

The Impact of Climate Change on Flexible Road Pavement Infrastructure

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ABSTRACT :Climate change presents a critical threat to essential infrastructure, particularly road networks, which serve as the indispensable backbone of socioeconomic activity globally. This study evaluates the consequences of climate change on road infrastructure in Edo State, Nigeria, by examining ten-year historical climatic trends (2013–2023), assessing road vulnerability, and identifying climate-related failure modes. The state's tropical climate, characterised by heavy seasonal rainfall and intense heat, has driven significant road deterioration (including potholes, flooding, erosion, and pavement cracking) in major towns like Benin City, Ekpoma, and Auchi. Analysis of climate data revealed an increase in annual precipitation from approximately 1,500 mm to 1,900 mm over the period, a 25% surge that directly correlates with the frequency of extreme rainfall events. Physical and statistical analysis established that increased rainfall causes waterlogging and subgrade saturation, weakening road foundations, while higher temperatures contribute to asphalt softening and subsequent rutting. The pervasive failure is attributed to critically low adaptive capacity, poor maintenance, and outdated engineering standards that fail to factor in future climate risks. The research concludes by proposing vital mitigation and adaptation strategies, focusing on robust engineering and policy reforms, to foster climate-resilient road networks.

KEYWORDS:Climate Change, Road Infrastructure, Pavement Deterioration, Subgrade Saturation, Climate Adaptation

Date of Submission: 12-12-2025

Date of acceptance: 20-12-2025

I. INTRODUCTION

Climate change has emerged as one of the most pressing global challenges of the twenty-first century, significantly influencing global economies, ecosystems, and infrastructure systems. Variations in temperature, shifts in precipitation patterns, and the escalating frequency of extreme weather events collectively disrupt the structural integrity of transport infrastructure globally (IPCC, 2021). Road networks, which serve as the indispensable foundation for socioeconomic activities, are proving to be exceptionally vulnerable to this climate variability.

In developing nations like Nigeria, limited resources, an often-inadequate maintenance culture, and a distinct lack of comprehensive climate-resilient planning for infrastructure often compound the challenge (Shortridge & Camp,

2019). Edo State, situated within the South-South geopolitical zone, experiences a harsh tropical climate defined by intense rainfall and excessive heat. These adverse climatic conditions, frequently exacerbated by deficient drainage systems and substandard construction practices, have precipitated significant deterioration across the road infrastructure. Roads in cities such as Benin City, Ekpoma, and Auchi frequently suffer from potholes, flooding, erosion, and pavement cracking, all demonstrably linked to changes in climate patterns (Ugwusihiwu et al., 2019).

The consequences of climate change on road infrastructure are multifaceted. Increased rainfall intensity leads to waterlogging and subgrade saturation, fundamentally undermining the structural capacity of the road foundation. On the other hand, elevated temperatures contribute

directly to the softening of asphalt, resulting in surface cracking and rut formation. In recent years, Edo State has witnessed a noticeable increase in road failures, particularly evident during and immediately following the rainy season. These damages not only impede transport but also endanger lives and drastically inflate vehicle operating costs (Anthony et al., 2024).

Despite the critical role of road transport in national development, there remains a critical dearth of structured analysis and empirical data quantifying the extent to which climate change is responsible for the observed road degradation in Edo State. Roads are routinely built without adequate consideration for future climate risks, which only intensifies the impact of climate change, leading to greater structural damage, higher costs, and increased hardship (Shortridge & Camp, 2019). While substantial evidence connects these escalating problems to climate variability, the specific statistical weighting of thermal versus hydrological stressors is largely unquantified within the regional context. This study is thus designed to bridge this gap by meticulously examining the relationship between key climate change variables and the sustained performance of road infrastructure in Edo State, thereby providing an evidence base for adaptation.

This research focused exclusively on evaluating the effects of climate change on the road infrastructure within Edo State, Nigeria, covering roads in Benin City, Okada, Ekpoma, and their surrounding areas. The technical scope includes a ten-year climatic analysis (2013–2023), a road condition evaluation, and the use of both field surveys and secondary data to establish clear climate–infrastructure linkages. The analysis concentrated on how fluctuations in climate variables such as increased temperatures, altered rainfall patterns, and extreme weather affect the performance, durability, and maintenance needs of road networks. Other transport infrastructure, such as railways and airports, are beyond the confines of this research.

The study is significant as it provides valuable, evidence-based insights for policymakers, urban planners, and civil engineers. By formally linking established climatic trends to observed road conditions, the findings will effectively guide the future design and maintenance of roads to withstand projected climate conditions. Furthermore, this work contributes substantively to the national dialogue on infrastructure climate adaptation and supports the attainment of both Sustainable Development Goal 9 (Industry, Innovation and Infrastructure) and Goal 13 (Climate Action).

Climate change is broadly understood as a significant and lasting alteration in the statistical

distribution of weather patterns over extended periods. The dominant concern is anthropogenic climate change, driven by industrial activities that increase greenhouse gas (GHG) emissions (IPCC, 2021). Globally, road infrastructure systems are increasingly recognised as critical assets vulnerable to climate-induced stresses, including flooding, heatwaves, storms, and sea-level rise (de Abreu et al., 2022; Singh et al., 2018). Research in high-income countries, such as the United States and Canada, uses predictive models to quantify impacts and prioritise vulnerable segments, spurring innovations like elevated roadbeds and reinforced embankments (Mallick et al., 2018; Swanson et al., 2021). Asian countries like Japan and South Korea, which face intense monsoonal rainfalls, have deployed smart infrastructure and IoT sensors for real-time monitoring and early-warning systems (Ye et al., 2024; Cheong et al., 2023).

In Sub-Saharan Africa, the empirical literature on road infrastructure vulnerability, though growing, is comparatively sparse and constrained by data limitations (Osuteye et al., 2017; Schweikert et al., 2016). Studies in Ghana, Kenya, and Ethiopia reveal that infrastructure fragility is exacerbated by poor initial design, substandard construction materials, and inadequate maintenance (Twerefou et al., 2015; Mbengei et al., 2025). For instance, flooding and waterlogging, caused by inadequate drainage and rapid urbanisation, are primary contributors to surface degradation and road closures in Ghana (Yiran et al., 2024; Owusu-Ansah, 2016).

Africa remains profoundly vulnerable to the adverse effects of climate change (Trisos et al., 2021). In Nigeria, this manifests through unpredictable rainfall, prolonged dry spells, and a general rise in temperature (Ugwusihwu et al., 2019). Intense rainfall and deficient stormwater drainage are identified as primary contributors to highway degradation in southern Nigeria (Odufa & Owolabi, 2018). The Federal Ministry of Works and Housing (FMW&H, 2022) and the Federal Roads Maintenance Agency (FERMA, 2022) have both identified thousands of kilometres of roads at high risk of climate-related damage, advocating for increased capacity and climate-smart engineering. Empirical studies in Lagos demonstrated how poor urban planning and blocked drains exacerbate floodwater accumulation, leading to accelerated pavement deterioration (Onifade et al., 2023). In southeastern Nigeria, gully erosion is a major concern, linked to land degradation and deforestation (Egboka et al., 2021). These findings resonate with broader national challenges, including inadequate maintenance, poor drainage design, and weak enforcement of construction standards (Beitelmal et al., 2024; Mwelu et al., 2018). Nigerian researchers emphasise the need to

mainstream climate adaptation into infrastructure planning, yet institutional capacity constraints and inconsistent funding hamper effective implementation (Ologeh et al., 2017; Olaniyi et al., 2024).

Theoretical Framework

This study adopts the Climate Risk and Resilience Framework, which assesses infrastructure vulnerability based on three core dimensions: Exposure (the degree to which roads are subject to climate hazards), Sensitivity (how severely roads are physically affected), and Adaptive Capacity (the ability of the system to absorb or adjust to impacts). The framework is supplemented by Systems Theory, which views road networks as interconnected components of a complex socio-technical system sensitive to climatic feedback loops. Furthermore, Resilience Theory provides a paradigm by focusing on the system's capacity to absorb, adapt, and transform in response to climate shocks, stressing the need for flexible, sustainable designs.

III. METHODOLOGY

Study Area

This research focused exclusively on road infrastructure within Edo State, Nigeria. The state features a tropical wet-and-dry climate with two distinct seasons and high annual rainfall ranging from 1,500 mm to 2,500 mm, with average temperatures typically hovering between 27°C and 32°C (Agbebaku, 2015). The terrain consists of undulating plains and low-lying flood-prone areas, making the road network highly susceptible to damage from extreme rainfall and heat-related pavement deterioration (NiMet, 2023; Edo SEMA, 2022). The specific road corridors covered in the study included those within Benin City, Okada town, Ekpoma town, and their environs.

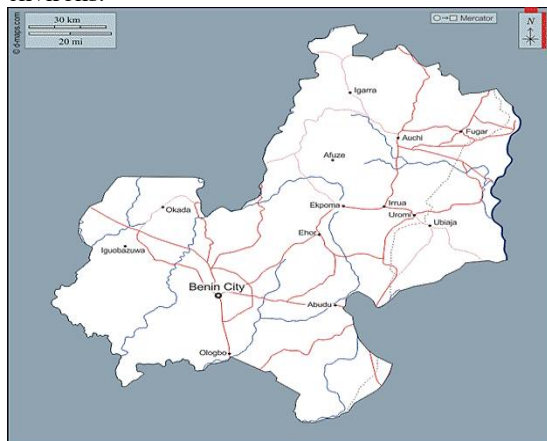


Figure 1: Map showing study area (source: Google Earth).

Research Design and Data Collection

A descriptive and analytical mixed-methods research design was employed, combining several approaches to ensure triangulation of findings.

- i. **Historical Climatic Trend Analysis (2013–2023):** This involved collecting and analysing historical data on key climate variables, including rainfall and temperature, over a ten-year period from the Nigerian Meteorological Agency (NiMet).
- ii. **Visual Condition Surveys:** Physical, in-field inspections were conducted on targeted road corridors (e.g., Benin–Lagos Road, Benin–Auchi Road, Ekpoma–Irrua Road) to assess the extent and type of physical damage and to perform a Road Condition Index (RCI) assessment.
- iii. **Stakeholder Surveys:** Structured questionnaires (N=120) were distributed to gather public and expert opinions on the impact of climate change and road failures. Respondents included engineers, commercial drivers, and community residents.
- iv. **Key Informant Interviews:** Semi-structured interviews were conducted with officials from the Federal Roads Maintenance Agency (FERMA), the Edo State Emergency Management Agency (SEMA), and senior civil engineers.

Data Analysis

Primary data were gathered through the distribution of a structured questionnaire to obtain public and expert perspectives. Secondary data were sourced from peer-reviewed journals and institutional reports such as those from the Nigerian Meteorological Agency (NiMet, 2022). All data collected were subjected to statistical and thematic analysis using the Statistical Package for Social Sciences (SPSS). This included:

- i. **Trend Analysis:** For plotting and interpreting rainfall and temperature patterns over the ten-year period.
- ii. **Statistical Analysis:** Descriptive and inferential statistics were used to establish the relationship between the observed climate variables and road damage types.
- iii. **Thematic Analysis:** Applied to interpret qualitative responses from stakeholders.

IV. RESULTS AND DISCUSSION

Climatic Trend Analysis (2013–2023)

The analysis of historical climate data confirmed a significant and escalating stress on the road network.

1. **Rainfall Patterns:** Annual precipitation revealed an increasing trend over the past decade, rising from approximately 1,500 mm in 2013 to 1,900 mm in 2023, representing a 25% increase. Crucially, the number of days

with heavy rainfall (>50 mm/day) also increased, particularly in 2018, 2021, and 2023. This surge in the volume and frequency of heavy rainfall events has exceeded the drainage design capacities of many roads in Edo State.

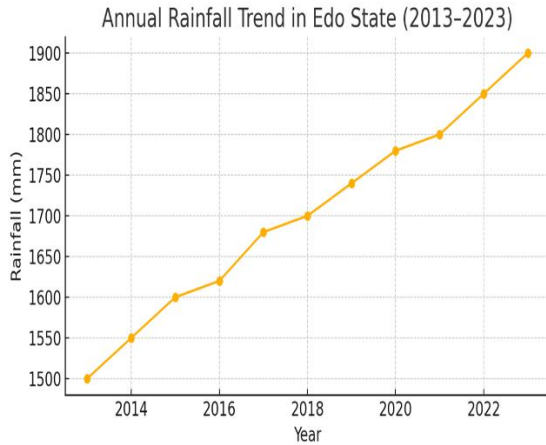


Figure 2: Annual Rainfall Trend in Edo State (2013–2023) (Source: NiMET, 2023)

- Temperature Trends:** Average annual temperatures rose steadily, increasing from 28.4°C in 2013 to 30.0°C in 2023, with noticeable spikes during the dry season.

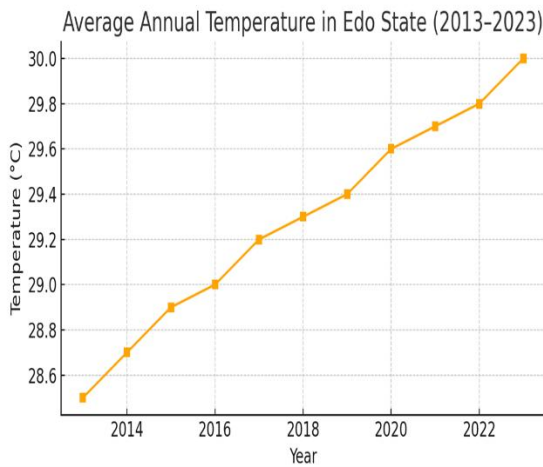


Figure 3: Average Annual Temperature in Edo State (2013–2023) (Source: NiMET, 2023)

Road Condition and Discussion of Failure Modes

Physical inspections and survey data confirmed the severe impact of these climatic trends. The most frequently observed damages aligned directly with the hydrological and thermal stresses documented:

Table1: Summary of Observed Road Damage Types (N = 20 Locations)

Damage Type	Occurrences (%)
Potholes	40
Cracking	25
Flooded Sections (Drainage Collapse)	20
Rutting/Subsidence	15

(Source: Field Survey)

The prevalence of potholes (40%) and flooded sections (20%) along the Benin–Auchi Expressway, Benin-Asaba Expressway, and Uselu–Ugbowo strongly indicates that hydro-mechanical stress is the dominant failure mode, driven by the 25% increase in precipitation. This confirms that the observed surge in heavy rainfall has led to extensive waterlogging and subgrade saturation, fundamentally weakening the road foundations and causing loss of load-bearing capacity (Mndawe et al., 2015). The direct linkage between roads lacking proper drainage and pronounced waterlogging and gully erosion corroborates findings in the literature (Adegoke & Sojobi, 2015). This also supports the work of Odunfa & Owolabi (2018), who observed similar trends and premature pavement deterioration in Lagos.

On the other hand, the steady rise in temperature (up to 30.0°C) contributes to cracking (25%) and rutting (15%). Higher temperatures increase the susceptibility of asphalt to rutting and cracking, which aligns with the literature on thermal expansion and asphalt softening (Benrazavi et al., 2016; IPCC, 2021). However, the overwhelming frequency of water-induced failures suggests the thermal component is a chronic stressor that exacerbates, rather than initiates, the structural collapse caused by acute hydrological shock events.



Plate1: Benin – Asaba Road failed portion due to flooding (source: Field survey, 2025).



Plate 2: Benin City – Road washed away by flood (Source: Field Survey, 2025).



Plate 3: Ekpoma town- overwhelming flood due to climate change (Source: Field Survey, 2025).



Plate 4: Potholes Caused by High Temperatures (Source: Field Survey, 2025).



Plate 5: Street in Benin submerged due to impact of flooding (Source: Field Survey, 2025).



Plate 6: Tomline Area Uselu Benin City (Source: Field Survey, 2025).

Public Perception and Climate-Infrastructure Linkages

Survey responses indicate that over 70% of the public recognizes climate change as a major contributor to road damage. This perception is crucial, as it reflects growing public awareness of environmental stressors. However, 60% also blamed poor construction practices, 55% mentioned inadequate drainage as a major factor 20% were unsure and 10% disagreed, citing poor maintenance as the root cause suggesting that while climate change exacerbates damage, pre-existing weaknesses in infrastructure design and implementation are significant. 52% of respondents reported being stranded at least once due to flooded roads while 45% experienced vehicle damage from potholes or waterlogged roads.

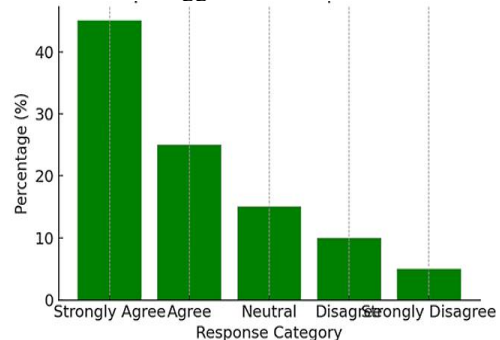


Figure 4: Respondents’ Perception of Climate Impact on Road Infrastructure (Source: Field survey).

The overall high level of public awareness of the severity and frequency of these climate-related failures confirms that the impacts are tangible and severe (Louw et al., 2019). The scale of the physical damage strongly suggests that the prevailing engineering standards and maintenance regimes in the region are critically insufficient to address the increasing intensity of current climate stressors.

Key Informant Interview Highlights

Interviews with engineers and agency officials revealed that

1. Maintenance costs have risen due to recurrent weather-related damages.
2. Lack of dedicated funding for climate adaptation.
3. Roads are still designed using outdated rainfall intensity-duration-frequency (IDF) curves.
4. There is no existing policy that mandates climate resilience standards for local road construction.

This institutional weakness supports the conclusions of OECD (2020), which highlighted that low- and middle-income countries often have insufficient institutional frameworks for climate-resilient infrastructure development.

V. CONCLUSION AND RECOMMENDATIONS

Conclusion

This study empirically confirmed that the road network in Edo State, Nigeria, is critically vulnerable to climate change. The analysis of the 2013–2023 period revealed a significant 25% increase in annual precipitation and corresponding increases in the frequency of heavy rainfall days. The high prevalence of hydro-mechanical failures, specifically potholes (40%) and flooded sections (20%), demonstrates

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that hydrological stress is the dominant climate driver of road deterioration. Existing road design and drainage capacities have been demonstrably exceeded by the escalating intensity of rainfall. The concurrent rise in temperature acts as a secondary, chronic stressor, accelerating thermal-related damage.

Recommendations

Based on the quantified evidence, the following targeted mitigation and adaptation strategies are urgently recommended:

1. Engineering Design Mandates: New and rehabilitated road projects must integrate updated NiMet climate projections. Design standards, particularly for drainage and subgrade protection, must be upgraded to accommodate the demonstrated increase in extreme precipitation volume and frequency.
2. Drainage System Resilience: Immediate attention must be paid to upgrading and maintaining existing stormwater drainage infrastructure, specifically increasing channel capacity to mitigate waterlogging and subsequent subgrade saturation.
3. Materials Selection: Given the steady rise in temperature, the use of modified, high-performance-graded asphalt binders should be mandated to enhance rutting and cracking resistance, thereby addressing the thermal component of deterioration.
4. Policy and Planning: The State Ministry of Works should implement a mandatory Climate Risk Assessment (CRA) phase for all road projects and institutionalise a dedicated Road Condition Index (RCI) monitoring programme to enable proactive, data-driven maintenance prioritisation, moving away from reactive repair.

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