastructure. By utilizing resilience theory, we may examine how the interconnections among different elements within the transportation system can affect its capacity to adapt and react to the effects of climate change. This methodology can assist in identifying crucial areas for intervention, such as advocating for sustainable transportation alternatives and encouraging community involvement. Ultimately, this will result in the development of more robust and sustainable transportation systems in Nigeria. An example of a strategic point for intervention could involve allocating resources towards sustainable energy options for transportation, such as electric automobiles or biofuels. Implementing this measure will not only result in a reduction in greenhouse gas emissions, but also a decrease in the dependence on fossil fuels, enhancing the transportation system's ability to withstand potential disruptions in the future. Integrating climate change considerations into infrastructure planning and design helps guarantee that transportation systems are constructed to endure and recuperate from severe weather occurrences, hence augmenting their resilience.

### *4.6. Implementing Policies and Incentives to Encourage the Use of Low-Carbon Transportation Options, Such as Electric Vehicles and Public Transportation*

The application of resilience theory can provide a novel viewpoint on encouraging the uptake of low-carbon transportation alternatives in Nigeria. Policymakers can find crucial leverage areas to encourage sustainable transportation choices by comprehending the intricate socio-ecological systems within the country. Integrating renewable energy sources into public transportation infrastructure and providing financial incentives for electric vehicle purchases can decrease carbon emissions and improve the overall resilience of Nigeria's transportation industry. Allocating resources towards the enhancement of cost-effective and proficient public transportation networks can effectively mitigate traffic congestion [61] and enhance the air quality in metropolitan areas [76]. In addition, advocating for the utilization of bicycles and establishing pedestrian-friendly infrastructure can foster the adoption of active forms of transportation, diminish dependence on automobiles powered by fossil fuels, and cultivate a better way of life for the Nigerian population.

### *4.7. Collaborating with Other Sectors, Such as Urban Planning and Energy, to Develop Integrated Solutions That Address Both Transportation and Climate Change Challenges*

Resilience transport theory highlights the significance of constructing adaptable and pliable transportation systems capable of enduring and recuperating from disturbances triggered by climate change. Nigeria can achieve comprehensive solutions to transportation difficulties and climate change consequences by engaging in partnerships with sectors such as urban planning and energy. This method guarantees that the transportation infrastructure is planned to be environmentally friendly, productive, and able to withstand changing environmental conditions, ultimately leading to a more sustainable future for Nigeria. Nigeria may diminish its carbon footprint and decrease its dependence on fossil fuels by integrating renewable energy sources into its transportation networks. Not only would this help to alleviate the impacts of climate change, but it would also foster a more pristine and healthier environment for its residents.

### *4.8. Investing in Research and Development of Innovative Technologies That Can Improve the Efficiency and Sustainability of Transportation Systems*

Resilience theory provides a new viewpoint on the importance of investing in the research and development of cutting-edge technology to improve the effectiveness and long-term viability of transportation systems in Nigeria. Through the implementation of a resilience approach, policymakers can proactively prepare for and adjust to possible disruptions, such as the effects of climate change or limited resources. This will guarantee that the transportation sector maintains its strength and flexibility in the face of upcoming obstacles. Resilience theory highlights the importance of using a comprehensive approach that takes into account social, economic, and environmental aspects in order to promote long-term sustainability [60]. This implies that policymakers should give equal importance to the establishment of inclusive and fair transportation networks that cater to the needs of all individuals [58], foster economic progress [77], and minimize adverse environmental effects [78], in addition to focusing on infrastructure and technical progress. Nigeria can establish a robust and enduring transportation system that aligns with the country's broader development objectives by integrating these ideas into transportation planning and decision-making processes.

### *4.9. Establishing Partnerships with Private Sector Companies to Promote Sustainable Practices and Support the Development of Green Transportation Initiatives*

The notion of resilience highlights the significance of expanding collaborations in order to improve the long-term viability of green transportation efforts in Nigeria. By involving private sector enterprises, the nation may leverage their specialized knowledge, assets, and inventive approaches to tackle obstacles and guarantee the achievement of sustainable practices. The notion of resilience emphasizes the importance of having governance institutions that can successfully handle uncertainties and adjust to new situations. This would allow Nigeria to actively respond to new possibilities and dangers in the green transportation sector. These flexible systems of governance can also promote cooperation and the exchange of information among many stakeholders, such as government entities, businesses, and non-profit groups. By utilizing a multi-stakeholder approach, sustainable transportation projects in Nigeria can be significantly improved in terms of efficacy and impact. This can be achieved by harnessing a wide range of perspectives and experiences. Through the promotion of open conversation and inclusivity, these adaptive governance systems can guarantee that all pertinent views are acknowledged and considered in decision-making processes [72]. They can assist in identifying and resolving potential obstacles or difficulties that may occur during the implementation of environmentally friendly transportation initiatives, ultimately resulting in more successful and sustainable results.

### *4.10. Implementing Policies and Regulations That Incentivize the Use of Clean and Renewable Energy Sources in Transportation*

Resilience theory proposes that the adoption of policies and regulations that provide incentives for the utilization of clean and renewable energy sources in transportation in Nigeria will strengthen the country's capacity to adjust and rebound from environmental shocks and disturbances. Nigeria can enhance the resilience of its transportation sector and decrease its reliance on fossil fuels by advocating for the implementation of sustainable energy practices. This will mitigate the risks associated with resource scarcity, price changes, and climate change consequences. Adopting clean and renewable energy sources for transportation can aid in the reduction in air pollution and the enhancement of public health in Nigeria. This transition would not only have a positive impact on the environment but also generate new employment prospects and foster economic expansion in the renewable energy industry. Allocating funds towards the development of renewable energy infrastructure for transportation in Nigeria would facilitate the expansion of energy sources and decrease the country's dependence on imported fossil fuels [56]. This would bolster energy security and mitigate the country's vulnerability to geopolitical dangers linked to its reliance on oil. In addition, the promotion of clean transportation solutions has the potential to enhance the quality of life for Nigerians by adapting to traffic congestion and minimizing noise pollution in metropolitan areas.

## 5. Policy Implications for the Transportation Scenarios for Adaptation Strategies Proposed in Lagos, Nigeria

The policy consequences of the transportation scenarios outlined in Lagos's adaptation strategy are substantial. First and foremost, it is important to have extensive infrastructure development in place to effectively support the transportation systems described in these scenarios. This includes the allocation of resources towards the development and enhancement of road networks, public transportation systems, and intermodal connections. The objective is to guarantee the smooth and environmentally friendly transportation of goods and individuals. Efforts should focus on giving priority to the implementation of clean and renewable energy sources for transportation in order to decrease carbon emissions and alleviate the effects of climate change. The policy implications of the transportation scenarios for the proposed adaptation solutions in Nigeria, as shown in Figure 4, are as follows:

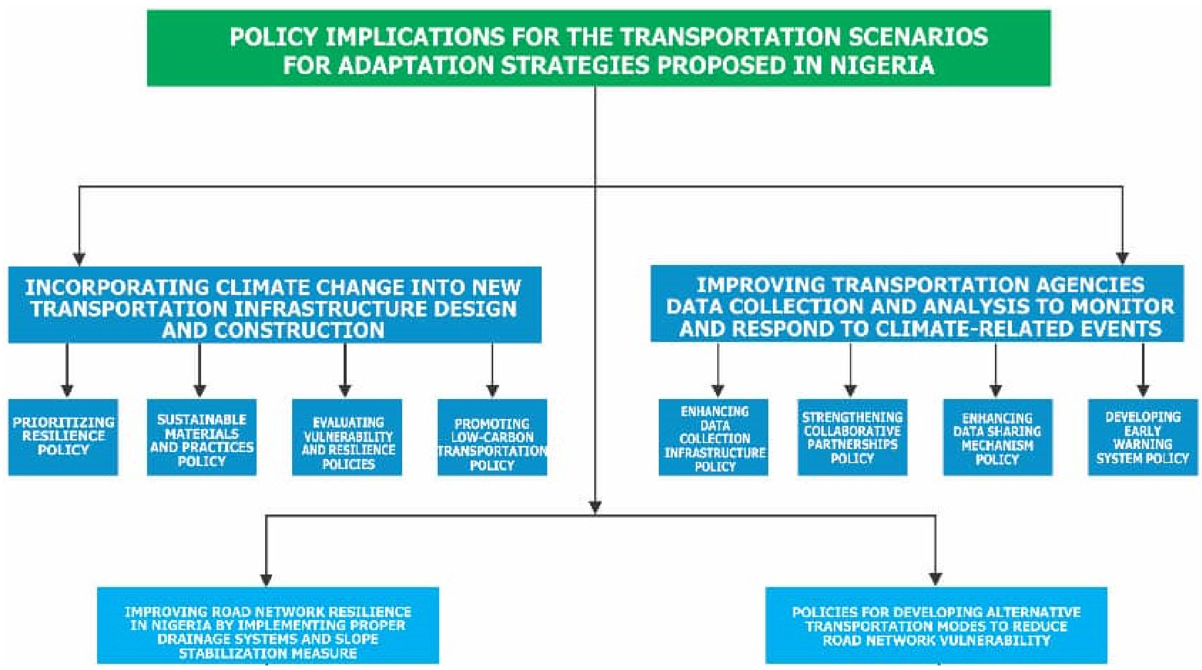


**Figure 4.** Policy implications for the transportation scenarios for adaptation strategies proposed in Nigeria.

### *5.1. Policy Considerations for Improving Road Network Resilience in Nigeria by Implementing Proper Drainage Systems and Slope Stabilization Measures*

#### 5.1.1. Enhancing Emergency Response and Recovery Mechanisms Policy

To enhance the resilience of road networks in Nigeria, it is necessary to establish a strong emergency response and recovery processes. This includes the establishment of effective communication lines, the training of emergency personnel, and the coordination with pertinent agencies to promptly resolve any disruptions resulting from natural disasters or accidents. Allocating resources towards acquiring cutting-edge technology and state-of-the-art equipment for emergency response teams can enhance their efficiency in handling interruptions in the road network. Implementing routine drills and simulations can guarantee that all parties involved are adequately equipped to manage unexpected occurrences and mitigate the consequences for transportation systems.

#### 5.1.2. Implementing Regular Maintenance and Inspection Programs Policy

Implementing thorough maintenance and inspection protocols is crucial for guaranteeing the prolonged resilience of road networks. Regular inspections can help identify potential vulnerabilities in drainage systems, pavement conditions, and other critical elements of infrastructure. To mitigate interruptions and minimize the occurrence of unplanned breakdowns, road authorities might adopt proactive methods to address these concerns. Engaging in regular maintenance activities, such as repairing potholes and controlling vegetation, can efficiently maintain the safety and efficiency of road networks while reducing the likelihood of disruptions caused by worsening conditions. The use of advanced technologies such as remote sensing and data analytics can enhance the efficiency of maintenance activities by providing real-time monitoring and predictive analysis. This allows road authorities to efficiently prioritize and allocate their resources, ensuring that crucial infrastructure elements are consistently inspected and repaired promptly to avert any significant hazards.

#### 5.1.3. Integrating Climate Change Adaptation Strategies and Policy

Incorporating climate change adaptation strategies into road network planning and design in Nigeria is essential due to the ongoing and severe difficulties posed by climate change to infrastructure. This can involve implementing strategies such as constructing raised highways, using flood-resistant materials, and enhancing stormwater management systems to strengthen the ability of road networks to withstand severe weather conditions. Utilizing green infrastructure measures such as rain gardens and permeable pavements can effectively alleviate the consequences of intense rainfall and minimize the likelihood of floods.

#### 5.1.4. Strengthening Infrastructure Maintenance and Rehabilitation Policy

To enhance the overall resilience of road networks to extreme weather events, it is important to prioritize regular maintenance and prompt rehabilitation. This will avoid deterioration and limit disruptions caused by drainage issues or unstable slopes. This encompasses routine inspections and maintenance of drainage systems, along with adapting to any possible weaknesses in the road infrastructure. It is possible to significantly increase the resilience of road networks to withstand erosion and landslides brought on by extreme weather conditions by using cutting-edge techniques like slope stabilization measures.

#### 5.1.5. Promoting Sustainable Infrastructure Development Policy

Implementing efficient drainage systems and slope stabilization policies is vital for sustainable infrastructure development in Nigeria, as it enhances the resilience of road networks. Implementing these techniques can mitigate erosion and landslides, therefore maintaining the durability and effectiveness of roads even in the presence of fluctuating climate conditions. Integrating renewable energy sources into infrastructure projects can enhance sustainability endeavors and diminish greenhouse gas emissions.

#### 5.1.6. Adapting to Climate Change Impacts Policy

Nigeria can enhance its ability to cope with shifting climate patterns and minimize the susceptibility of road networks to severe weather events like intense rainfall and landslides by implementing adequate drainage systems and slope stabilization measures. Adopting climate-resilient road designs, such as elevated or reinforced infrastructure, can also aid in reducing the effects of increasing sea levels and heightened flooding. The implementation of a policy that incorporates green areas and flora along roadways can yield natural cooling effects, mitigate the urban heat island phenomenon, and enhance air quality.

#### 5.1.7. Ensuring Efficient Transportation Networks Policy

By installing robust drainage systems and enacting strategies to stabilize slopes, the negative impacts of heavy rainfall and landslides on roads can be substantially reduced. By investing resources in advanced smart transportation technologies, such as real-time traffic monitoring and intelligent traffic management systems, it is possible to improve the efficiency of transportation networks and reduce congestion.

### *5.2. Policies for Developing Alternative Transportation Modes to Reduce Road Network Vulnerability*

In order to kickstart the advancement of different modes of transportation in Lagos, Nigeria, it is crucial to invest resources towards building infrastructure that supports non-motorized ways of transportation, such as cycling and walking. This involves the creation of dedicated bike lanes, pedestrian pathways, and the improvement of sidewalks to encourage the use of these eco-friendly transportation options within the city.

Moreover, governments should give precedence to the expansion of public transportation options, such as buses and light rail systems, with the aim of providing economical and effective alternatives to driving. By investing in a reliable public transportation infrastructure, a larger portion of the population will have access to key areas of the city without relying on personal vehicles. This will lead to a reduction in traffic congestion and pollutants generated by vehicles on the road.

In order to encourage individuals who still rely on driving to adopt electric vehicles and other environmentally friendly energy sources, it is essential to develop incentives or advantages. This could involve offering incentives for the purchase of electric vehicles, implementing a city-wide infrastructure of charging stations, and creating legislation that prioritizes environmentally friendly vehicles in urban planning decisions. Lagos can reduce its susceptibility to road network vulnerabilities and improve air quality and the overall quality of life for its residents by promoting the use of sustainable transportation options.

### *5.3. Policies for Incorporating Climate Change into New Transportation Infrastructure Design and Construction*

It is imperative that these policies give utmost importance to sustainability and resilience, considering the city's susceptibility to severe weather events and the increasing sea level. Additionally, it is crucial for them to take into account the significance of advocating for public transportation and non-motorized means of transportation in order to mitigate greenhouse gas emissions.

Furthermore, the rules should have provisions to guarantee that new infrastructure is constructed using materials and procedures that minimize the environmental impact and carbon footprint. This may entail utilizing recycled materials, adopting environmentally friendly construction methods, and integrating renewable energy sources into transportation networks.

It is imperative for these policies to engage stakeholders from many sectors, such as government agencies, private firms, community organizations, and academic institutions. Collaboration among these sectors is crucial for creating inventive solutions that tackle the concerns of climate change while simultaneously fulfilling the increasing transportation demands of Lagos's fast-rising population.

### *5.4. Policy Options for Improving Transportation Agencies' Data Collection and Analysis to Monitor and Respond to Climate-Related Events*

An effective policy approach would involve allocating resources towards the adoption of cutting-edge data gathering technology, such as remote sensing and GIS mapping, in order to enhance the precision and promptness of climate-related data. These devices can offer up-to-the-minute data on weather patterns, instances of flooding, and other climate-related occurrences, enabling transportation organizations to make better-informed choices in addressing emergencies.

Another policy alternative is to forge alliances with nearby colleges and research institutions in order to bolster data analytics capabilities. Transportation agencies can enhance their understanding of the effects of climate change on infrastructure and devise resilience measures by partnering with climate science and environmental monitoring professionals. Moreover, these collaborations can enhance the agency's ability to develop and maintain the necessary resources for continuous data gathering and analysis.

Finally, incorporating climate change considerations into long-term transportation planning procedures helps guarantee that infrastructure investments are able to withstand future climate-related catastrophes. To proactively address vulnerabilities and limit the possible implications of extreme weather events on their operations, transportation agencies can integrate climate risk assessments into project evaluations and prioritize adaptation measures. Implementing this comprehensive strategy can contribute to the development of a transportation system in Lagos, Nigeria, that is both environmentally friendly and capable of withstanding challenges.

## 6. Conclusions, Recommendations, and Directions for Further Study

Ultimately, it is imperative for Lagos state government to thoroughly investigate and execute various inventive adaptation solutions and policy frameworks suggested in this research in order to alleviate climate-related risks to transportation infrastructure. Lagos city can maintain the uninterrupted functioning of transportation systems in the face of climate change by investing in resilient infrastructure solutions, such as elevated roadways and flood-resistant bridges. In addition, the adoption of sustainable transportation measures such as the promotion of public transport, the encouragement of electric vehicle usage, and the integration of renewable energy sources into transportation systems can effectively decrease greenhouse gas emissions. The implementation of advanced monitoring and early warning systems can aid in the identification of potential risks and facilitate prompt responses, ultimately adapting to the impact of climate change on transportation infrastructure in Lagos, Nigeria. Lagos city must prioritize adaptation measures and engage in collaboration with international organizations and neighboring nations to effectively handle the problems that climate change presents to transportation infrastructure. This can encompass the dissemination of optimal methodologies, the exchange of expertise, and the procurement of financial backing for the implementation of sustainable and resilient transportation solutions. Lagos can effectively reduce the adverse effects of climate change on its transportation industry and provide a sustainable future for its population by implementing proactive measures and promoting international cooperation.

The deficiencies and constraints of this paper are as follows:

1. One potential obstacle to studying adaptation solutions for adapting to climate-related hazards to transportation infrastructure in Lagos city is the absence of comprehensive data on the individual vulnerabilities and dangers that different forms of transportation infrastructure in the country face. This constraint may occur as a result of restricted resources and capabilities for data gathering and processing, which presents difficulties in formulating specific adaptation strategies for different types of infrastructure.
2. The efficacy of adaptation measures may also be constrained by variables such as insufficient finance, political determination, and collaboration among many parties engaged in transportation infrastructure design and management. Lack of adequate finance poses challenges in implementing essential modifications and enhancements to enhance the resilience of transportation infrastructure against the impacts of climate change. Additionally, the absence of political determination and collaboration among stakeholders might impede the execution of adaptation methods since many parties may possess contradictory agendas and interests. Hence, it is imperative to tackle these difficulties in order to guarantee the enduring viability and robustness of transportation infrastructure in light of climate change.

The suggested steps to meet a specific transportation infrastructure need in Lagos have not been thoroughly analyzed in quantitative terms, necessitating a more comprehensive and detailed investigation. This study also proposed that future research may investigate the following recommendations:

1. Examine the feasibility of incorporating sustainable energy sources into transportation infrastructure in Lagos with the aim of decreasing greenhouse gas emissions and improving resistance to climate-related risks. This may entail conducting research on the viability and efficacy of installing solar-powered street lighting, electric vehicle charging stations, and maybe investigating the utilization of biofuels for public transit.
2. Analyze the impact of nature-based solutions on reducing climate-related risks to transportation infrastructure in Lagos. This may entail conducting research on the efficacy of strategies such as tree planting and the establishment of green areas along roadways to mitigate heat island effects and enhance air quality.
3. Conduct a thorough examination of the economic expenses and advantages linked to various adaptation options for transportation infrastructure in Lagos, including both immediate and long-lasting effects. This study should take into account variables such as the expenses associated with implementing infrastructure enhancements, the possibility of generating employment opportunities in the construction and maintenance industries, and the potential for enhanced economic output coming from improved transportation networks. Furthermore, it should evaluate the possible cost reductions in relation to the prevention of damages and disruptions caused by climate-related occurrences.

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