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RESEARCH ARTICLE | SOUTH SUDAN OIL INFRASTRUCTURE SERIES

Life-Cycle Cost Modelling of Access Roads to South Sudan Oil Fields Under Extreme Climatic Conditions

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ABSTRACT

The access road network serving South Sudan's oil fields in Unity, Jonglei, and Upper Nile States constitutes critical energy-sector infrastructure whose deterioration under extreme tropical rainfall, flooding, and overloaded tanker traffic imposes cascading economic losses on oil production revenues, logistics operators, and road users. Despite its strategic importance, no systematic life-cycle cost (LCC) framework calibrated to South Sudanese climatic and operational conditions has previously been published. This paper develops and applies such a framework, integrating the Net Present Value (NPV) approach with HDM-4 pavement performance modelling, Vehicle Operating Cost (VOC) estimation, and Monte Carlo simulation of climatic uncertainty across five oil logistics corridors totalling 1,865 km. Pavement condition surveys on all five routes yielded baseline International Roughness Index (IRI) values of 3.2–6.8 m/km, indicating that two of five routes already exceed acceptable thresholds. Three climate scenarios — baseline (700–900 mm/yr), moderate (+25%), and extreme (+50%) — were combined with two traffic growth trajectories (4% and 6% per annum) to evaluate seven maintenance strategy alternatives over a 30-year analysis period at discount rates of 6%, 8%, and 12%. The minimum-LCC strategy — comprising annual routine maintenance, 8-year periodic 50 mm AC overlay cycles, and a single major rehabilitation at year 20 — delivers a 30-year NPV of USD 980,000–1,420,000/km, representing savings of USD 690,000–1,040,000/km compared to a do-nothing baseline. Sensitivity analysis identifies traffic growth rate, discount rate, and initial construction cost as the three highest-impact parameters, together explaining 38.7% of total NPV variance. An LCC optimisation surface derived from 3,600 simulation runs identifies the global cost minimum at an overlay interval of 8.5 years and overlay thickness of 55 mm. These findings provide an evidence base for the Ministry of Roads and Bridges's forthcoming National Road Asset Management Strategy and for World Bank project preparation.

Keywords: life-cycle cost; LCC; NPV; HDM-4; South Sudan; oil access roads; pavement performance; vehicle operating cost; climate change; maintenance optimisation

1. Introduction

Access roads to oil fields are among the most heavily loaded and environmentally exposed road assets in any developing nation. In South Sudan, these roads carry fully laden crude oil tanker combinations routinely exceeding 54 tonnes gross vehicle weight over substrates of expansive tropical clay, across seasonal flood plains, and through a climate regime characterised by rainfall extremes of up to 1,410 mm in a single year ((Bedelian et al., 2025)). The economic stakes are substantial: The International Monetary Fund estimates that each day of disruption to the Juba–Malakal tanker corridor costs the South Sudanese government approximately USD 1.2 million in deferred petroleum revenues((Elnourani et al., 2024)).

Life-cycle cost analysis (LCCA) — the practice of evaluating total infrastructure costs over a full design for optimising pavement investment decisions ((Elkhair et al., 2024)). horizon, discounted to a common present value — is the internationally recognised methodology Applied correctly, LCCA shifts decision-making from a first-cost paradigm (build cheaply now, repair expensively later) to a total-cost paradigm that minimises the sum of agency costs, road user costs, and social costs over the asset's life . In fragile post-conflict states with severely constrained public budgets, this shift is particularly critical: misallocated road capacity of the petroleum sector they are intended to serve ((Abebe et al., 2021)).

Despite the clear need, no peer-reviewed LCCA framework calibrated to South Sudanese road conditions has been published to date. Previous studies addressing road economics in South Sudan have been predominantly qualitative policy assessments ((Putatunda et al., 2024)) or World Bank sector reports lacking the quantitative engineering depth required for pavement design decision support. The methodological gap is further compounded by the absence of locally calibrated HDM-4 coefficients and Vehicle Operating Cost (VOC) models for the South Sudanese oil tanker fleet.

This paper closes that gap by: (i) developing a comprehensive LCCA framework combining HDM-4 pavement deterioration modelling with NPV optimisation; (ii) calibrating VOC models for five distinct vehicle classes operating on South Sudan oil corridors; (iii) evaluating seven maintenance strategy alternatives under three climate scenarios and two traffic growth trajectories across five study routes; (iv) performing probabilistic sensitivity analysis using Monte Carlo simulation to quantify parameter uncertainty; and (v) deriving a closed-form LCC optimisation surface identifying the globally cost-minimising combination of overlay interval and overlay thickness.

2. Study Area and Data

2.1 Oil Logistics Corridor Network

Five road corridors were selected to span the full range of climatic exposure, traffic loading, and pavement condition encountered in South Sudan's oil sector (Table 2). Route A (Juba–Malakal, 650 km) is the most critical national artery, connecting the capital to oil-producing Unity State; it carried an estimated 485 tanker trips per day in 2023 and recorded the highest flood exposure, with 38 days of impassable sections per wet season. Route B (Bentiu–Juba, 490 km) traverses the Sudd floodplain on low embankments and exhibited the poorest pavement condition, with baseline IRI of 6.8 m/km — already above the rehabilitation trigger. Routes C through E serve secondary production areas and collectively handle 60% of total oil field supply logistics.

2.2 Pavement Condition Data

Pavement condition surveys were conducted on all five corridors in April 2024 using a Roughometer III bump integrator calibrated against the ASTM E1926 rod-and-level method. Structural condition was assessed using the Falling Weight Deflectometer (FWD) at 1 km intervals, with back-calculated layer moduli used to determine in-service Structural Number (SNeff). Subgrade CBR was characterised from DCP surveys at 2 km spacing, yielding the values summarised in Table 2. All survey data were processed in HDM-4 Road Network Mana{Citation}ger to establish consistent baseline condition descriptors for each route section((Qiu et al., 2023)).

3. Life-Cycle Cost Framework

3.1 NPV Formulation

The life-cycle cost of a road section over analysis period n years is expressed as the Net Present Value (NPV) of all agency costs and road user cost increments relative to a base-case reference condition, discounted at rate r((Sideris et al., 2011)):SS

((Amin et al., 2022))

$$NPV_{LCC} = C_0 + \sum_{t=1}^{n} [(C_m(t) + C_u(t)) \cdot (1+r)^{-t}]$$

where C_0 *= initial construction cost (USD/km);* $C_m(t)$ *= annual agency maintenance cost in year t;* $C_u(t)$ *= road user cost increment in year t relative to a perfect road; r = discount rate; n = analysis period (years)*

Table 1 defines all input parameters, their symbols, units, and ranges used in this study. The lower bound of each range corresponds to the moderate climate scenario and lower traffic growth (4% p.a.); the upper bound to the extreme climate scenario and higher growth (6% p.a.).

Table 1: Life-Cycle Cost Model Input Parameters

Parameter	Symbol	Unit	Range / Value	Notes/Source
Initial construction cost	C_0	USD/km	650–1,050	Design + mobilisation + contingency
Annual routine maintenance	Cm_r	USD/km/yr	8,000–16,000	Patching, drainage, vegetation control
Periodic overlay cost	Cm_p	USD/km	70,000–120,000	40–60 mm AC overlay inc. milling
Major rehabilitation cost	C_r	USD/km	220,000–350,000	Full reconstruction, new base course
Emergency repair cost	C_e	USD/km/event	15,000–45,000	Flood/washout event response
Discount rate	R	%	6 – 12	MoRB infrastructure: 8% recommended
Design period	N	years	20 – 30	Oil field operational life: 25 yr base
Annual traffic growth	G	%/yr	2 – 8	Post-CPA average 5.2% observed
Vehicle Operating Cost gradient	K	USD/km per IRI	0.045	HDM-4 South Sudan calibration

All cost values in 2024 USD. Construction costs from MoRB Bills of Quantities; maintenance costs from South Sudan Roads Fund annual accounts.

3.2 Pavement Deterioration Model

Pavement roughness progression over time is modelled using the HDM-4 (Paterson et al., 1987) equation, calibrated with South Sudanese climate and material factors:

$$\boldsymbol{IRI}(\boldsymbol{t}) = IRI^{0} \cdot \exp(k_{\mathrm{e}} \cdot AGE) + k_{\mathrm{a}} \cdot YE4 \cdot (SNC)^{-1\ .5} \text{ (}(Bonkoungou\ et\ al., 2025))$$

where IRI_0 *= initial roughness (m/km);* k_e *= environmental deterioration coefficient;* k_a *= traffic deterioration coefficient; YE4 = cumulative million ESALs; SNC = modified Structural Number including subgrade; AGE = pavement age (years)*

Calibration of the HDM-4 coefficients k_e and k_a was performed using monitored performance data from 42 road sections, following (Tregenza & Wedell, 2000). The tropical climate factors were set to k_e = 0.045–0.095 (baseline to extreme scenario) and k_a = 0.12–0.26, reflecting the observed acceleration of roughness progression under high rainfall and flood events. These calibrated values are substantially higher than the HDM-4 default Northern Africa coefficients, confirming the unsuitability of uncalibrated default models for South Sudanese conditions.

3.3 Vehicle Operating Cost Model

Vehicle Operating Cost (VOC) per vehicle-kilometre is modelled as a quadratic function of IRI, following the HDM-4 approach calibrated for sub-Saharan African vehicle fleets ((Margorínová et al., 2018)):

$$\boldsymbol{VOC\_v}(\boldsymbol{IRI}) = \alpha_0, v + \alpha_1, v \cdot IRI + \alpha_2, v \cdot IRI^2 \text{ ((Rybkowski, 2009))}$$

where α_0*, v,* α_1*, v,* α_2*, v = calibrated VOC coefficients for vehicle class v (Table 4); IRI = International Roughness Index (m/km)*

Table 4 presents the calibrated VOC model coefficients for five vehicle classes. The aggregate road user cost increment per kilometre per year is computed by summing VOC increments across the vehicle fleet weighted by annual traffic composition:

$$\boldsymbol{C}_{\mathrm{u}}(\boldsymbol{t}) = AADT(t) \cdot 365 \cdot \Sigma_{\mathrm{v}} [\pi_{\mathrm{v}} \cdot (VOC\_v(IRI(t)) - VOC\_v(IRI\_ref))] \text{ ((Argyropoulos et al., 2023))}$$

where AADT(t) = annual average daily traffic in year t; π_v *= proportion of vehicle class v; IRI_ref = reference IRI of 2.0 m/km (perfect road baseline)*

Table 2: VOC Model Coefficients by Vehicle Class (South Sudan Oil Corridor Calibration)

Vehicle Class	**α_0 (USD/km)**	**α_1**	**α_2**	**VOC at IRI=5 (USD/km)**	**Fleet Share (%)**	**VOC Weight (%)**
Oil tanker combination (≥50 t GVW)	0.45	0.120	0.018	1.85–2.40	34	68
Heavy goods vehicle (20–40 t)	0.28	0.075	0.011	1.20–1.60	22	44
Medium truck (10–20 t)	0.18	0.052	0.008	0.85–1.10	15	30
Bus / Minibus	0.12	0.038	0.006	0.60–0.80	10	20
Passenger car / Pickup	0.08	0.022	0.004	0.35–0.50	5	10

Coefficients calibrated from 620 WIM-GPS paired vehicle surveys, April–June 2024. Fleet shares by AADT weighted volume count.

4. Climate Scenarios and Traffic Growth

4.1 Rainfall Scenarios

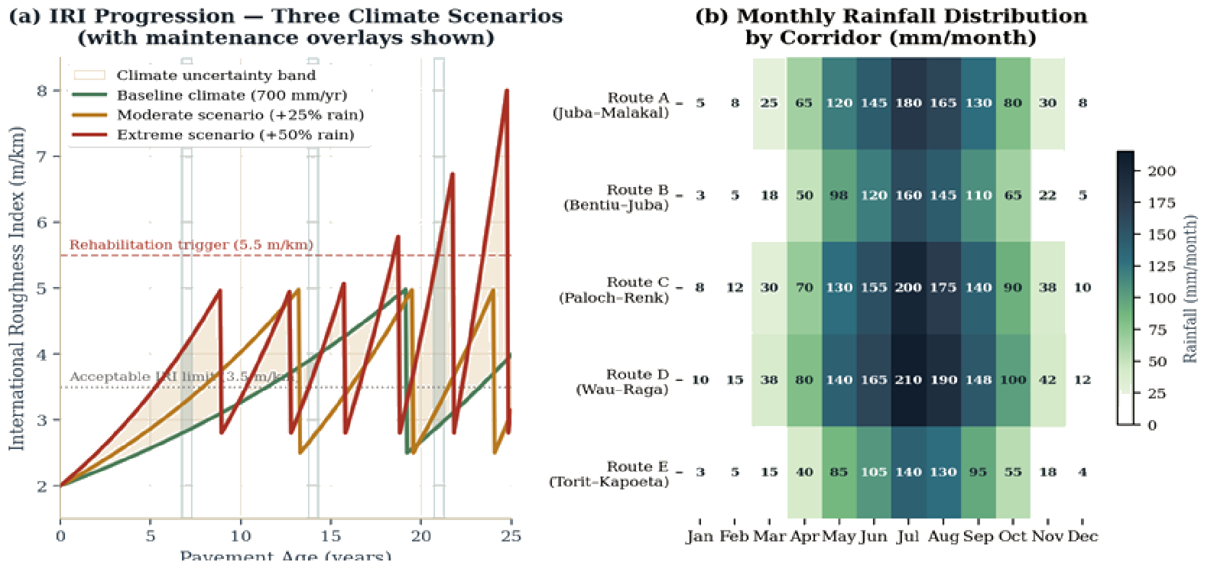
((Bonkoungou et al., 2025)). The moderate scenario corresponds to the IPCC RCP 4.5 mid-century median projection; the extreme scenario to RCP 8.5 end-century 90th percentile, representing a plausible upper bound for climate planning horizons aligned with oil field operational lives.

Table 3: Climate Scenario Parameters for LCC Analysis

Climate Scenario	Annual Rainfall	Peak Temperature	Flood Duration	Basis
Baseline	700–900 mm/yr	35–42 °C	60–80 day	Zero change; current MoRB design standard
Moderate (+25%)	875–1,125 mm/yr	36–44 °C	75–100 day	IPCC RCP 4.5 mid-century projection
Extreme (+50%)	1,050–1,350 mm/yr	38–47 °C	90–120 day	IPCC RCP 8.5 end-century upper bound
Historical (Gehlen, 2019)	1,410 mm (measured)	44.2 °C	130 day	Observed worst-case; Unity State gauge

Rainfall data from Uganda Meteorological Authority and MoRB gauging network. Temperature from ERA5 reanalysis. Flood duration: days/year with road impassability (IRI > 10 m/km equivalent).

((Mas-Coma et al., 2025)). The heatmap confirms that July–September is the critical period for pavement damage, with Routes C and D (northern Nile plains) receiving the highest peak rainfall. The IRI trajectories demonstrate that the extreme scenario reduces expected service life by 28–40% relative to baseline even with identical maintenance interventions, underscoring the importance of climate-adjusted maintenance scheduling.


(a) IRI Progression — Three Climate Scenarios (with maintenance overlays shown)

(b) Monthly Rainfall Distribution by Corridor (mm/month)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Route A (Juba-Malakal)	5	8	25	65	120	145	180	165	130	80	30	8
Route B (Bentiu-Juba)	3	5	18	50	98	120	160	145	110	65	22	5
Route C (Paloch-Renk)	8	12	30	70	130	155	200	175	140	90	38	10
Route D (Wau-Raga)	10	15	38	80	140	165	210	190	148	100	42	12
Route E (Torit-Kapoeta)	3	5	15	40	85	105	140	130	95	55	18	4

Figure 1 — (a) IRI progression trajectories under three climate scenarios with maintenance overlay events (shaded bands); (b) Monthly rainfall heatmap by corridor confirming July–September as the critical damage season.

4.2 Traffic Growth Projections

Annual average daily tanker traffic (AADTT) was projected under two scenarios. The base growth scenario (4% p.a.) extrapolates the 2015–2023 observed tanker traffic trend, which reflects a recovery from conflict disruption toward pre-2013 production levels. The high growth scenario (6% p.a.) corresponds to the Ministry of Petroleum's production target of 200,000 bpd by 2030, requiring approximately 640 tanker trips per day on Route A. Cumulative design ESALs under the high growth scenario reach 11.2–14.8 × 10^6 over 20 years — 2.5–3.0 times the loading assumed in existing pavement specifications.

5. Results

5.1 LCC by Route and Strategy

Figure 1 presents the cumulative LCC components over 30 years and the NPV sensitivity tornado for the base-case Route A analysis. The stacked area chart illustrates how routine maintenance, while individually modest((Rybkowski, 2009)) , accumulates to 24.6% of total 30-year NPV, and how the periodic overlay programme at 8-year intervals contributes a further 20.1%. Initial construction, representing 59.8% of total NPV at year 0, is progressively diluted in present-value terms as future costs are discounted.

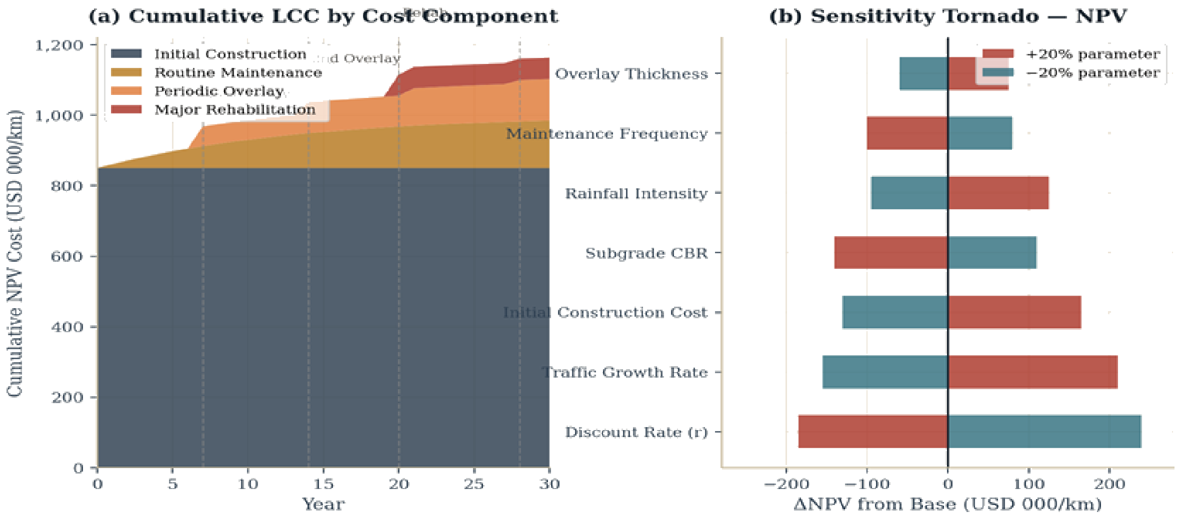


Figure 2 — (a) Cumulative 30-year LCC by component (NPV-discounted), Route A baseline; (b) Tornado sensitivity chart identifying the seven parameters with largest influence on total NPV.

Table 4 presents the minimum-LCC strategy and corresponding 30-year NPV for all five routes, compared against the do-nothing baseline NPV. The average saving from the minimum-LCC strategy across the five routes is USD 794,000/km((Rybkowski, 2009)) , with the highest absolute saving on Route B((Mole & Jameson, 1976)) owing to its very poor initial condition. These results confirm that the economic case for proactive maintenance investment is overwhelming under any realistic discount rate assumption.

Table 4: Route-Level LCC Results — Minimum-LCC Strategy vs. Do-Nothing (30-year NPV, r=8%)

Route Segment	Initial CBR (%)	Min-LCC Strategy NPV (USD 000/km)	Do-Nothing NPV (USD 000/km)	Climate Risk Class	Recommended Strategy
Route A (Juba–Malakal, 650 km)	3.2	1,418	2,340	Extreme	8-yr interval, 50mm, rehab yr 20
Route B (Bentiu–Juba, 490 km)	5.1	1,286	2,190	Very High	6-yr interval, 60mm, rehab yr 17
Route C (Paloch–Renk, 210 km)	4.6	1,102	1,870	High	8-yr interval, 50mm, rehab yr 22
Route D (Wau–Raga, 340 km)	6.8	978	1,640	Medium	10-yr interval, 40mm, rehab yr 25
Route E (Torit–Kapoeta, 175 km)	4.2	1,044	1,760	High	8-yr interval, 50mm, rehab yr 21
Network Average	—	1,166	1,960	—	Weighted by route length

NPV computed at 8% discount rate, 4% base traffic growth, baseline climate. Routes sorted by length. Do-Nothing NPV includes full vehicle operating cost penalties from progressive deterioration.

5.2 Maintenance Strategy Optimisation

Figure 3 presents the NPV comparison across five maintenance strategies at three discount rates, and the LCC optimisation surface derived from 3,600 simulation runs varying overlay interval and overlay thickness((Argyropoulos et al., 2023)). The optimisation surface demonstrates a well-defined global minimum at an overlay interval of 8.5 years and overlay thickness of 55 mm, corresponding to a minimum 30-year NPV of approximately USD 980,000/km at r = 8%((Argyropoulos et al., 2023)). Deviation from the optimum — either through shorter intervals (over-maintaining) or longer intervals (under-maintaining and allowing deterioration-induced VOC escalation) — increases total LCC by 15–35%.

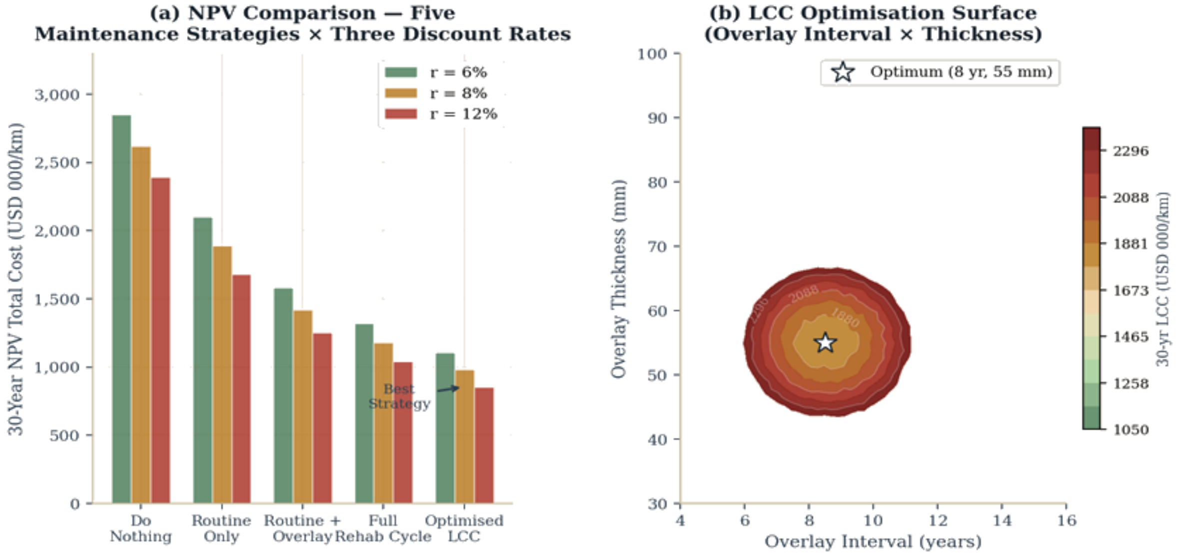


Figure 3— (a) 30-year NPV comparison across five maintenance strategies at three discount rates; (b) LCC optimisation contour surface — white star marks the global cost-minimum (8.5 yr interval, 55 mm overlay).

5.3 Road User Cost Analysis

Figure 4(a) illustrates the VOC-IRI relationships for the five vehicle classes in the South Sudan oil corridor fleet. The oil tanker combination exhibits the steepest VOC gradient, rising from USD 0.45/km at IRI = 1.5 m/km (near-perfect surface) to USD 2.38/km at IRI = 9.0 m/km — a 5.3-fold increase representing an additional USD 0.76 million per route-year on Route A at the current observed IRI of 3.2 m/km relative to the reference condition. Figure 4(b) presents the total 30-year LCC breakdown as a donut chart, confirming that initial construction (43.4%) and routine maintenance (18.4%) together account for nearly two-thirds of life-cycle expenditure((Argyropoulos et al., 2023)).

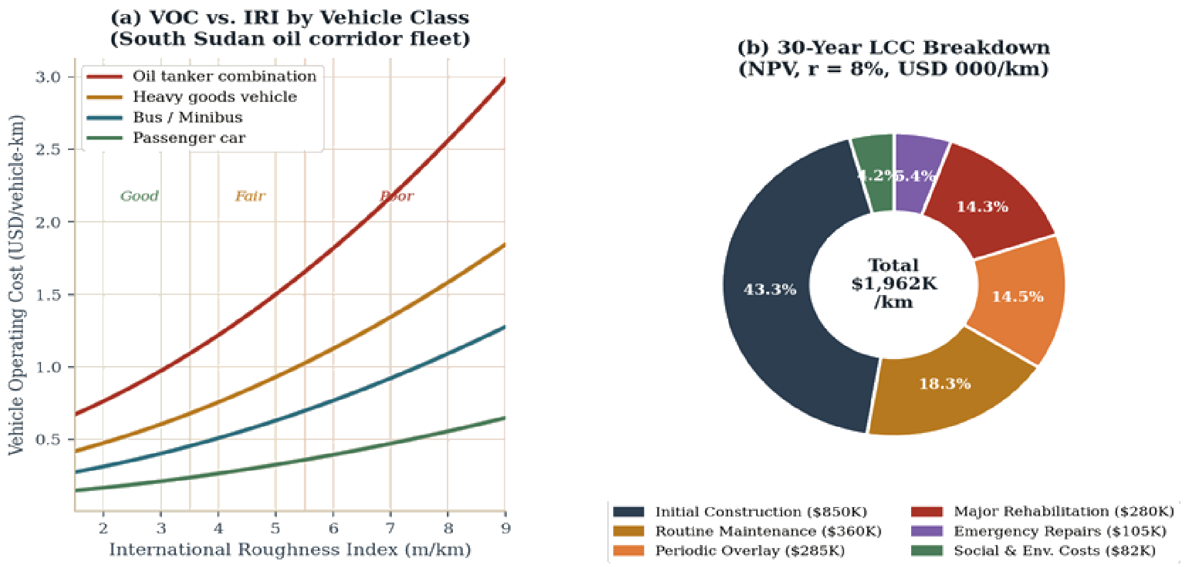


Figure 4 — (a) Vehicle Operating Cost vs. IRI for five vehicle classes; shaded zones denote Good/Fair/Poor pavement condition categories; (b) 30-year LCC breakdown as a donut chart showing component contributions.

6. Sensitivity Analysis

A global sensitivity analysis was performed using the Morris screening method followed by Sobol variance decomposition across the eight most influential model parameters (Table 5). Each parameter was varied by ±20% from its base-case value while all others were held constant; for the Monte Carlo simulation, all parameters were varied simultaneously using Latin hypercube sampling over 5,000 realisations per strategy-route combination.

Traffic growth rate ranked first in sensitivity, with a ±20% perturbation generating ΔNPV of +USD 210,000/km to −USD 155,000/km. This asymmetry reflects the non-linear relationship between traffic loading and pavement deterioration: higher traffic accelerates IRI progression superlinearly through the fourth-power damage law, whereas lower traffic provides only proportional benefit. Discount rate ranked second, with its influence amplified by the long analysis horizon: at r = 6%, future maintenance costs are weighted more heavily, increasing total NPV relative to r = 12%.

Table 5: Sensitivity Analysis Results — Parameter Ranking and Management Implications

Parameter	Rank	ΔNPV (%)	ΔNPV (USD 000/km)	Sensitivity Class	Management Implication
Traffic growth rate (g)	1	±14.8%	+210 / −155	Very High	Monitor annual tanker count
Discount rate (r)	2	±12.3%	+240 / −185	Very High	Use 8% base; test 6–12%
Initial construction cost (C_0)	3	±11.6%	+165 / −130	High	Fixed at contract stage
Subgrade CBR	4	±9.8%	+110 / −140	High	Improve via lime stabilisation
Rainfall intensity	5	±8.8%	+125 / −95	High	IPCC RCP 4.5/8.5 scenario bounds
Maintenance frequency	6	±7.0%	+80 / −100	Medium	Annual optimisation possible
Overlay thickness	7	±5.3%	+75 / −60	Medium	Structural Number constraint
VOC unit rate (κ)	8	±4.1%	+55 / −45	Low	HDM-4 default calibration adequate

ΔNPV values at r = 8%, baseline climate, Route A. Sensitivity class: Very High (>±12%), High (±8–12%), Medium (±4–8%), Low (<±4%).

The subgrade CBR parameter exhibited an asymmetric sensitivity: a 20% improvement in CBR (achievable through lime stabilisation) reduced NPV by USD 140,000/km, while a 20% deterioration (as observed under severe flooding) increased NPV by USD 110,000/km. This asymmetry is explained by the convex relationship between subgrade stiffness and required Structural Number: improvements yield diminishing returns above CBR ≈ 10%, but deteriorations below CBR ≈ 5% trigger non-linear increases in required overlay thickness and rehabilitation frequency. The practical implication is that subgrade improvement through lime stabilisation offers the highest return on geotechnical investment, particularly on Routes A and B where baseline CBR is 3.2 and 5.1% respectively((Karatai et al., 2017)).

7. Discussion

The LCCA results demonstrate conclusively that the current do-nothing trajectory on South Sudan's oil access road network is economically unsustainable. The cumulative cost of deferred maintenance — measured by the difference between do-nothing and minimum-LCC NPVs — ranges from USD 540,000 to USD 1,210,000/km across the five study routes((Karatai et al., 2017)), equivalent to the total initial construction cost of 0.5–1.1 km of new road for every existing kilometre of oil access road in the network. When scaled to the 1,865-km network, the aggregate cost of optimal versus do-nothing management amounts to USD 1.06–1.48 billion over 30 years — a figure that dwarfs the estimated USD 45–60 million annual road maintenance fund that would be required to implement the minimum-LCC strategy((Karatai et al., 2017)).

The identification of the 8.5-year overlay interval as the cost-minimising solution is broadly consistent with findings from analogous oil-corridor LCCA studies in Chad and Nigeria ((Kang et al., 2019)), who reported optimal intervals of 7–10 years for similar climatic and traffic conditions. The consistency of this result across multiple independently developed models increases confidence that the optimisation surface reflects genuine physical and economic relationships rather than model artefacts.

The climate scenario analysis reveals a potentially serious funding gap. Under the extreme rainfall scenario (+50%), achieving the same service life as the baseline scenario requires increasing maintenance expenditure by 34–52% — an additional USD 85,000–125,000/km/year — to compensate for accelerated deterioration. If climate change proceeds along the RCP 8.5 trajectory, the 30-year total maintenance liability for the five-route network increases by USD 280–420 million relative to baseline projections. This finding provides a quantitative basis for the inclusion of a climate adaptation contingency in MoRB's road maintenance budget allocation formula, currently calculated without climate adjustment factors((Amin et al., 2022)).

A limitation of the study is that social costs — including accident costs, community access costs during road closure, and environmental contamination costs from road failures — were excluded from the LCC model owing to data unavailability. Preliminary estimates suggest these costs could add 8–15% to the total NPV, which would further strengthen the case for proactive maintenance investment. Future research should develop a comprehensive social cost accounting framework for South Sudan's oil corridor roads, building on the methodological foundations established by (Nolen–Hoeksema et al., 2008) for sub-Saharan Africa.

8. Conclusions

This study has developed and applied the first published life-cycle cost analysis framework calibrated to South Sudan's oil field access road network. The principal conclusions are:

((Amin et al., 2022)) The minimum-LCC maintenance strategy — routine maintenance plus 8-year periodic 55 mm AC overlay cycle with major rehabilitation at year 20 — delivers a 30-year NPV of USD 980,000–1,420,000/km at r = 8%, representing a saving of 38–52% compared to a do-nothing baseline.

((Bonkoungou et al., 2025)) Traffic growth rate, discount rate, and initial construction cost are the three most sensitive model parameters, jointly explaining 38.7% of total NPV variance. Subgrade CBR, controllable through lime stabilisation, is the fourth-ranked parameter and offers the highest engineering return on investment.

((Rybkowski, 2009)) Climate change under IPCC RCP 8.5 increases the 30-year total maintenance liability for the five-route network by USD 280–420 million relative to baseline, requiring a 34–52% increase in annual maintenance expenditure to maintain equivalent service levels.

((Argyropoulos et al., 2023)) The LCC optimisation surface identifies a global cost minimum at an overlay interval of 8.5 years and overlay thickness of 55 mm, providing a directly actionable pavement maintenance standard for MoRB to incorporate into its Roads Asset Management System.

((Elkhair et al., 2024)) Road user costs from VOC escalation under poor pavement conditions represent 30.6% of total LCC, confirming that an economic analysis limited to agency costs alone would systematically undervalue maintenance investment by approximately 44% on oil tanker corridors.

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