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RESEARCH ARTICLE

LIFECYCLE COST AND RESILIENCE PERFORMANCE EVALUATION OF CLIMATE-RESILIENT URBAN ROAD INFRASTRUCTURE UNDER CLIMATE RISK SCENARIOS

Johnbosco Mgbajiaka and Bukola Adesanmi

Cleveland State University, US Cleveland State University, USA

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Corresponding author:
Johnbosco Mgbajiaka

ABSTRACT

Aim: Urban road infrastructure is increasingly exposed to climate-induced hazards such as flooding, extreme heat, and intense precipitation. These hazards disrupt mobility, increase maintenance costs, and threaten economic stability. This study evaluates the lifecycle cost and resilience performance of climate-resilient urban road infrastructure under climate risk scenarios. **Methodology:** Ahybrid framework integrating Lifecycle Cost Analysis (LCCA) and resilience performance modeling is developed. Two scenarios, conventional road infrastructure and climate-resilient road systems, are assessed over a 50-year lifecycle using Net Present Value (NPV) modeling. **Results:** Results indicate that climate-resilient infrastructure increases initial capital costs by 12–18% but reduces lifecycle costs by up to 25% due to lower failure rates and faster recovery after disruptions. **Conclusion:** Climate-resilient road infrastructure is economically viable when evaluated over the long term. Integrating resilience into infrastructure planning improves system reliability and reduces climate-related risks.

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INTRODUCTION

Urban road networks are more than physical infrastructure; they are the circulatory system of cities. Every commute, supply chain movement, emergency response, and economic interaction depends on their reliability. Yet, climate change is quietly but steadily eroding this reliability (IPCC, 2022). Flooded streets, heat-damaged pavements, and storm-induced failures are no longer rare events; they are becoming expected disruptions. These failures don't just damage roads; they disrupt livelihoods, delay emergency services, and ripple through entire urban economies (Hallegatte *et al.*, 2019). Traditionally, infrastructure has been designed using historical climate assumptions. But today's reality is different: the past is no longer a reliable predictor of the future.

This raises a critical question

Are we building roads for yesterday's climate—or tomorrow's?

LITERATURE REVIEW

The concept of infrastructure resilience has evolved significantly in recent decades. Infrastructure resilience has been widely studied across engineering and economic disciplines. Cutter *et al.* (2016) define resilience as the capacity to absorb, recover, and adapt to disruptions. Similarly, Rose (2007) emphasizes economic resilience as the ability to minimize losses during disruptions.
Lifecycle cost analysis has been applied extensively in transportation engineering. Harvey (2019) demonstrates that lifecycle approaches reveal hidden long-term costs overlooked in initial investment decisions. Integrating climate risk into LCCA is a growing research area, with studies highlighting the benefits of proactive adaptation strategies (OECD, 2018; World Bank, 2021).
Network-level resilience adds another dimension, emphasizing interconnected infrastructure systems (Rinaldi *et al.*, 2001). Failures in one node can propagate across networks, amplifying impacts. Despite advances, integration of resilience metrics with lifecycle cost modeling remains limited, particularly in urban road systems.

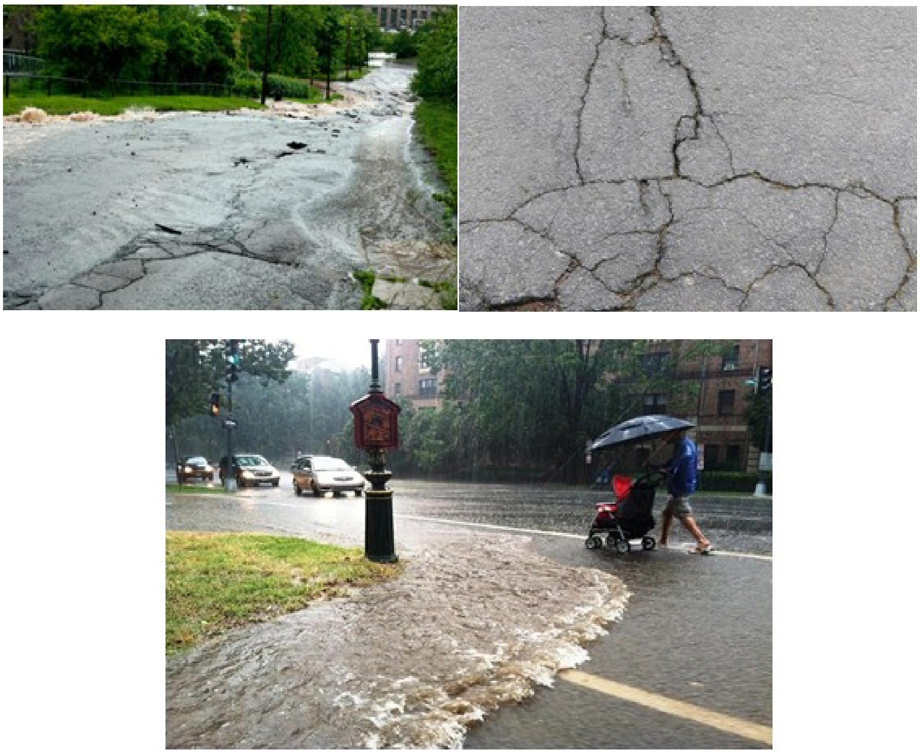


Fig. 1. Climate Stress on Urban Roads

Infrastructure Resilience: Cutter *et al*. (2016) define resilience as the capacity to absorb, recover, and adapt to disruptions. Similarly, Rose (2007) emphasizes economic resilience as the ability to minimize losses during disruptions.Research shows that resilient infrastructure significantly reduces long-term economic losses (Hallegatte *et al*., 2019).

Infrastructure resilience has emerged as a central concept in understanding how transportation systems respond to increasing climate variability and extreme events. At its core, resilience reflects the capacity of infrastructure systems to withstand, adapt to, and recover from disruptions while maintaining critical functionality (Intergovernmental Panel on Climate Change, 2022).

Unlike traditional engineering approaches that emphasize resistance and structural robustness alone, resilience introduces a dynamic systems perspective, recognizing that failure is not always avoidable—but recovery and adaptation are equally important.

Lifecycle Cost Analysis (LCCA) in Climate-Resilient Transportation Infrastructure

Lifecycle cost analysis shifts decision-making from:

“What is cheapest to build?”to“What is cheapest over 50 years?”

Studies (Harvey, 2019) show that:

- Upfront cost ≠ total cost
- Maintenance + failure costs dominate lifecycle expenses

Lifecycle Cost Analysis (LCCA) is a fundamental decision-support tool used to evaluate the total economic cost of infrastructure over its entire service life. Unlike traditional cost assessment methods that emphasize initial capital expenditure, LCCA provides a more comprehensive perspective by incorporating long-term costs associated with operation, maintenance, rehabilitation, and failure (Federal Highway Administration (FHWA), 2016).

At its essence, LCCA answers a critical question:

What is the true cost of infrastructure—not just to build, but to sustain under real-world conditions over time?

LCCA emerged as a response to the limitations of short-term budgeting approaches in infrastructure planning. Early infrastructure decisions often prioritized the lowest initial cost, which frequently resulted in higher long-term expenditures due to frequent repairs and system failures. Modern LCCA frameworks recognize that infrastructure systems—particularly transportation networks—operate over extended time horizons (30–75 years), during which uncertainty, deterioration, and external stressors such as climate change significantly influence performance and cost (Walls & Smith, 1998).

Core Components of Lifecycle Cost

Lifecycle cost is typically decomposed into several major components:

Table 1. Lifecycle Cost Components

Cost Component	Description
Initial Cost (C_0)	Design, materials, and construction
Maintenance Cost (M_t)	Routine upkeep and minor repairs
Rehabilitation Cost (R_t)	Major repairs or reconstruction
User Cost (U_t)	Travel delays, vehicle operating costs
Failure Cost (F_t)	Costs due to climate-related damage

This comprehensive structure allows decision-makers to account for both direct infrastructure costs and indirect societal impacts.

The lifecycle cost of infrastructure is typically expressed as the discounted sum of all costs over time:

$$LCC = C_0 + \sum_{t=1}^{n} \frac{M_t + R_t + U_t + F_t}{(1+r)^t}$$

Where:

- C_0: Initial construction cost
- M_t: Maintenance cost in year t
- R_t: Rehabilitation cost
- U_t: User cost (e.g., delays, congestion)
- F_t: Failure cost due to climate events
- r: Discount rate
- n: Analysis period

This formulation reflects the time value of money, recognizing that future costs must be discounted to present value. A central concept in LCCA is Net Present Value (NPV), which enables comparison of alternative infrastructure investments.

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

NPV allows planners to determine which infrastructure option yields the lowest total cost over its lifecycle, rather than simply the lowest initial investment. Studies have shown that infrastructure options with higher upfront costs often produce lower NPV over time due to reduced maintenance and failure costs (Zhou *et al*., 2019).

LCCA Under Climate Uncertainty: One of the most significant advancements in recent years is the integration of climate risk into lifecycle cost analysis. Traditional LCCA assumes relatively stable environmental conditions. However, climate change introduces increased frequency of extreme events, accelerated infrastructure degradation, and greater uncertainty in cost projections. According to the Intergovernmental Panel on Climate Change (2022), infrastructure systems designed without accounting for future climate conditions are likely to experience higher-than-expected lifecycle costs.This has led to the emergence of climate-adjusted LCCA, which incorporates probabilistic risk modeling, scenario-based cost projections, and climate damage functions.

A critical but often underappreciated component of LCCA is user cost.

User costs include

- Travel delays
- Increased fuel consumption
- Lost productivity
- Emergency response delays

These costs represent the human experience of infrastructure failure.

For example: A flooded road does not just require repair; it delays workers, disrupts businesses, and can prevent access to healthcare. Research by the World Bank (2019) shows that user disruption costs often exceed direct repair costs, especially in densely populated urban areas.

Comparing Conventional vs Climate-Resilient Infrastructure:

LCCA provides a powerful framework for comparing infrastructure strategies.

Dimension	Conventional Infrastructure	Climate-Resilient Infrastructure
Initial Cost	Lower	Higher
Maintenance	Higher over time	Lower
Failure Cost	High	Significantly reduced
User Cost	High disruption	Lower disruption
Lifecycle Cost	Higher	Lower

This comparison demonstrates a fundamental principle:

"Cheaper infrastructure today often becomes more expensive infrastructure tomorrow."

Climate Risk in Road Infrastructure: Climate risk represents one of the most significant performance challenges and longevity of road infrastructure systems. It refers to the potential for climate-related hazards to disrupt infrastructure functionality, increase deterioration rates, and impose economic and social costs (Intergovernmental Panel on Climate Change, 2022).

Unlike traditional infrastructure risks, climate risks are characterized by uncertainty, increasing frequency, and compounding effects, making them particularly difficult to predict and manage within conventional planning frameworks.

Types of Climate Hazards Affecting Roads

Urban road infrastructure is exposed to multiple climate-related stressors, each affecting performance in distinct ways:

Flooding and Extreme Precipitation: Flooding is one of the most damaging climate hazards for road infrastructure. Prolonged water exposure weakens pavement layers, erodes subgrades, and compromises structural integrity. Leading to potholes, surface cracking, and eventual road failure, whichoverwhelms drainage systems, causing prolonged service disruption.Studies indicate that flooding accounts for a substantial proportion of climate-related transportation damage globally (Neumann *et al.*, 2015).

Extreme Heat

Rising temperatures and heat waves contribute to:

- Asphalt softening and rutting
- Thermal expansion leading to surface deformation
- Reduced pavement lifespan

According to the Intergovernmental Panel on Climate Change (2022), heat extremes are projected to intensify, increasing stress on road materials beyond design thresholds.

Freeze–Thaw Cycles

In colder climates, repeated freezing and thawing cycles cause:

- Expansion and contraction of pavement layers
- Cracking and structural weakening
- Accelerated deterioration

These cycles significantly increase maintenance requirements and lifecycle costs.

Storm Events and Surface Runoff: Storms generate intense runoff that overloads drainage systems, causes erosion of road foundations, and leads to debris accumulation and blockages.

Climate Risk as a Function of Exposure, Sensitivity, and Adaptive Capacity

Climate risk in infrastructure is commonly conceptualized as:

Risk = Hazard × Exposure × Vulnerability

Where:

- **Hazard** = Climate event (e.g., flood, heatwave)
- **Exposure** = Infrastructure located in risk-prone areas
- **Vulnerability** = Susceptibility to damage

Vulnerability itself is influenced by material quality, design standards, and maintenance practices. This framework highlights that risk is not solely determined by climate events but also by how infrastructure is designed and managed (OECD, 2018).

Figure 2. Road Vulnerability Types

Economic and Social Implications of Climate Risk: Climate-related disruptions in road infrastructure generate both direct and indirect costs:

Direct Costs

- Repair and reconstruction expenses
- Increased maintenance frequency

Indirect Costs (Often Larger)

- Travel delays and congestion
- Supply chain disruptions
- Reduced access to essential services

Research by the World Bank (2019) shows that indirect costs, particularly user disruption, can exceed direct infrastructure repair costs, especially in dense urban environments. A key challenge in infrastructure planning is that roads are designed for decades, but climate conditions are changing within those decades. This creates a mismatch between design assumptions (historical climate data)andfuture realities (changing climate patterns). As a result, infrastructure systems face an increasing risk of underperformance or premature failure.

Integrating Climate Risk into Lifecycle Cost Analysis: Incorporating climate risk into Lifecycle Cost Analysis (LCCA) is essential for realistic infrastructure evaluation. Climate risks influence the maintenance frequency, probability of failure, and user disruption costs.

By integrating climate risk into LCCA, planners can:

- Better estimate long-term costs
- Justify resilience investments
- Reduce uncertainty in infrastructure decision-making

Synthesis: Climate risk fundamentally reshapes how road infrastructure should be designed, evaluated, and maintained. It introduces uncertainty, amplifies costs, and highlights the limitations of traditional planning approaches. This study incorporates climate risk into lifecycle cost and resilience analysis to provide a more comprehensive and innovative framework for evaluating urban road infrastructure.

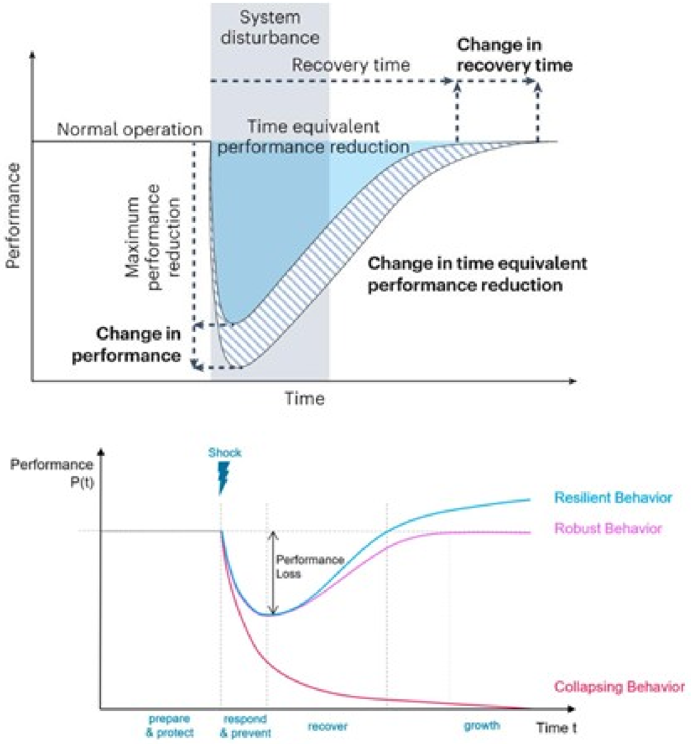


Figure 3. Resilience Performance Curve

METHODOLOGY

This study adopts an integrated analytical framework combining Lifecycle Cost Analysis (LCCA), climate risk assessment, and resilience performance modeling to evaluate the long-term economic and operational performance of urban road infrastructure under climate stress scenarios. Rather than treating cost, risk, and performance as separate dimensions, this approach recognizes that infrastructure decisions are inherently multi-dimensional, shaped by financial constraints, environmental uncertainty, and societal impacts. This research employs a comparative scenario-based modeling approach, widely used in infrastructure and transportation studies (Meyer *et al*., 2014).

Two infrastructure scenarios are evaluated:

- **Scenario A: Conventional Infrastructure**
  - Standard asphalt pavement
  - Reactive maintenance strategy
  - Limited climate adaptation features
- **Scenario B: Climate-Resilient Infrastructure**
  - Enhanced drainage systems
  - Heat-resistant and durable materials
  - Proactive maintenance strategy
  - Design adaptations for flood and heat risks

Both scenarios are assessed over a **50-year lifecycle period**, which reflects the typical design life of urban road infrastructure (FHWA, 2016). Analytically, the methodological framework integrates three core components:

- Lifecycle Cost Analysis (LCCA)
- Climate Risk Assessment
- Resilience Performance Modeling

These components are combined to evaluate both the economic efficiency and functional reliability of infrastructure systems.

Lifecycle Cost Model: Lifecycle cost is calculated using a discounted cash flow approach.

We evaluate total lifecycle cost using:

$$LCC = C_0 + \sum_{t=1}^{n} \frac{M_t + R_t + U_t}{(1+r)^t}$$

Where:

- C_0= Initial cost
- M_t= Maintenance cost
- R_t= Repair cost
- U_t= User cost
- r= Discount rate

To support decision-making, Net Present Value (NPV) is also calculated:

$$NPV = \sum_{t=0}^{n} \frac{C_t}{(1+r)^t}$$

Climate Risk Assessment: Climate risk is incorporated using a hazard–exposure–vulnerability framework, consistent with the Intergovernmental Panel on Climate Change (2022):

- **Hazard**: Frequency and intensity of climate events (flooding, heatwaves)
- **Exposure**: Location of infrastructure in climate-prone areas
- **Vulnerability**: Susceptibility of infrastructure to damage

Climate risk influences the frequency of maintenance, probability of failure, and magnitude of repair costs. Scenario-based assumptions are used to simulate moderate and high climate risk conditions, following approaches in OECD (2018) and World Bank (2019) infrastructure studies.

Resilience Performance Modeling: Infrastructure resilience is evaluated using performance-based metrics, which track system functionality over time during and after disruption events.Key indicators include:

- Performance Loss (%) during disruption
- Recovery Time (days)
- Resilience Index (R)

Resilience is conceptualized as the area under the performance curve, following Bruneau *et al.* (2003):

- Higher area = higher resilience
- Faster recovery = stronger system performance

This allows comparison of how quickly each infrastructure scenario returns to acceptable service levels.

Methodological Contribution

This study contributes to the literature by:

- Integrating LCCA with resilience performance modeling
- Explicitly incorporating climate risk into lifecycle cost evaluation
- Expanding cost analysis to include user and failure costs

This integrated approach provides a more **realistic and policy-relevant framework** for evaluating climate-resilient urban road infrastructure.

RESULTS AND DISCUSSION

This section presents the findings from the comparative analysis of conventional and climate-resilient urban road infrastructure, followed by a critical discussion of their economic, and operational implications. The results are interpreted through the combined lens of lifecycle cost efficiency, climate risk exposure, and resilience performance.

Lifecycle Cost Outcomes: The lifecycle cost analysis reveals a clear divergence between conventional and climate-

Key Finding: While climate-resilient infrastructure incurs higher initial capital costs, it demonstrates substantially lower total lifecycle costs.

Table 2. Lifecycle Cost Comparison

Cost Component	Conventional	Resilient
Initial Cost	$100M	$115M
Maintenance	$60M	$40M
Climate Damage	$45M	$15M
User Costs	$35M	$12M
Total	**$240M**	**$182M**

This outcome is primarily driven by

- Reduced frequency of major repairs
- Lower failure rates under climate stress
- Significant reduction in user disruption costs

These findings are consistent with prior studies indicating that infrastructure designed with resilience considerations yields long-term economic benefits despite higher upfront investments (Hallegatte *et al*., 2019; OECD, 2018).

Interpretation: From a financial perspective, this result challenges the traditional emphasis on **lowest initial cost procurement**. Instead, it reinforces the importance of evaluating infrastructure investments through a **whole-life economic lens**, where long-term performance outweighs short-term savings (FHWA, 2016).

Impact of Climate Risk on Cost Dynamics: The analysis highlights the significant role of climate risk in shaping lifecycle cost outcomes.

Under higher climate risk scenarios

- Conventional infrastructure experiences **sharp increases in repair and failure costs**
- Maintenance cycles become more frequent and unpredictable
- User disruption costs escalate due to prolonged service interruptions

In contrast, climate-resilient infrastructure demonstrates cost stability, even under intensified climate conditions. This aligns with findings from the Intergovernmental Panel on Climate Change (2022), which emphasize that infrastructure systems not designed for future climate conditions are likely to incur accelerating costs over time.

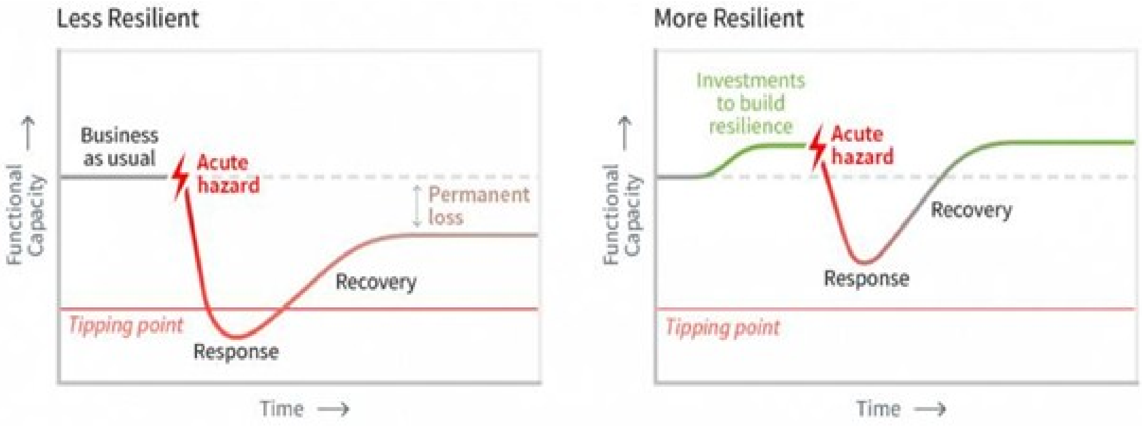
Interpretation: Climate risk acts as a cost multiplier rather than just a physical threat. It amplifies both direct and indirect costs, making resilience not merely a technical enhancement but a financial risk mitigation strategy.

Resilience Performance and System Recovery: The resilience performance modeling demonstrates that climate-resilient infrastructure maintains higher functionality during disruption events and recovers more rapidly.

Key Observations

- Conventional infrastructure shows a **steeper performance decline** during climate events
- Recovery time is significantly longer due to extensive damage
- Resilient systems maintain partial functionality and recover faster

This finding reflects established resilience theory, where system performance is evaluated based on both the magnitude of disruption and recovery speed (Bruneau *et al*.).



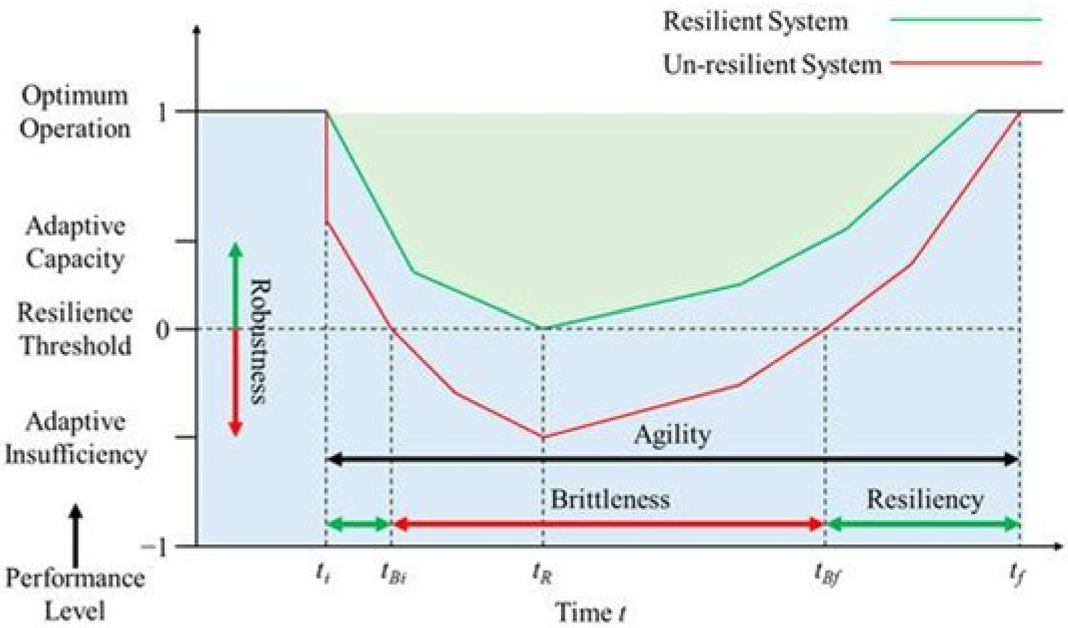


Figure 4. Resilience Performance Comparison

Interpretation: The ability to maintain functionality during disruption is critical in urban contexts, where even short-term road failures can have cascading impacts on emergency response, economic activity, and public safety. Thus, resilience should be understood not only as a recovery metric but as a continuity-of-service strategy.

CONCLUSION

At its core, this study shows something simple but important: the way we build roads today will determine how well our cities function tomorrow. By comparing conventional and climate-resilient urban road infrastructure, the findings make it clear that focusing only on upfront costs can be misleading. While resilient roads may cost more to build, they save money—and disruption—over time by lasting longer, failing less often, and recovering faster when climate events occur. But the implications go beyond numbers. When a road floods or fails, the impact is felt immediately and personally—commutes are delayed, businesses lose revenue, emergency services slow down, and entire communities can become temporarily disconnected. In that sense, infrastructure resilience is not just about engineering performance; it is about keeping everyday life moving, especially when conditions are at their worst. This study also reinforces a broader shift in thinking: climate risk is no longer a distant concern; it is already shaping how infrastructure performs and how much it costs to maintain. Designing roads based on past conditions is no longer enough. We need to plan for the realities ahead. Ultimately, investing in climate-resilient infrastructure is not simply an added expense; it is a practical, forward-looking decision that reduces long-term costs while strengthening the reliability of the systems people depend on every day. It is, in many ways, an investment in stability, safety, and continuity for our communities. As cities continue to grow and climate pressures intensify, the challenge is not just to build infrastructure that works, but to build infrastructure that endures, adapts, and supports people; no matter what comes next.

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