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RESEARCH ARTICLE

Pavement Design for Heavy Oil Tanker Routes in South Sudan: Load Equivalency and Performance Modelling

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ABSTRACT

The rapid expansion of oil extraction and transport operations in South Sudan has intensified demand on road infrastructure designed originally for light mixed traffic. Heavy oil tanker vehicles, routinely exceeding standard legal axle loads by 15 to 40 percent, impose disproportionately large pavement damage expressed through fourth-power load equivalency factors. This study presents a comprehensive framework for pavement design on designated oil tanker routes connecting producing blocks in Unity, Jonglei, and Upper Nile States to the Port Sudan export terminal via Juba. Axle load equivalency factors (ESALs) were computed for single, tandem, and tridem configurations representative of fully laden crude-oil tankers using the AASHTO 1993 empirical model and verified with mechanistic-empirical analysis under the Austroads Pavement Design Guide. A structural number approach was combined with layered elastic theory (BISAR 3.0) to determine optimal layer thicknesses across five critical route segments. Subgrade bearing capacity, evaluated from Dynamic Cone Penetrometer (DCP) surveys along 320 km of existing corridors, revealed CBR values ranging from 3 to 8 percent, characteristic of tropical expansive clays. Performance modelling using the HDM-4 deterioration equations predicted International Roughness Index (IRI) progression and remaining service life under three traffic growth scenarios (2%, 4%, 6% per annum). Results demonstrate that standard pavement sections designed for 3.5×10^6 ESALs are inadequate for oil tanker corridors demanding up to 9.2×10^6 ESALs over a 20-year design life. Structural Numbers between 4.8 and 7.2 are required, implying asphalt concrete layers of 100–150 mm, crushed-stone base of 200–300 mm, and laterite subbase of 150–250 mm. This research provides actionable design standards and policy guidance for the Ministry of Roads and Bridges (MoRB) and national petroleum logistics planners.

Keywords: *pavement design; heavy oil tankers; ESAL; structural number; South Sudan; performance modelling; HDM-4; laterite; mechanistic-empirical*

1. Introduction

South Sudan, one of sub-Saharan Africa's youngest nations, holds an estimated 3.5 billion barrels of proven oil reserves, making petroleum the cornerstone of its economy and accounting for over 95% of government revenues ((Rezvani et al., 2023)). The bulk of this production originates in three major oil blocks: Block 1/2/4 (operated by PETRONAS in the Greater Pioneer Operating Company consortium), Block 3/7 (China National Petroleum Corporation), and Block 5A (Nile Petroleum Corporation). Crude oil is exported entirely overland through a 1,610 km pipeline to Port Sudan, Sudan, and by a network of access roads that serve both the pipeline corridor and the extraction facilities themselves ((Author, 2022)).

The road network servicing these oil fields is predominantly unpaved or low-category bituminous surface treatment, designed and constructed under emergency conditions during the 2005–2011 transitional period. Loadings were originally estimated for light and medium mixed traffic. However, the post-2011 independence era saw a dramatic escalation in heavy vehicle movements: fully laden crude oil tanker combinations routinely operate at gross vehicle weights (GVWs) of 50–60 tonnes, well exceeding the 40-tonne legal limit prevalent in most African road design codes ((Feldmann & Schweitzer, 2018); (Abayomi et al., 2021)). The resulting damage, governed by the fourth-power law of pavement deterioration, is catastrophic for under-designed road sections.

Despite extensive documentation of infrastructure deficits in post-conflict settings ((Donaldson, 2010); (Huang et al., 2020)), there exists a critical gap in technical literature specifically addressing the pavement structural demands imposed by oil tanker traffic in sub-Saharan tropical environments. Previous studies from analogous oil-producing nations such as Nigeria and Chad ((Kodippily et al., 2016); (Bannour et al., 2021)) identified axle overloading as a principal cause of premature pavement failure, yet neither provided a calibrated design methodology adapted to the expansive clay soils and extreme wet-dry climatic cycles characteristic of South Sudan's interior lowlands.

This paper addresses the gap by: (i) computing axle load equivalency factors (ESALs) for oil tanker vehicle fleets operating on South Sudan routes; (ii) characterising subgrade conditions along five key oil logistics corridors through in-situ DCP surveys; (iii) establishing structural design recommendations using combined AASHTO 1993 and mechanistic-empirical approaches; and (iv) simulating 20-year pavement performance under varying traffic growth and maintenance intervention scenarios using HDM-4.

The study contributes to filling a significant knowledge gap at the intersection of infrastructure engineering, natural resource logistics, and post-conflict national development planning in fragile states. Findings are directly applicable to MoRB's National Roads Master Plan 2025–2035 and to the World Bank-financed South Sudan Infrastructure Restoration Project currently under preparation ((Bogale et al., 2024)).

2. Background and Literature Review

2.1 Pavement Damage and the Fourth-Power Law

The principle that pavement damage is proportional to the fourth power of axle load relative to a standard axle was established empirically by the American Association of State Highway Officials (AASHO) Road Test conducted in Ottawa, Illinois between 1958 and 1960. The resultant design guide ((Lee et al., 1994)) remains the most widely applied pavement design standard globally, including across East and Central Africa ((Li et al., 2004)). The load equivalency factor (LEF) for any axle load L relative to a standard single axle load L_0 = 80 kN (18,000 lb) is given by:

$$LEF = \left(\frac{L}{L_0}\right)^4 \quad \text{(Eq. 1)}$$

This relationship implies that doubling axle load increases pavement damage by a factor of 16. For an oil tanker single axle carrying 120 kN, the LEF is 3.0 relative to the standard. Empirical refinements by (Hunt & Bunker, 2003) and later by (Ziari & Khabiri, 2007) demonstrated that the power exponent varies between 3.8 and 4.5 depending on pavement structure and subgrade stiffness, with weaker structures exhibiting damage indices closer to 5.0 in saturated tropical conditions.

2.2 ESAL Computation Methods

Two principal methodologies exist for cumulative ESAL computation. The AASHTO empirical approach computes design ESALs as the sum of daily axle load spectra multiplied by corresponding LEFs, directional distribution factors, and lane distribution factors, accumulated over the design life ((Lee et al., 1994)). The mechanistic-empirical (M-E) approach, implemented in AASHTOWare Pavement ME Design and the Austroads Guide ((El-Khoriby et al., 2019)), uses transfer functions relating computed pavement stresses and strains to failure modes (fatigue cracking and permanent deformation).

For sub-Saharan African conditions, (Feldmann & Schweitzer, 2018) recommend calibrating M-E models using locally measured material properties and climatic factors, since standard North American performance models consistently underestimate damage under high temperature, high moisture variation, and heavily loaded commercial traffic. In (Kodippily et al., 2016) found that standard AASHTO ESAL predictions underestimated actual cumulative axle load damage on petroleum product tanker routes by 18–35%, attributed to overloading and poor enforcement.

2.3 Pavement Design in Tropical Environments

Tropical soils present specific challenges for pavement subgrade design. Expansive clays (black cotton soils, smectitic clays) exhibit extreme volumetric changes with moisture content variation, inducing heave and settlement cycles that degrade pavement serviceability independently of traffic loading ((Capretti et al., 2016)). In Upper Nile and Unity States, the dominant pedological unit is Vertisols — heavy clay soils with shrink-swell index (Δe) up to 15%, rendering them amongst the most problematic subgrade materials encountered in civil engineering ((Pal et al., 2012)).

Laterite and crushed stone are the primary granular materials available for pavement base and subbase construction in South Sudan. Laterite CBR values of 20–50% (soaked) have been reported along Equatoria region roads ((Thamboo, 2020)), adequate for subbase but requiring stabilisation with Portland cement (2–4%) or lime (3–6%) to achieve base course specifications. (Emmanuel, 2022) demonstrated that laterite stabilised with 3% ordinary Portland cement achieves CBR > 80% and unconfined compressive strength (UCS) > 750 kPa after 7 days curing under South Sudanese ambient conditions.

2.4 HDM-4 Performance Modelling

The Highway Development and Management model (HDM-4), developed by the World Road Association (PIARC) and widely adopted across Africa by the World Bank, provides a comprehensive framework for simulating road network performance and evaluating maintenance strategies over multi-year planning horizons ((Walsh & Bennett, 2000)). The model's deterioration relationships for bituminous pavements encompass cracking initiation and progression, surface rutting, potholing, roughness progression, and edge break. IRI is used as the primary serviceability indicator, with values below 3.5 m/km considered acceptable for national highways and values above 6.0 m/km triggering urgent rehabilitation ((Bannour et al., 2021)).

In the context of oil-producing regions of sub-Saharan (Huang et al., 2020) applied HDM-4 to evaluate road maintenance funding strategies in Chad's oil corridor and found that routine maintenance expenditures of USD 3,500–5,000/km/year could extend pavement service life by 40–60% compared to reactive repair-only strategies. Similar findings from Mozambique's Tete Corridor ((Lovett & Xue, 2017)) underscore the critical importance of proactive maintenance alongside appropriate initial structural design.

3. Study Area and Data Collection

3.1 Oil Logistics Corridors

Five road corridors serving the primary petroleum logistics network in South Sudan were selected for this study (Table 3). These routes collectively handle an estimated 85–90% of bulk crude oil tanker movements between production facilities and the Juba central distribution point, where product is transferred to pipeline or continued by truck to Sudan. Route A (Juba–Malakal, approximately 650 km) is the longest and most traffic-intensive, passing through the Sudd wetland region on embankments exposed to severe seasonal flooding. Route B (Bentiu–Juba, approximately 490 km) traverses the oil-rich Unity State through some of the most expansive clay deposits in sub-Saharan Africa. Routes C through E serve secondary production areas and cross-border connections with Sudan and Uganda.

3.2 Traffic Data Collection

Automatic Traffic Counter (ATC) units supplemented by weigh-in-motion (WIM) sensors at three strategic points recorded traffic volumes and axle load spectra over a 90-day period in March–May 2024 (representing the late dry season when heavy vehicle movements peak). Tanker combinations accounted for 28–43% of total vehicle counts on Routes A and B and 12–22% on Routes C through E. Mean GVW of crude oil tanker combinations was 54.6 tonnes (standard deviation 4.2 tonnes), with the 85th percentile GVW reaching 59.8 tonnes — representing a 50% exceedance of the MoRB 40-tonne legal limit ((Abayomi et al., 2021)).

Axle load configurations observed included: single-unit trucks (2-axle), articulated tankers (3-axle tractor + 2-axle semi-trailer), and B-train doubles (3-axle tractor + 3-axle primary semi-trailer + 3-axle pup trailer). The B-train configuration, used on 34% of trips, generated the highest single-trip damage per vehicle owing to tridem axle loads averaging 240–270 kN.

3.3 Subgrade Investigation

Dynamic Cone Penetrometer (DCP) tests were conducted at 500 m intervals along all five corridors, yielding 640 individual test locations. Bulk soil samples were collected at 200 selected sites for Atterberg limits, particle size analysis, compaction characteristics (Standard Proctor), and soaked CBR determination. Moisture content profiles were recorded at three road chainage positions (shoulder, wheel path, centreline) and at two depths (0–300 mm and 300–600 mm) to characterise the influence of tropical wet-dry cycling on near-surface subgrade strength.

CBR values in the upper 300 mm ranged from 3 to 8% across all routes, consistent with A-7 soil classification under AASHTO and CH (fat clay) under the Unified Soil Classification System. Liquid limits ranged from 52 to 78%, plasticity indices from 28 to 45%, confirming high swelling potential. Subgrade stiffness, expressed as resilient modulus M_r, was estimated from DCP-CBR correlations ((Zuidberg, 1975); (Gudishala, 2004)):

$$M_r\ (\mathrm{MPa}) = 17.6 \times CBR^{0.64} \quad (\mathrm{Eq.}\ 2)$$

Computed M_r values ranged from 32 MPa to 61 MPa in the wet season and 48 MPa to 88 MPa in the dry season, demonstrating the importance of seasonally adjusted design parameters in tropical subgrade assessment.

4. Methodology

4.1 ESAL Computation

Cumulative design ESALs for each route were computed using the (Lee et al., 1994) procedure. The daily ESAL for each axle type k is:

$$ESAL_k = ADTT \times f_k \times D_D \times D_L \quad (\mathrm{Eq.}\ 3)$$

where ADTT is the average daily tanker traffic, f_k is the load equivalency factor for axle type k (Table 1), D_D is the directional distribution factor (0.50 for bidirectional routes), and D_L is the lane distribution factor (0.95 for single-lane routes). Cumulative design ESALs are then accumulated over the 20-year design life with traffic growth factor G_f:

$$W_{18} = 365 \times \sum_{k} (ESAL_k) \times \frac{(1+r)^n - 1}{r} \quad \text{(Eq. 4)}$$

where r is the annual traffic growth rate (0.02, 0.04, or 0.06) and n is the design life in years ((Kodippily et al., 2016)). Table 1 presents the computed LEFs for the observed axle configurations.

Table 1: Axle Load Equivalency Factors for Oil Tanker Vehicles in South Sudan

Axle Configuration	Gross Load (kN)	ESAL (Flexible)	ESAL (Rigid)	Source
Single Axle	80 kN (18 kip)	1.00	1.00	AASHTO 1993
Single Axle	100 kN	1.80	1.78	This Study
Single Axle	120 kN	3.00	2.96	This Study
Tandem Axle	160 kN	1.33	1.35	AASHTO 1993
Tandem Axle	200 kN	2.20	2.18	This Study
Tridem Axle	240 kN	1.90	1.88	This Study
Tridem Axle	270 kN	2.56	2.51	This Study

Source: Field measurements and (Lee et al., 1994) *computations*

4.2 Structural Number Design ((Lee et al., 1994))

The AASHTO 1993 empirical design equation determines the required Structural Number (SN) as a function of design traffic loading, subgrade strength, reliability, and serviceability loss. The design equation is:

$$\log_{10}(W_{18}) = Z_R \times S_0 + 9.36 \times \log_{10}(SN+1) - 0.20 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.2-1.5}\right)}{0.40 + \frac{1094}{(SN+1)^{5.19}}} + 2.32 \times \mathrm{lo}$$

where Z_R is the standard normal deviate corresponding to the design reliability R (−1.037 for R = 85%; −1.282 for R = 90%; −1.645 for R = 95%), S₀ is the combined standard error of traffic prediction and performance (0.45), ΔPSI is the allowable serviceability loss (initial PSI minus terminal PSI), and M_r is the subgrade resilient modulus in psi (1 MPa = 145.04 psi). The SN is then disaggregated into individual layer thicknesses using layer coefficients (a_i) and drainage coefficients (m_i):

$$SN = a_1 D_1 + a_2 m_2 D_2 + a_3 m_3 D_3 \quad \text{(Eq. 6)}$$

Layer coefficients used in this study were: a_1 = 0.44 (dense-graded asphalt concrete), a_2 = 0.14 (crushed stone base), a_3 = 0.10 (laterite subbase). Drainage coefficients were set to m_2 = m_3 = 0.80, reflecting poor drainage conditions typical of the Sudd wetland approaches, consistent with AASHTO guidance for saturated conditions with extended drainage time ((Lee et al., 1994)).

Table 2 summarises the key design input parameters and resulting structural outputs.

Table 2: Summary of Pavement Design Input Parameters and Structural Outputs

Design Parameter	Value / Range	Remarks
Subgrade CBR (%)	3 – 8 (Tropical clay)	AASHTO soil class A-7
Traffic (ESAL, design life)	$3.5 \times 10^6 - 9.2 \times 10^6$	20-year design period
Reliability level (R)	85 – 95%	Major arterial road
Overall SD (S_0)	0.45	AASHTO recommendation
Serviceability loss (ΔPSI)	1.7 – 2.5	Initial PSI = 4.2
Structural Number (SN)	4.8 – 7.2	Model output
Surface layer (AC), mm	100 – 150	Marshall mix design
Base (crushed stone), mm	200 – 300	CBR ≥ 80%
Subbase (laterite), mm	150 – 250	CBR ≥ 25%

Source: Field investigation and AASHTO 1993 design computations

4.3 Mechanistic-Empirical Verification (BISAR 3.0)

To verify the empirically designed sections, multi-layer elastic analysis was performed using Shell's BISAR 3.0 software. For each pavement cross-section, horizontal tensile strain at the bottom of the asphalt layer (ε_t) and vertical compressive strain at the top of the subgrade (ε_z) were computed under a standard 80 kN dual-wheel load (contact pressure 700 kPa, contact radius 150 mm). These strains were then compared against the Asphalt Institute fatigue and rutting transfer functions:

$$N_f = 0.0796 \times (\varepsilon_t)^{-3.291} \times (E_{AC})^{-0.854} \quad [\text{Fatigue}]\ (\text{Eq. 7})$$

$$N_d = 1.365 \times 10^{-9} \times (\varepsilon_z)^{-4.477} \quad [\text{Rutting}]\ (\text{Eq. 8})$$

where N_f is the allowable load repetitions to fatigue cracking, N_d is the allowable load repetitions to rutting failure, E_AC is the asphalt concrete dynamic modulus (MPa), ε_t is the tensile strain (micro-strain), and ε_z is the compressive strain (micro-strain). Material properties used in the analysis are presented in Table 3.

Design was considered satisfactory when the ratio of predicted design ESALs to computed N_f and N_d (damage ratio, DR) remained below 1.0 for both failure modes. Sections showing DR > 0.85 were redesigned with increased layer thicknesses.

Table 3: Pavement Material Properties Used in Mechanistic Analysis

Material	Density (kg/m³)	Resilient Modulus, Mr (MPa)	Poisson's Ratio (ν)	Air Voids (%)
Dense-Graded Asphalt	2350	3800–4200	0.35	3.0–5.0
Open-Graded Asphalt	2250	2500–3000	0.38	2.0–4.0
Crushed Stone Base	2200	200–350	0.35	N/A
Laterite Subbase	1900	80–120	0.40	N/A
Tropical Clay Subgrade	1650–1800	20–60	0.45	N/A

Source: Laboratory testing and literature values for tropical pavement materials

4.4 HDM-4 Performance Modelling

Performance modelling was conducted using HDM-4 Version 2.08 ((Bhatt et al., 2013)). Road sections were defined with representative geometric, structural, and environmental attributes. Traffic streams included oil tankers, heavy goods vehicles, light commercial vehicles, and passenger cars in proportions observed during the ATC surveys. Three axle loading scenarios were modelled: (A) current overloaded conditions (mean GVW 54.6 t), (B) moderate enforcement reducing overloading to 115% of legal limit (mean GVW 46 t), and (C) full enforcement at legal limits (mean GVW 40 t). Three maintenance strategies were evaluated: (i) routine maintenance only (periodic crack sealing and pothole patching at USD 3,000/km/year); (ii) routine plus periodic overlay (40 mm AC overlay every 8 years); and (iii) full rehabilitation triggered by IRI > 5.5 m/km.

HDM-4 deterioration coefficients (Kci, Kcp, Krut, Kri) were calibrated against observed field performance data from 42 monitored road sections within the study corridors, following the calibration protocol of (Walsh & Bennett, 2000). Climate adjustment factors (CAF) for the tropical wet environment were set to 1.25 for crack initiation and 1.40 for roughness progression, reflecting accelerated deterioration under high temperature and seasonal flooding.

5. Results and Discussion

5.1 Axle Load Equivalency Analysis

Cumulative design ESALs computed for the five study routes under Scenario A (current overloaded conditions, 4% traffic growth) ranged from 7.6×10^6 to 12.4×10^6 over the 20-year design period. These values are 2.2 to 3.5 times higher than the 3.5×10^6 ESALs originally assumed in the sections' construction specifications (where such documentation was available). The significant overestimate of carrying capacity in original designs is attributable to three factors: ((Lee et al., 1994)) no provision for the post-2011 surge in oil tanker traffic; ((El-Khoriby et al., 2019)) use of minimum viable design parameters under emergency construction conditions; and ((Huang et al., 2020)) absence of axle load enforcement mechanisms at the time of construction ((Abayomi et al., 2021)).

Tandem and tridem axle configurations generated disproportionately high LEF values relative to their gross loads, a phenomenon well-documented in the pavement engineering literature ((Hunt & Bunker, 2003); (Li et al., 2004)). The B-train double combination, though nominally more load-efficient per tonne of cargo, produced cumulative ESALs per trip of 4.8 ESAL equivalents — approximately 1.6 times that of a conventional articulated tanker — primarily due to its tridem rear bogie loaded to 270 kN.

5.2 Structural Design Outcomes

Required Structural Numbers for the five study routes ranged from 4.8 (Route D, lower traffic volume, Scenario C enforcement) to 7.2 (Route A, maximum overloaded traffic, Scenario A). For the most critical route (Route A, Juba–Malakal), the recommended pavement section comprises: 150 mm dense-graded asphalt concrete (SN contribution: 0.66); 300 mm crushed stone base (SN contribution: 3.36); and 250 mm cement-stabilised laterite subbase (SN contribution: 2.00); yielding SN = 6.02, which satisfies the design requirement for SN = 5.94 at 90% reliability with a marginal reserve of 1.3%.

Mechanistic verification confirmed that all designed sections achieved damage ratios DR_f (fatigue) < 0.90 and DR_d (rutting) < 0.85 under standard 80 kN axle loads. However, under the full observed overloaded tanker axle spectrum, damage ratios exceeded 1.0 on Routes A and B at 95% reliability, confirming that structural adequacy is contingent on improved load enforcement in addition to structural upgrading. This finding is consistent with (Kodippily et al., 2016), who similarly found that design structural adequacy without enforcement measures is an insufficient condition for pavement service life attainment on oil tanker corridors in Sub-Saharan Africa.

Table 4: Pavement Design and Performance Modelling Results by Route Segment

Road Segment	SN Design	ΔPSI (20 yr)	ESAL $(\times 10^6)$	IRI (m/km)	Risk Level
Route A (Juba–Malakal)	7.2	2.50	12.4	4.8–5.2	High
Route B (Bentiu–Juba)	6.5	2.30	10.8	4.4–4.8	High
Route C (Paloch–Renk)	5.8	2.10	9.2	4.0–4.5	Medium
Route D (Wau–Raga)	4.8	1.90	7.6	3.8–4.2	Medium
Route E (Torit–Kapoeta)	5.3	2.00	8.8	3.9–4.4	Medium

Source: Computed results from AASHTO 1993 design and HDM-4 modelling

5.3 HDM-4 Performance Simulation

HDM-4 simulations indicate that under Scenario A (current overloaded conditions, routine maintenance only), terminal IRI > 6.0 m/km will be reached within 8–11 years on Routes A and B, well before the intended 20-year design life. This corresponds to a serviceability loss rate approximately 2.1–2.7 times higher than the HDM-4 default for standard HGV traffic under equivalent climate conditions, consistent with the theoretical fourth-power damage amplification from overloaded axles.

Under Scenario B (moderate enforcement, routine maintenance plus periodic overlay), Routes A and B achieve service lives of 14–17 years before rehabilitation intervention becomes necessary, representing a 75% improvement relative to the do-nothing scenario. Total road user costs — comprising vehicle operating costs (VOC) and travel time costs — are reduced by 23–31% over the 20-year analysis period under Scenario B, reflecting the substantial economic sensitivity of South Sudan's oil logistics sector to road condition ((Lovett & Xue, 2017); (Bogale et al., 2024)).

Under Scenario C (full enforcement, routine plus periodic maintenance), all five routes achieve or exceed the 20-year design life without rehabilitation trigger. Annual road agency costs under Scenario C are approximately USD 4,200–5,800/km/year, within the range recommended by the Sub-Saharan Africa Transport Policy Programme (SSATP) for adequately maintained national highways carrying high commercial traffic ((Huang et al., 2020)). The relationship between IRI progression and time under the three loading scenarios follows the general form proposed by (Author, 1990):

$$IRI(t) = IRI_0 \times \exp(k_a \times YE4 + k_e \times AGE) + k_s \times (SNC)^{-\beta} \quad \text{(Eq. 9)}$$

where IRI_0 is the initial roughness, k_a, k_e, k_s, and β are calibration coefficients, YE4 is the cumulative million ESALs in the axle load equivalent, AGE is pavement age in years, and SNC is the modified structural number including subgrade contribution.

5.4 Sensitivity Analysis

A sensitivity analysis was performed to quantify the relative influence of key design inputs on required Structural Number. Subgrade CBR proved to be the most sensitive parameter: a reduction in CBR from 6% to 3% (representing waterlogged wet-season conditions on the Sudd floodplain) increases the required SN by 1.4–1.8 units, equivalent to approximately 60 mm additional asphalt concrete or 150 mm additional base course. This finding underscores the critical importance of subgrade drainage and moisture control in pavement design for the Sudd region corridors.

Traffic growth rate assumption had a moderate influence: the difference in required SN between 2% and 6% annual traffic growth over a 20-year life was 0.6–0.8 SN units.

Reliability level had a comparatively smaller effect: upgrading from 85% to 95% reliability required only 0.4–0.5 additional SN units for the range of design conditions studied. These relative sensitivities suggest that engineering resources are most effectively directed towards subgrade improvement and drainage provision rather than higher reliability targets in the South Sudan context.

6. Proposed Design Framework for Oil Tanker Routes

Based on the foregoing analysis, a six-step engineering design framework is proposed for heavy oil tanker routes in South Sudan and analogous sub-Saharan contexts:

> Step 1 — Fleet Characterisation: Conduct WIM surveys to determine axle load spectra; classify vehicles by configuration; compute fleet-representative ESAL per vehicle trip for each route corridor.
>
> Step 2 — Traffic Loading Projection: Apply traffic growth forecasts disaggregated by vehicle class and loading scenario (enforced, partially enforced, unenforced); compute design ESAL for 20-year horizon at target reliability.
>
> Step 3 — Subgrade Assessment: Execute DCP surveys at minimum 500 m intervals; collect samples for CBR, Atterberg limits, and compaction; apply seasonal adjustment factors for tropical wet-dry cycling; adopt design CBR at the 20th percentile of the distribution.
>
> Step 4 — Empirical Structural Design: Apply AASHTO 1993 design equation to determine SN; disaggregate into AC, base, and subbase using locally determined layer coefficients and drainage coefficients calibrated to the tropical environment.
>
> Step 5 — Mechanistic Verification: Perform multi-layer elastic analysis (BISAR or equivalent); verify fatigue and rutting damage ratios under representative overloaded axle spectrum; redesign if DR > 0.85.
>
> Step 6 — Performance Modelling and Maintenance Planning: Simulate 20-year performance using HDM-4 or equivalent; optimise maintenance strategy (routine, periodic, rehabilitation) within agency budget constraints; embed enforcement scenarios to quantify load control co-benefits.

This framework integrates the empirical reliability of the AASHTO 1993 approach — well-understood and accepted by African road authorities — with the mechanistic rigour needed to account for extreme axle loads and tropical material behaviour not fully captured by the original AASHTO Road Test conditions. It is consistent with the guidance of (Feldmann & Schweitzer, 2018) and extends the methodology to the specific operational context of oil logistics corridors in fragile post-conflict states.

7. Policy and Institutional Implications

The findings of this study have direct implications for road sector governance and petroleum logistics planning in South Sudan. The most important policy recommendation is the urgent establishment of a functional axle load control system. South Sudan currently lacks weigh-in-motion stations on any national highway, and static weigh bridges are absent from all oil logistics corridors ((Abayomi et al., 2021)). The economic case for load control investment is overwhelming: HDM-4 analysis shows that enforcing legal load limits (Scenario C) reduces 20-year road network life-cycle costs by USD 380–520 million compared to the current uncontrolled scenario across the five study corridors alone, against an estimated one-time cost of USD 12–15 million for a comprehensive WIM and enforcement infrastructure ((Bogale et al., 2024)).

A second policy priority is the adoption of updated pavement design standards reflecting the oil tanker loading environment. The current MoRB technical specifications cite the Uganda Road Design (Pangborn, 2010) as a reference document — itself adapted from British Overseas Road Note 31. This guidance was developed for standard commercial traffic in East Africa and does not address the systematic overloading characteristic of South Sudan's oil logistics sector. The design framework proposed in this paper, informed by calibrated local data, provides a technical basis for a South Sudan-specific design standard to be promulgated by MoRB in the forthcoming roads sector reform programme ((Abayomi et al., 2021)).

Third, coordination between the Ministry of Petroleum and Mining and MoRB in road maintenance funding is essential. The oil companies operating Block 1/2/4 and Block 3/7 currently make infrastructure contributions through community development funds and social licence agreements, but these are not systematically directed toward the road corridors most heavily damaged by their logistics operations. A road user charge mechanism or a dedicated oil sector infrastructure levy, modelled on Chad's Fonds d'Entretien Routier Autonome (FERA), could generate sustainable financing for the estimated USD 4,200–5,800/km/year maintenance expenditure required on oil tanker corridors ((Huang et al., 2020)).

8. Limitations and Future Research

Several limitations should be acknowledged. First, WIM data collection was limited to the dry-season peak period; wet-season axle load distributions, which may differ owing to changes in vehicle loading practices and accessibility constraints, require future seasonal monitoring campaigns. Second, HDM-4 calibration was based on 42 monitored sections, a sample size that, while adequate for the present study, does not fully capture the spatial heterogeneity of subgrade conditions along 320 km of corridors. Third, the study did not model the interaction between pavement deterioration and bridge scour on the numerous watercourse crossings, which represent discrete vulnerability points during flood events.

Future research directions include: (i) development of a full M-E design catalogue for South Sudanese conditions using AASHTOWare Pavement ME Design with locally calibrated inputs; (ii) incorporation of climate change projections (increased intensity of extreme rainfall events under IPCC RCP 4.5 and 8.5 scenarios) into long-term pavement performance modelling; (iii) evaluation of alternative low-carbon surface treatments (recycled asphalt pavement, geopolymer stabilisation) for reducing construction carbon footprint; and (iv) network-level optimisation of maintenance investment allocation using stochastic programming models.

9. Conclusion

This study has presented a comprehensive technical investigation of pavement design requirements for heavy oil tanker routes in South Sudan, integrating axle load equivalency analysis, empirical structural design, mechanistic verification, and long-term performance modelling. The principal conclusions are:

((Lee et al., 1994)) Heavy oil tanker vehicles operating on South Sudan corridors generate cumulative design ESALs of 7.6 × 10^6 to 12.4 × 10^6 over 20 years — between 2.2 and 3.5 times the loading assumed in original road construction specifications.

((El-Khoriby et al., 2019)) Subgrade CBR values of 3–8% characterise all five study corridors, requiring conservative design approaches with Structural Numbers of 4.8 to 7.2 to achieve 20-year design life under oil tanker traffic.

((Huang et al., 2020)) HDM-4 performance modelling demonstrates that structural upgrading alone is insufficient: axle load enforcement reducing mean GVW from 54.6 t to legal limits provides a 75% extension of pavement service life and a 23–31% reduction in road user costs.

((Walsh & Bennett, 2000)) A six-step integrated design framework — covering fleet characterisation, traffic loading projection, subgrade assessment, empirical design, mechanistic verification, and performance-based maintenance planning — is proposed as the basis for MoRB-specific design standards.

((Hunt & Bunker, 2003)) Policy interventions — weigh-in-motion infrastructure, revised design standards, and dedicated oil sector road maintenance financing — are necessary complements to structural engineering solutions if South Sudan is to sustainably maintain the road infrastructure underpinning its petroleum economy.

The results are directly applicable to the planning and design phase of the South Sudan National Roads Master Plan 2025–2035, with the potential to significantly reduce premature pavement failure and associated economic losses on the nation's most critical logistics corridors.

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