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A Data-Driven Approach as a Panacea to the Economic Rehabilitation of the Benin–Auchi Expressway

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KEYWORDS

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ABSTRACT

This study evaluates pavement performance, traffic growth, and economic implications along the Agbede–Ewu 10 km section of the Benin–Auchi Expressway, a corridor experiencing rapid deterioration due to heavy freight movement, steep gradients, and high rainfall. Pavement Condition Index (PCI) data collected from 2020 to 2025 show a steady decline from 53.25 to 39.0, reflecting a shift from fair to poor condition, while average daily traffic (ADT) increased from 5,000 to 5,796 vehicles, compounding structural stress. Vehicle operating costs (VOC) and maintenance expenditures were analysed, and cost–benefit evaluation of rehabilitation strategies was performed. Overlay resurfacing over 6.7 km yielded the highest benefit-cost ratio (BCR = 1.83), while full reconstruction of the most deteriorated 2.5 km mid-segment incurred a total cost of ₦2.33 billion but provided an NPV of ₦1.65 billion. The study highlights the need for timely preventive maintenance and targeted structural interventions to optimize corridor service life, reduce operational costs, and maintain safe and efficient traffic flow.

1. INTRODUCTION

Transportation infrastructure is vital to economic performance and regional integration. In Nigeria, road transport accounts for over 90% of passenger and freight movement (Federal Ministry of Works, 2022), making highways central to national productivity. The Benin–Auchi Expressway is one of southern Nigeria's most important corridors, connecting the industrial center of Benin City with the commercial hubs of Auchi, Okpella, and Lokoja. The Agbede–Ewu section (10 km) was selected for this study due to its unusually rapid degradation compared with neighboring segments. Structurally, the section is defined by steep gradients, heavy freight traffic, and high rainfall, which together impose stresses exceeding original pavement design assumptions. Frequent braking and traction on slopes accelerate surface wear, shear failure, and fatigue cracking, while heavy axle loads promote rutting and subgrade deformation.

Performance is further reduced by engineering deficiencies including inadequate pavement thickness, variable material quality, oxidation of bituminous layers, shoulder erosion, and ineffective drainage systems. Prolonged moisture exposure weakens the subgrade, leading to deformation, stripping of asphalt layers, and localized collapse. Between 2020 and 2025, maintenance interventions were largely reactive, involving patching and partial resurfacing without systematic assessment of traffic loading, material performance, or drainage condition. The lack of reliable data on axle loads, pavement strength, and environmental exposure limited the durability of repairs and resulted in repeated failure cycles.

This study therefore applies a data-driven pavement evaluation framework using mechanical, geospatial, and economic datasets to identify structurally deficient sections and prioritize rehabilitation based on performance and cost effectiveness. Similar approaches in Kenya and Ghana have achieved maintenance efficiency gains of up to 40% (Mwangi *et al.,* 2021; Osei & Amponsah, 2022). Accordingly, datasets representing conditions from 2020–2025 were analyzed for the Agbede–Ewu corridor to quantify deterioration mechanisms and estimate the benefits of targeted rehabilitation on transport efficiency and regional productivity

2. MATERIALS AND METHODS

2.1 Study Area Description

The Benin–Auchi Expressway spans about 120 km, linking Benin City to Auchi across mixed terrain and high-rainfall zones that accelerate pavement deterioration. Traffic along the route ranges from 4,000–9,000 average annual daily traffic (AADT), with heavy-truck movement influencing surface distress. This study focuses only on the Agbede–Ewu stretch, (Figure 1) a 10 km section known for rapid degradation due to steep gradients, concentrated freight loading, and inadequate drainage around the Ewu Hill approach. Its recurring pavement failures and high operational importance make it suitable for detailed structural and economic assessment.

2.2 Data Sources

Field data for this study were collected directly along the Benin–Auchi Expressway between Agbede and Ewu Junction, a corridor of approximately 10 km. For analysis, the corridor was divided into four sub-segments: 0.0–2.5 km, 2.5–5.0 km, 5.0–7.5 km and 7.5–10.0 km. Annual surveys between 2020 and 2025 provided pavement condition index (PCI) values determined in accordance with ASTM D6433 (2018), distress type–severity–extent maps, classified 24-h traffic counts with axle-load observations for computing ESALs, rebound deflection measurements from Falling Weight Deflectometer tests and speed–flow data from repeated floating-car runs. Occasional missing observations were interpolated using locally observed degradation patterns for the same sub-segment and survey year. Heavy-truck effects on deterioration were represented by the empirical relation

$$D = a \cdot \mathrm{ESAL}^{b} \qquad (1)$$

where D is a dimensionless deterioration index proportional to the cumulative PCI loss attributable to heavy-truck loading, and ESAL is the cumulative equivalent single-axle load repetitions along each sub-segment. The calibration coefficients a = 80 and b = 1.5 obtained by fitting the model to the 2020–2025 field data using nonlinear regression between observed PCI decline and computed ESALs for the four sub-segments. The exponent b > 1 reflects the strongly nonlinear increase in damage with axle load observed on the corridor, while the scale factor a was selected to reproduce the measured mean rate of PCI reduction across the 10 km section. Where field records were incomplete, validated Federal Ministry of Works archives and comparable South–South expressway datasets were used only for cross-validation; all primary values reported in the analysis are derived from the Benin–Auchi route observations.

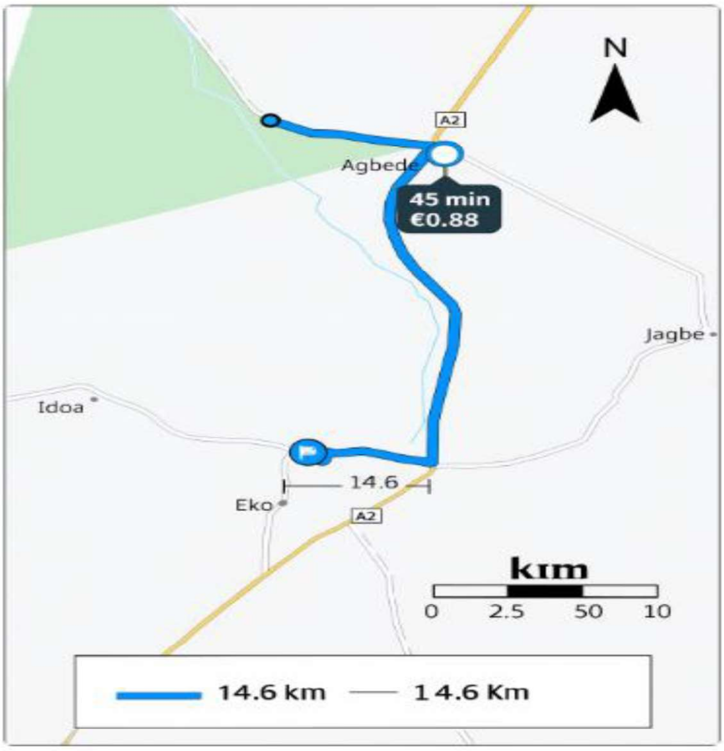

Figure 1: Agbede–Ewu Segment Used for Investigation.

2.3 Pavement Condition Index

The Pavement Condition Index (PCI) for the 10 km Agbede–Ewu corridor was determined using the ASTM D6433 method. Distresses were surveyed at 2.5 km intervals, converted to deduct values, and corrected for multiple distresses to obtain the Corrected Deduct Value (CDV). Yearly PCI values (2020–2025) were computed for each sub-segment. These measurements, combined with traffic counts, informed pavement deterioration trends, travel-delay estimation, and economic evaluation of rehabilitation strategies.

2.4. Traffic count

Traffic counts along the 10 km Agbede–Ewu corridor were conducted at strategic locations to capture representative traffic flow and vehicle speeds, using manual counting and speed guns.

Observers recorded vehicles by type during peak and off-peak periods, extrapolating to average daily traffic (ADT) and validating simulated data. Speed measurements provided prevailing speeds and volume-speed relationships for pavement analysis. Count and speed data were averaged per sub-segment and combined with historical trends and a 3% annual growth rate to produce traffic datasets for 2020–2025, informing PCI deterioration modeling and delay calculations.

2.5. Vehicle Operating Cost

Vehicle Operating Costs (VOC) were estimated using operational data from transport agencies along the corridor, including God is Good, Afemai Line, Edo Line, and Muyi Line. Data on fuel, maintenance, driver wages, and vehicle types were combined with traffic counts to calculate VOC per vehicle per kilometer using:

$$VOC = C_f + C_m + C_d + C_t \quad (2)$$

Where C_f, C_m, C_d, and C_t represent fuel, maintenance, driver wages, and tire/other operating costs per kilometer, respectively. Total VOC for each sub-segment was then computed and integrated into Net Present Value (NPV) and Benefit-Cost Ratio (BCR) analyses to quantify the economic benefits of pavement rehabilitation.

2.6. Economic Analysis Framework

The economic evaluation was carried out using life-cycle cost–benefit analysis with Net Present Value (NPV) as the primary decision indicator. All costs and benefits were discounted to 2025 present values using a real discount rate of 10% per annum. A 20-year analysis period was adopted, representing the expected service life of major highway rehabilitation works in Nigeria. NPV was computed as:

$$NPV = \sum_{t=0}^{20} \frac{B_t - C_t}{(1 + 0.10)^t} \quad (3)$$

costs in year t. Benefits included savings in vehicle operating costs and travel time due to improved pavement condition, while costs consisted of initial rehabilitation, periodic maintenance, and the residual value at the end of the project life. Traffic was assumed to grow at 3% annually. A rehabilitation option was considered economically justified when NPV was positive.

3. RESULTS AND DISCUSSION

3.1 Pavement Deterioration Trend (2020–2025)

The PCI values derived using the ASTM D6433 (2018) standard (Table 1) show a consistent decline along the Agbede–Ewu 10 km corridor between 2020 and 2025, with average PCI reducing from 53.25 to 39.00 (Table 1). ASTM D6433 (2018) provides a systematic field procedure for pavement condition evaluation based on visual identification, severity rating, and density measurement of surface distresses, which are converted into Corrected Deduct Values (CDV) and aggregated to compute PCI. The observed decline therefore reflects the progressive accumulation of structural and functional distresses along the corridor and is consistent with trends reported for Nigerian highways exposed to heavy axle loads, inadequate drainage, and weak subgrade conditions (Noaman *et al.,* 2020; Nnochiri *et al.,* 2022).

Table 1. PCI Values and Average for Agbede-Ewu Corridor

Year	0-2,5km	2.5-5km	5-7.5km	7.5-10km	Average PCI
2020	55	50	48	60	53.25
2021	53	46	44	58	50.25
2022	50	42	40	56	47.00
2023	48	39	37	54	44.50
2024	46	35	33	52	41.50
2025	44	32	30	50	39.00

Figure 2 shows non-uniform deterioration, with the mid-segments (2.5–7.5 km) degrading more rapidly than terminal sections, confirming findings by Olalusi and Ojo (2019) on the effects of freight concentration and drainage deficiencies. These trends are important for pavement management since reduced PCI is associated with higher vehicle operating costs and reduced serviceability (FHWA, 2016; Akande & Oloruntoba, 2018). The PCI pattern is well explained by the empirical deterioration model:

$$PCI = a - b \ln (ESAL) \quad (4)$$

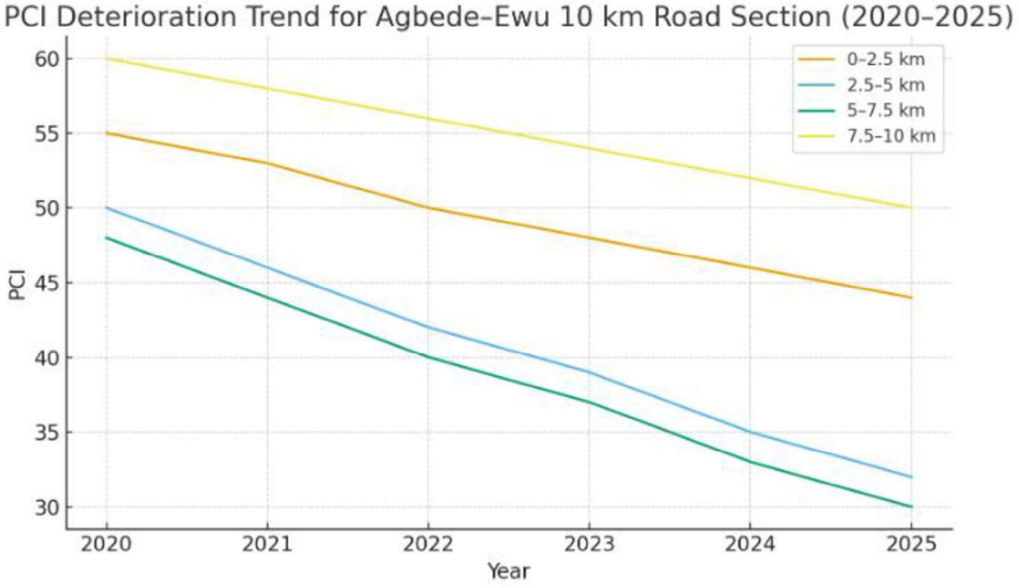

Figure 2: PCI Deterioration Trend for Agbede-Ewu Corridor

where a = 80 (represents baseline pavement serviceability) and b = 1.5 (indicates high sensitivity to cumulative axle loading). The observed mean PCI loss of about 2.9 points per year reflects a nonlinear ESAL effect, with faster decline in high-traffic mid-segments and slower deterioration toward the corridor ends. The baseline constant further indicates that the pavement entered the analysis period in a pre-degraded state. Collectively, the adopted constants reproduce both the rate and curvature of the trend in Figure 2, confirming traffic loading as the dominant deterioration mechanism and justifying targeted structural rehabilitation in critical segments and preventive maintenance in relatively stable sections.

3.2. Traffic Volume Growth (2020–2025)

Traffic counts and spot-speed measurements were averaged for each sub-segment and combined with historical trends to generate annual traffic datasets for the period 2020–2025. As shown in Table 2, average daily traffic increased from approximately 5,000 veh/day in 2020 to 5,796 veh/day in 2025, corresponding to an annual growth rate of about 3%. This observed growth aligns with the low-growth traffic forecast adopted by the Federal Ministry of Works (2013) for comparable federal highways in Nigeria, thereby validating the application of a 3% annual traffic growth rate for traffic projection, PCI deterioration modeling, and delay analysis in this study. Increased traffic accelerates roughness accumulation and structural distress and supports the case for predictive maintenance and targeted rehabilitation.

Table 2: Average Daily Traffic

Year	ADT (Veh/day)
2020	5,000
2021	5,150
2022	5,304
2023	5,464
2024	5,628
2025	5,796

This rise in traffic implies higher axle repetitions, which accelerate cumulative pavement damage following the fourth-power law, where stress increases with the fourth power of axle load. The Pavement Condition Index (PCI), a standard metric for road surface quality, captures the resulting deterioration, with higher traffic reducing PCI more rapidly through increased roughness and structural distress. Mechanistic-empirical models relate cumulative loading to PCI decline, highlighting that accelerated traffic growth shortens effective service life and necessitates proactive maintenance planning. Observed trends in Table 3 demonstrate the correlation between increasing traffic and decreasing PCI, confirming that higher ADT directly impacts pavement performance. Relevant standards and studies include ASTM D6433 for PCI surveys, the fourth-power law in pavement design, and empirical PCI damage models from mechanistic-empirical studies.

Figure 3 shows that from 2020 to 2025, the PCI declines from 53.25 to 39.00 as average daily traffic rises from 5,000 to 5,796 vehicles. This indicates that higher traffic accelerates pavement deterioration and shortens its service life

Between 2020 and 2025, the corridor experiences a continuous decline in pavement condition, with the average PCI dropping from 53.25 to 39.0. This shift indicates a transition from fair to poor pavement condition, suggesting that the surface is increasingly susceptible to structural damage, rutting, and cracking. At the same time, the average daily traffic steadily increases from 5,000 to 5,796 vehicles per day, adding additional stress to the pavement. The combination of deteriorating pavement and growing traffic volumes accelerates wear and increases the likelihood of safety hazards, higher vehicle operating costs, and more frequent maintenance needs. Without timely intervention, the route could face significant degradation. Therefore, implementing preventive maintenance measures now, such as crack sealing or thin overlays, along with planning for structural rehabilitation within the next few years, is essential to maintain the corridor's performance and ensure safety and efficiency for users.

Table 3. Average PCI vs Average Traffic

Year	Average PCI	Average Traffic Veh/day
2020	53.25	5,000
2021	50.25	5,150
2022	47.00	5,304
2023	44.50	5,464
2024	41.50	5,628
2025	39.00	5,796

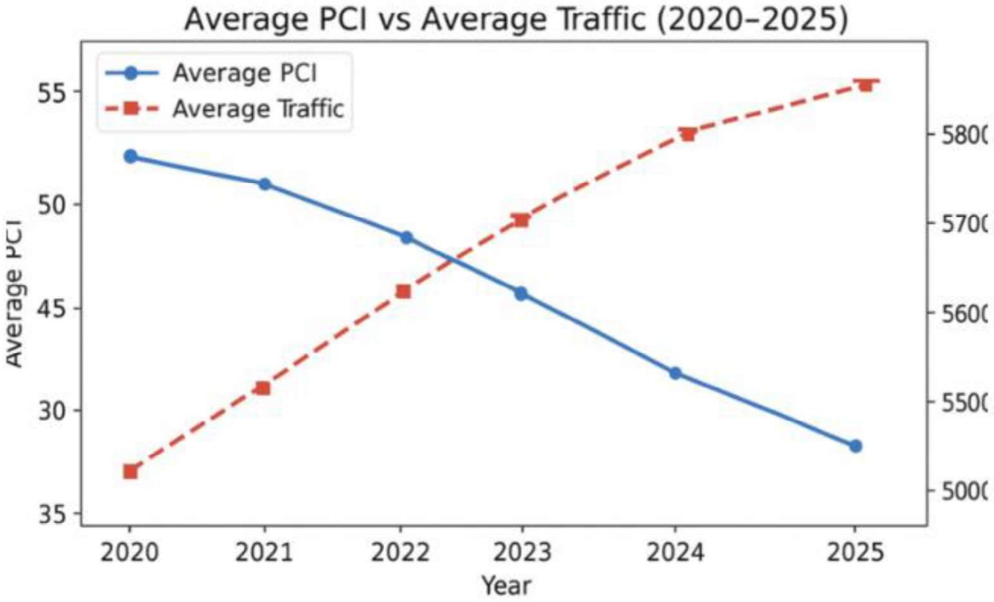

Figure 3: Relationship between the PCI and Traffic

3.3. Cost–Benefit Analysis of Rehabilitation Strategies

Vehicle operating costs (VOC) were computed as the sum of four components per vehicle-kilometre: fuel cost C_f, maintenance and repair cost C_m, congestion-related delay cost C_d, and travel time cost C_t. Representative average unit costs (₦/km) for a medium commercial vehicle, derived from local fuel prices, wage rates and fleet-maintenance records for 2023, are summarized in Table 3.3 and were applied uniformly along the corridor. These values represent operation on a "good" pavement ($\text{PCI} \geq 80$); deterioration in pavement condition was then allowed to increase VOC through a PCI-dependent adjustment factor.

$$\text{VOC (PCI)} = C_f\,(\text{PCI}) + C_m\,(\text{PCI}) + C_d\,(\text{PCI}) + C_t\,(\text{PCI}) \qquad (5)$$

Each component was expressed as a linear function of PCI:

$$C_x(PCI) = C_{x,0}\left[1 + \alpha_x \frac{(100 - PCI)}{100}\right] \qquad (6)$$

Using these VOC (Table 4) in relationships and the PCI trajectories from the deterioration model (Table 2), the life-cycle economic analysis was carried out over the specified project analysis period and discount rate. Table 4 summarizes the resulting cost–benefit indicators for the three rehabilitation strategies evaluated along the Agbede–Ewu corridor. Routine maintenance, applied over the full 10 km, incurs the lowest total cost (₦1.25 bn) and yields an NPV of ₦0.84 bn with a benefit–cost ratio (BCR) of 1.46.

Table 4: Average VOC Input Costs Adopted in the Economic Analysis

Cost Component	**Symbol**	**Description**	**Unit Cost (₦/km)**
Fuel	C_f	Fuel and Lubricants per km	160
Maintenance and repair	C_m	Tyres, spares, workshop and servicing	45
Delay	C_d	Time lost in queues and speed reductions	25
Travel time	C_t	Driver wage and vehicle capital time cost	60
Total base VOC (good PCI)	-----	**Sum of components on good pavement**	**290**

where $C_{x,0}$ (in equation 6) is the unit cost on a near-perfect pavement (PCI =100) and α_x is a sensitivity coefficient reflecting how strongly that component responds to surface distress and roughness. In practice, this means that as PCI decreases (rougher, more deteriorated pavement), fuel and maintenance costs rise due to increased rolling resistance and dynamic loads, while delay and time costs increase due to lower operating speeds. For the representative medium commercial vehicle considered, the combined VOC increases by approximately 30–40% when PCI drops from about 80 (good condition) to 40 (poor condition), and the economic benefit of rehabilitation is computed as the difference in VOC before and after intervention, multiplied by traffic volume and discounted over the analysis period.

Based on the VOC inputs and deterioration model, the corridor-level economic evaluation was performed for all rehabilitation scenarios. The results are presented in Table 5.

Routine maintenance yields the lowest capital cost and a positive NPV (Figure 4), confirming its economic viability for preserving serviceability across the corridor. However, overlay resurfacing achieves the highest benefit–cost ratio (1.83), indicating that it provides the greatest economic return per unit cost by significantly reducing VOC in the moderately deteriorated segments. Full reconstruction delivers the greatest absolute NPV (₦1.65 bn) and annual benefit (₦1.28 bn) but has a marginally lower BCR due to its higher initial investment, making it economically justified only where structural failure is advanced.

Table 5. Cost–benefit Analysis of Rehabilitation

Strategy	Scope (km)	Total cost (₦ bn)	Annual Benefit (₦ bn)	NPV (₦ bn)	BCR
Routine maintenance	10.0	1.25	0.57	0.84	1.46
Overlay resurfacing	6.7	1.71	0.92	1.43	1.83
Full reconstruction	2.5	2.33	1.28	1.65	1.71

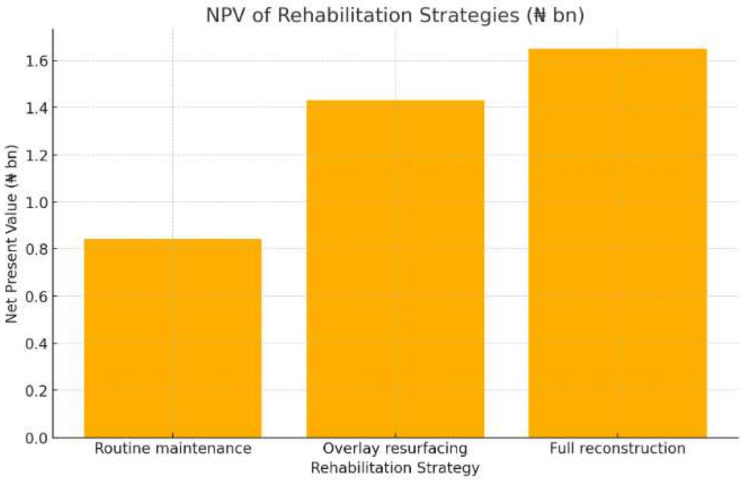

Figure 4: NPV of Rehabilitation Strategies (₦ bn)

The Benefit–Cost Ratio (BCR) represents the economic efficiency of each rehabilitation option by comparing total discounted benefits to total costs. A BCR greater than 1 indicates that the strategy is economically viable, with higher values implying better investment returns. As shown in Figure 5, Overlay resurfacing is the most cost-effective option with a **BCR of 1.83,** meaning every ₦1 spent returns about **₦1.83** in benefits. Full reconstruction follows with a **BCR of 1.71,** while routine maintenance has the lowest return at **1.46,** though all options remain economically viable (BCR > 1).

4. CONCLUSION

Between 2020 and 2025, the Agbede–Ewu corridor exhibited a clear deterioration pattern, with the average PCI falling from 53.25 to 39.0. This decline reflects both the accumulation of structural and functional distresses and the influence of concentrated heavy-truck traffic on weaker subgrade sections, particularly in the mid-segment (2.5–7.5 km), where degradation was most pronounced. The terminal sections deteriorated at a slower rate due to intermittent maintenance and lower axle-load exposure. Simultaneously, traffic volumes increased steadily by approximately 3% per year, rising from 5,000 to 5,796 vehicles/day, compounding pavement stress and accelerating roughness and structural damage. The combined effect of deteriorating pavement and growing traffic heightens the risk of safety hazards, increases vehicle operating costs, and shortens the effective service life of the corridor. Economic analysis shows that overlay resurfacing yields the highest benefit-cost ratio, while full reconstruction is necessary for the most deteriorated mid-segment. Overall, the findings highlight the urgent need for proactive maintenance and targeted structural rehabilitation to sustain pavement performance, optimize lifecycle costs, and maintain safety and efficiency along this critical route.

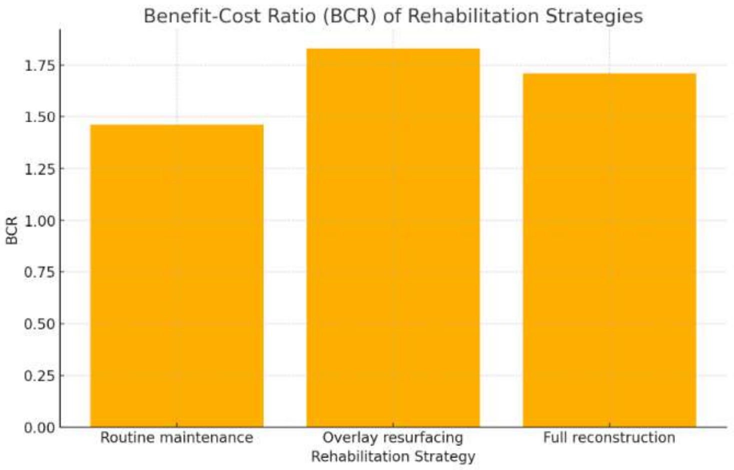

Figure 5. Benefit Cost Ratio of Rehabilitation Strategies

5. RECOMMENDATIONS

Based on the observed traffic growth and pavement performance along the 10 km Agbede–Ewu corridor, the following recommendations are made to maintain serviceability and extend the road's effective life. The recommendations include:

1. Implement routine maintenance and periodic overlay resurfacing to address increasing surface distress as reflected in declining PCI values.
2. Monitor traffic volumes continuously, using manual counts and speed-volume observations, to update load projections and calibrate pavement performance models.
3. Prioritize rehabilitation for sub-segments showing accelerated deterioration due to higher axle loads, ensuring resources target the most critical sections.
4. Incorporate mechanistic-empirical modelling in pavement management to predict PCI decline under projected traffic growth and schedule timely interventions.

5. Explore traffic management strategies, such as load restrictions for heavy vehicles during peak periods, to reduce cumulative damage.
6. Maintain a comprehensive PCI database along the corridor to track performance trends, support maintenance decisions, and validate the effectiveness of interventions.

This approach ensures proactive management of the corridor, mitigating accelerated deterioration from increasing traffic and preserving pavement functionality.

NOMENCLATURE

a	Baseline pavement serviceability
b	High serviceability to cumulative axle loading

Subscripts

$C_{x,0}$	Unit cost
$C_{f},$	Fuel cost
C_{m}	Maintenance cost
C_{d}	Driver wages and damage cost
C_{t}	Tire and other cost

Abbreviations

AADT	Average annual daily traffic
ESAL	Equivalent standard axle load
PCI	Pavement condition index
CDV	Corrected deduct value
ADT	Average daily traffic
VOC	Vehicle operating cost
NPV	Net present value
BCR	Benefit-cost ratio

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