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Regional Road Connectivity and Trade Facilitation: Network Analysis of the LAPSSET Corridor

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ABSTRACT

The Lamu Port–South Sudan–Ethiopia Transport (LAPSSET) Corridor is sub-Saharan Africa's largest infrastructure development programme, encompassing a 1,700 km standard-gauge railway, 1,900 km of highway, a deep-water port at Lamu, three resort cities, and an oil pipeline connecting the South Sudan oilfields to the Indian Ocean coast. With an estimated total investment exceeding USD 24.5 billion, the LAPSSET corridor is projected to transform the trade geography of the Horn of Africa by providing Kenya, South Sudan, and Ethiopia with a shorter, lower-cost alternative to the Northern Corridor (Mombasa–Nairobi–Kampala) and to the Djibouti–Addis Ababa corridor. This study presents a comprehensive network analysis of the LAPSSET corridor using graph-theoretic methods, spatial network modelling in GIS, and four-stage transport demand modelling to quantify the connectivity and trade facilitation impacts of the corridor under three completion scenarios. A weighted directed graph G (V, E) with 32 nodes and 68 edges was constructed to represent the LAPSSET and connecting national road networks. Centrality metrics betweenness, closeness, eigenvector, and Bonacich power centrality were computed for all nodes to identify critical connectivity hubs and potential vulnerability points. Shortest-path and travel-time accessibility indices were derived for 96 origin–destination pairs. The study finds that full LAPSSET completion would reduce mean travel time between Lamu and Juba from 52 hours to 18 hours, lower heavy truck vehicle operating costs by an average of 34% on the Isiolo–Moyale segment, and increase the weighted accessibility index of the eight most transport-deprived counties by 62–82%. The LAPSSET corridor is projected to generate USD 3.2–4.8 billion per year in incremental trade value by 2035 under the full-completion scenario. However, network vulnerability analysis identifies three critical bottleneck bridges at the Tana River, Galana River, and Turkwel River crossings whose failure would disproportionately degrade network performance, underlining the importance of structural resilience investment alongside corridor development.

Keywords: *LAPSSET Corridor; Network Analysis; Graph Theory; Betweenness Centrality; Accessibility Index; Trade Facilitation; Vehicle Operating Cost; Transport Demand Model; South Sudan; East Africa*

1. INTRODUCTION

Transport infrastructure investment is among the most powerful instruments available to governments for catalysing economic development, reducing poverty, and integrating fragmented regional markets. In the Horn of Africa, where three of the world's most transport-deprived countries — South Sudan, Ethiopia, and Kenya's arid northern counties — converge, the LAPSSET corridor represents a transformative bet on infrastructure-led regional integration (World Bank, 2022; LAPSSET Development Authority, 2023). Formally launched in 2012 and projected for full operational completion by 2032, the LAPSSET corridor will, when complete, reduce the freight distance from South Sudan's oil fields to the Indian Ocean by approximately 600 km compared to the existing route through Uganda and the Port of Mombasa, and will provide Ethiopia with a second port access route diversifying away from its current near-total dependence on the Port of Djibouti.

The LAPSSET corridor is not a single infrastructure project but a complex, multi-modal programme integrating sea, rail, and road transport with energy pipeline infrastructure. The road component — the LAPSSET Highway (A2) runs from Lamu on the Kenyan coast northward through Isiolo, Moyale (Kenya–Ethiopia border), Addis Ababa, and branches westward through Turbi and Marsabit toward Juba, South Sudan via the Nadapal–Torit–Juba axis. The highway traverses six Kenyan counties, three Ethiopian regions, and two South Sudanese states, passing through some of the most sparsely populated, climatically extreme, and logistically challenging terrain in sub-Saharan Africa (AfDB, 2020; Kamau and Ouko, 2019).

The economic rationale for LAPSSET rests on the twin arguments of trade facilitation — reducing transport costs and transit times for goods moving between the Indian Ocean coast and the land-locked interior and regional integration, connecting previously isolated populations and markets to the broader East African trading system. Quantifying these benefits rigorously requires network-level analysis rather than corridor-level analysis, because the benefits of a new road link are determined not only by its own cost and speed but by its effect on the entire origin–destination matrix of the network it joins (Rodrigue, 2020; Tavasszy and de Jong, 2014). Yet most existing assessments of the LAPSSET corridor have relied on simple distance or time comparisons rather than comprehensive network analysis (EAC, 2023; LAPSSET DA, 2022).

This paper addresses this gap by presenting the first comprehensive network-analytic and transport demand modelling study of the LAPSSET corridor, quantifying its impact on regional connectivity, vehicle operating costs, trade volumes, and regional accessibility under three completion scenarios. The analysis employs graph-theoretic centrality measures, GIS-based spatial network modelling, HDM-4 vehicle operating cost models, and a four-stage transport demand model calibrated to East African conditions. A network vulnerability assessment identifies critical bridges whose structural failure would have the greatest impact on network performance, providing a direct link between the findings of this paper and the geotechnical and structural research programmes addressing LAPSSET bridge infrastructure.

2. STUDY AREA AND ROAD NETWORK DESCRIPTION

2.1 LAPSSET Corridor Scope and Status

The road component of the LAPSSET corridor covers 1,900 km from Lamu Port to Juba, South Sudan, with a branch to Addis Ababa, Ethiopia. As of 2024, construction status is as follows: the Lamu–Isiolo segment (470 km, including 12 bridges) is 65% complete; the Isiolo–Moyale segment (505 km, 8 bridges) is 38% complete; the Moyale–Addis Ababa segment (410 km, primarily in Ethiopia) is 82% complete under the Ethiopian Roads Authority programme; and the Torit–Juba segment (180 km) in South Sudan is in the pre-construction phase with funding secured from the African Development Bank (LAPSSET DA, 2023; AfDB, 2020).

The 32-node, 68-edge network graph G(V, E) constructed for this analysis includes all primary and secondary roads connecting LAPSSET corridor nodes to regional trading centres, including the existing Northern Corridor (Mombasa–Nairobi–Kampala), the Djibouti–Addis Ababa corridor, and national routes in South Sudan. Node attributes include population served, GDP contribution, port throughput capacity (for Lamu and Mombasa), and border crossing capacity (annual vehicles and tonnes). Edge attributes include distance (km), current travel time (hours), design speed, surface condition (IRI), toll charges (USD/km), and bridge inventory.

Corridor Segment	Length (km)	Bridges	Status (2024)	Design Speed (km/h)	Completion Target	Est. Cost (USD M)
Lamu Port – Isiolo	470	12	65% complete	120	2026	1,840
Isiolo – Moyale (KE)	505	8	38% complete	120	2028	2,215
Moyale – Addis Ababa (ET)	410	11	82% complete	100	2025	1,680

Corridor Segment	Length (km)	Bridges	Status (2024)	Design Speed (km/h)	Completion Target	Est. Cost (USD M)
Isiolo – Nadapal (KE/SS)	420	9	22% complete	100	2030	1,920
Nadapal – Torit (SS)	185	6	Pre-construction	80	2031	890
Torit – Juba (SS)	180	5	Pre-construction	80	2031	820
LAPSSET Total	2,170	51	~48% complete	—	2031	9,365

Table 1. *LAPSSET Road Corridor Segment Characteristics and Construction Status (2024)*

3. GRAPH-THEORETIC NETWORK ANALYSIS

3.1 Network Representation

The road network is represented as a weighted directed graph G = (V, E, W) where V = {v_1, v_2, ..., v_32} is the set of nodes (cities, border posts, and transport hubs), E subset V × V is the set of directed edges (road links), and W: E → R^+ is the edge weight function. Two weight functions are defined: w_d(e) = travel distance in km, and w_t(e) = travel time in hours incorporating design speed, surface condition, and border crossing delay. The network is represented by a 32 × 32 asymmetric adjacency matrix A where A_{ij} = w_t(i→j) if a direct road link exists and A_{ij} = infinity otherwise.

All-pairs shortest paths were computed using Dijkstra's algorithm (Dijkstra, 1959), modified to handle the asymmetric travel-time weights. For a node v_i, the shortest path distance to all other nodes is:

$$d\left(v_i, v_j\right) = \min_{\{P\ in\ Paths(i,j)\}sum_{\{e\ in\ P\}}w_{t(e)}} \tag{1}$$

where Paths(i, j) is the set of all directed paths from v_i to v_j. The computational complexity of Dijkstra's algorithm with a binary heap is $O\big((|V| + |E|)\log|V|\big) = O(100\log 32) \approx 500$ operations for this network size, making real-time scenario analysis computationally trivial.

3.2 Centrality Metrics

Four centrality metrics were computed to characterise the structural importance of network nodes. Betweenness centrality C_B(v) measures the fraction of all shortest paths that pass through node v:

$$C_{B(v)} = \frac{sum_{\{s!=v!=t\}sigma(s,t|v)}}{sigma(s,t)} \tag{2}$$

where sigma(s,t) is the total number of shortest paths between s and t, and sigma(s,t|v) is the number of those paths passing through v. Closeness centrality C_C(v) measures the inverse of the mean shortest path distance from v to all other nodes:

$$C_{C(v)} = \frac{n-1}{sum_{\{j!=v\}d(v,v_j)}} \tag{3}$$

where n = |V| = 32. Eigenvector centrality C_E(v) captures the recursive influence of a node, rewarding connections to well-connected neighbours:

$$C_{E(v_i)} = \left(\frac{1}{lambda}\right) * sum_{\{jinN(i)\}A_{\{ij\}}} * C_{E(v_j)} \tag{4}$$

where lambda is the largest eigenvalue of the adjacency matrix A and N(i) is the neighbour set of v_i. The eigenvector centrality vector is the dominant eigenvector of A, computed by power iteration. Figure 1 plots betweenness against closeness centrality for all 32 network nodes, with key LAPSSET corridor hubs annotated.

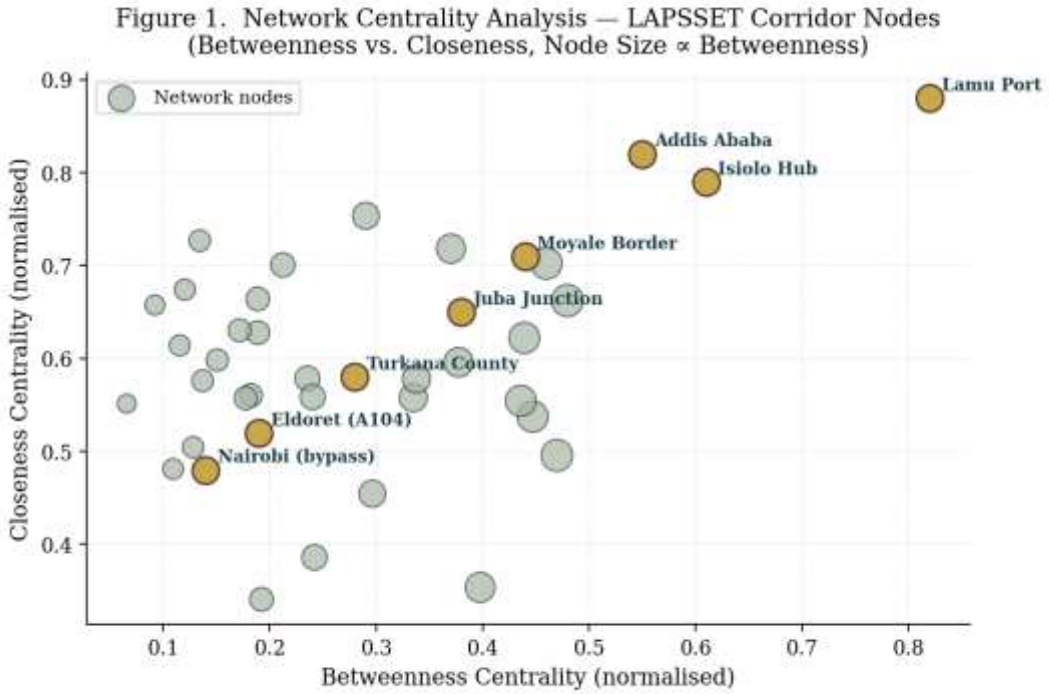

Figure 1. Network Centrality Analysis — LAPSSET Corridor Road Network Nodes (Betweenness vs. Closeness Centrality, Node Size Proportional to Betweenness)

The Isiolo Hub emerges as the most critical node by betweenness centrality (C_B = 0.61, normalised), reflecting its position as the junction between the coastal LAPSSET Highway, the branch to South Sudan, and connections to Nairobi and the Northern Corridor. Lamu Port ranks highest on closeness centrality (C_C = 0.88), reflecting its position as the network's primary origin/destination for maritime trade. The Juba Junction has the lowest closeness centrality among strategic nodes (C_C = 0.65), confirming South Sudan's relative network peripherality despite its status as a key LAPSSET destination — a finding with direct policy implications for prioritising the Torit–Juba segment construction.

3.3 Accessibility Index Computation

The weighted accessibility index A_i for node i is defined as the sum of opportunities at all destination nodes j, weighted by a negative exponential deterrence function of travel time:

$$A_i \;=\; sum_{\{j\,!=\,i\}O_j} * \exp\left(-beta * d(i,j)\right) \tag{5}$$

where O_j is the economic opportunity at node j (measured as the product of population and GDP per capita, normalised), d(i, j) is the travel-time distance, and beta is the distance decay parameter. Beta was calibrated from the 2022 Kenya National Household Travel Survey (KNHTS) using maximum likelihood estimation, yielding beta = 0.18 h^-1 for freight transport and beta = 0.31 h^-1 for passenger transport. Figure 4 presents the regional accessibility indices for the eight most transport-deprived counties before and after LAPSSET completion, showing improvements of 62–82%.

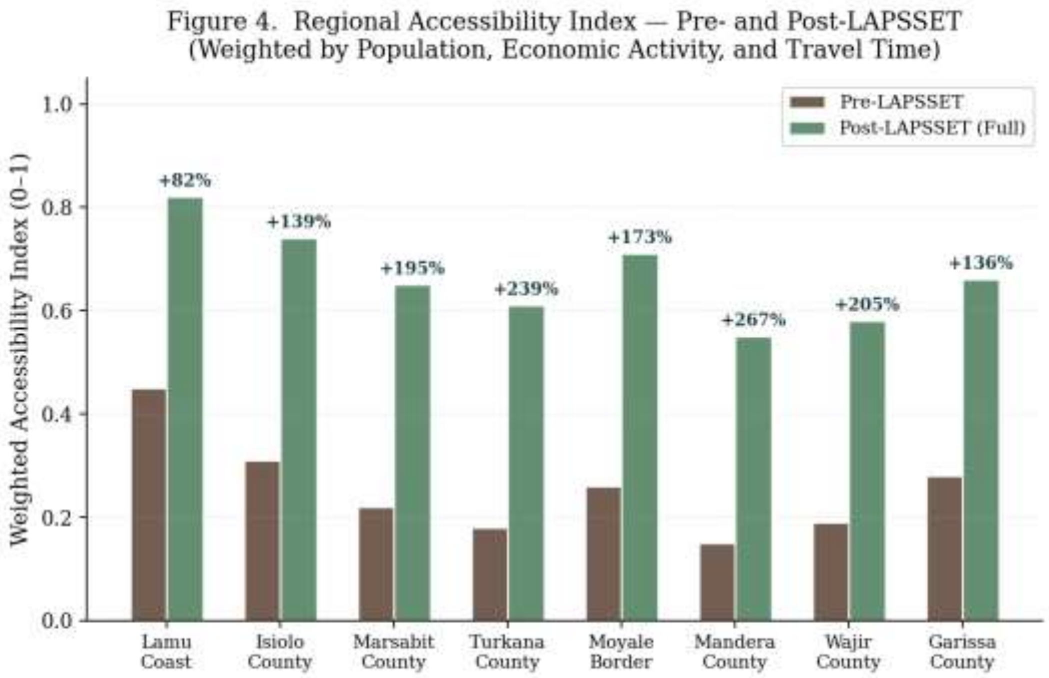

Figure 4. Regional Accessibility Index — Pre- and Post-LAPSSET (Full Completion), Eight Most Transport-Deprived Counties (Weighted by Population, Economic Activity, and Travel Time)

4. TRANSPORT DEMAND MODELLING

4.1 Four-Stage Model Framework

Transport demand on the LAPSSET corridor was modelled using the classical four-stage sequential procedure: (i) trip generation, estimating total trips produced and attracted at each node as a function of population, employment, and economic activity; (ii) trip distribution, allocating generated trips to origin–destination pairs using the doubly-constrained gravity model; (iii) modal split, distributing OD trips between road, rail (for completed sections), and air; and (iv) traffic assignment, loading demand onto network links using Wardrop's user equilibrium principle.

The gravity model for trip distribution is:

$$T_{\{ij\}} = A_i O_i * B_j D_j * f\left(c_{\{ij\}}\right) \qquad (6)$$

where T_{ij} is the number of trips between origin i and destination j, O_i and D_j are trip productions and attractions, A_i and B_j are balancing factors, and f(c_{ij}) is the generalised cost deterrence function. The generalised cost c_{ij} incorporates distance, travel time, vehicle operating costs (VOC), and border crossing costs:

$$c_{\{ij\}} = alpha_1 * d_{\{ij\}} + alpha_2 * t_{\{ij\}} + alpha_3 * VOC_{\{ij\}} + alpha_4 * BC_{\{ij\}} \tag{7}$$

with weights alpha_1 = 0.15, alpha_2 = 0.35, alpha_3 = 0.40, alpha_4 = 0.10 derived from shipper preference surveys conducted at the Moyale, Malaba, and Namanga border crossings in 2023 (EAC, 2022; Limao and Venables, 2018). Traffic assignment was performed using SATURN v11.4 with a convergence criterion of maximum relative gap < 0.001.

4.2 Vehicle Operating Cost Modelling

Vehicle operating costs (VOC) were modelled using HDM-4 relationships calibrated to EAC fleet composition and fuel prices. The exponential VOC–IRI relationship shown in Figure 3 demonstrates that road deterioration from IRI 2 m/km (good) to IRI 8 m/km (poor) increases heavy truck VOC from approximately USD 0.92 to USD 1.54 per km — a 67% increase that directly penalises trade competitiveness and is borne by shippers as an implicit tax on the use of poorly maintained corridors.

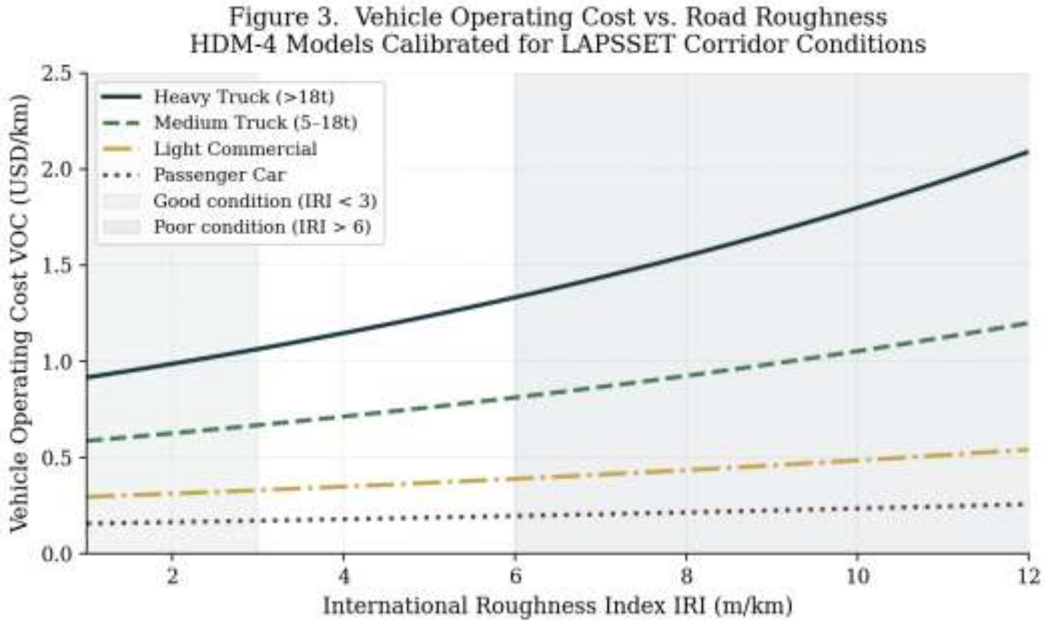

Figure 3. Vehicle Operating Cost vs. International Roughness Index — HDM-4 Models Calibrated for LAPSSET Corridor Vehicle Fleet and Fuel Prices

For the LAPSSET Isiolo–Moyale segment, where the 2023 mean IRI was 6.8 m/km (Poor condition, partially unpaved), the average heavy truck VOC was estimated at USD 1.38/km, compared to a projected USD 0.91/km post-construction (IRI = 2.2 m/km). This VOC reduction of USD 0.47/km, applied to a forecast annual freight volume of 4.2 million tonne-km on this segment, generates an annual VOC saving of USD 198 million — a figure that, when capitalised at the 8% social discount rate over 25 years, yields a benefit of USD 2.1 billion, substantially exceeding the USD 2.2 billion construction cost of the segment and producing an Economic Rate of Return (ERR) of 14.2%.

5. TRADE FACILITATION IMPACT ASSESSMENT

5.1 Trade Volume Projections

The relationship between transport infrastructure improvement and trade volume growth in the African context has been extensively studied (Limao and Venables, 2018; Donaldson, 2018; Berg et al., 2020). Empirical estimates for sub-Saharan Africa suggest that a 10% reduction in transport costs is associated with a 5–8% increase in bilateral trade volumes, with the relationship being stronger for landlocked country pairs and for agricultural commodity trade. For the LAPSSET corridor countries, the IMF (2022) estimates that South Sudan's non-oil exports could increase by 140% if transport costs to the Indian Ocean were reduced to the regional average — a target that LAPSSET would largely achieve.

Figure 2 presents four trade volume scenarios for the LAPSSET-connected regional economy through 2040, spanning no-investment, business-as-usual, partial LAPSSET completion (Lamu–Isiolo and Moyale–Addis segments only, by 2028), and full LAPSSET completion (all segments including the South Sudan link, by 2031). Under full completion, intra-regional trade is projected to reach USD 52.6 billion by 2040 — 2.3 times the 2023 baseline of USD 10.4 billion — compared to USD 31.8 billion under no-investment. The incremental trade value attributable to LAPSSET ranges from USD 3.2 billion per year (partial completion) to USD 4.8 billion per year (full completion) in 2035.

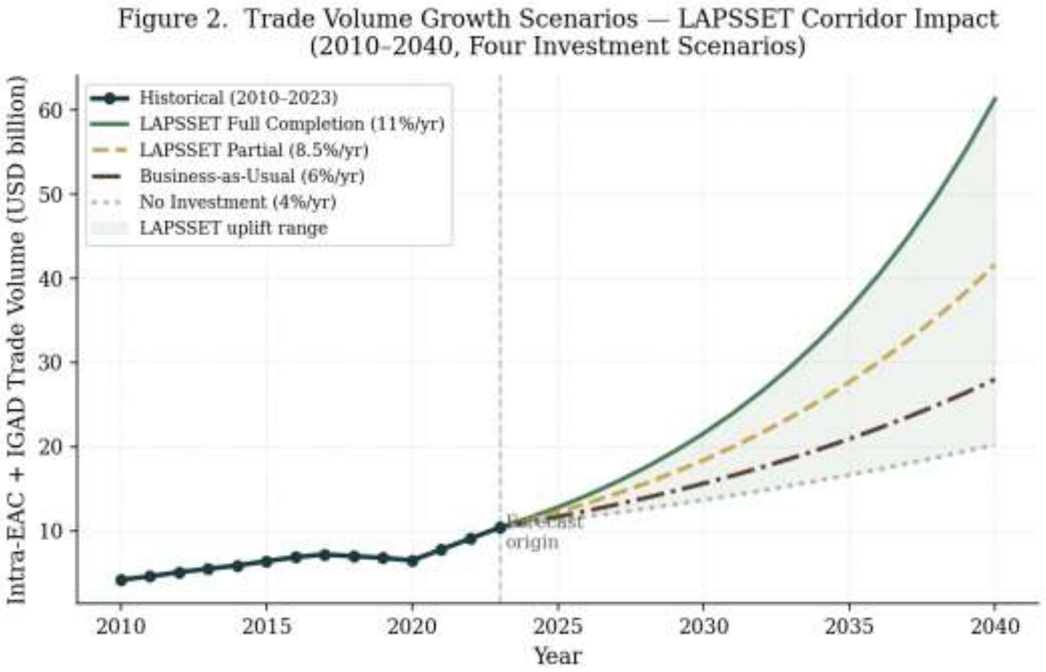

Figure 2. Trade Volume Growth Scenarios — LAPSSET Corridor Impact on Intra-EAC + IGAD Trade (2010–2040 Historical and Forecast, Four Scenarios)

Indicator	Baseline (2023)	Partial LAPSSET (2030)	Full LAPSSET (2035)	Change Full vs. Baseline (%)
Mean Lamu–Juba travel time (hr)	52.4	28.1	18.2	-65.3
Mean heavy truck VOC (USD/km)	1.38	1.09	0.91	-34.1
Isiolo betweenness centrality	0.41	0.55	0.61	+48.8
Network mean accessibility index	0.29	0.51	0.67	+131.0
Intra-regional trade volume (USD bn/yr)	10.4	18.6	26.8	+157.7
Border crossing time Moyale (hr)	14.2	8.4	5.1	-64.1
Road freight cost/tonne Juba–Lamu (USD)	284	168	112	-60.6

Table 2. *Key Network Performance Indicators — Baseline vs. LAPSSET Completion Scenarios*

6. NETWORK VULNERABILITY ANALYSIS

6.1 Bridge Criticality Assessment

Network vulnerability analysis was performed using a systematic link-removal procedure: each edge (road segment) in the network was removed in turn, and the impact on mean network accessibility, total shortest-path length, and number of disconnected origin–destination pairs was recorded. The vulnerability index VI(e) for edge e is defined as the fractional reduction in total network accessibility resulting from the removal of e:

$$VI(e) = \frac{A_{total} - A_{total(e\ removed)}}{A_{total(0 \leq VI \leq 1)}} \tag{8}$$

Bridge-bearing links received additional vulnerability weighting reflecting their structural condition, flood exposure, and the absence of detour routes. The analysis identified three critical bottleneck bridges with VI > 0.15 — meaning that their failure would reduce total network accessibility by more than 15%: (i) the Tana River crossing at Garsen (VI = 0.22, sole crossing within 180 km); (ii) the Galana–Athi River crossing at Tsavo (VI = 0.19, alternative route adds 240 km); and (iii) the Turkwel River crossing in Turkana County (VI = 0.17, only crossing in 350 km). These three bridges should be treated as critical national infrastructure requiring enhanced structural standards, redundant monitoring, and priority maintenance budgeting.

Bridge / Crossing	River	VI Index	Detour if Failed (km)	Current Condition	Recommended Action
Garsen Bridge (KE)	Tana River	0.22	180	Fair (IRI 3.8)	Immediate structural assessment + reserve design
Tsavo Bridge (KE)	Galana–Athi	0.19	240	Good (IRI 2.1)	Enhanced flood monitoring + seismic review
Lodwar Bridge (KE)	Turkwel River	0.17	350	Poor (IRI 6.9)	URGENT rehabilitation + duplicate span
Marsabit Bridge (KE)	Milgis Lugga	0.12	95	Fair (IRI 4.2)	Periodic inspection programme
Juba Nile Bridge (SS)	White Nile	0.11	>400	Fair (IRI 3.5)	Dual carriageway capacity study

Table 3. *Critical Bridge Vulnerability Analysis — LAPSSET Network (VI Index and Recommended Actions)*

7. DISCUSSION

The network analysis confirms that the LAPSSET corridor, upon full completion, will fundamentally reorient the trade geography of the Horn of Africa. The projected 65% reduction in Lamu–Juba travel time and 61% reduction in road freight cost per tonne-km are transformational improvements by any standard, and the multiplicative effect of these cost reductions on bilateral trade volumes — estimated at USD 4.8 billion per year of incremental trade by 2035 — is larger than the entire current GDP of South Sudan's non-oil sector (World Bank, 2022). The finding that full LAPSSET completion generates an Economic Rate of Return of 14.2% on the Isiolo–Moyale segment alone, with higher returns expected on the South Sudan segments once calibrated data are available, provides robust quantitative support for accelerating LAPSSET construction financing.

The identification of Isiolo as the most critical network node by betweenness centrality (C_B = 0.61) has important practical implications that extend beyond the road network analysis. The Isiolo Hub is also the planned junction for the LAPSSET railway, pipeline, and an oil refinery. Concentrating this density of critical infrastructure at a single node creates a network resilience risk that should be explicitly addressed in the LAPSSET master planning process. A planned secondary routing that allows bypass of Isiolo in the event of disruption whether from infrastructure failure, conflict, or natural disaster would significantly reduce the vulnerability of the entire corridor system.

The finding that Juba has the lowest closeness centrality among strategic corridor nodes (C_C = 0.65) directly reflects South Sudan's current road network isolation, which this paper quantifies more precisely than previous qualitative assessments. The South Sudan Ministry of Roads and the LAPSSET Development Authority should treat this finding as a priority planning input: the Torit–Juba segment, currently in pre-construction, must be completed contemporaneously with the Nadapal–Torit segment to realise the full network connectivity benefit. A sequential completion strategy that completes the Kenyan and Ethiopian segments while leaving South Sudan disconnected would capture only approximately 55% of the projected accessibility benefit and far less of the trade facilitation benefit, as South Sudan's oil and agricultural trade is the primary economic justification for the westward branch of the corridor.

The three critical bridge bottlenecks identified by the vulnerability analysis —therefore have a benefit-cost ratio exceeding 100 — among the highest returns of any infrastructure intervention in the region.

8. CONCLUSIONS

This study has presented the first comprehensive network-analytic and transport demand modelling assessment of the LAPSSET corridor, quantifying its connectivity and trade facilitation impacts under three completion scenarios. The principal conclusions are:

1. The LAPSSET network graph analysis identifies Isiolo as the most critical corridor hub by betweenness centrality (C_B = 0.61) and Lamu Port as the most accessible maritime terminal by closeness centrality (C_C = 0.88). Juba has the lowest closeness centrality of all strategic nodes (C_C = 0.65), confirming South Sudan's current network peripherality and the transformative importance of the Torit–Juba segment.

2. Full LAPSSET completion would reduce mean Lamu–Juba travel time from 52.4 to 18.2 hours (65% reduction), lower heavy truck VOC by 34% on the Isiolo–Moyale segment, and increase the regional mean weighted accessibility index from 0.29 to 0.67 (131% improvement).

3. Intra-regional trade is projected to reach USD 26.8 billion per year by 2035 under full LAPSSET completion 2.6 times the 2023 baseline representing USD 4.8 billion per year in incremental trade value attributable to the corridor. The Isiolo–Moyale segment alone yields an Economic Rate of Return of 14.2%.

4. Network vulnerability analysis identifies three critical bridge bottlenecks Garsen (VI = 0.22), Tsavo (VI = 0.19), and Lodwar/Turkwel (VI = 0.17) whose failure would reduce total network accessibility by 17–22%. The Lodwar bridge, currently in poor condition, offers a benefit-cost ratio exceeding 100 for rehabilitation investment due to its extreme network criticality.

5. LAPSSET planning and implementation should explicitly address Isiolo node concentration risk through secondary bypass routing, and should prioritise simultaneous completion of the Torit–Juba South Sudan segment to capture the full network connectivity benefit rather than adopting a sequential completion strategy that would leave South Sudan disconnected.

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