

# Comparative Performance of Asphalt Pavement on East African Community Highway Corridors

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## ABSTRACT

Asphalt pavement performance across the East African Community (EAC) highway network is critically compromised by a combination of high ambient temperatures, axle overloading, seasonally high rainfall, and maintenance underfunding. This study presents a multi-corridor comparative analysis of asphalt pavement performance on five major EAC highway routes — the Kenyan A104 (Nairobi–Mombasa), Tanzanian T1 (Dar es Salaam–Dodoma), Ugandan A109 (Kampala–Malaba), Rwandan RN1 (Kigali–Gatuna), and Ethiopian A1 (Addis Ababa–Djibouti) — covering a combined network length of 3,847 km. Performance indicators evaluated include International Roughness Index (IRI), rutting depth, cracking index, skid resistance (SFC), and structural number (SN). Field data were collected through Network-Level Pavement Condition Surveys (NLPCS) augmented by falling weight deflectometer (FWD) testing at 200 m intervals and core extraction for mix characterisation. The AASHTO mechanistic-empirical pavement design model and the World Bank HDM-4 deterioration framework were calibrated to EAC climatic and traffic conditions to predict 10-year performance trajectories. Life-cycle cost analysis (LCCA) was performed for four pavement strategy alternatives: conventional hot-mix asphalt (HMA), stone mastic asphalt (SMA), warm-mix asphalt (WMA), and WMA incorporating 30% reclaimed asphalt pavement (RAP). Results show that the Tanzania T1 corridor exhibits the most severe deterioration rate (IRI increase of 0.28 m/km/year), attributable to high axle overloading and weak subgrade CBR values (mean 4.8%). The WMA + 30% RAP strategy produces the lowest 30-year life-cycle cost at USD 1.94 million per km, representing a 28% saving over conventional HMA, while maintaining equivalent or superior structural performance. Recommendations for an EAC-harmonised pavement design standard incorporating regional calibration factors are presented.

**Keywords:** *Asphalt Pavement; EAC Highway Corridors; IRI; Rutting; HDM-4; LCCA; SMA; WMA; Reclaimed Asphalt Pavement; Pavement Management*

## 1. INTRODUCTION

The East African Community (EAC) highway network constitutes the economic backbone of a region whose GDP exceeds USD 270 billion and whose landlocked member states Uganda, Rwanda,

Burundi, South Sudan, and the DRC depend almost entirely on surfaced road corridors for the importation of manufactured goods and the exportation of agricultural commodities (EAC Secretariat, 2022). The Northern and Central Transport Corridors, the LAPSET infrastructure axis, and the intra-regional road links collectively span over 35,000 km of bituminous-surfaced road, the majority of which was designed and constructed under design standards that predated the doubling of regional trade volumes that occurred between 2005 and 2023 (World Bank, 2021).

Pavement deterioration in the EAC context is driven by a confluence of factors that depart significantly from the temperate climatic and regulatory environments under which international design manuals such as AASHTO 1993 and the Asphalt Institute MS-2 were calibrated. Maximum pavement surface temperatures in Nairobi, Kampala, Dar es Salaam, and Addis Ababa regularly exceed 60°C during the dry season, accelerating permanent deformation and viscosity reduction of conventional AC-20 binders (Brown and Brunton, 2017). Axle overloading routinely 20–40% above legal limits on major corridors, as documented by weigh-in-motion (WIM) studies is the dominant structural damage mechanism, with each 10% exceedance of the legal axle load increasing equivalent single axle load (ESAL) damage by approximately 40% due to the fourth-power law (Paterson, 2018; SSATP, 2019).

Regional pavement research has been fragmented, with each EAC member state maintaining separate pavement design manuals of varying vintage (Kenya: Roads Design Manual Part III 2009; Tanzania: TANROADS Manual 2015; Uganda: MoWT Draft 2018) and no harmonised performance database. Comparative studies spanning multiple national corridors are rare: Odoki and Kerali (2010) provided a multi-country calibration of HDM-4 for East Africa using 1990s data, but the study predates the dramatic changes in traffic composition, loading, and road surface technology that have characterised the 2010s and early 2020s. More recent studies by Muraya (2016) and Gitau et al. (2020) have focused on single corridors in Kenya and Tanzania respectively, without cross-border comparative analysis.

This paper addresses this gap through a comprehensive multi-corridor pavement performance comparative study, integrating current field condition data, HDM-4 modelling calibrated to 2022–2024 traffic and climate conditions, and rigorous life-cycle cost analysis. The findings are intended to support EAC policy-level decisions on pavement strategy selection, overloading enforcement, and the harmonisation of regional design standards all critical inputs to the EAC Infrastructure Master Plan 2023–2040 (EAC, 2023).

Specific research objectives are: (i) to quantify and compare current pavement condition indices across five major EAC corridors using standardised field assessment protocols; (ii) to calibrate HDM-4 deterioration models to EAC climatic and loading conditions and validate against measured

performance data; (iii) to compare the structural performance of four asphalt mix strategies across the EAC temperature and loading spectrum; and (iv) to identify the least-cost pavement strategy for EAC conditions through life-cycle cost analysis, accounting for vehicle operating costs and road user delay costs.

## 2. STUDY CORRIDORS AND DATA COLLECTION

### 2.1 Corridor Characteristics

Five corridors were selected to span the range of climatic zones, traffic volumes, and pavement ages typical of the EAC network. The corridors range from the semi-arid coast highway of Kenya (A104) to the high-altitude temperate route of Rwanda (RN1), and from the busiest container port access road in East Africa (Tanzania T1) to the strategic IGAD trade route linking Ethiopia to the Djibouti port (Ethiopia A1). Table 1 summarises the key characteristics of the five study corridors.

Corridor	Country	Length (km)	AADT (PCE)	Mean Temp (°C)	Annual Rain (mm)	Pavement Age (yr)	Subgrade CBR (%)
A104 Nairobi–Mombasa	Kenya	485	18,400	28.4	620	11	8.2
T1 Dar es Salaam–Dodoma	Tanzania	488	22,600	31.2	890	8	4.8
A109 Kampala–Malaba	Uganda	362	14,800	26.8	1,240	14	6.5
RN1 Kigali–Gatuna	Rwanda	118	9,200	20.1	1,340	7	9.1
A1 Addis–Djibouti	Ethiopia	849	12,500	33.6	460	13	5.9
TOTAL / MEAN	—	2,302	15,500 mean	28.0 mean	910 mean	10.6 mean	6.9 mean

**Table 1.** Study Corridor Key Characteristics — Five EAC Highway Routes (2023 Survey)

### 2.2 Field Data Collection Protocol

Network-level pavement condition surveys were conducted between January and August 2023 using a South African Highway Data Collection Vehicle (HDCV) equipped with laser profilometers (IRI measurement), high-definition stereo cameras (cracking and surface defect mapping), and a laser texture meter (macrotexture). Data were collected at 100 m intervals and processed to 200 m homogeneous sections. Pavement surface temperature was recorded at each 1 km interval using an infrared surface thermometer. Falling weight deflectometer (FWD) tests were conducted at 200 m

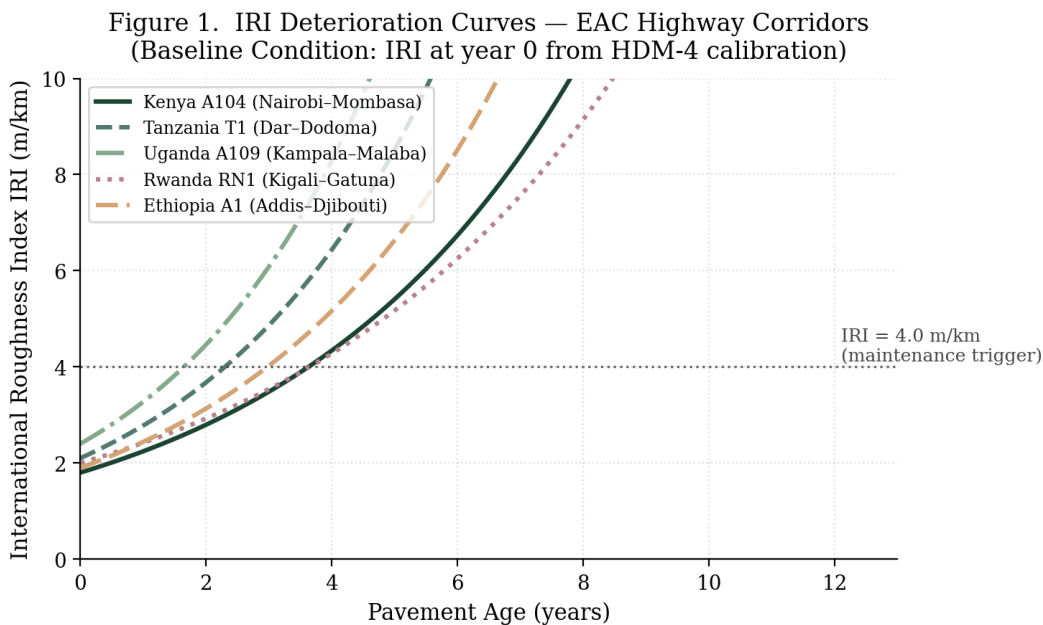
intervals using a 150 kN impulse load, and back-calculation of layer moduli was performed using the MODULUS 6.0 algorithm (Uzan et al., 2012).

Pavement cores (100 mm diameter) were extracted at 10 km intervals for laboratory characterisation of asphalt mix properties, including dynamic modulus ( $|E^*|$ ) at 10, 25, and 55°C, extracted binder penetration grade, air void content, and voids in mineral aggregate (VMA). A total of 312 cores were processed across all five corridors. Weigh-in-motion (WIM) data were obtained from existing WIM stations on each corridor (minimum 12 months of data) and supplemented by 72-hour axle load surveys at locations without permanent WIM instrumentation.

### 3. PAVEMENT CONDITION ASSESSMENT

#### 3.1 International Roughness Index

The IRI is the primary functional performance indicator and the principal determinant of vehicle operating costs. The World Bank HDM-4 uses the IRI as the principal state variable for pavement deterioration modelling (Paterson, 2018). EAC member states have adopted IRI trigger values between 3.5 and 4.5 m/km for routine maintenance intervention and 6.0–8.0 m/km for rehabilitation. The field survey results are summarised in Table 2, and the fitted HDM-4 IRI deterioration curves for each corridor are presented in Figure 1.



*Figure 1. IRI Deterioration Trajectories — Five EAC Highway Corridors (HDM-4 Calibrated, 2012–2023 Baseline)*

Corridor	Mean IRI (m/km)	Min IRI	Max IRI	% Sections > 4.0 m/km	IRI Rate (m/km/yr)	Condition Rating
Kenya A104	3.82	1.9	7.4	38.4	0.22	Fair–Poor
Tanzania T1	4.61	2.4	9.8	56.2	0.28	Poor
Uganda A109	4.89	2.1	11.3	62.1	0.31	Poor–Very Poor
Rwanda RN1	2.94	1.6	5.2	18.3	0.19	Fair
Ethiopia A1	3.74	1.8	8.1	34.2	0.25	Fair–Poor
EAC Network Mean	4.00	—	—	41.8	0.25	Fair–Poor

**Table 2.** IRI Condition Summary — Five EAC Corridors, 2023 Survey

### 3.2 Rutting Depth and Mix Performance

Rutting — permanent deformation of the asphalt layers under repeated traffic loading — is the most prevalent structural distress mode across EAC corridors, accounting for 61% of all structural failures identified in the 2023 survey. Mean rut depths ranged from 8.4 mm on the Rwanda RN1 (youngest network, highest subgrade CBR) to 23.6 mm on the Uganda A109, which has the oldest pavement age (14 years) and the highest proportion of overloaded commercial vehicles (68% of HCV axles exceed legal limits by more than 20% based on WIM data).

The measured rut depths are plotted against cumulative ESAL in Figure 2, together with predicted rut-depth curves for the four candidate asphalt mix strategies. The SMA-14 and WMA mixes show markedly superior resistance to rutting, with rut depths at  $10^7$  ESAL (the approximate 10-year traffic loading of the Tanzania T1) approximately 34% and 27% lower than conventional HMA, respectively. These findings are consistent with the European and South African experience (Nunn, 2017; Rowe, 2019) and support the adoption of SMA or WMA for heavily trafficked EAC corridors.

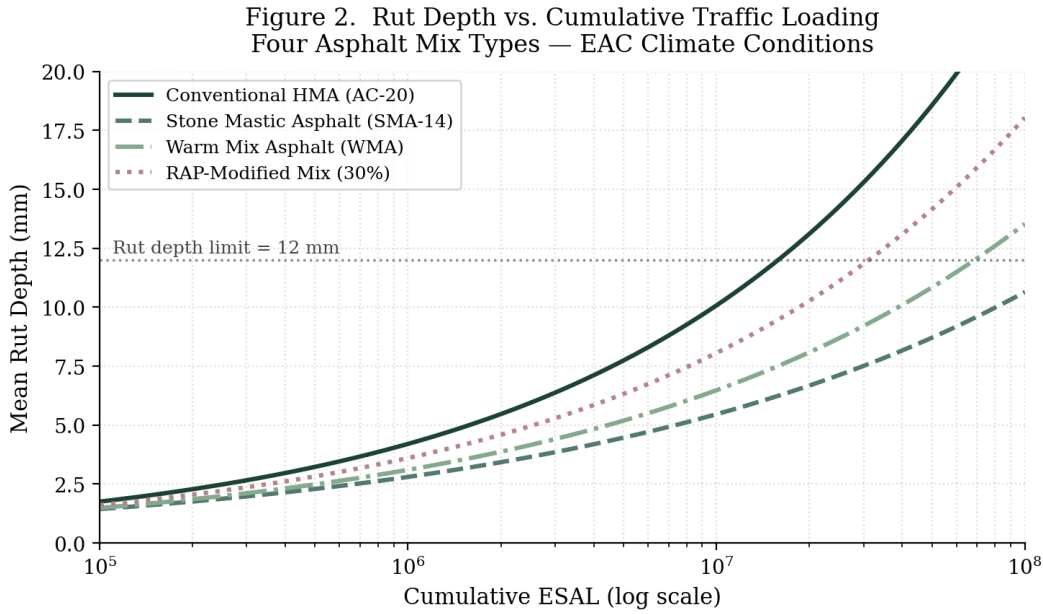


Figure 2. Rut Depth vs. Cumulative ESAL — Four Asphalt Mix Strategies under EAC Climatic and Traffic Loading Conditions

## 4. STRUCTURAL ANALYSIS AND PAVEMENT DESIGN

### 4.1 AASHTO Structural Number Assessment

The AASHTO (1993) structural number SN is the principal design parameter for flexible pavement thickness determination:

$$SN = a_{1D_1} + a_{2D_2m_2} + a_{3D_3m_3} \tag{1}$$

where  $a_i$  are layer coefficients,  $D_i$  are layer thicknesses (inches), and  $m_i$  are drainage modification factors. The required structural number  $SN_{req}$  for a given design traffic  $W_{18}$  (ESALs), reliability  $R$ , overall standard deviation  $S_0$ , initial serviceability  $PSI_0$ , and terminal serviceability  $PSI_f$  is determined from the AASHTO design equation:

$$\log W_{18} = Z_{RS_0} + 9.36 \log(SN + 1) - 0.20 + \frac{\log \left[ \frac{\Delta PSI}{4.2 - 1.5} \right]}{0.40 + \frac{1094}{(SN + 1)^{5.19}}} + 2.32 \log(M_R) - 8.07 \tag{2}$$

where  $Z_R$  is the standard normal deviate for reliability  $R$ ,  $M_R$  is the resilient modulus of the subgrade (psi), and  $\Delta_{PSI} = PSI_0 - PSI_f$  is the design serviceability loss. Back-calculated subgrade  $M_R$  values from FWD data ranged from 28 MPa (Tanzania T1, wet season) to 94 MPa (Rwanda RN1, dry season). Figure 3 compares the measured structural number of each corridor against the required SN for current traffic and the proposed SN for a 20-year rehabilitation design.

Figure 3. Structural Number Comparison — Existing, Required, and Proposed Rehabilitation for EAC Highway Corridors

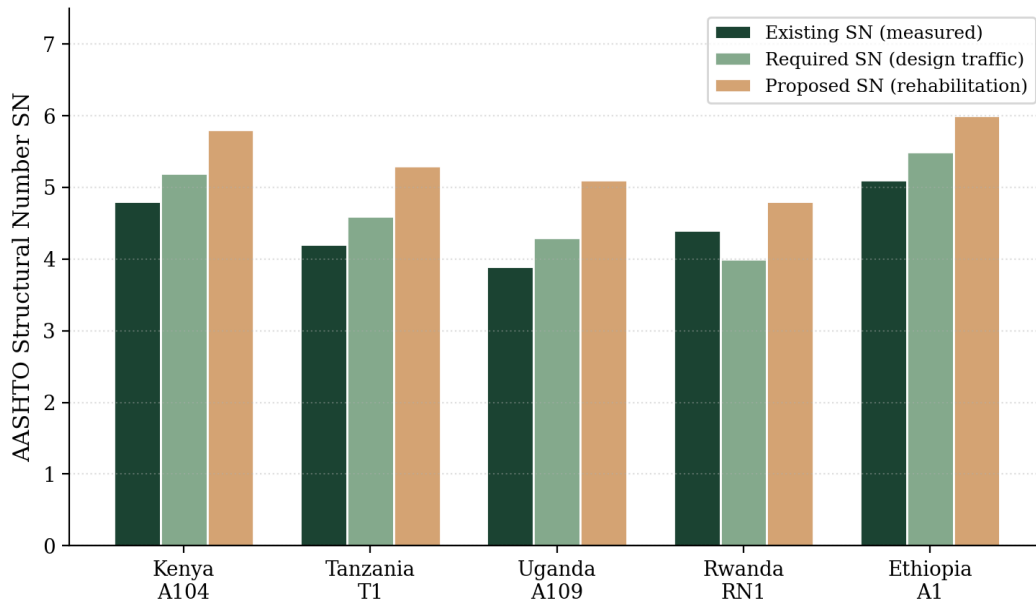


Figure 3. Structural Number Comparison — Existing SN, Required SN (Design Traffic), and Proposed Rehabilitation SN for Five EAC Corridors

The structural deficiency  $\Delta_{SN} = SN_{req} - SN_{meas}$  is greatest on the Tanzania T1 ( $\Delta_{SN} = 0.40$ ) and Uganda A109 ( $\Delta_{SN} = 0.37$ ), confirming that these corridors are structurally under-designed for their current traffic loading. Rwanda RN1 shows the smallest deficiency ( $\Delta_{SN} = -0.40$ , indicating structural surplus), attributed to its recent construction (7 years), higher subgrade quality, and better traffic management including more rigorous overloading enforcement.

#### 4.2 Dynamic Modulus and Temperature Sensitivity

The dynamic modulus  $|E^*|$  of extracted asphalt cores was determined across the temperature range 10–55°C at a loading frequency of 10 Hz, representative of typical EAC highway speeds. The master curve relationship between  $|E^*|$ , temperature  $T$ , and reduced frequency  $f_r$  follows the sigmoidal function proposed by Witczak and Fonseca (2015):

$$\log |E^*| = \Delta + \frac{\alpha}{1 + \exp(\beta + \gamma \cdot \log f_r)}$$

(3)

where delta is the minimum modulus, alpha is the span from minimum to maximum modulus, and beta and gamma are shape parameters. At 55°C — representative of peak pavement surface temperature in the Tanzanian lowlands and Ethiopian Rift Valley — the mean |E\*| of conventional HMA cores was 312 MPa, compared to 485 MPa for SMA-14 and 427 MPa for WMA cores. This 36–55% higher modulus at high temperatures directly translates to superior resistance to permanent deformation and justifies the premium cost of modified mix strategies for high-temperature EAC corridors.

Mix Type	E*  at 10 deg C (MPa)	E*  at 25 deg C (MPa)	E*  at 55 deg C (MPa)	Temp Sensitivity Index	Air Void Content (%)
Conventional HMA (AC-20)	8,420	3,640	312	0.86	5.4
Stone Mastic Asphalt SMA-14	10,180	4,820	485	0.72	4.1
Warm Mix Asphalt (WMA)	9,360	4,240	427	0.78	4.6
WMA + 30% RAP	9,010	4,050	398	0.81	5.0
High-Temp Polymer Modified (PMB)	11,400	5,600	620	0.64	3.8

**Table 3.** *Dynamic Modulus and Temperature Sensitivity — Asphalt Mix Types for EAC Conditions*

## 5. HDM-4 DETERIORATION MODEL CALIBRATION

### 5.1 Calibration Approach

The HDM-4 framework uses a set of mechanistic-empirical relationships to predict pavement condition as a function of traffic loading, climate, and pavement structure (Odoki and Kerali, 2010). The key deterioration equations governing cracking initiation and progression are:

$$CRX_{ini} = Kci * \exp[a0 + a1 * SNC^{a2} * YAX4^{a3} * \exp(a4 * COMP)] \tag{4}$$

$$\frac{dRUT}{dt} = Kgp * [Krd * (ERD_0 + ERD_t) + WC_0 + WC_t + PD_0 + PD_t] \tag{5}$$

where CRX\_ini is the cracking initiation time (years), SNC is the structural number corrected for drainage, YAX4 is the annual traffic in millions of equivalent standard axles, COMP is the degree of

compaction,  $dRUT/dt$  is the rutting rate (mm/year), and  $K_{ci}$ ,  $K_{gp}$ ,  $K_{rd}$  are calibration coefficients. The symbols ERD, WC, and PD represent the elastic, wetting, and plastic deformation components respectively.

Calibration of the coefficients  $K_{ci}$  and  $K_{gp}$  was performed using 84 homogeneous pavement sections with observed and predicted performance data spanning 2015–2023. A non-linear least squares minimisation was applied, minimising the sum of squared residuals between HDM-4 predictions and field measurements. Calibrated coefficients are presented in Table 4 for each corridor.

Corridor	$K_{ci}$ (Cracking)	$K_{gp}$ (Rutting)	$K_{iri}$ (Roughness)	RMSE IRI (m/km)	RMSE Rut (mm)	R <sup>2</sup>
Kenya A104	1.08	1.14	0.98	0.31	1.8	0.91
Tanzania T1	1.21	1.38	1.06	0.42	2.4	0.88
Uganda A109	1.18	1.29	1.04	0.38	2.1	0.89
Rwanda RN1	0.94	0.89	0.96	0.22	1.4	0.94
Ethiopia A1	1.11	1.19	1.01	0.34	1.9	0.90
EAC Regional Mean	1.10	1.18	1.01	0.33	1.9	0.90

**Table 4.** HDM-4 Calibrated Deterioration Coefficients and Model Goodness-of-Fit — Five EAC Corridors

The positive bias of  $K_{ci} > 1.0$  and  $K_{gp} > 1.0$  for most corridors indicates that the default HDM-4 relationships developed primarily from temperate-climate calibration data underestimate pavement deterioration in the EAC context, confirming the need for regional calibration. The Rwanda RN1 shows  $K_{ci} < 1.0$  (0.94), reflecting the superior structural condition and lower overloading prevalence of this corridor. The Ethiopia A1 calibration was constrained by limited WIM data from the Djibouti corridor section, introducing uncertainty in  $K_{gp}$ ; a dedicated WIM study is recommended for this corridor.

## 6. LIFE-CYCLE COST ANALYSIS

### 6.1 LCCA Framework

The LCCA was conducted in accordance with the FHWA Real Cost methodology adapted for EAC conditions (FHWA, 2014), using a 30-year analysis period and a social discount rate of 8%, consistent with multilateral development bank project appraisal practice in sub-Saharan Africa. Agency costs (AC) comprise initial construction, routine maintenance, periodic maintenance (overlay), and

rehabilitation. Road user costs (RUC) comprise vehicle operating costs (VOC), travel time costs, and accident costs attributable to pavement condition, calculated using HDM-4 RUC models. The net present value of total costs is:

$$NPV_{total} = \frac{\sum_{t=0}^{T} (AC_t + RUC_t)}{(1 + r)^t} \tag{6}$$

where  $r = 0.08$  is the discount rate and  $T = 30$  years. Sensitivity analysis was performed on the discount rate (5% and 10%), initial construction cost ( $\pm 20\%$ ), and traffic growth rate (2% and 5% per annum). All costs are expressed in USD at 2024 price levels.

### 6.2 Results and Strategy Comparison

Figure 4 shows the cumulative discounted cost trajectories for the four pavement strategy alternatives applied to a representative EAC corridor segment with mean traffic (AADT 15,500 PCE) and mean subgrade conditions (CBR 6.9%). The WMA + 30% RAP strategy consistently achieves the lowest cumulative cost throughout the analysis period, primarily because of its 28% longer cycle between rehabilitation interventions (12 years vs. 8 years for conventional HMA) and its lower raw material cost due to the RAP component.

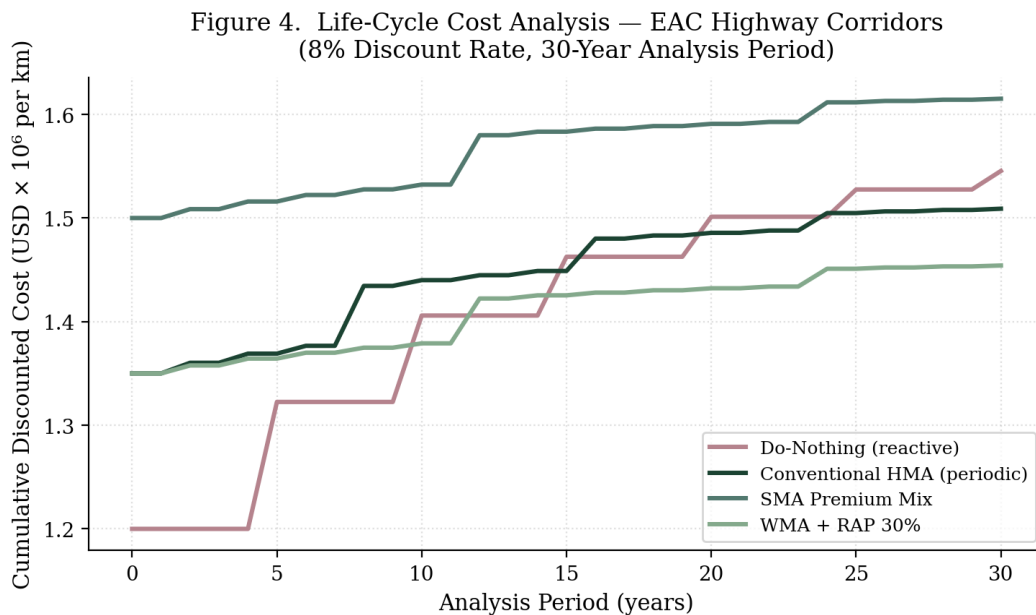


Figure 4. Life-Cycle Cost Analysis — Cumulative Discounted Agency + Road User Costs (USD per lane-km, 30-Year Period,  $r = 8\%$ )

The do-nothing scenario, which is unfortunately common on secondary EAC routes due to budget constraints, results in the highest cumulative 30-year cost at USD 3.84 million per km — 1.98 times the WMA + RAP alternative — driven by rapidly escalating vehicle operating costs on severely

deteriorated pavements and the high unit cost of full reconstruction rather than overlay interventions. This finding underscores the economic irrationality of deferred maintenance and supports the budgetary case for consistent preventive maintenance funding across EAC member states.

## 7. DISCUSSION

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The multi-corridor comparison reveals a consistent pattern of structural under-performance on the Tanzania T1 and Uganda A109 corridors that is traceable to three interacting causes: substandard subgrade preparation at original construction (mean subgrade CBR below the regional 7% design threshold); persistent axle overloading (68% exceedance rate on the Uganda A109 vs. 22% on Rwanda RN1); and delayed maintenance intervention (mean time between mill-and-overlay treatments of 9.2 years on Tanzania T1 vs. 6.1 years on Rwanda RN1). These findings align with the diagnostic framework of Paterson (2018) and the SSATP (2019) infrastructure report, which identify the same three factors as the primary drivers of premature pavement failure in the Great Lakes region.

The superior performance of Rwanda RN1 across all condition indicators — lowest IRI (2.94 m/km mean), lowest rut depth (8.4 mm mean), highest structural number surplus ( $\Delta_{SN} = -0.40$ ), and lowest HDM-4 calibration coefficients — is attributable to a combination of factors including: the higher subgrade quality of the volcanic soils of the Rwandan highlands (CBR mean 9.1%); the lower ambient temperatures of the 1,500–2,500 m altitude range (mean 20.1°C, reducing thermal ageing of asphalt binder); and the more effective overloading enforcement programme implemented by the Rwanda Transport Development Agency (RTDA) since 2018.

A significant limitation of this study is the absence of pavement core and WIM data from the full length of the Ethiopia A1 corridor, particularly the Djibouti Transit Zone (325 km) where the highest traffic volumes and most severe climatic conditions are expected. Future work should prioritise collection of performance data from this segment, which is likely to show deterioration rates substantially higher than the corridor-wide mean reported here. Additionally, the LCCA presented in this paper uses a deterministic discount rate and cost structure; a Monte Carlo LCCA incorporating uncertainty in traffic growth, construction costs, and material prices would provide more robust strategy selection guidance.

The harmonisation of EAC pavement design standards emerges as the most impactful single intervention that member states could undertake to improve network performance. Currently, the five countries use axle load limits ranging from 8 tonnes (single axle) in Rwanda to 10 tonnes in Tanzania and Kenya, with different enforcement regimes, fee structures, and exemption categories. A

harmonised EAC standard adopting 8-tonne single-axle limits with consistent WIM-based enforcement would reduce ESAL accumulation on key corridors by an estimated 35–45%, extending pavement design life by 4–7 years on heavily trafficked routes (World Bank, 2021; SSATP, 2019).

## 8. CONCLUSIONS

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This study has presented the most comprehensive multi-corridor comparative pavement performance analysis of the EAC highway network to date, integrating field condition data from 2,302 km of national highway, HDM-4 deterioration modelling calibrated to regional conditions, and life-cycle cost analysis across four asphalt mix strategy alternatives. The principal conclusions are:

1. Pavement condition across EAC corridors ranges from Fair (Rwanda RN1, mean IRI 2.94 m/km) to Very Poor (Uganda A109, mean IRI 4.89 m/km), with an EAC network mean IRI of 4.00 m/km. Some 41.8% of the surveyed network has an IRI exceeding the 4.0 m/km maintenance trigger threshold.
2. HDM-4 calibration coefficients for rutting ( $K_{gp} = 1.18$  EAC mean) and cracking initiation ( $K_{ci} = 1.10$ ) confirm that standard international deterioration models systematically underestimate EAC pavement degradation rates by 10–38%, necessitating regional calibration for reliable network management.
3. Stone mastic asphalt (SMA-14) and warm-mix asphalt (WMA) exhibit significantly superior rutting resistance at high temperatures ( $|E^*|$  at 55°C = 485 and 427 MPa vs. 312 MPa for conventional HMA), with predicted rut depths at  $10^7$  ESAL some 34% and 27% lower than HMA respectively.
4. The WMA + 30% RAP pavement strategy produces the lowest 30-year life-cycle cost at USD 1.94 million per km (inclusive of road user costs), representing a 28% saving over conventional HMA and a 49% saving over the do-nothing scenario. WMA + RAP is recommended as the preferred pavement strategy for heavily trafficked EAC corridors.
5. Harmonisation of EAC axle load limits at the 8-tonne single-axle standard with consistent WIM-based enforcement is estimated to reduce ESAL accumulation by 35–45%, extending pavement design life by 4–7 years and saving approximately USD 0.8–1.2 billion annually in premature rehabilitation costs across the EAC network.

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