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LIFE CYCLE IMPROVEMENT MODEL FOR PAVEMENT STRUCTURE OF THE AUCHI-OKENE HIGHWAY, NIGERIA

P. C. OGUM, J. WASIU, and A.O. IBRAHIM

[1,2]*Department of Civil Engineering, Faculty of Engineering, Edo State University Iyamho, Edo State, Nigeria*

[*]*Correspondent Author: prosperdon19@gmail.com*

Abstract

The Auchi–Okene highway is a vital transportation route in Nigeria but faces persistent challenges of pavement deterioration, high maintenance costs, and suboptimal performance. This study develops a Life Cycle Improvement Model (LCIM) tailored to enhance the durability, cost-efficiency, and sustainability of the highway's pavement structure. The model integrates traffic analysis, material evaluation, environmental considerations, and life cycle cost analysis (LCCA) to provide a systematic framework for pavement management. Using cost data from the Bill of Engineering Measurement and Evaluation (BEME), the LCCA was applied to compare traditional designs with improved alternatives, incorporating resurfacing and embankment protection measures. The findings revealed that although the Life-Cycle Improvement Model (LCIM), which introduced resurfacing and embankment protection, has higher initial cost of 17%, but offers more sustainable outcomes through enhanced durability and reduced frequency of major rehabilitations. Validation with the Markov chain model further reinforced these outcomes. At the end of the 50-year period, the LCCA produced a total cost of ₦2.83 billion, whereas the LCIM projected ₦3.6 billion. The higher figure for LCIM reflects proactive investment in structural improvements, proving that LCIM is a more inclusive, realistic and sustainable strategy for long-term pavement management over the 50-year analysis period along the Okene–Auchi highway compared to LCCA

Keywords

Life cycle cost analysis, BEME, life cycle improvement model, reliability, sustainability

1. INTRODUCTION

The Auchi-Okene Highway is a critical transportation route in Nigeria, linking key economic centers and facilitating regional trade. However, like many highways in developing regions, it faces significant challenges related to pavement deterioration, maintenance costs, and overall performance. To address these issues, there is a growing need for effective life cycle improvement models that can enhance the pavement structure's durability and cost-effectiveness.

There is also a need to ensure that pavement performs optimally to provide a comfortable riding surface for motorists. Pavement performance is influenced by various factors, including traffic loads, environmental conditions, and material properties. Understanding the structural capacity of flexible pavements is crucial for assessing their performance and predicting future conditions (Afolabi, and Osunde, 2018). Advanced performance evaluation techniques, such as distress surveys and condition modeling, provide valuable insights into the current state of the pavement and help in forecasting its future performance.

It is also worthwhile to ensure that pavements meet their life cycle especially when huge amounts of money is expended on construction and maintenance. Life cycle cost analysis (LCCA) is a key component in pavement management, providing a comprehensive view of the costs associated with pavement construction, maintenance, and rehabilitation over its entire lifespan. Life cycle cost analysis enables decision-makers to select the most cost-effective pavement rehabilitation techniques by considering both initial and future costs; this approach helps in balancing economic considerations with pavement performance and longevity (Adeyemo and Akinmoladun, 2019). Implementing a life cycle improvement model involves integrating various strategies to optimize pavement performance and extend its service life. This includes regular maintenance schedules, appropriate material selection, and advanced construction methods. Recent research has shown that adopting a holistic approach to pavement management can lead to significant improvements in both performance and cost-effectiveness (Ojo and Raji, 2024). Technological advancements play a significant role in improving pavement performance. Innovations in materials and construction techniques have led to the development of high-performance asphalt and concrete mixtures that enhance pavement durability. Ibrahim and Usman (2022) highlighted the importance of incorporating these advancements into pavement design to address the challenges posed by tropical climates and high traffic volumes.

Implementing a life cycle improvement model involves integrating various strategies to optimize pavement performance and extend its service life. This includes regular maintenance schedules, appropriate material selection, and advanced construction methods (Ibrahim and Usman, 2022).

The Auchi-Okene highway requires a comprehensive approach to address its pavement challenges effectively. By leveraging recent advancements in pavement management, life cycle cost analysis, and sustainable practices, a life cycle improvement model can be developed to enhance the highway's performance and sustainability. This model will contribute to better decision-making and more efficient use of resources, ultimately benefiting the region's economic and social development.

The Life cycle assessment of highway pavement structure has been studied by some researchers. Chukwuma and Olufemi (2021) discussed recent advancements in sustainable pavement practices, such as the use of recycled materials and eco-friendly construction techniques. These practices not only improve pavement durability but also reduce environmental impact, aligning with global trends towards greener infrastructure solutions. Technological advancements play a significant role in improving pavement performance (Chukwuma and Olufemi, 2021). Innovations in materials and construction techniques have led to the development of high-performance asphalt and concrete mixtures that enhance pavement durability. Lytton et al. (2021) stressed the role of moisture and temperature, while Mamlouk and Zaniewski (2022) highlighted material quality and the use of recycled aggregates. Tighe and Smith (2019) promoted pavement management systems for timely interventions.

These studies have some notable gaps in the development of comprehensive life cycle improvement models. Therefore, this study aims to fill this gap by developing a comprehensive life cycle improvement model (LCIM) which will optimize the durability, cost-efficiency, and long-term performance of the road and its specifically designed for the Okene-Auchi highway pavement structure. The study was achieved by developing a comprehensive mathematical life cycle improvement model from life cycle cost analysis equation using the data from the bill of engineering measurement and evaluation (BEME) of the Okene Auchi -highway to evaluate the economic feasibility then carryout validation of the model using Markov's chain model.

2. MATERIALS AND METHOD

2.1 Data Acquisition

Cost estimates were derived from the Bill of engineering measurement and evaluation (BEME) of Okene Auchi –highway, sourced from the Federal Ministry of Works with current price rates as at 2025. From the bill of engineering measurement and evaluation (BEME), the cost per kilometer of road for the pavement component are given below:

i. Cost of Site clearing and Earthworks (C_1) C_1) = ₦192,819.335.4

ii. Cost of Culverts and Drain (C_2) C_2) = ₦57,988,993.07

iii. Cost of Pavement and Surfacing (C_3) (C_3) = ₦1,823,301,263

2.2 Life cycle cost analysis (LCCA)

In order to ensure the chosen pavement solution is both financially viable and sustainable over the entire road life span, the life cycle cost analysis was carried out and this was achieved through the use of LCCA mathematical equation to compare the total cost of different pavement design components over their life cycle and the economic implication of different pavement components was assessed by calculating the present value of initial and long-term costs.

The LCCA mathematical equation is given as Eq. (1) below.

$$LCCA = I + \sum_{n}^{n} Cn \left[\frac{1}{(1+r)^n}\right]$$

$$LCCA = I + \sum_{n}^{n} Cn \left[\frac{1}{(1+r)^n}\right]$$

(1)

Where: I = Contract sum (initial rehabilitation cost)
Cn = Cost of pavement components for rehabilitation at nth year
r = Discount rate
n = Analysis period

With this equation, the present value of the pavement over its design life cycle was calculated, which helped to determine the most cost effective solution. Inflation significantly impacts the cost of materials and labour over the pavements life span , therefore a real discount rate which ranges from 3% to 5% is factored in the LCCA to account for this impact without needing to predict specific inflation rate for each year. Most federal projects adopt a discount rate of 3%. Therefore a discount rate of 3% was adopted in this study to factor in the impact of inflation over the pavement life span.

2.3 Development of life cycle improvement model:

This presents the development of the Life-Cycle Improvement Model (LCIM) tailored for the Auchi–Okene highway. As a way of improving the pavement life span and sustainable pavement performance, certain items were introduced which were not part of the original design and the BEME. The Items include:

i. Cost of resurfacing includes spraying with tack coat at the rate of 0.4-0.45litres/m^2, then lay and compact asphaltic concrete wearing course to a compacted thickness of 40mm.

ii. Cost of embankment protection with retaining walls at some critical locations.

2.4 Model validation using Markov's chain model

Markov's Chain Model is a mathematical model used by decision makers (managers) to describe the sequence of events in which the probability of the next event depends only on the current state or the probability of current state depends on the state of past events. This was achieved through:

i. translating the LCCA and LCIM data into probability table P^1
ii. translating the LCCA and LCIM probability table to matrix form
iii. generate the cost matrix of LCCA and LCIM through resource allocation (Economic Efficiency)
iv. the matrix was rewritten to form a new cost matrix R^1
v. calculate the cost yield V_{ij} for LCCA and LCIM using Recursive equation given as eq. (2) below.

$$V_{ij} = R^1 P^1 \; V_{ij} = R^1 P^1 \tag{2}$$

Where, P^1 = Transition probability matrix
R^1 = Cost matrix generated through resource allocation(economic efficiency)
V_{ij} = Total cost at the end of analysis year

3. RESULTS AND DISCUSSION

3.1 Life-cycle cost analysis (LCCA)

From the LCCA mathematical equation given in eq. (1) above, a discount rate of 3% as applicable in most federal project was adopted to factor in the impact of inflation over the pavement life span and analysis period of 50years.

From the bill of engineering measurement and evaluation (BEME), the cost per kilometer of road for the pavement component are given below:

i. Cost of Site clearing and Earthworks (C_1) C_1) = ₦192, 819, 335.40
ii. Cost of Culverts and Drain (C_2) C_2) = ₦57, 988,993.07
iii. Cost of Pavement and Surfacing (C_3) (C_3) = ₦1, 823, 301, 263

From the LCCA Equation given as eq. 1 above,

$$LCCA = I + (C1 + C2 + C3)\left[\frac{1}{(1+r)^n}\right]$$ $$LCCA = I + (C1 + C2 + C3)\left[\frac{1}{(1+r)^n}\right]$$ (3)

$$LCCA = I + \left[C_1\left(\frac{1}{(1+r)^n}\right) + C_2\left(\frac{1}{(1+r)^n}\right) + C_3\left(\frac{1}{(1+r)^n}\right)\right]$$

$$LCCA = I + \left[C_1\left(\frac{1}{(1+r)^n}\right) + C_2\left(\frac{1}{(1+r)^n}\right) + C_3\left(\frac{1}{(1+r)^n}\right)\right]$$ (4)

C_1 at first year = 192,819,335.4

C_1 at 10^{th} year = 192,819,335.4 $\left(\frac{1}{(1+0.03)^{10}}\right) = ₦$ $\left(\frac{1}{(1+0.03)^{10}}\right) = ₦$ 336,714,361.80

C_1 @ 20^{th} year = 192,819,335.4(0.55) = ₦298,869,969.90
0.55) = ₦298,869,969.90

C_1 @ 30^{th} year = 192,819,335.4 (0.41) = ₦271,875,262.90
(0.41) = ₦271,875,262.90

C_1 @ 40^{th} year = 192,819,335.4(0. 0.31) = ₦252, 593,329.40

C_1 @ 50^{th} years = 192,819,335.4 (0.23) = ₦237,167,782.50
(0.23) = ₦237,167,782.50

C_2@ first yea = ₦ 57,988,993.07
C_2@ 10th year = 57,988,993.07 (0.75) = ₦101,480,737.90
C_2@ 20th year = 57,988,993.07 (0.55) = ₦89,882,939.26
C_2@ 30th year = 57,988,993.07 (0.41) = ₦81,764,480.23
C_2@ 40th year = 57,988,993.07 (0.31) = ₦75,965,580.92
C_2@ 50th year = 57,988,993.07 (0.23) = ₦ 71,326,461.48
C_3 @ first year = 1,823,301,263
C_3 @10thyear = 1,823,301,263(0.75) = ₦3,190,777,210.00
C_3 @ 20thyear = 1,823,301,263 (0.55) = ₦2,826,116,958.00
C_3 @ 30thyear = 1,823, 301,263 (0.41) = ₦2,570,854,781.00
C_3 @ 40thyear = 1,823, 301,263 (0.31) = ₦2,388,524,655.00
C_3 @ 50thyear = 1,823, 301,263 (0.23) = ₦ 2,242,660,553.00
The result of the life cycle analysis from the BEME for 50 years analysis is given in the Table 1:

Table 1: Table showing the result of the LCCA from the BEME for 50 years analysis

Pavement option	**Analysis period from now to 50 year**						**Initial cost ₦/km**	**50yrs rehab. cost ₦/km**
	C_1	C_{10}	C_{20}	C_{30}	C_{40}	C_{50}		
Site Clearing and Earthworks	192,819 335.4	336,714,361.80	298,869,969.90	271,875,262.90	252,593,329.40	237,167,782.50	192 819 335.4	237,167,782.50
Culverts& Drain	57,988 993.03	101,480,737.90	89,882,939.26	81,764,480.23	75,965,580.92	71,326,461.48	57988 993.3	71,326,461.48
Pavement and Surfacing	1823301263.00	3,190,777,210.00	2,826,116,958.00	2,570,854,781.00	2,388,524,655.00	2,242,660,553.00	1823301263.00	2,242,660,553.00
Total LCCA	2,074,109,591.47	3,628,972,310.00	3,214,869,867.00	2,924,494,524.00	2,717,083,565.00	2,551,154,797.00	2074109591.47	2,551,154,797.00

Table 1 is the result extracted from the calculations of LCCA and the results indicate that pavement and surfacing works consistently account for the largest share of expenditure across the analysis period. At year 1 (C1), pavement and surfacing costs stood at ₦2.94 billion, declining steadily to ₦1.98 billion at year 50 (C50). This downward trend suggests reduced rehabilitation needs over time due to maintenance interventions. Site clearing and earthworks costs reduced from ₦311 million at C1 to ₦209 million by C50, while culverts and drainage declined from ₦93.6 million at C1 to ₦63.0 million at C50. The overall total LCCA peaked at ₦3.35 billion at C10, before declining progressively to ₦2.25 billion at C50. This demonstrates that although initial investments are substantial, cumulative rehabilitation costs gradually diminish with time, reflecting efficiency gains from periodic maintenance strategies

3.2 Life-cycle improvement model (LCIM)

Incorporating life cycle improvement model (LCIM) by introducing:

i. costs of resurfacing including spraying with tack coat at the rate of 0.4 – 0.45 litres/m^2, then lay and compact asphaltic concrete weaning course to a compacted thickness of 40mm
ii. cost of embankment protection with retaining walls at some critical locations. The LCIM Equation Becomes:

$$\boldsymbol{LCCA = I + (C1 + C2 + C3 + C4 + C5)\left[\frac{1}{(1+r)^n}\right]}$$

$$\boldsymbol{LCCA = I + (C1 + C2 + C3 + C4 + C5)\left[\frac{1}{(1+r)^n}\right]} \quad (5)$$

From eq. (5),

C_1 = Cost of site clearing and earthworks = N192,819,335.4
C_2 = Cost of culverts and drain = ₦57,988,993.07
C_3 = Cost of pavement and surfacing = ₦1,823,301,263
C_4 = Cost of tack coat and wearing course = ₦336,000,000
C_5 = Cost of retaining wall as embankment protection = ₦25,624,000
C_4 @ first year = ₦336,000,000
C_4 @ 10th year = 336,000,000 (0.75) = ₦588,000,000.00
C_4 @ 20th year = 336,000,000 (0.55) = ₦520,800,000.00
C_4 @ 30th year = 336,000,000 (0.41) = ₦473,760,000.00
C_4 @ 40th year = 336,000,000 (0.31) = ₦440,160,000.00
C_4 @ 50th year = 336,000,000 (0.23) = ₦413,280,000.00
C_5 @ 1st year = N25,624,000
C_5 @ 10th year = N25,624,000 (0.75) = ₦44,842,000.00
C_5 @ 20th year = N25,624,000 (0.55) = ₦39,717,200.00
C_5 @ 30th year = N25,624,000 (0.41) = ₦35,769,840.00
C_5 @ 40th year = N25,624,000 (0.31) = ₦33,567,440.00
C_5 @ 50th year = N25,624,000 (0.23) = ₦31,517,520.00

Table 2: Table showing the result of the LCIM for analysis period of 50 years

Pavement option	**Analysis period from now to 50 year**						**Initial cost ₦km**	**50yrs rehab. cost ₦km**
	C_1	C_{10}	C_{20}	C_{30}	C_{40}	C_{50}		
Site cleaning and earth works	192819 335.4	336,714,3 61.80	298,869, 969.90	271,875, 262.90	252,593, 329.40	237,167 ,782.50	192 819 335.4	237,167,782.50
Culverts and drain	57988 993.03	101,480,7 37.90	89,882,9 39.26	81,764,4 80.23	75,965,5 80.92	71,326, 461.48	57988 993.3	71,326,461.48
Pavement and surfacing	1823301 263.00	3,190,777, 210.00	2,826,11 6,958.00	2,570,85 4,781.00	2,388,52 4,655.00	2,242,6 60,553. 00	182330 1263.0 0	2,242,660,553.00

Tack coat and wearing course	336000,00 0,00	588,000, 000.00	520,800, 000.00	473,760, 000.00	440,160, 000.00	413,280 ,000.00	336,00 0,000	413,280,000.00
Embankment/ retaining wall	25624000	44,842,0 00.00	39,717,2 00.00	35,769,8 40.00	33,567,4 40.00	31,517, 520.00	256240 00	31,517,520.00
Total LCIM	2,435,733, 591.47	4,261,81 4,310.00	3,775,38 7,067.00	3,434,02 4364.00	3,190,81 1,005.00	2,995,9 52,317. 00	245573 359147	2,995,952,317.00

Table 2 is the results extracted from the calculations of the life cycle improvement model (LCIM) which extends the LCCA by incorporating additional cost components such as tack coat, wearing course, and embankment/retaining walls. The results show that total LCIM figures are consistently higher than LCCA values across all years. At C1, total LCIM stood at ₦3.93 billion, compared to ₦3.35 billion for LCCA. By C50, total LCIM declined to ₦2.65 billion, still higher than the corresponding LCCA value of ₦2.25 billion. Tack coat and wearing course costs reduced from ₦542 million at C1 to ₦365 million at C50, while embankment/retaining wall costs decreased from ₦41.3 million at C1 to ₦27.8 million at C50. These results imply that while LCIM captures a broader scope of costs, the general trend mirrors that of LCCA: costs peak at earlier stages and decline with long-term maintenance, showing the economic benefits of sustained rehabilitation investments.

Table 3 is the results extracted from the calculations of the percentage errors of LCCA and LCIM. The comparison of LCCA and LCIM shows a consistent variation across the 50-year lifespan. The absolute error between the two models ranges from ₦361.6 million at year 0 to ₦581.6 million at year 10, before gradually declining to ₦393 million by year 50. Importantly, the percentage error remains stable, fluctuating only slightly between 17.43% and 17.44%.

Table 3 : Percentage Errors for LCCA and LCIM over 50-Year Lifespan

n	LCCA	LCIM	Absolute Error	% Error
0	2,074,109,591.47	2,435,733,591.40	361,623,999.93	17.44
10	3,628,972,310.00	4,261,814,310.00	632,842,000.00	17.44
20	3,214,869,867.00	3,775,387,067.00	560,517,200.00	17.44
30	2,924,494,524.00	3,434,024,364.00	509,529,840.00	17.43
40	2,717,083,565.00	3,190,811,005.00	473,727,440.00	17.44
50	2,551,154,797.00	2,995,952,317.00	444,797,520.00	17.44

This consistency suggests that LCIM estimates are systematically higher than LCCA values by approximately 17%, largely due to the inclusion of additional cost elements absent in LCCA. Therefore, LCIM provides a more comprehensive estimate, while LCCA offers a conservative approximation of long-term pavement costs.

3.3 Life-cycle cost validation using Markov's chain model

Translating the LCCA data into probability table is given in the Table 4 below

Table 4 : LCCA Probability table

P1	P2	P3	P4	P5	P6
0.09	0.09	0.09	0.09	0.09	0.09
0.03	0.03	0.03	0.03	0.03	0.03
0.88	0.88	0.88	0.88	0.88	0.88

Table 4 is the results extracted from the calculations of the probabilities of LCCA
Translating the LCCA probability table to transition probability matrix form

$$\begin{pmatrix} 0.09 & 0.09 & 0.09 & 0.09 & 0.09 \\ 0.03 & 0.03 & 0.03 & 0.03 & 0.03 \\ 0.88 & 0.88 & 0.88 & 0.88 & 0.88 \end{pmatrix} \begin{matrix} 0.09 \\ 0.03 \\ 0.88 \end{matrix}$$

The transition probability matrix P^1 formed a left stochastic matrix ; the columns sum to 1

Table 5: LCIM Probability table

P1	**P2**	**P3**	**P4**	**P5**	**P6**
0.08	0.08	0.08	0.08	0.08	0.08
0.03	0.03	0.02	0.02	0.02	0.02
0.75	0.75	0.75	0.75	0.75	0.75
0.14	0.14	0.14	0.14	0.14	0.14
0.01	0.01	0.01	0.01	0.01	0.01

Table 5 is the results extracted from the calculations of the probabilities of LCIM

Translating the LCIM probability table to matrix form

$$\begin{pmatrix} 0.08 & 0.08 & 0.08 & 0.08 & 0.08 \\ 0.02 & 0.02 & 0.02 & 0.02 & 0.02 \\ 0.75 & 0.75 & 0.75 & 0.75 & 0.75 \\ 0.14 & 0.14 & 0.14 & 0.14 & 0.14 \\ 0.01 & 0.01 & 0.01 & 0.01 & 0.01 \end{pmatrix} \begin{matrix} 0.08 \\ 0.02 \\ 0.75 \\ 0.14 \\ 0.01 \end{matrix}$$

Table 6 : Generating LCCA Matrix through resource allocation (Economic efficiency)

	C0	**C10**	**C20**	**C30**	**C40**	**C50**
Economic Efficiency	20.74×10^8	36.28×10^8	32.15×10^8	29.25×10^8	27.17×10^8	25.51×10^8
30% site clearing and earth works	6.2×10^8	11.0×10^8	9.7×10^8	8.8×10^8	8.2×10^8	7.7×10^8
20% culvert and drain	4.2×10^8	7.3×10^8	6.4×10^8	5.9×10^8	5.4×10^8	5.1×10^8
50% pavement and surfacing	10.4×10^8	18.1×10^8	16.1×10^8	14.6×10^8	13.6×10^8	12.8×10^8

Table 6 is the results extracted from the generated LCCA matrix through resource allocation

Table 7 : The LCCA matrix is rewritten as

		Site clearing and earth works	**culvert and drain**	**pavement and surfacing**
C0	20.74 x 10^8	6.2 x 10^8	4.2 x 10^8	10.4 x 10^8
C10	36.28 x 10^8	11.0 x 10^8	7.3 x 10^8	18.1 x 10^8
C20	32.15x 10^8	9.7 x 10^8	6.4 x 10^8	16.1x 10^8
C30	29.25 x 10^8	8.8 x 10^8	5.9 x 10^8	14.6x 10^8
C40	27.17 x 10^8	8.2 x 10^8	5.4 x 10^8	13.6 x 10^8
C50	25.51 x 10^8	7.7 x 10^8	5.1 x 10^8	12.8x 10^8

Table 7 is the results extracted from the transposed LCCA matrix

Table 8: The LCIM matrix generated through resource allocation (economic efficiency)

	C1	**C10**	**C20**	**C30**	**C40**	**C50**
Economic Efficiency	24.36×10^8	42.6×10^8	37.8×10^8	34.3×10^8	31.9×10^8	30.0×10^8
20% site clearing and earth works	4.9×10^8	8.5×10^8	7.6×10^8	6.3×10^8	6.4×10^8	6.0×10^8
10% culvert and drain	2.4×10^8	4.3×10^8	3.8×10^8	3.4×10^8	3.2×10^8	3.0×10^8
40% pavement and surfacing	9.7×10^8	17.0×10^8	15.1×10^8	13.7×10^8	12.8×10^8	12.0×10^8
25% resurfacing	6.1×10^8	10.7×10^8	9.5×10^8	8.6×10^8	8.0×10^8	7.5×10^8
5% embankment protection	1.2×10^8	2.1×10^8	1.9×10^8	1.7×10^8	16.0×10^8	1.5×10^8

Table 8 is the results extracted from the generated LCIM matrix through resource allocation

Table 9: The LCIM matrix is rewritten as

		Site clearing and earth	**culvert and drain**	**pavement and surfacing**	**Resurface**	**Embankment protection**
C0	24.36×10^8	4.9×10^8	2.4×10^8	9.7×10^8	6.1×10^8	1.2×10^8
C10	42.6×10^8	8.5×10^8	4.3×10^8	17.0×10^8	10.7×10^8	2.1×10^8
C20	37.8×10^8	7.6×10^8	3.8×10^8	15.1×10^8	9.5×10^8	1.9×10^8
C30	34.3×10^8	6.3×10^8	3.4×10^8	13.7×10^8	8.6×10^8	1.7×10^8
C40	31.9×10^8	6.4×10^8	3.2×10^8	12.8×10^8	8.0×10^8	16.0×10^8
C50	30.0×10^8	6.0×10^8	3.0×10^8	12.0×10^8	7.5×10^8	1.5×10^8

Table 9 is the results extracted from the transposed LCIM matrix

a. From Recursive equation given as eq. (2) above, calculation of V_{ij} considering the case in which no improvement is made on the pavement that is LCCA

$$Vij = R^1 P^1 \, Vij = R^1 P^1$$

Where $P^1 P^1 =$

$$\begin{pmatrix} 0.09 & 0.09 & 0.09 & 0.09 & 0.09 \\ 0.03 & 0.03 & 0.03 & 0.03 & 0.03 \\ 0.88 & 0.88 & 0.88 & 0.88 & 0.88 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

R^1 R^1 =

6.2 x 10^8	4.2 x10^8	10.4 x10^8	0	0
11 x 10^8	7.3 x 10^8	18.1 x 10^8	0	0
9.7 x 10^8	6.4 x10^8	16.1 x10^8	0	0
8.8 x 10^8	5.9 x10^8	14.6 x10^8	0	0
8.2 x 10^8	5.4 x10^8	13.6 x10^8	0	0
7.7 x 10^8	5.1 x10^8	12.8x10^8	0	0

$$V_{ij} = 5.6\,x\,10^7 + 3.8\,x\,10^7 + 9.4\,x\,10^7 + 0 + 0 = 1.9\,x\,10^8$$

$$V_2 = 3.5\,x\,10^7 + 2.2\,x\,10^7 + 5.4\,x\,10^7 = 11.1\,x\,10^7$$

$$V_3 = 85.4\,x\,10^7 + 56.3\,x\,10^7 + 141.7\,x\,10^7 = 9.9\,x\,10^7$$

Total cost after 50years $= \underline{2.83\,x\,10^9} = \underline{2.83\,x\,10^9}$

Thus, the LCCA cost ₦ 2.83 billion at the end of 50years

b. Calculation of the cost V_{ij} V_{ij}, considering the case of improvement on the pavement that is LCIM

$P^2 = P^2$ =

0.08	0.08	0.08	0.08	0.08	0.08
0.02	0.02	0.02	0.02	0.02	0.02
0.75	0.75	0.75	0.75	0.75	0.75
0.14	0.14	0.14	0.14	0.14	0.14
0.01	0.01	0.01	0.01	0.01	0.01
0	0	0	0	0	0

R^2 R^2 =

4.9 x 10^8	2.4 x10^8	9.7 x10^8	6.1 x10^8	1.2 x10^8	0
8.5 x 10^8	4.3 x 10^8	17.0 x10^8	10.7 x10^8	2.1 x10^8	0
7.6 x 10^8	3.8 x10^8	15.1 x10^8	9.5 x 10^8	1.9 x10^8	0
6.3 x 10^8	3.4 x10^8	13.7 x10^8	8.6 x10^8	1.7 x10^8	0
6.4 x 10^8	3.2 x10^8	12.8 x10^8	8.0 x10^8	16.0 x10^8	0
6.0 x 10^8	3.0 x10^8	12.0 x10^8	7.5 x10^8	1.5 x10^8	0

$$V_1 = 3.9\,x\,10^7 + 1.9x\,10^7 + 7.8\,x\,10^7 + 4.9\,x10^7 + 1.0\,x\,10^7 = 19.5\,x\,10^7$$

$$V_2 = 1.7\,x\,10^7 + 0.9\,x\,10^7 + 3.4\,x\,10^7 + 2.1\,x10^7 + 0.4\,x\,10^7 = 8.5\,x\,10^7$$

$$V_3 = 57\,x\,10^7 + 28.5\,x\,10^7 + 113.3\,x\,10^7 + 71.3\,x\,10^7 + 14.3\,x\,10^7$$
$$= 28.4\,x\,10^8$$
$$V_4 = 8.8\,x\,10^7 + 4.8\,x\,10^7 + 19.2\,x\,10^7 + 12.0\,x10^7 + 2.4\,x\,10^7$$
$$= 47.2\,x\,10^7$$
$$V_5 = 0.64\,x\,10^7 + 0.32\,x\,10^7 + 1.3x\,10^7 + 0.8\,x10^7 + 1.6x\,10^7 = 4.7x\,10^7$$

Total cost after 50years $\underline{= 3.6\,x\,10^9} \underline{= 3.6\,x\,10^9}$
Thus, the LCIM cost ₦ 3.6 billion at the end of 50years

3.4 Interpretation of Life-Cycle Cost Validation using Markov's Chain Model

The life-cycle cost validation was carried out using Markov's chain model for both the **Life-Cycle Cost Analysis (LCCA)** and the **Life-Cycle Improvement Model (LCIM)**. Probability tables and transition matrices were developed for each case, ensuring stochastic consistency (columns summing to one). Resource allocation matrices were then constructed to capture the distribution of costs across site clearing, culverts and drains, pavement, resurfacing, and embankment protection.

The **LCCA** results showed that after 50 years, the total cost amounted to **₦2.83 billion**, reflecting deterioration without proactive improvement. Conversely, the **LCIM**, which incorporated additional interventions such as resurfacing and embankment protection, resulted in a higher cost of **₦3.6 billion** at the end of the same period. This widening gap underscores the effect of additional cost considerations in LCIM, proving that LCIM is a more inclusive and realistic measure of long-term investment and sustainable strategy over the 50-year analysis period compared to LCCA.

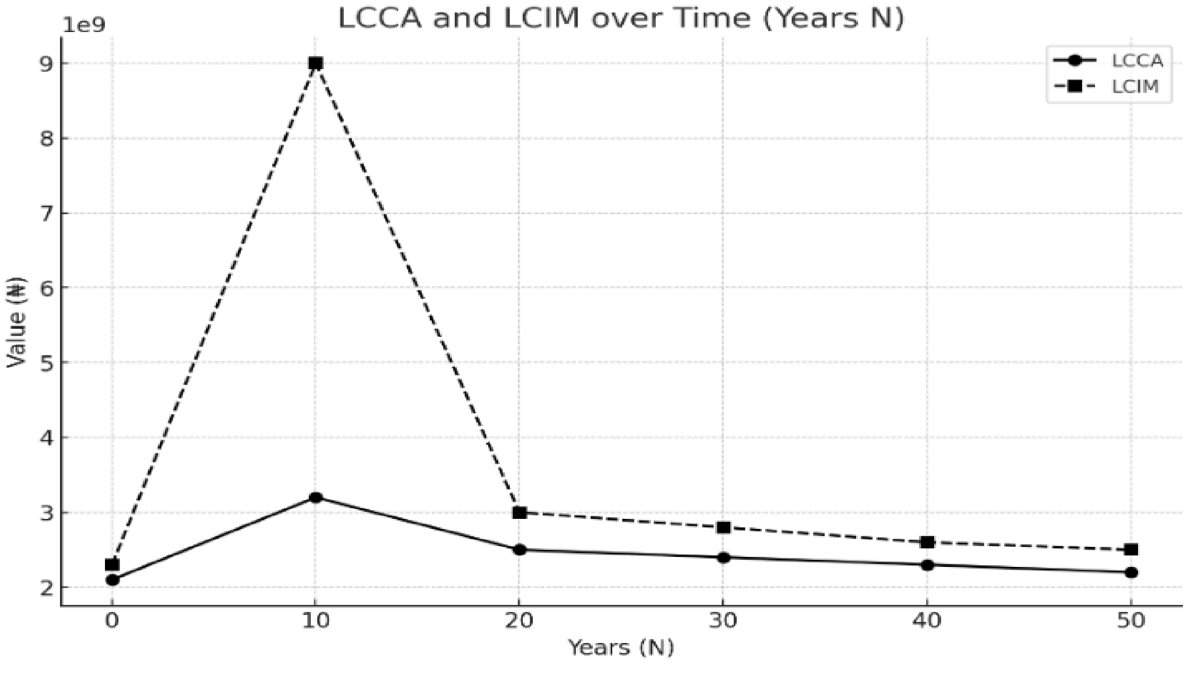

Figure 1: Line chart comparing life cycle cost for the traditional design vs. LCIM over 50 years

Figure 1 is graphical representation extracted from the calculations of LCCA and LCIM. The line chart shows that although the **LCIM pavement design was** initially approximately 17% costlier than the LCCA design but visually shows a decline from the 10th year with long-term rehabilitation, showing the economic benefits of sustained rehabilitation investments.

4. CONCLUSION

This study developed and validated a **life cycle improvement model (LCIM)** for the pavement structure of the Auchi–Okene highway. The traditional life cycle cost analysis (LCCA) provided baseline cost estimates but was limited in capturing the true long-term investment needs of the pavement. By incorporating resurfacing and embankment protection measures, the life cycle improvement model (LCIM) offered a more **comprehensive and realistic framework** for pavement management.

The findings revealed that:

1. Although the LCIM has a higher initial cost of 17%, it offers more sustainable outcomes through enhanced durability and reduced frequency of major rehabilitations.
2. Validation with the Markov chain model further reinforced these outcomes. At the end of the 50-year period, the LCCA produced a total cost of ₦2.83 billion, whereas the LCIM projected ₦3.6 billion. The higher figure for LCIM reflects proactive investment in structural improvements, proving that LCIM is a more inclusive, realistic and sustainable strategy for long-term pavement management over the 50-year analysis period along the Okene–Auchi highway compared to LCCA
3. Both models showed a decline in costs after year 10, highlighting the economic benefits of sustained rehabilitation and timely interventions.
4. Overall, the LCIM has proven to be a technically sound, economically viable, and more reliable solution for sustainable pavement management of the Auchi–Okene highway.

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