ADDIS ABABA UNIVERSITY

COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT

AFRICAN RAILWAY CENTER OF EXCELLENCE

RAILWAY TRACK STRUCTURE INTEROPERABILITY ANALYSIS IN EAST AFRICA RAILWAY LINES

A Research Report Submitted to the School of Graduate Studies of Addis Ababa University in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Railway Engineering (Civil Infrastructure)

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March, 2025

Addis Ababa

The undersigned have examined the thesis entitled **“Railway Track Structure Interoperability Analysis in East Africa Railway Lines”** presented by **Hiwot Mezgebu**, a candidate for the degree of **Master of Science,** and at this moment certify that it is worthy of acceptance.

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I certify that the “Railway Track Structure Interoperability Analysis in East Africa Railway Lines” research project is entirely original and hasn't been submitted to another institution for evaluation. Materials taken from other sources have been properly cited and credited.

Hiwot Mezgebu

March, 2025

ABSTRACT

This research intends to indicate the interoperability of railway track structure in EARN. This study applied a literature review and python-based interoperability analysis, Root Cause Analysis (RCA) and Failure Mode Effect Analysis (FMEA) and validation. interoperability model was used for the interoperability score while RCA and FMEA model were used for technical barrier analysis of track structure at each group of network lines. Main influencing factors involved in the analysis were gauge, axel load, speed of passenger and freight, rail weight, rail joint type, fastening system type, rail pad static stiffness, sleeper type, spacing and density, ballast type, thickness, and gradation, sub ballast type, thickness, and gradation, and sub grade type, thickness, and gradation variations which were demonstrated in terms of compatibility and RPN. Ethio-Kenya, Kenya-Uganda, Kenya-Tanzania, Uganda-Tanzania were use as grouped lines. Multi-criteria decision-making (MCDM) was applied for identification of feasible solutions against several criteria, such as cost effectiveness, implementation complexity, and maintenance needs.

Based on analysis, Ethio-Kenya and Uganda-Tanzania cross border railway are highly interoperable, however, the remains railway groups are not interoperable. Gauge, axle load, rail weight, and sleeper type are critical barriers which are RPN is more than 200. In addressing them, this research work identifies five important priority solutions standardization of track structure components (44.6%), upgrading of the track structure (22%), speed and load monitoring systems (18.9%), dual gauge systems (9.4%), and provision of transition switches (5.1%).

Finally, the analysis was validated using expert judgment and sensitivity analysis and to match close. By prioritizing standardization, infrastructure upgrades, and smart monitoring systems, East Africa can unlock the full potential of its railway corridors, fostering economic integration and regional trade. The future of East Africa's railway interoperability starts now with informed decision-making and bold implementation.

Keywords: *Interoperability, Track structure, East Africa Railway Network, Technical Barriers, solutions,*

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LIST OF ACRONYMS

AKH	Awash-Kombolcha-Haragebya
ANP	Analytical Network Process
ARTC	Australian Rail Track Corporation
BCA	British Colonial Authorities
BRDS	British Railway Design Standard
CCCC	China Communications Construction Corporation
CCECC	China Civil Engineering Construction Corporation
CRDS	Chinese Railway Design Standard
CGR	Cape Gauge Railway
CRBC	China Road and Bridge Corporation
CRCC	China Railway Group Ltd.
EAC	East Africa Community
EARMP	East Africa Railway Master Plan
EARN	East Africa Railway Networks
ERDS	European Railway Design Standard
GRDS	Germany Railway Design Standard
KRC	Kenya Railway Corporation
MCDM	Multi-Criteria Decision Method
MGR	Meter Gauge Railway
NOP	Non-Operable
OP	Operable
SGR	Standard Gauge Railway
TAZRA	Tanzania-Zambia Railway Authority
TRC	Tanzania Railway Corporation
UIC	International Union of Railways
URC	Uganda Railway Corporation

1 INTRODUCTION

1.1 Background

Interoperability, of railway system is indeed of the critical issue in the industry, is the capability of diverse railway networks to operate seamlessly and harmonically across borders, ensuring the uninterrupted movement of trains without requiring transshipment or extensive modifications to accomplish the required levels of performance for these lines [1], [2]. Historically, railway interoperability dates back to the early years of railway development when independent railway companies adopted varying technical standards and practices. Driven by strategic and national interests, especially during wartime and colonialization, countries intentionally implemented different track gauges and structure, signaling systems, and technical standards to hinder military invasions [3].

In Africa, railways serve as strategic lifelines, linking landlocked nations to vital seaports and promoting trade among countries within the region. However, most railway systems originated in the early 20th century during European colonial rule, designed primarily to serve colonial economic and administrative interests rather than regional connectivity [4]–[6].

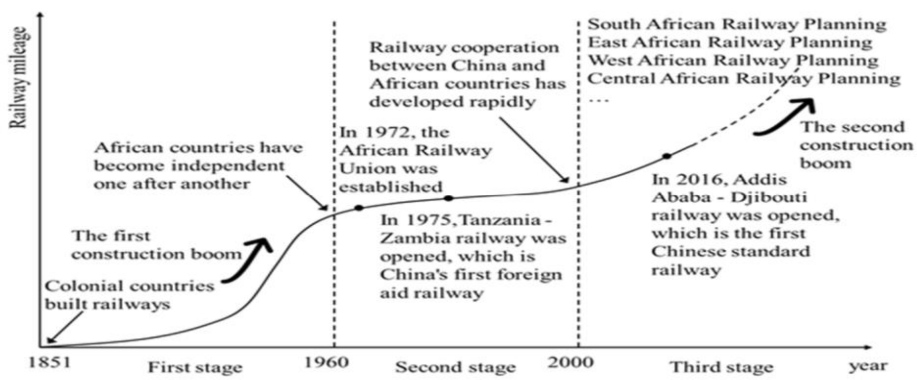


Figure 1-1 The period of construction of railway networks in Africa [5]

This historical context has led to a lack of standardization across rail networks, with countries adopting different gauges, track structures, signaling systems, and other technical standards. Consequently, this disparity has created operational inefficiencies, such as the need for transshipment at border crossings and delays due to incompatible technical systems. These challenges have impeded the full potential of the railway network as a tool for promoting regional integration and economic growth [7], [8].

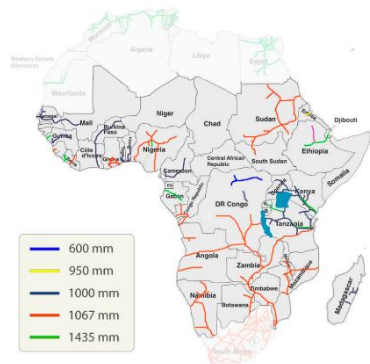


Figure 1-2 Railway track gauge variation in Africa [8].

In recent years, however, there has been a renewed focus on railway development in East Africa, driven by the African Union's Agenda 2063 [9], which emphasizes regional integration, trade, and infrastructure development. The East African Railway Corporation (EARC) has spearheaded efforts to extend and modernize the rail network, with a focus on improving interoperability and harmonizing technical standards [10]–[12]. Despite these efforts, significant challenges remain, particularly regarding the integration of existing networks with new systems, requiring substantial technical and regulatory adjustments. For instance, varying track gauges (1000mm, 1067mm, and 1435mm), axle load limits, rail profiles, and other structural inconsistencies remain major obstacles to the seamless movement of trains across borders.

Given these persistent challenges, a study of the interoperability of railway track structures in East Africa is crucial. Understanding the technical and operational barriers to interoperability will allow for the identification of feasible solutions to improve regional connectivity, reduce operational inefficiencies, and enhance safety. This research will explore these issues by assessing the compatibility of track components across the network, focusing on the technical and structural differences between the rail systems of Ethiopia, Kenya, Tanzania, and Uganda. Through the use of multi-criteria decision-making (MCDM) methods and interoperability models, the study aims to propose practical solutions that will not only enhance the technical aspects of the railway systems but also contribute to the broader goals of regional economic integration and sustainable development.

1.2 Statement of the Problem

Most railway track structures in the region were originally constructed during the colonial era, primarily to serve external interests. While newly developed SGR lines have been introduced in some corridors, the majority of the network still relies on aging MGR track structure. For instance, the Mombasa-Nairobi-Kampala railway, a critical link between Kenya and Uganda, has suffered significant deterioration since the 1980s. The Nairobi-Kisumu section was closed in 2012 due to poor track conditions, with passenger services resuming only in 2021 following partial rehabilitation, while freight services remain constrained. Similarly, the Mombasa-Taveta-Moshi railway (connecting Kenya and Tanzania) continues to experience misalignment, worn-out sleepers, and broken rails, limiting its reliability. Tanzania railway lines has seen a drastic reduction in speed from 70 km/h to 30 km/h due to track degradation, significantly affecting freight capacity and regional trade. Uganda and Tanzania also face similar track condition issues, with train speeds restricted to 20–50 km/h, reducing transport efficiency.

Additionally, the SGR line from Mombasa to Naivasha terminates without a direct connection to Uganda's MGR at Malaba, requiring cargo to be manually offloaded, increasing costs and delays. Similar at Namanga and Taveta-Holili (Kenya-Tanzania borders) and along the Mombasa-Dar es Salaam corridor. Despite both Ethiopia and Kenya developing SGR systems, a direct rail connection between the two countries remains absent, further limiting regional integration.

This research aims to conduct an in-depth analysis of railway track structure interoperability in the region by assessing the current interoperability state, identifying technical bottlenecks, and evaluating their impact on rail operations. Through advanced engineering analysis and interoperability assessment methods, the study will propose technical solutions for enhancing structural integration across East African railway networks. Addressing these issues is crucial to unlocking the full potential of regional railway infrastructure and fostering economic growth through seamless and efficient rail transport systems.

1.3 Research Questions

1. How do the differences in track structure parameters between EARN impact the interoperability of cross-border railway operations?
2. What are the technical and operational barriers that hinder track structure interoperability in EARN**?**
3. What are the potential practical technical solutions needed to ensure effective interoperability of railway track structures in the EARNs**?**

1.4 Objectives of the Study

1.4.1 General Objective

This research aims to comprehensively analyze railway track structure interoperability in EARN.

1.4.2 Specific Objectives

1. To analyze the existing railway track structure interoperability status of EARN;
2. To identify technical challenges for interoperability of railways track structure in EARN; and
3. To recommend a possible practical technical solution regarding railway track structures interoperability issues in EARN.

1.5 Scopes and Limitations of the Study

The research focused on the analysis of railway track structure interoperability within the selected network lines in Ethiopia, Kenya, Tanzania, and Uganda. The research analyzed the gauge, rail, rail pad, fastening systems, track sleepers, ballast, sub-ballast, and subgrade of the structure on the railway interoperability using python programing and MCDM. However, due to various constraints the study limited on assessing technical documents and standards and analyzing the connectivity of the structures without any physical measurement in the network. This study doesn't cover the geometry of track, civil engineering structures, lineside systems and facilities, socio-political aspect within the region. Additionally, it does not encompass life time cost, environmental impact assessment associated with construction and operation.

1.6 Significance of Study

Analyzing the interoperability of track structures in East Africa's railway network is vital for undertaking the technical challenges that disrupt efficient train operations across borders. This study aims to significantly influence the region's transport infrastructure by pinpointing structural inconsistencies and proposing engineering solutions to enhance railway compatibility and integration. A thorough examination of core track components such as rail gauge, rail profile, axle load capacity, track bed materials, sleeper types, and fastening systems will be conducted, shedding light on the technical obstacles rooted in historical variations in track design and construction standards. The research will pinpoint targeted solutions to harmonize railway infrastructure, ultimately providing actionable recommendations for policymakers and railway operators. By focusing on standardizing track structures, this study seeks to facilitate the development of a cohesive, interoperable East African railway network. The anticipated outcome of this research is to bolster regional economic integration, streamline transport logistics, and encourage sustainable infrastructure development across East Africa.

1.7 Organization of the Study

Chapter 1: Introduction provides background information on a research topic. It explores the justification for the study by highlighting its significance in the key problems with the interoperability of railway track structures in the region with a statement of problems, specific research questions, objectives, scopes and limitations, significance, and organization.

Chapter 2: Literature review conducted on theoretical background of railway network, track structures, and interoperability of railway track system. These are reviewed and discussed with their impact, relation, the gap in the literature are highlighted, and how the research will fill these gaps is explained.

Chapter 3: The Research methodology and analysis is briefly described and presented.

Chapter 4: Briefly discuss the findings on the track structure interoperability from Python and MCDM Interoperability was evaluated is shown and the results are presented in the form of graphs and tables along with their analysis and implication.

Chapter 5: Key findings of the research are highlighted, and areas for future exploration are suggested.

2 LITERATURE REVIEW

2.1 Introduction

In the literature review process, well-known scientific Journals, including Google Scholar, IEEE Xplore, Research Gate, Science Direct, Scopus, Semantic Scholar, and Directory of open access Journals has been used to search for relevant published literature, and Lit maps to the topics under consideration. Keywords and phrases “Railway”, “Track Structure”, “East Africa railway network”, “Railway interoperability”, “Standardization”, and “Technical specification” and many other related words and phrases were used to collect related research articles, journals, reports, books, standards, and technical specifications which are written in English until April 21, 2024 using the Boolean operator. ‘‘Interoperability’’ AND (‘‘East Africa Railway Network’’ OR ‘‘Track Structure’’ OR “state” OR “Standardization” OR “Technical Specification” OR “Analysis” OR “Technical Solutions” OR “MCDM”).

2.2 Railway Networks

Railways have a history spanning over 2,000 years, with their modern form emerging during the Industrial Revolution. By the late 19th century, railways had become integral to global economic systems, particularly through colonial networks in Africa, Asia, and South America. These railways played a vital role in strengthening imperial power, facilitating the movement of labor and raw materials, and enabling the expansion of European economic systems. As a result, they significantly altered the landscape of international trade, contributing to the globalization of commerce during the colonial era [16].

A million kilometers of railway networks are available in the world, United States of America (37%) and Oceania (1%) has the longest and the shortest railway network lines. In addition to this Europe and Asia have rapid development of the network lines. However, variation of gauge, uneven distribution, and limited connectivity and investment are defects to hinder the operation of some network lines like Africa [17].

2.2.1 Africa Railway Networks

Africa's railway networks profound colonial color[1], and different spatial organization modes have been formed in geographical space to support military movements and to transport goods produced in large mining or farming operations [6]. Many African railway networks were split along new country borders after independence, which diminished their markets and economies of scale and rendered some networks unusable. A large portion of the infrastructure is now antiquated, which results in subpart performance and safety requirements. Further impeding smooth regional communication are structural variances and discrepancies in track gauges. Many nations have significant portions of railways that are out of commission due to years of poor maintenance and little investment, necessitating significant efforts to restore them [18]–[20]

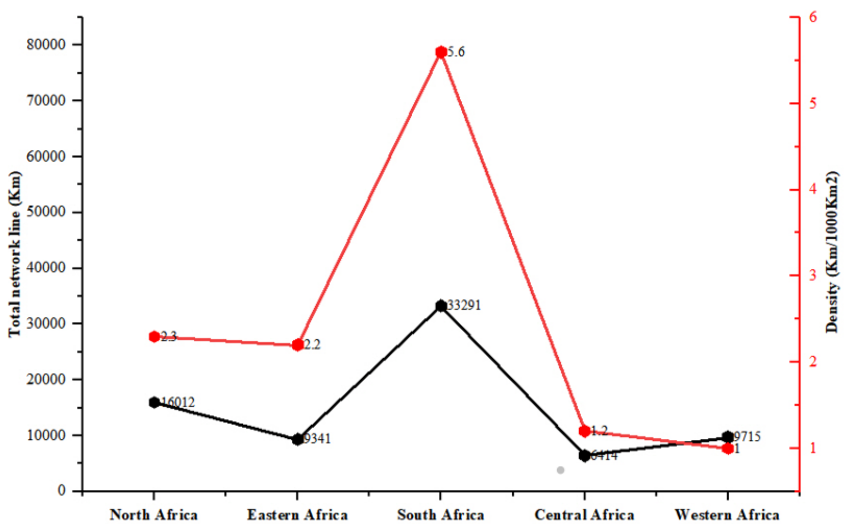


Figure 2-1 Comparative railway density in Africa [19], [20] .

2.2.2 East Africa Railway Networks

The railway network in East Africa traces its origins to the Uganda Railway, inaugurated in 1898, which connected Mombasa to Kisumu on Lake Victoria [21], with extensions to ports along the lake, including in Tanzania, (then German East Africa). Initially constructed for political reasons and later expanded with branches and feeder lines, the network grew to include vital routes like the Magadi line

[1] Except Ethiopia and Liberia countries are colonized under different Europe countries until

and a direct connection to Kampala via Jinja [22]. Development continued into the mid-20th century, with the completion of significant lines such as the Western and Northern Uganda lines. However, 91% of Uganda's railway networks are not operable except Malaba to Kampala (a single line of 251km). The total length of the MGR network along the Northern Corridor is 8,206 km, with Kenya contributing 1,787 km, Uganda accounting for 1,221 km, the Democratic Republic of Congo (DRC) covering 5,033 km, and South Sudan spanning 165 km [23].

In Tanzania, the railway system, initially built by the Germans, expanded from Tanga inland and later connected with the main Uganda railway. Branch lines, including one to Mwanza on Lake Victoria, provided alternative routes for traffic to Uganda and redirected traffic away from Mombasa. The merging of the Kenya and Uganda Railway with Tanganyika Railways and Ports Services in 1948 formed the East African Railways and Harbors, which was dissolved in 1977, leading to separate railway corporations for each country, all currently undergoing concession processes [24]. Beyond the main systems, the Djibouti-Ethiopian railway, constructed 784 km- long with 1000mm gauge in 1896, linked Djibouti to Addis Ababa but has faced disrepair since the late 1970s. Similarly, the Eritrean Railway, built 950 mm gauge from the Red Sea port of Massawa to Ghinda, Asmara, and Agordat in the late 19th century, is undergoing reconstruction after being dismantled in the 1970s [20].

Sudan boasts a 4,800 km railway network, predominantly on a 1067 mm gauge, originating with lines linked to military operations and later expanding to facilitate commercial traffic. Despite challenges and deterioration over time, the Sudan Railways Corporation manages the network, with some concessions granted to employees for specific services [24]. However, Rwanda is currently not served by any railway system In Burundi's absence of rail infrastructure and access to the sea, road transport dominates [25], [26].

2.2.2.1 Ethiopia

The recently launched standard gauge railway, equipped with 1,435mm gauge tracks and 25kv electrification, represents Africa's inaugural environmentally conscious cross-border railway network. Serving as Ethiopia's principal international standard gauge railway, it establishes a vital link between the country's capital, Addis Ababa, and the Port of Doraleh. [27] The railway corridor spans a total length of 743.44km with 115 km double track section between Sebeta to Adama, while the remaining line is single track [28]. Of this total length 645.44 (86.81%) are situated in Ethiopia [29]. It has 20 stations, 17 of which (85%) are located within Ethiopian [30]. Awash–Kombolcha–Haragebya–Mekelle has 608km constructed under Chinese and Turkish companies from Awash–Kombolcha–Haragebya (392 Km) and Haragebya–Mekelle (216 Km) respectively. Nowadays, due to the current political situation, this network line is not operable [31].

2.2.2.2 Kenya

Currently, Kenya has the MGR and SGR lines. Kenya has 3,334 km of meter gauge railway [32], one of these Mombasa to Malaba has a total network of 2,046 Km spread across the country, consisting of the mainline (1,082 Km) running along the Northern Corridor from as well as seven branch lines. On May 2017 marked the completion of the first standard gauge railway (SGR) totaling 472km between Mombasa and Nairobi[2] and expand to Suswa and Naivasha [33].

2.2.2.3 Tanzania

The main line of TRC compromised the central corridor, a MGR connecting Dar es Salaam in the east with the central and western area of the country and terminating at Kigoma on Lake Tanganyika in the west was constructed to Lake Tanganyika by 1914 and several branch lines built over the next 50 years [34]. The TAZARA (Tanzania Zambia Railway Authority) or Freedom Railway was built in 1969-1974 with Chinese assistance to connect Tanzania and Zambia during the Cold War with 1067mm gauge. 1,860 km in length, of which 975 km is in Tanzania and 885 km in Zambia [35].

2.2.2.4 Uganda

Uganda's total rail network spans 1,250 km, but only 265 km is currently operational due to abandonment or closures. In response, Uganda Railways Corporation (URC) has launched an ambitious revitalization effort aimed at accelerating development and boosting trade. Additionally, URC has resumed cargo services to the Port of Dar es Salaam in Tanzania after more than a decade of inactivity [36].

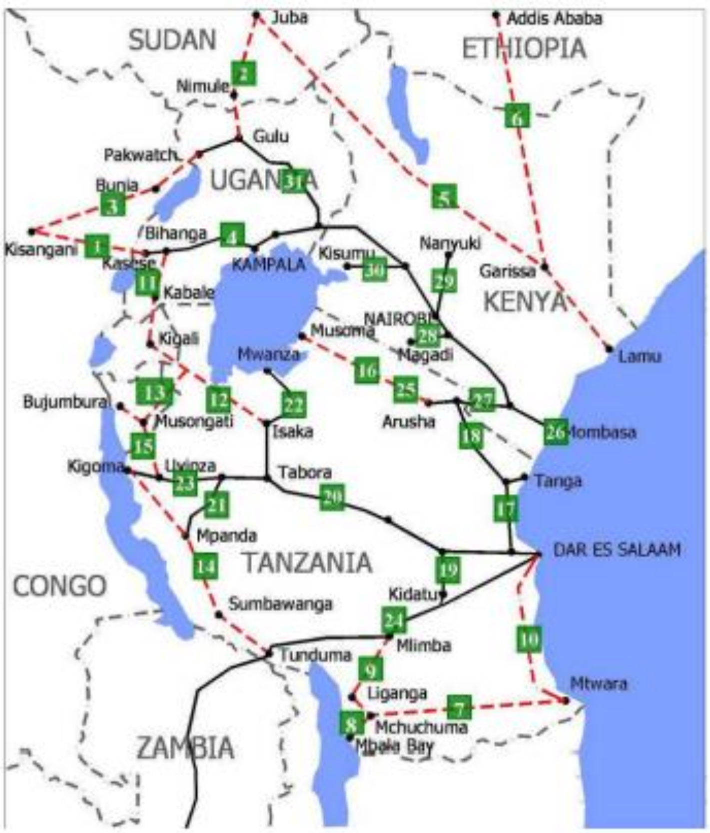
[2] This network line was constructed with meter gauge during the colonization of Kenya by British. Before decade it reconstructed as SGR and the first network line in Kenya.

Table 2-1 Railway lines in Ethiopia, Kenya, Tanzania, and Uganda

Country	Route line	Length (Km)	Operable Length (Km)	Year of Construction	Year of Operation Started	Current Situation
Ethiopia	Addis Ababa- Djibouti	759	759	2011-2015	2016	OP
	Awash-Kombolcha-Haragebya	392	0	2015-2018	N/A	NOP
	Haragebya-Mekelle	216	0	2017-2020	N/A	NOP
Kenya	Mombasa-Nairobi	472	472	2013	2017	OP
	Nairobi- Suswa	121	121	2018	2019	OP
	Nairobi-Naivasha	120	120	2017	N/A	OP
	Nairobi - Nakuru	160	160	The late 1890s	The early 1900s	OP
	Nairobi - Nanyuki	212	212	The early 1900s	The Early 1900s	OP
	Nakuru - Kisumu	217	217	The early 1900s	The early 1900s	OP
	Nairobi - Thinka	50	50	The early 1900s	The Early 1900s	OP
Tanzania	Dar es Salaam- Morogoro	1254	1254	The early 1900s	The early 1900s	OP
	Morogoro - Tabora	379	379	1891-1914	1914	OP
	Tabora- Mpanda	210	210	1911-1929	1929	OP
	Dar es Salaam- Tanga	331	331	1912	1912	OP
	Dar es Salaam- Moshi/Arusha	640	640	1926-1934	1934	OP
	Dar es Salaam- Ifakara	563	563	1949-1956	1956	OP
	Manyoni - Singida	134	134	1963-1975	1975	OP
	Morogoro - Makutupora	426	426	2012-2016	2016	OP
Uganda	Malabama - Kampala	251	251	1895-1902	1902	OP
	Tororo – Mbale	55	55	1929	1929	OP
	Kampala-Port bell line	80	9	Early 20th	Early 20th	OP
	Kampala-Nalukolongo	5	5	Early 20th	Early 20th	OP
	Tororo-Gulu-Pakwach	504	0	1929	1964	NOP
	Nalukolongo-Kasese	330	0	1956	N/A	NOP
	Jinja-Mbulamuti-Busembatia & Mbulamuti-Namasagali loop	171	0	Early 20th	Early 20th	NOP
	Jinja Port and Tororo Cement Factory	10	0	1928-1931	1931	NOP

2.2.3 Proposed East Africa Railway Network Lines

The East Africa Railway Master Plan (EARMP) is a strategic initiative aimed at developing an integrated and efficient railway network across the East African region with the objectives of infrastructure development, interoperability and standardization, trade facilitation, capacity building, and institutional strengthening, as well as sustainability and environmental considerations. The EARMP seeks to promote regional connectivity, enhance trade facilitation, and foster economic development through the expansion, modernization, and interoperability of railway infrastructure within member states of the East African Community (EAC) [12], [37].



Link	Location
1	Kasese – Kisanani
2	Gulu – Nimule – Juba
3	Pakwach – Buia – Kisangani
4	Tororo – Kampala – Bihanga – Kasese
5	Lamu – Garissa – Juba
6	Garissa – Addis Ababa
7	Liganga – Mchuchuma – Mtwara
8	Mchuchuma – Mbamba Bay
9	Liganga – Mlimba
10	Dar es Salaam – Mtwara
11	Kigali – Kabale – Bihanga
12	Isaka – Keza – Kigali
13	Keza – Musongati (a branch from, and part of, Isaka – Keza – Kigali Line)
14	Tunduma – Sumbawanga – Mpanda – Kigoma
15	Uvinza – Gihofi – Nyanza – Lac – Bujumbura
16	Arusha – Musoma
17	Dar – Ruvu – Korogwe – Tanga
18	Dar – Ruvu – Korogwe – Moshi – Arusha
19	Dar – Ruvu – Kilosa – Kidatu
20	Dar – Ruvu Kilosa – Dodoma – Singida – Tabora
21	Dar/Tabora Line – Kaliua – Mpanda
22	Dar/Tabora Line – Isaka – Mwanza
23	Dar/Tabora Line – Uvinza – Kigoma
24	Dar – "Kilombero" Ifakara – Chita – Mlimba – Mbeya – Tunduma
25	Arusha – Natron
26	Mombasa MAIN LINE to Tororo
27	Mombasa – Voi – Taveta – Arusha
28	Mombasa – Voi – Konza – Magadi
29	Mombasa – Nanyuki
30	Mombasa – Kisumu (Lake Port)
31	Tororo – Gulu - Pakwach

Figure 2-2 Proposed East Africa railway networks[3] [12].

[3] Red lines indicated the newly proposed network lines and the black one is indicated the network that are need habitation

2.3 Interoperability in The Railway Industry

According to the European Union, Directive 2008/57/EC railway interoperability is defined as "*Interoperability means the ability of a rail system to allow the safe and uninterrupted movement of trains which accomplish the required levels of performance for these lines. This ability depends on all the regulatory, technical, and operational conditions which must be met to satisfy the essential requirements*" [38], [39]. The technical, organizational, legal, and technological systems necessary for smooth and safe train operations are all included in interoperability. It first appeared when railways were just getting started and there were difficulties due to different technical standards and practices among independent businesses [13]–[15]. As railroads spread throughout Europe and North America in the 19th century, problems with operational procedures, signaling systems, and uneven track gauges brought attention to the need for standardization. The need for interoperability, which focuses on simplifying operations and facilitating the effective movement of people and goods across networks, increased as rail networks linked disparate regions [40].

[41] Stated that as rail system interoperability increases, the following useful results should be anticipated standardized components, economies of scale, operational flexibility, uniform standards and specifications, Minimal commodity transshipment, reduced travel time, future network development facilitation, and increased road transport competitiveness. All phases of a candidate project's lifecycle, including strategic planning, design, construction, implementation, commissioning, operation, performance monitoring, maintenance, modification, decommissioning, and disposal, should take it into account [38], [42].

According to Jacyna and Szkopiński [14], Integrating various rail systems and guaranteeing safe and continuous train operations across nations with adoption of interoperability in its rail transport system. The study identifies the primary railway system components that heavily rely on interoperability, such as power supply, operation systems, and control-command and signaling systems. It lists rolling stock, infrastructure, energy, command control, and signaling as necessary components for interoperability. recommend creating a simulation model that considers the limits, advantages, and costs of various stakeholders.

W.Walker [3] Political, financial, technological, commercial, institutional & organizational, administrative, social, and cultural are some of the classified obstacles that impede the adoption of interoperability in railway networks. The achievement of operational interoperability is essential to ensuring the intended level of railway competitiveness in the market, even when large investments in technological interoperability are essential. Through the removal of technical incompatibilities and the maintenance of uniform standards across various networks, it enhances railway operations' efficiency, safety, and dependability while also fostering social benefits, economic cooperation, and an open railway market.

2.3.1 Interoperability Implementation Subsystems in the Railway Industry

EU Commission regulates the Technical Specification of Interoperability (TSI) to function in the union by defining the technical and operational standards that define the requirements for each subsystem or part of a subsystem to ensure the interoperability of the railway system. These are Infrastructure, signaling and control command, Rolling stock, telematics, safety in tunnels, and operation and traffic management [43]–[45]

2.4 Railway Civil Infrastructure Subsystem

The railway track and other civil engineering structures, systems, and premises that support railway traffic are collectively referred to as "railway infrastructure." In order to prevent accidents and lower operating and maintenance expenses, the railway infrastructure must be managed rigorously and effectively. It necessitates a thorough understanding of the assets, how they interact, and how each single parameter affects the overall performance of the infrastructure [46], [47].

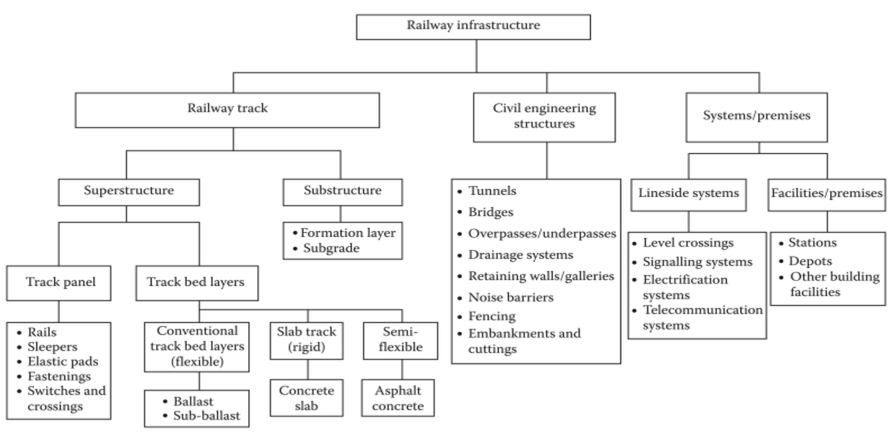


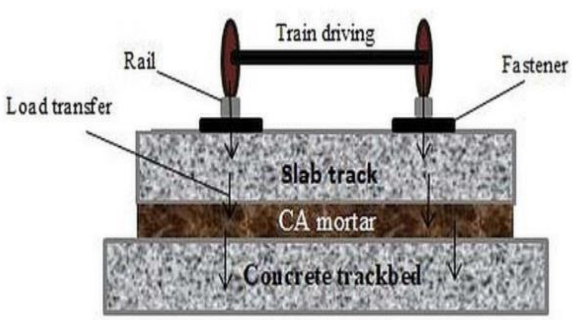
Figure 2-3 The part of the infrastructure subsystem [47]

To provide dependable, secure, and effective service, all of these resources are dispersed and connected throughout the railway network. Subsystems, which include track systems and other infrastructure elements, are essential to the development, functioning, upkeep, and lifespan of the entire railway network. Every subsystem affects the overall network's lifetime and performance, which in turn affects its sustainability and efficiency [48].

2.4.1 Railway Track Structures

Railway track structure interoperability is a key aspect in rail transport which is the ability of different railway structures, load, speed, and components to work together seamlessly and efficiently to enable the safe and uninterrupted movement of trains across different networks, regions, and countries which accomplish the required levels of performance for these lines. Regulatory, technical, and operational conditions are the essential requirements to be an interoperable network [13]–[15].

The qualities or characteristics of the track are already complicated. Each system component must fulfill its distinct responsibilities in a satisfactory manner in response to the environmental circumstances and traffic loads placed on the system in order to fulfill this job. The mechanical characteristics and component geometry of each track structure differ. Axle loads, operating speeds, track curvature, urban or rural environments, transitions, level crossings, bridges, tunnels, and soil type are some of the variables that affect these variations [49]–[51].



[a] [b]

Figure 2-4 [a] Schematic representation of layer arrangement slab track [52], [b] covered track Blackpool's tramway [53].

Table 2-2 Advantages and disadvantages of track type [54]

Track Type	Advantages	Disadvantages
Ballasted	Low construction costs and inherent vibration-damping	Ballast may degrade and need replacement or realignment i.e. costly and time-consuming
Covered	Track areas can be used by other modes of transport	Replacement is costly, timely, and disruptive to other traffic since the track is embedded in the road surface
Slab	Maintenance free	Costly and difficult to adapt/change

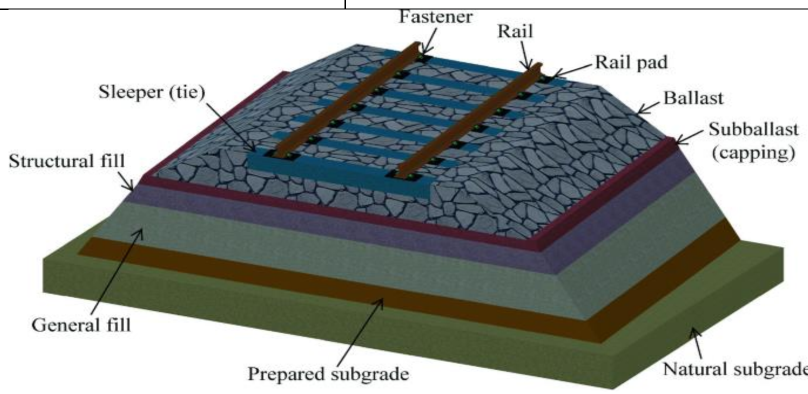


Figure 2-5 Component of ballasted railway track [55].

Conventional ballasted rail tracks, which are extensively utilized in the world, constitute the majority of train infrastructure [56]. The Superstructure and the substructure are the group of conventional tracks. The track superstructure consists of the rails, rail pad fastening system, and sleepers, while the substructure includes the ballast, sub-ballast, and subgrade layers that provide support to the track superstructure [55].

The gauge is the distance between the inner sides of the head of rails of the two rails that make up the track. It is a critical parameter in railway systems, as it determines the compatibility of trains with the tracks [57]. As indicated in Table 2.6, various rail gauges have been adopted by different railways in the world, due to historical and other considerations [52]

Table 2-3 Various rail gauges on world railways [52].

Type of Gauge	Gauge (mm)	Total length (%)	Countries
Standard gauge	1435	62	England, USA, Canada, Turkey, Persia, and China

Broad gauge	1676	6	India, Pakistan, Ceylon, Brazil, Argentina
Broad gauge	1524	9	Russia, Finland
Cape gauge	1067	8	Africa, Japan, Java, Australia, and New Zealand
Meter Gauge	1000	9	India, France, Switzerland, and Argentina
other gauges	Different Gauge	6	Various countries

The rails are the main component of the track and are typically made of steel and required to serve as both a running surface and as a load-bearing design element [50] to meet high wear resistance, high deform resistance, high fatigue strength, high yield strength, good weldability, good texture, profile evenness and dimensions correctness, and low residual stresses after production [58].

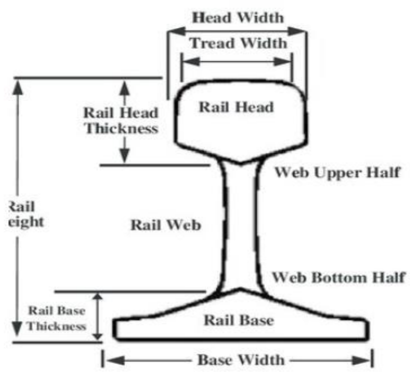
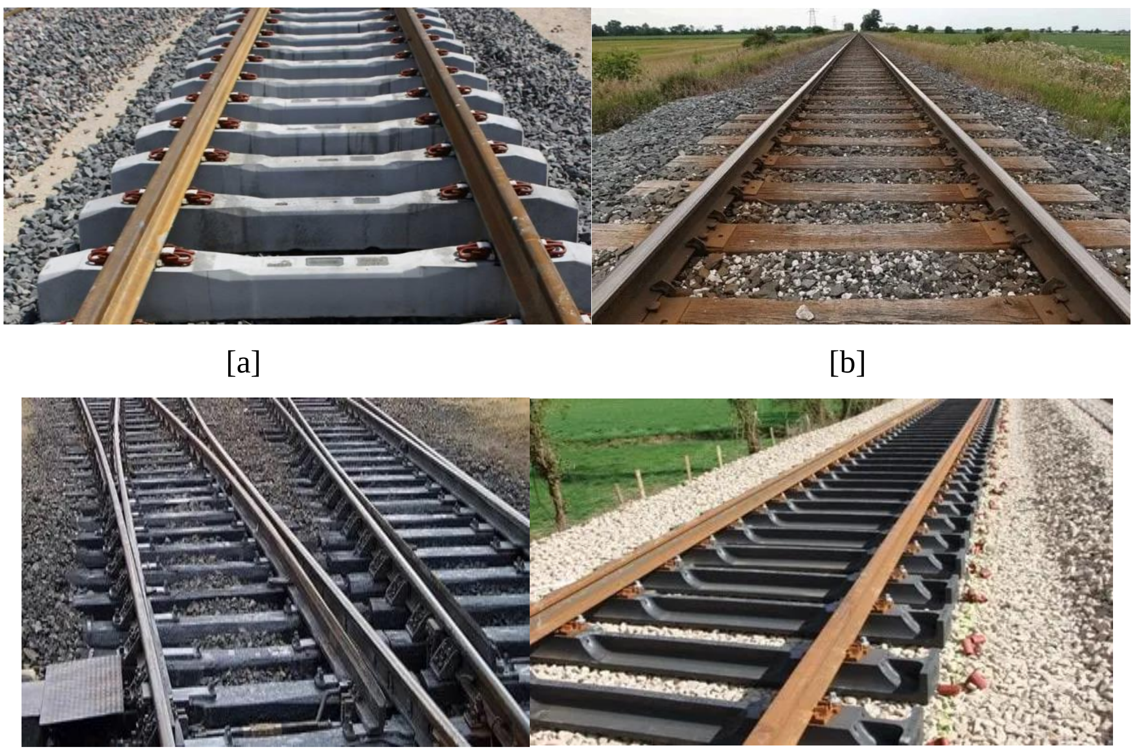


Figure 2-6 Rail profile standardized cross-section [59]

According to [60], [61] Local considerations including curve radius, tonnage, slopes, speed, cant on curves, axle load, and rolling stock type influence the choice of rail grade. Wear and rolling contact fatigue (RCF) faults are influenced by these elements. Lubrication and grinding are two rail maintenance techniques that reduce wear and RCF. The greater investment cost of premium steel grades can be justified by lower maintenance and operating expenses, providing better performance, safety, and availability, according to economic considerations such life cycle cost (LCC).

Sleepers are safety-critical, primary structural essential components, hold rails, distribute weight, and resist forces [62]. Their quality is crucial for safe and reliable railways, requiring them to be strong, moderately heavy, stiff, affordable, and compatible with track systems [63]. Traditionally, timber was the standard material for railway sleepers until the mid-twentieth century, despite its recognized durability limitations. Even today, many railways continue to use timber sleepers due to their advantages, including good resilience, ease of handling, adaptability to non-standard situations, and electrical insulation properties [54]. Steel sleepers offer benefits like long service life, dimensional accuracy, and positive residual value but are limited by insulation issues, maintenance challenges, and high costs. The use of concrete sleepers increased after World War II due to wood shortages, the adoption of continuous welded rail (CWR), and advances in concrete and pre-stressing technology [54], [57], [64], [65]. Reinforced concrete currently dominates due to its durability and low maintenance costs [66]. New technologies like composite sleepers made from recycled materials are also emerging, offering improved resistance to wear and tear, environmental benefits, and better vibration management [67], [68]. Finally, sleepers rest on ballast, a layer of crushed rock providing stability and drainage [69].



[a] [b]

[c] [d]

Figure 2-7 [a] Concrete sleeper, [b] timber sleeper, [c] steel sleeper, and [d] composite sleeper

Tie spacing depends on the type of material and track, speed, and load requirements. It affects rail flexural stress, compressive stress on ballast and roadbeds, lateral resistance of the track structure, and the flexural stress in the ties themselves. The consequences of increasing tie spacing are higher rail bending moments and corresponding deflections and stresses within the individual ties; and can reduce the fatigue life of the rail even though the stress levels are within allowable limits [68]. Rail fastening is components that form the structural connection between rail and sleeper [70], [71] to secure the rail to the sleepers, ensuring its stability. The selection of fastening greatly depends on the properties and structure of the sleeper, and upcoming load [57], [72]

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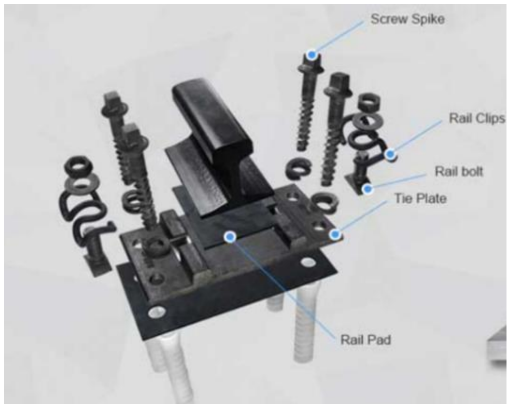

Figure 2-8 Railway fastening system components [71]

With the introduction of concrete sleepers, the spikes used for wooden sleepers were replaced by double elastic fastenings, where the rail is secured by a spring with rubber pads. Spring clips are now an essential component of the concrete tie system in ballasted track structures. Rail pads, made of rubber or polymer, are placed between the rail seat and the concrete sleeper to protect the sleepers from wear and impact while also serving as electrical insulators for the rails [50],

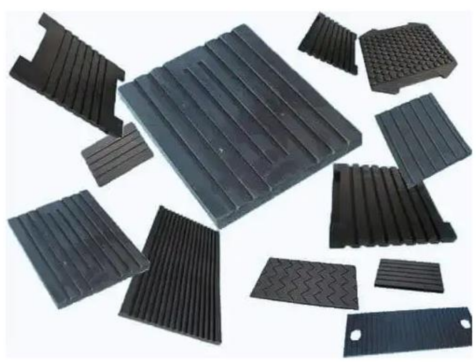

Figure 2-9 Different types of rail pads (AGICO rail pads).

The primary purpose is to prevent rail temperature rise, which can alter material properties. Pads and fasteners allow limited vertical and rotational rail movement relative to the sleeper [73]. Wood sleepers do not require resilient pads as they provide natural flexibility. Ballast, a crushed granular layer placed between sleepers, ensures track stability by minimizing movement, absorbing loads, and facilitating drainage. High-quality ballast with strong load-bearing capacity, wear resistance, and elasticity is essential to prevent degradation, fouling, pumping, and settlement [74].

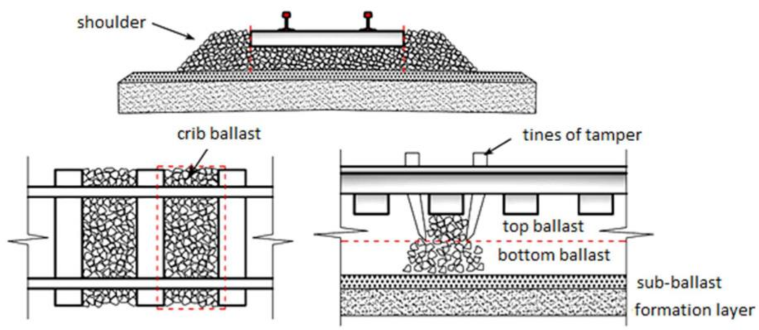

Figure 2-10 Typical section of ballast bed [75].

The chosen type of ballast material usually depends on local availability. The most important ones are to resist vertical, lateral, and longitudinal forces applied to the sleepers and to provide resiliency and energy absorption for the track. The best choice of material will not necessarily be the highest quality material or the material that has the lowest delivered cost but includes cost-effective choice considering traffic, environmental conditions, and cost of material delivered to the site [64]. The track performance of the railway mainly depends on the thickness of the ballast layer and the track deformation and degradation characteristics of the corresponding layer [51].

Supporting the ballast, distributing traffic loads, and keeping tiny particles from the subgrade from combining with the ballast are the main purposes of the sub-ballast. It helps with drainage as well. The material must be frost-resistant and have sufficient drainage, rigidity, and bearing capacity. Usually, this material is sand or gravel with particle sizes between 0 and 150 mm. The depth of the sub-ballast is determined by the ground's frost depth, making sure it is sufficiently thick to shield the subgrade from freezing temperatures. If the frost spreads farther, the thickness can be raised, but 800 mm is the minimum. It is sufficient to have a 500 mm sub-ballast layer for rails constructed on bedrock [76].

The subgrade is the load-bearing layer earth's surface leveled off for the formation track bed. An additional layer is laid on the earth to obtain an exact profile of the track bed [77], [78]. The main functions of subgrade according to Selig E.T [79] are to: provide a stable platform to construct the track, limit progressive settlement from repeated traffic loading, limit consolidation settlement, prevent massive slope failure, and restrict swelling or shrinking from water content change. If the subgrade soil cannot achieve its required function, a capping layer of granular material is placed between the natural ground or the embankment fill material and the ballast to improve the capacity of the track structure and to minimize its ongoing costs of maintenance, especially issues related to track geometry [80].

2.5 Essential Requirements of Interoperability of Railway Track Structures

Table 2-4 The essential requirements of interoperability of railway track structures.

Requirements	Characteristic
Technical Compatibility	The ability of physical characteristics of the track structure allows trains to operate safely, efficiently, and work together seamlessly [81].
Safety	The measures and protocols put in place to protect passengers, staff, and goods while ensuring smooth and reliable train operations [82], [83].
Reliability and Availability	The probability that a railway track structure system can perform its required function under specific conditions for a given time interval without failure [130].
Environmentally Friendly	The criteria for an environmentally friendly railway track structure system are energy efficiency, reduction of carbon footprint, and the use of sustainable materials [85].
Accessibility	It ensures that the system can be easily used and accessed by a wide range of users, including passengers with disabilities, the elderly, and those with reduced functional abilities [86], [87].
Health	The ability to support the efficient and safe movement of people and goods while minimizing negative impacts on public health [88].

2.6 Railway Track Structure Interoperability Barriers

[89] stated that interoperability barriers in railways track system can be categorized as non-technological, related to organizational aspects, and technological in nature.

Table 2-5 Railway track structure interoperability barriers [89] .

Non-Technological	Technological
Railway regulations/ standard difference	Track gauge;
Investment and funding disparities	Rail profile and material
Cultural and Language differences	Inconsistence of sleeper
Political factors	Train design Speed
Different business practices	Axel load
Legal and jurisdictional issues	Track deterioration
Inconsistent cargo security measures	Ballast shoulder height
Variations in infrastructure usage payment calculations	Quality of sleeper, ballast, and subgrade

2.7 Track Structure Interoperability Practice and Technology

2.7.1 Dual/ Variable Gauge

Different gauge railway system is worldwide barrier. Dual or variable gauge track system are proposed as technological solution in different countries. Dual/ Variable gauge, which involves laying two sets of rails with different gauge widths on the same track bed to allowing trains of different gauges to operate on the same track, has recently been installed in the large section of different railway lines [90]–[93].

[a] [b]

Figure 2-11 Dual gauge railway line in [a] Spain [154], [b] Japan [91]

Spain developed dual gauge track line for 1435mm and 1668mm gauge [92], [93] since 1992. Japan developed variable gauge system for through operation between standard gauge shinkansen and narrow gauge (1067mm) conventional section for 300Km/hr and 130Km/hr since 1994 [91]. [90] stated Europe developed variable gauge tracks at different section of country borders to develop the interoperability between the states. The Australian Rail Track Corporation (ARTC) has conducted technical feasibility studies regarding dual gauge rail systems to enhance interoperability and improve network efficiency across different rail gauges [94].

2.7.2 Develop Speed and load Monitoring System

Recent research has focused on developing railway track structure monitoring systems to enhance safety and efficiency. These systems utilize various sensors and technologies to continuously assess track structure conditions and train parameters. Ultrasonic sensors can detect cracks and control signals and train speeds [95], while IoT sensors and edge computing enable real-time monitoring of train speed and loading with high accuracy [96]. IoT-based smart systems can monitor track strength, vibration, load, and alignment, providing information to substations, drivers, and central monitoring offices [97]. By implementing these technologies, railway operators can potentially reduce accidents, improve maintenance efficiency and cost, and ensure safer rail transportation and also improve the interoperability between the cross-border railway lines.

2.7.3 Standardization of Track Structure Components

This process involves creating uniform technical and operational standards that ensure different railway track systems can work together seamlessly. It enhanced safety (reduce the risk of accidents and improve overall safety), operational efficiency and cost effective (reducing the need for custom solutions and facilitating bulk procurement). Different countries standardize their track system depends on their nature and interlinking to their neighborhood countries. [98] Europe developed technical specification for interoperability (TSI), china developed track structure technical standard, Australia National Framework for Rail Interoperability (NFRI) [99].

The African Union (AU) has recently proposed a standardized framework for railway systems as part of its broader Agenda 2063, which aims to enhance connectivity and economic growth across the continent. Central to this initiative is the Integrated High-Speed Train Network, designed to connect all African capitals and commercial centers, thereby improving efficiency and reducing transport costs. The AU is also implementing the Program for Infrastructure Development in Africa (PIDA), which seeks to harmonize technical specifications and regulatory frameworks to facilitate seamless cross-border railway operations. This push for standardization reflects a commitment to regional integration and aims to leverage digital technologies in railway operations, enhancing service delivery across member states [100].

2.7.4 Provision of Transition Switch

Installing transition switches at gauge-change points improves operational efficiency and reduces delays caused by mechanical and logistical mismatches [101]–[103]

2.7.5 Upgrade of Track Structure Design

This process is enhancing the components, materials, and configurations used in the railway track structure system to improve its performance, durability, and compatibility with modern trains and higher operational demands [104].

Table 2-6 Country change their track structure design

No	Country	Old Track Design System	Recent Track Design System
1	China	Ballasted	Slab
2	Spain	Ballasted	Slab
3	France	Ballasted	Slab
4	Japan	Ballasted	Slab
5	USA	Ballasted	Slab

2.8 Multi-Criteria Decision-making (MCDM)

MCDM, a branch of operations research (OR), systematically evaluates and selects the optimal solution from a set of alternatives. This process considers multiple criteria to address common decision-making challenges in various applications **[105].**

2.8.1 Analytical Network Process (ANP)

The Analytic Network Process (ANP), developed by Saaty in 1996, evolved from the Analytic Hierarchy Process (AHP), which he introduced in the 1980s [106]. AHP is a multi-criteria decision-making method that uses pairwise comparisons to generate ratio scales and prioritize options based on a hierarchical representation of complex problems. ANP extends this approach by structuring elements into hierarchies or feedback networks and conducting pairwise comparisons to determine relative importance weights [107]. Determine the weight using $W_i = \frac{1}{n}\sum_{j=1}^{n} a'_{ij}$ depending on Saaty' scale.

Table 2-7 Fundamental Saaty's scales of relative importance

Importance	Degree of Importance	Explanation
1	Equal Importance	Two attributes with equal contribution to the objective.
3	Moderate Importance	Judgment slightly favors one activity over the other
5	Strong Importance	Judgment strongly favors one activity over the other
7	Very Strong Importance	An activity is favored very strongly over another, its dominance is demonstrated in practice
9	Extremely Importance	The evidence favoring one activity over the other is of the highest possible order of affirmation
2,4,6,8	Intermediate values that signify (weak, Moderate Plus, Strong Plus, and (Very, Very Strong)	

Consistency is verified by calculating the consistency index ($\mathrm{CI} = \frac{\lambda - \mathrm{n}}{\mathrm{n}-1}$) and consistency ratio ($CR = \frac{\mathrm{CI}}{\mathrm{Random\ Index}}$). A comparison matrix is considered consistent if CR is less than 0.1.

Table 2-8 Average random consistency index (R.I)

N	1	2	3	4	5	6	7	8	9	10
R.I	0	0	0.52	0.89	1.11	1.25	1.35	1.4	1.45	1.49

2.9 Summary of Literature Review

The significance of researching railway track structural interoperability in East African Railway Networks (EARNs) is examined in this article. As was mentioned, interoperability is more than just network connectivity. Colonial economic and strategic activities gave rise to railways in Kenya, Uganda, Tanzania, and Ethiopia. It is essential to regularly assess the components of the track construction in order to detect obstacles and enhance cross-border interoperability. The article stresses the need for appropriate methodology in interoperability study and lists some ways to improve track structure compatibility.

Table 2-9 The summary of the literature review

SN	Publisher	Year	Researcher	Title	Methodology	Findings	Gap
[21]	Archives of Transport	2014	Janusz Szkopiński	The certain approach to the assessment of interoperability of railway lines	Using systematic approach by numerical expression.	It covers the main interoperability implementation area in European Union networks.	it doesn't consider each component and generally assesses the subsystems. Lack of information on the complexity and challenges associated with meeting the interoperability requirement on railway lines.
[68]	Advances in Intelligent Systems and Computing	2020	Luka Lazarević, Zdenka Popović, and Nikola Mirković	Interoperability of Railway Infrastructure in the Republic of Serbia	Technical measures of the structural parameters.	It presents the hierarchical scheme for harmonization of legal and technical regulations for the railway system.	It doesn't check the connectivity of the networks. lacks discussion on the economic implications and cost-effectiveness of implementing interoperability measures
[72]	KTH	2021	Kebron temedo tana	Interoperability Study of the European and Chinese Railway Signaling Systems	Technical compatibility analysis	Providing two basic technical solutions. As upgrading Ethio -Djibouti railway line from the current CTCS level 0 to CTCS level 2 and installing ERTMS.	It is considered only a signaling system.
[26]	Transportation Research Record	2008	Walker, Warren E, Baarse, Gerrit Van Velzen, Andre Jarvi.	Assessing barriers to improving rail interoperability in European countries	Using Analytical framework, interview, and BSS evaluation.	Identify the critical barriers that hinder interoperability in the EU.	it is subjective and doesn't consider the economic aspects.
[101]	EDP Sciences	2023	Maxim Arbuzov, Volodymyr Andrieiev*, and Stanislav Kosturechko	Solving the problem of switching from one track gauge to another in the context of the requirements of interoperability specifications for classical infrastructure	Finite Element Modeling, Strength and Stability Calculations, and Experimental verification	A promising solution for switching between different track gauges is the implementation of a combined track design, which aligns with European standards, the design of the combined track introduces new challenges, including ensuring the strength and stability of the track structure and determining permissible train speeds	it doesn't consider the effect on track structure.
[43]	Budapest University of Technology and Economics	2008	Gy, Bessenyei	Theoretical principles for quantitative evaluation	using FEM, and compatibility matrix	identify the interoperability between track structure and rolling stock	it doesn't consider the root causes of poor interoperability. It calculates the overall interoperability of line.

3 METHODOLOGY

3.1 Introduction

The research process is structured into four key phases, as illustrated in Figure 3.1. The Pre-Analysis Phase involves conducting a comprehensive literature review, collecting relevant data, determining track structure parameters, and selecting network lines for analysis. Data is gathered, the Analysis Phase follows, utilizing Anaconda Navigator with Jupyter Notebook (version 7.0.8) in Python. This phase commences, employing a Compatibility Model to identify the interoperability of the grouped network lines**,** Root Cause Analysis (RCA)**,** and Failure Mode and Effects Analysis (FMEA) to assess interoperability challenges. The Risk Priority Number (RPN) is evaluated, and if deemed unacceptable, the research moves to the solution development phase**.** Here, Multi-Criteria Decision Making (MCDM) is applied to develop technical solutions. The consistency of the decision matrix is checked, and if the proposed solutions meet acceptability criteria, the study progresses to the validation and reporting phase**.** This phase involves expert surveys conducting via JotForm, and sensitivity analysis conducting by ±10% and ±20% of each criterion to validate findings. If the analysis is acceptable, the study is finalized and reported; otherwise, refinements are made iteratively based on feedback.

3.2 Research Design

This research adopts a systematic, applied mixed-methods approach**,** combining descriptive, analytical, and decision-based research. It identifies gaps through a **l**iterature review and data collection**,** analyzes interoperability challenges using Compatibility Modeling, RCA, and FMEA, and develops solutions through MCDM. Expert validation and sensitivity analysis ensure reliability, making the study both theoretically sound and practically applicable to railway infrastructure development.

3.3 Data Collection

In the railway industry, the technical specifications of the track infrastructure are often considered sensitive, and secure, and require a multi-faceted approach due to the complexity and scale of railway systems. However, this study employed a secondary data sources to ensure a compressive analysis of railway track structure interoperability in the region. Ethiopian, Kenya, Tanzania, and Uganda government policy documents, infrastructure development plans, project progress reports from

Kenya's, Tanzania's, and Uganda's Ministry of Transport, KRC, TRC, and URC are the secondary data resources for the analysis.

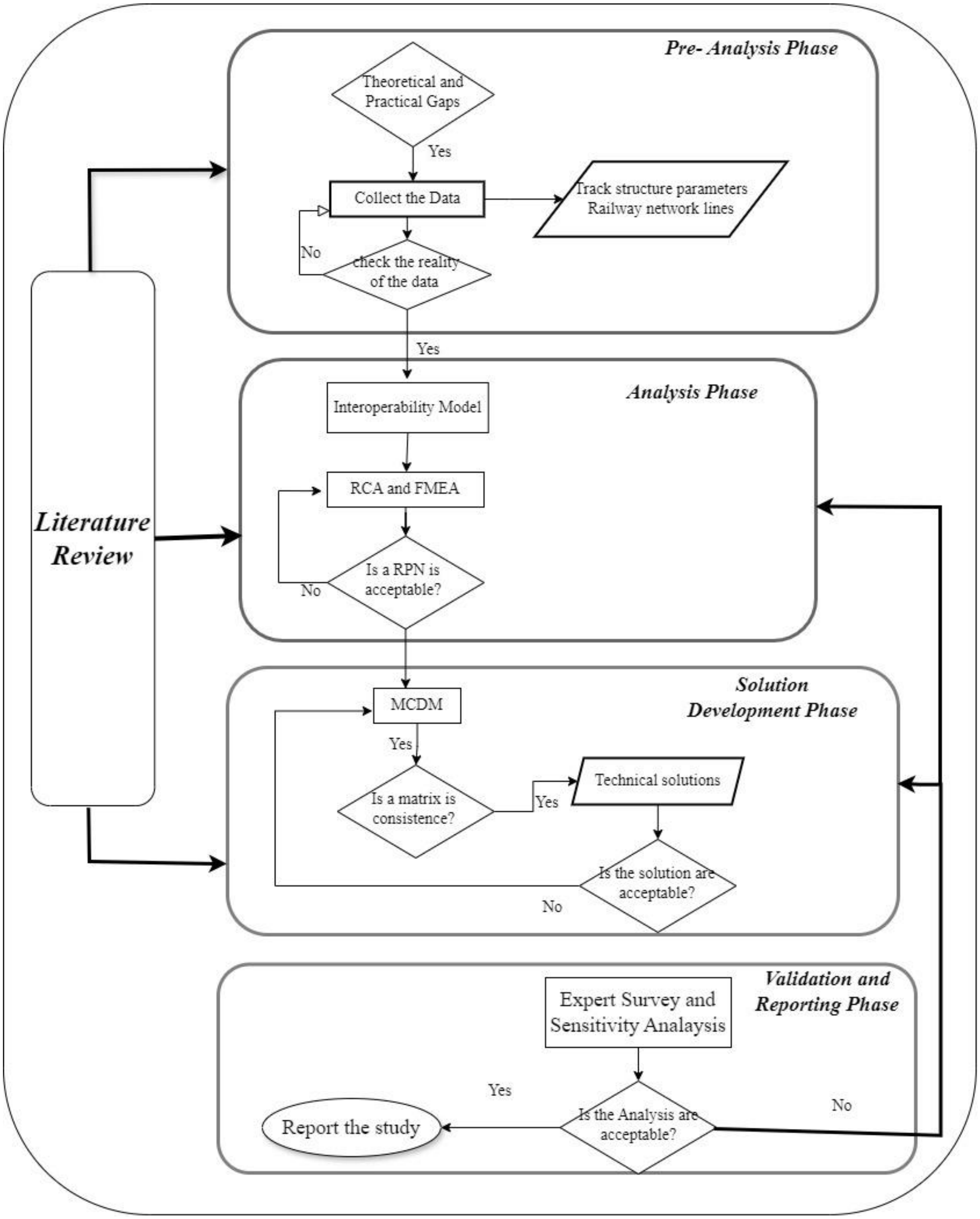

Figure 3-1 Schematic of research methodology.

3.3.1 Sampling Method

The selection of railway network lines is based on their cross border, gauge type, and track structure characteristics to ensure a comprehensive analysis of interoperability across the region.

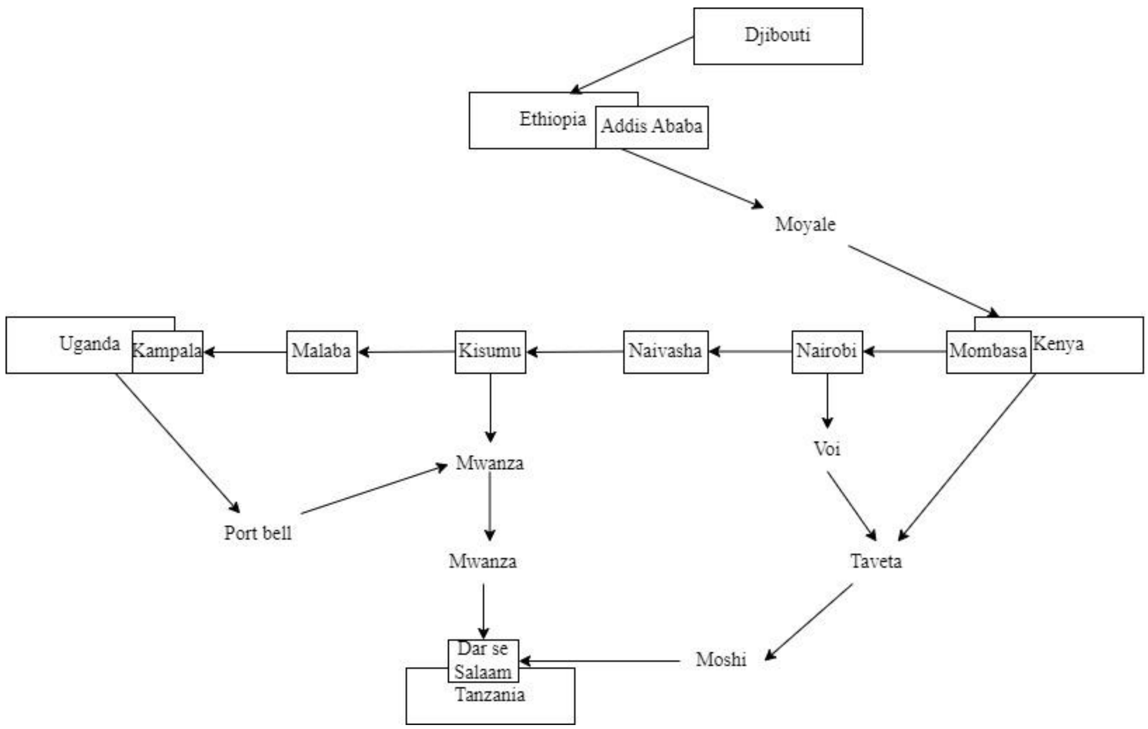

Figure 3-2 Selected railway lines in the region

Grouped network lines for analysis

Table 3-1 Grouped network lines for analysis

Cross Border	Route Lines
Ethiopia	Addis Ababa- Djibouti
Ethio-Kenya	Addis Ababa- Moyale
Kenya	Mombasa-Nairobi-Naivasha
Kenya-Uganda	Naivasha-Kisumu-Malaba
Uganda	Malaba - Kampala
Kenya-Tanzania	Mombasa-Taveta-Moshi
Tanzania	Dar es Salaam- Moshi/Arusha
Kenya-Tanzania	Nairobi-Voi-Taveta
Kenya-Tanzania	Kisumu-Mwanza-Isaka-Dar es Salaam
Uganda-Tanzania	Kampala-Port bell line-Mawaza

3.4 Data Analysis

3.4.1 Interoperability Analysis

Interoperability analysis was conducted using a Python-based interoperability model, where parameters were compared systematically. If two parameters had the same value, they were assigned a score of 1 otherwise, they were assigned 0. However, for speed and axle load, a conditional approach was applied a lower-speed passenger or freight train was considered interoperable on a higher-speed track, and a lower-axle-load train could operate on a higher-axle-load track. Conversely, heavier trains were not interoperable on lower-rated tracks, ensuring a realistic assessment of operational constraints.

3.4.2 Technical Barrier Analysis

The technical barriers were conducting using RCA to identify the root causes of problems by asking "Why" multiple times until the fundamental cause is uncovered. and FMEA to identify potential failure modes in a system, assess their effects, and prioritize actions based on the severity(S), occurrence(O), and detectability(D) of each failure.

$$RPN = S * O * D$$

Each factor is typically rated on a scale from 1 to 10, with higher values indicating greater risk. A higher RPN suggests a more critical failure mode that requires immediate attention.

3.5 Technical Solution Analysis Model Development

The developed model integrates the Analytic Network Process (ANP) for weighting and the Weighted Sum Model (WSM) for aggregation. There are five possible solution depending on seven criterions.

1. Standardize the track structure components (S1);
2. Upgrade track structure design (S2);
3. Dual/Variable gauge (S3);
4. Develop speed and load monitoring system (S4); and
5. Provision of transition switch (S5).

Criteria's to select appropriate possible practical technical solution for track structure interoperability are: -

1. Cost effectiveness (C1): it is crucial to assess the upfront and long-term including installation, maintenance, and operational financial impact of each proposed solution over the system's lifespan [108]–[110];
2. Implementation complexity (C2): this criterion evaluates how difficult it will be to implement each solution in terms of time, labor, and technical challenges [111], [112];
3. Operational efficiency (C3): this criterion examines how each solution contributes to the efficiency and reliability of the railway system's operations [108], [113], [114];
4. Scalability and flexibility (C4): this concerned on adaptability to the existing infrastructure, accommodated with future expansion, and modularity of the solutions [57], [108], [115] ;
5. Safety and durability (C5): this criterion assessed how each solution affects track stability, safety, and the ability to withstand the stresses of regular train traffic [116]–[118] ;
6. Environmental impact (C6): this criterion concerned on sustainability of materials and energy-efficient design [108]; and
7. Maintenance requirement (C7): this criterion assesses how much ongoing maintenance each solution requires [116], [119]–[124].

4 RESULTS AND DISCUSSIONS

This section aims to present and analyze the results of a study focused on enhancing the interoperability of railway track structures in East Africa. It provides an in-depth evaluation of the track structure interoperability scores for each railway network depends on each parameter, identifying key areas where compatibility issues exist. Furthermore, the section examines technical solutions proposed to address these challenges, such as standardization of track components, structure upgrades, and the introduction of transition mechanisms. The findings and implications are framed in the context of improving operational efficiency, safety, and overall connectivity within the region's rail network.

4.1 Interoperability of EARN

The analysis of track structure interoperability across the grouped railway networks on Fig 4-1 illustrated, the ET-ETKE-KE network group demonstrates full interoperability across all evaluated parameters, indicating uniformity in track structure design and operational standards, ensuring seamless connectivity. However, minor variations in ballast gradation suggest some differences in the track foundation materials, which may require stabilization measures to prevent degradation over time. In KE-KEUG-UG and KEUG-KETA3-TA significant drop in interoperability is observed at this transition, particularly in gauge, subgrade and sleeper-related parameters. The Ugandan (UG) network likely operates on a different track substructure, leading to reduced compatibility, observed discontinuity in axle load and speed interoperability further suggests that rolling stock operating in Kenya may face restrictions when entering Uganda, potentially requiring operational adjustments or track reinforcement.

Interoperability in KEUG-KETA-TA section improves significantly, with most parameters aligning closely across network groups. This indicates that the technical differences identified in the previous section are mitigated further along the network, likely due to infrastructure upgrades or standardized track specifications within the Tanzania railway segment. Speed and axle load interoperability remain largely stable, allowing for smoother operational transitions. The Uganda-Tanzania transition demonstrates a strong degree of interoperability, with scores consistently at 1 across most parameters. This suggests that both networks have been developed with similar structural and operational standards, ensuring smooth connectivity for freight and passenger operations. Minor inconsistencies in subgrade gradation, as indicated by slight variations in marker colors, could still require further assessment to prevent long-term track settlement issues. However, they are not standard gauge rails and not interoperable with SGR.

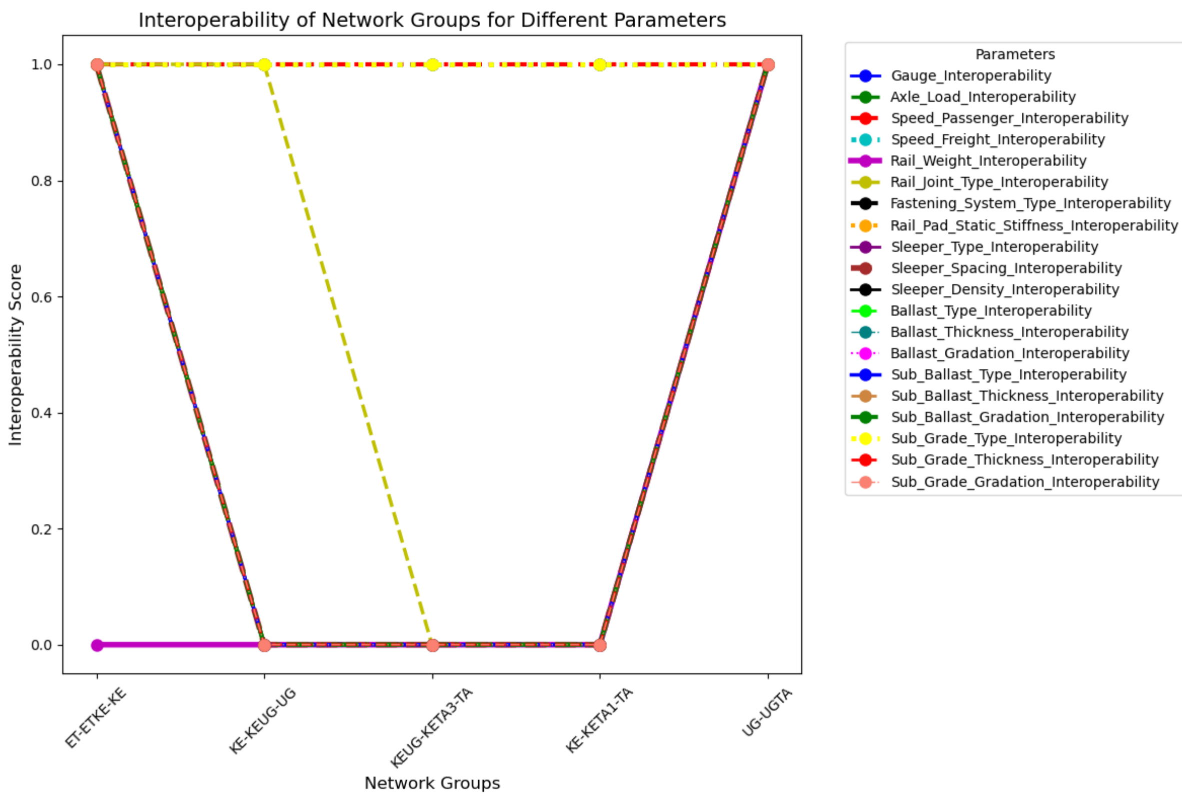

Figure 4-1 The interoperability of grouped railway lines due to each parameter.

Scenario 1- Freight Train from Ethiopia- Uganda

Consider a freight train transporting goods from Ethiopia to Uganda, passing through Kenya. Initially, the train operates seamlessly on Ethiopia's standard gauge railway (SGR), maintaining a uniform axle load, track gauge, and speed regulations. However, upon reaching the Kenya-Uganda border which is Naivasha, the train encounters a significant interoperability challenge due to a transition from standard gauge (1,435 mm) to meter gauge (1,000 mm). This gauge mismatch renders direct train movement impossible, necessitating a time-consuming and costly transshipment process where goods are unloaded from standard gauge wagons and reloaded onto meter gauge wagons. Furthermore, axle load limitations worsen the issue. Ethiopia and Kenya's SGR lines accommodate higher axle loads, but Uganda's meter gauge network has a lower axle load capacity. This discrepancy forces load reductions, increasing operational costs and inefficiencies. Speed limitations also contribute to non-interoperability, as the transition from high-speed SGR networks to lower-speed meter gauge lines results in extended travel times, disrupting supply chain reliability. The substructure differences, including variations in sub-grade material properties and track maintenance standards, further affect train stability and safety, requiring additional track reinforcement when transitioning between networks.

4.2 Technical Barriers

Through a comprehensive RPN analysis, several key factors, including track gauge, axle load, rail weight, and sleeper type, exceed the critical threshold of 200 (Annex-2), highlighting their significant influence on the interoperability and safety of the railway network. These parameters are crucial in determining the structural integrity and operational performance of the system. Variations in any of these factors can directly affect system reliability and load capacity, making them essential for maintaining smooth operations across diverse train types and ensuring long-term network stability.

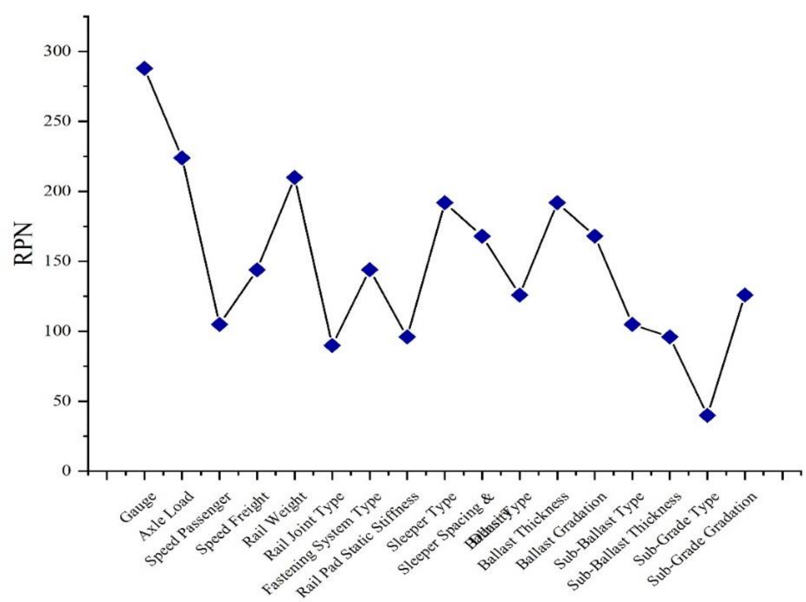

Figure 4-2 Critical technical barriers depend on RPN value

Significant variability is also observed across fastening system type, freight train speed, sleeper spacing and density, ballast thickness, and ballast gradation. These factors introduce variability in the RPN values, emphasizing their role in managing dynamic forces acting on the track during operation. The fastening system, for instance, plays a key role in absorbing and distributing forces, while freight speed affects the stress imposed on the track. Similarly, sleeper spacing and ballast properties influence track stability and load distribution, all of which contribute substantially to the risk of track degradation or failure.

In contrast, factors such as passenger train speed, rail joint type, rail pad static stiffness, ballast type, sub-ballast type, sub-ballast thickness, and sub-grade characteristics show lower RPN values, suggesting a relatively lower risk priority. While these elements are important, their impact on track performance is less critical compared to other parameters. However, their influence on track longevity and maintenance should not be overlooked, as over time, they can affect the overall operational efficiency and safety of the network.

Although RPN values fluctuate across different components, some areas show a downward trend in risk levels, indicating improvements in certain sub-structural components. These improvements, such as advancements in material quality and construction techniques, contribute to the enhanced durability and resilience of the track. The reduction in risk levels suggests that the sub-structural elements are becoming more robust, leading to fewer concerns regarding track degradation and greater operational stability.

4.3 Technical Solutions

It delves into the technical solutions critical for advancing interoperability within the East African EARN. These solutions are designed to overcome infrastructure disparities, optimize operational efficiency, and ensure the long-term sustainability of the region's interconnected railway systems. Fig 4-3 illustrates the weighted significance of defined criteria for enhancing track structure interoperability in the region for selected railway lines. Through analysis cost effectiveness, implementation complexity, operational efficiency are the critical criteria for implementing the solution.

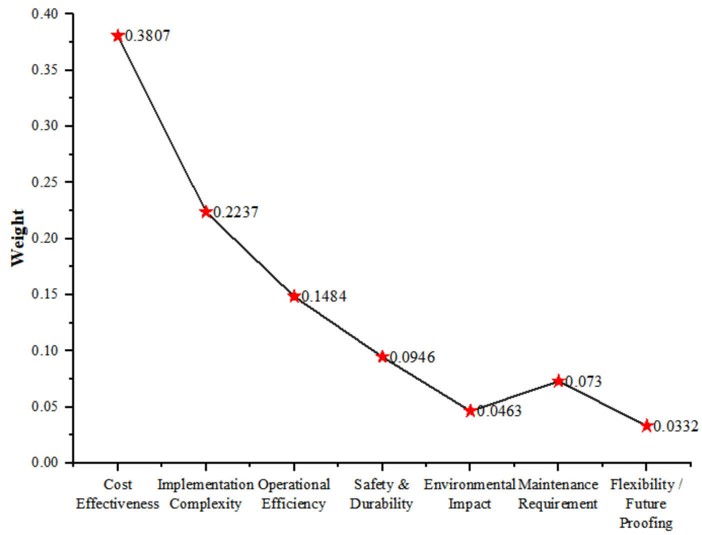

Figure 4-3 Weight of criteria

Considering the above criteria, Standardization of components (44.6%) is the most dominant solution, reflecting the region's recognition that unifying track structures, including rail gauge, fastening systems, and sleepers, is paramount for seamless cross-border operations. Upgrading the track structure (22%) is another critical solution, focusing on modernizing outdated rail systems to accommodate higher axle loads, faster speeds, and enhanced safety measures. This solution directly addresses the safety and durability criteria, ensuring that the region's infrastructure meets international standards, can withstand increasing operational demands, improve long-term maintenance requirements, as more durable materials and designs lead to fewer disruptions and lower operational costs.

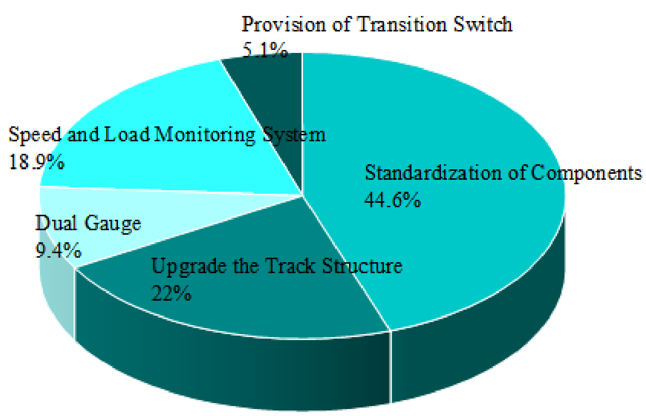

Figure 4-4 Weight of technical solutions

Speed and load monitoring systems (18.9%), ensure trains operate within safe parameters, directly enhancing operational efficiency and safety across the region helping to prevent overloading and minimizing wear on structure. Dual gauge (9.4%) by accommodating both narrow and standard gauges on the same track, it ensures continuous, efficient operations, reduces the need for transshipment, and improves cost-effectiveness. In parallel, provision of transition switches (5.1%) offers a practical solution to the challenge of gauge incompatibility, allowing trains to smoothly transition between tracks of different gauges. This enhances operational efficiency by eliminating bottlenecks at border crossings.

4.4 Validation of the Result

4.4.1 Expert Validation

To ensure a robust validation of the analysis of track structure interoperability within the EARN, it is recommended to engage railway experts and decision-makers through structured surveys or interviews. To assess the validity of the analysis model, a survey was administered via the JotForm online platform. The survey was structured to collect qualitative data on the model's effectiveness, incorporating sections for participants to rate the importance of each criterion within the analysis and evaluate its alignment with their practical decision-making needs.

Additionally, the questionnaire included an open-ended section to capture insights and suggestions for potential improvements. A carefully selected panel of 30 railway industry experts from various East African countries participated, ensuring a well-rounded and professional evaluation. These experts have backgrounds in various areas crucial to railway engineering, safety and infrastructure planning, project managers, and researchers. Their collective experience and roles in decision-making processes related to railway civil infrastructure interoperability will provide a well-rounded perspective. The survey was structured to gather ratings on a 1-5 scale, with 1 being not critical and 5 being extremely critical, across effect of track structure component on interoperability and 1 for not importance to highly important for technical solution for interoperability. Also, it included the open-ended questions on main technical barriers, and best practiced on interoperability was structured.

In the fig 4-5 below showed summarized survey result of experts. The analysis of the survey data reveals critical insights into the parameters influencing railway track structure interoperability. Notably, track gauge, axle load, rail weight, and sleeper type emerged as the most significant factors, underscoring their essential role in ensuring compatibility among various railway networks. The strong consensus on rail pad static stiffness, sleeper spacing, thickness of ballast, sub ballast, and sub grade further highlights their cruciality in maintaining track stability and structural integrity. Conversely, parameters such as sleeper density, sub-grade gradation, and fastening system type demonstrated lower consensus ratings, indicating a lack of uniformity in design practices and material choices amon different regions.

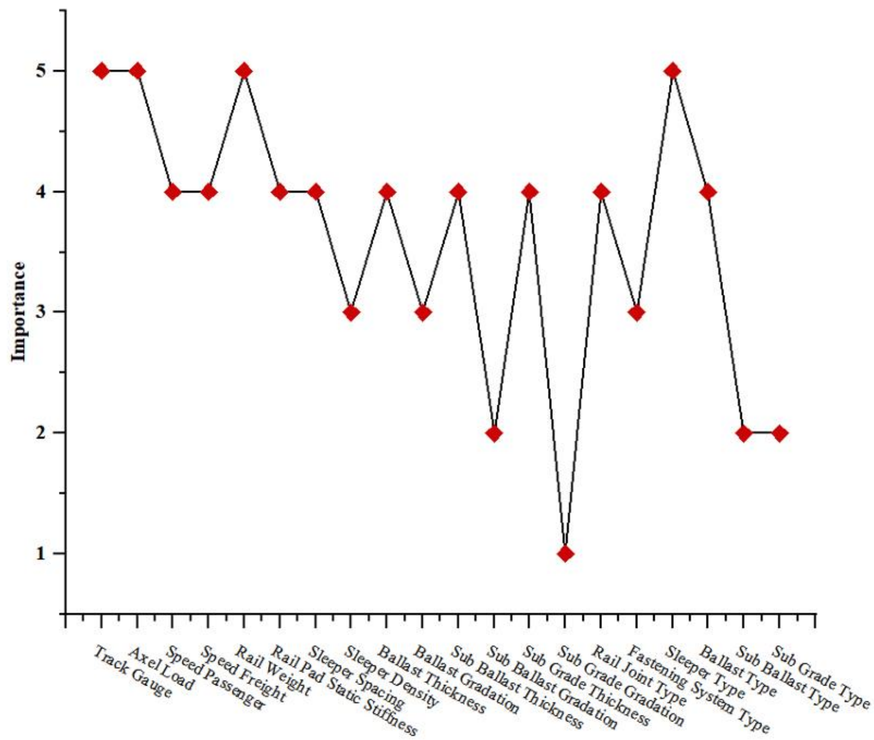

Figure 4-5 Summary of expert survey on track structure parameters on interoperability analysis

On analysis of technical solution of interoperability of track structure in the selected regions, the experts responded standardization of track structure scored, upgrade track structure design, and develop speed and load monitoring system are highly importance for track structure of EARN to become interoperable. Conversely dual gauge and provision of transition switch.

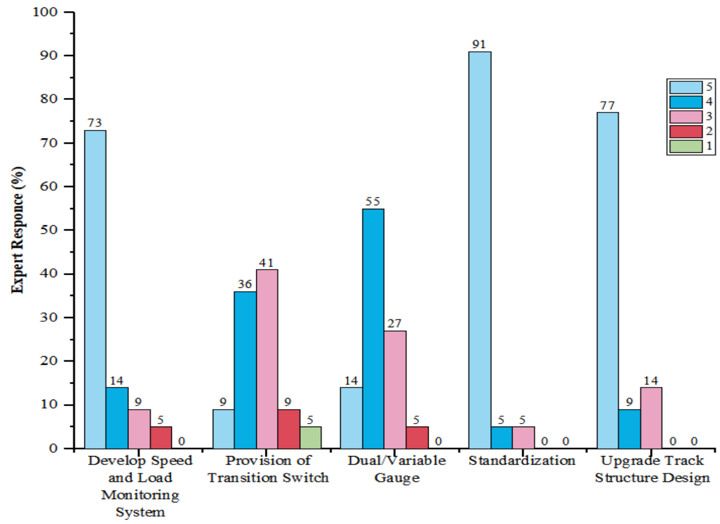

Figure 4-6 Expert response on technical solution.

4.4.2 Sensitivity Analysis

Sensitivity analysis was conducted to check the robustness of proposed technical solutions, considering changeability of the weight criteria. The weight for each criterion is changed with in ±10% and ±20%. On fig 4-7 illustrated standardization of track structure (S1) consistently exhibits the highest weight across all scenarios, indicating its strong resilience to changes in criteria weights.

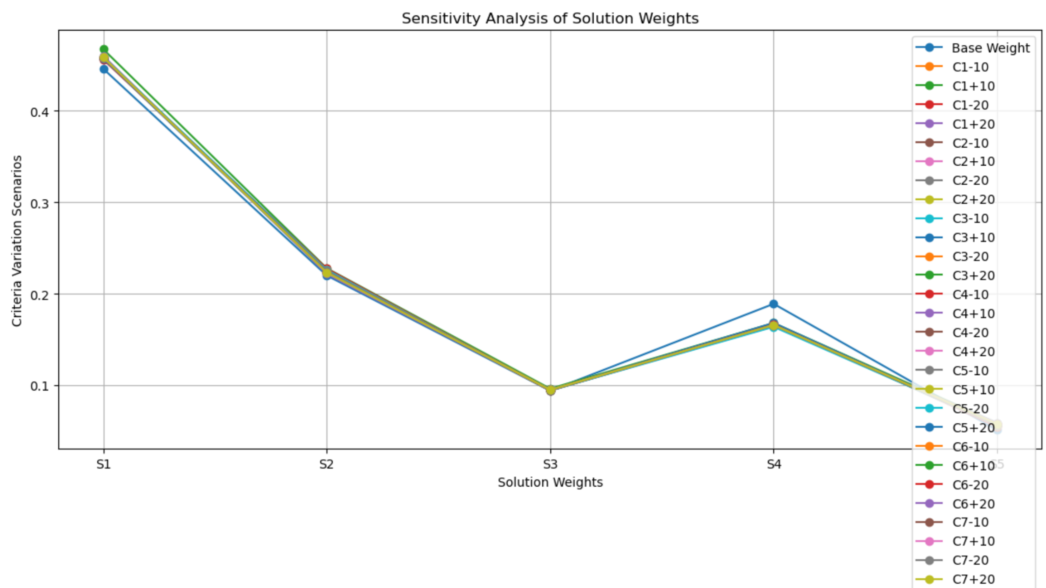

Figure 4-7 Sensitivity analysis on variation of criteria with ±10% and ±20%

This demonstrating its robustness and dominance as a preferred technical solution for railway interoperability. Conversely, dual/ variable gauge (S3) maintains the lowest weight, suggesting limited influence under different weighting conditions. The variations in upgrade track structure design (S2) and developed speed and load monitoring system (S4) weights remain relatively minor, indicating a degree of stability but with some sensitivity to specific criteria adjustments.

Provision of transition switch (S5) consistently maintains the lowest weight across all cases, reflecting its minimal impact and low sensitivity to changes in criteria weights. Overall, S1 and S2 emerge as the most dominant solutions, while S3 and S5 contribute the least, highlighting the varying significance of technical solutions in addressing interoperability challenges. The close alignment of most curves suggests that the ranking of solutions is not highly sensitive to moderate changes in criteria weights, reinforcing the reliability of the proposed solutions in decision-making.

5 CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORKS

5.1 Conclusions

Railway track structure interoperability is a cornerstone for achieving efficient, seamless train operations and fostering regional connectivity. As explained the previous chapters, the intention of the research was to compressively analyze the interoperability of railway track structure in EARN integrating insights from literature, rigorous methodology, and advanced analytical techniques to identifying the current state of interoperability, critical technical barriers of track structures by connecting the cross-border lines, and proposing the technical solutions.

Based on analysis performed, it has been found that interoperability of track structure depends on each parameter, due to high variation of parameters Kenya and Uganda, Kenya and Tanzania can't cross the border of each other. While Ethiopia to Kenya, Uganda to Tanzania can cross the border each other. It indicated that they have match closed track structure parameters. The RPN value of parameters increase the negative effect of parameters in the track structure of the region also increases.

By leveraging advanced engineering assessments, benchmarking best practices, and employing multi-criteria decision-making methodologies, this research provides actionable solutions for harmonizing the system across the region. Standardization of track components (44.6%), infrastructure upgrades (22%), develop speed and load monitoring system (18.9%), and the introduction of dual gauge systems (9.4%) or transition switches (5.1%) are emphasized as critical measures. Finally, validation step revealed that the devised methodology resulted close match for the expert survey and sensitivity analysis use this system to analyze interoperability barriers and solutions

5.2 Recommendations for Future Works

The present work has attempted to analysis of track structures interoperability in EARN by determination of the current situation of interoperability between the selected lines, identify the technical challenge, and solutions. Asper the limitation of the study, future work could involve: -

1. Additional railway track parameters, such as the geometry, turnouts and level crossing have the potential to be incorporated into the analysis. By doing so, a more comprehensive depiction of the track's interoperability can be achieved, encompassing broader spectrum;

2. By integrating the track structure interoperability analysis with rolling stock, a more enhanced interoperability analysis can be achieved. This improved analysis has the capability to assess both the structural and operational condition of the railway track system.
3. Conduct comprehensive studies of lifecycle cost analysis to evaluate the long-term economic impacts and cost savings associated with proposed solutions like dual-gauge systems and advanced monitoring technologies.

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ANNEXES

Annex 1: Python syntax to calculate interoperability score

```
import pandas as pd

import matplotlib.pyplot as plt

import seaborn as sns

# Load the csv file from the file path then standardize them.

data=pd.read_csv('C:\\hiwisho\\EARN_Final_1.csv')

print(data)

# Define network groups

groups = {

    "ET-ETKE-KE": ["ET", "ETKE", "KE"],

    "KE-KEUG-UG": ["KE", "KEUG", "UG"],

    "KEUG-KETA3-TA": ["KEUG", "KETA3", "TA"],

    "KE-KETA1-TA": ["KE", "KETA1", "TA"],

    "UG-UGTA": ["UG", "UGTA"]

# Function to check interoperability within a group depends on Gauge

def check_interoperability(group):

    gauges = df[df["Network_Line"].isin(group)]["Gauge(mm)"].unique()

    return 1 if len(gauges) == 1 else 0  # Score 1 if all gauges are the same, else 0

# Compute interoperability scores for each parameters

group_interoperability = {group: check_interoperability(networks) for group, networks in groups.items()}

result_df = pd.DataFrame(list(group_interoperability.items()), columns=["Network_Group", "Gauge_Interoperability"])

# Plot Bar Chart

plt.figure(figsize=(8, 5))

sns.barplot(x="Network_Group", y="Gauge_Interoperability", data=result_df, palette="viridis")

plt.ylim(0, 1.2)

plt.xlabel("Network Groups", fontsize=12)

plt.ylabel("Gauge Interoperability", fontsize=12)

plt.title("Gauge Interoperability of Network Groups", fontsize=14)

plt.xticks(rotation=45)

plt.grid(axis="y", linestyle="--", alpha=0.7)


# Show plot

plt.show
```

Annex 2 - The RCA and FMEA result

Parameter	Failure Mode	Effect	Severity (S)	Likelihood (L)	Detectability (D)	RPN
Gauge	Different gauges across networks	Operational delays, increased costs, and complexity in cross-border transport	9	8	4	288
Axle Load	Varying axle load capacities	Potential for track damage, reduced safety, and higher maintenance costs	8	7	4	224
Speed Passenger	Different speed limits	Delays and inefficiencies in regional passenger travel	7	5	3	105
Speed Freight	Varying freight speed limits	Increased operational delays and inefficiency in cross-border freight transport	8	6	3	144
Rail Weight	Differences in rail weight	Potential track failure, uneven wear, and higher maintenance costs	7	6	5	210
Rail Joint Type	Varying rail joint types	Track instability, increased maintenance, and safety concerns	5	6	3	90
Fastening System Type	Inconsistent fastening systems	Increased wear, track instability, and safety risks	8	6	3	144
Rail Pad Static Stiffness	Variation in rail pad stiffness	Uneven load distribution, increased track degradation, and higher operational costs	6	4	4	96
Sleeper Type	Varying sleeper materials (wood, steel, PSC)	Track instability, increased maintenance costs, and uneven load distribution	8	6	4	192
Sleeper Spacing & Density	Inconsistent sleeper spacing and density	Uneven load distribution, reduced track stability, and increased maintenance costs	7	6	4	168
Ballast Type	Variation in ballast material (gravel, crushed rock, etc.)	Poor track drainage, settlement issues, and increased track failure	7	6	3	126
Ballast Thickness	Varying ballast thickness	Track instability, increased track deformation, and frequent repairs	8	6	4	192
Ballast Gradation	Inconsistent ballast compaction and gradation	Poor track alignment, increased risk of derailment, and uneven load distribution	7	6	4	168
Sub-Ballast Type	Different sub-ballast materials	Uneven support for track, increased track deformation, and higher maintenance costs	7	5	3	105
Sub-Ballast Thickness	Variation in sub-ballast thickness	Track instability and increased risk of track deformation	8	6	2	96
Sub-Grade Type	Differences in sub-grade materials	Reduced track support, increased track settlement, and deformation	5	2	4	40
Sub-Grade Gradation	Inconsistent sub-grade compaction and gradation	Poor track alignment, increased risk of derailment, and uneven load distribution	7	6	3	126

Annex 3- Pairwise Comparisons for Criteria and Technical Solutions.

1. **Pairwise comparison for criteria**

	C1	NC1	C2	NC2	C3	NC3	C4	NC4	C5	NC5	C6	NC6	C7	NC7	SC	AC
C1	1	0.4299	4	0.625	3	0.3659	5	0.3333	7	0.2877	5	0.3191	5	0.2381	2.599	0.371
C2	1/4	0.1075	1	0.1563	3	0.3659	5	0.3333	5	0.2055	3	0.1915	3	0.1429	1.5027	0.215
C3	1/3	0.1433	1/3	0.0521	1	0.122	3	0.2	5	0.2055	3	0.1915	3	0.1429	1.0572	0.151
C4	1/5	0.086	1/5	0.0313	1/3	0.0407	1	0.0667	3	0.1233	3	0.1915	3	0.1429	0.6822	0.097
C5	1/7	0.0614	1/5	0.0313	1/5	0.0244	1/3	0.0222	1	0.0411	1/3	0.0213	3	0.1429	0.3445	0.049
C6	1/5	0.086	1/3	0.0521	1/3	0.0407	1/3	0.0222	3	0.1233	1	0.0638	3	0.1429	0.5309	0.076
C7	1/5	0.086	1/3	0.0521	1/3	0.0407	1/3	0.0222	1/3	0.0137	1/3	0.0213	1	0.0476	0.2835	0.041
SUM	2.3262	1	6.4	1	8 1/5	1	15	1	24.333	1	15.667	1	21	1	7	1

2. **Pairwise comparison for technical solutions**

C1	**S1**	**NS1**	**S2**	**NS2**	**S3**	**NS3**	**S4**	**NS4**	**S5**	**NS5**	**NSUM**	**ASUM**
S1	1	0.4976	3	0.5625	7	0.4884	3	0.439	5	0.3846	2.3721	0.4744
S2	1/3	0.1659	1	0.1875	3	0.2093	2	0.2927	2	0.1538	1.0092	0.2018
S3	1/7	0.0711	1/3	0.0625	1	0.0698	1/3	0.0488	3	0.2308	0.4829	0.0966
S4	1/3	0.1659	1/2	0.0938	3	0.2093	1	0.1463	2	0.1538	0.7691	0.1538
S5	1/5	0.0995	1/2	0.0938	1/3	0.0233	1/2	0.0732	1	0.0769	0.3666	0.0733
	2.0095	1	5.3333	1	14.333	1	6.8333	1	13	1	5	1
C2	**S1**	**NS1**	**S2**	**NS2**	**S3**	**NS3**	**S4**	**NS4**	**S5**	**NS5**	**NSUM**	**ASUM**
S1	1	0.4976	3	0.6164	3	0.2903	5	0.5245	7	0.3333	2.2622	0.4524
S2	1/3	0.1659	1	0.2055	3	0.2903	3	0.3147	5	0.2381	1.2145	0.2429
S3	1/3	0.1659	1/3	0.0685	1	0.0968	1/3	0.035	3	0.1429	0.509	0.1018
S4	1/5	0.0995	1/3	0.0685	3	0.2903	1	0.1049	5	0.2381	0.8013	0.1603
S5	1/7	0.0711	0.2	0.0411	1/3	0.0323	0.2	0.021	1	0.0476	0.213	0.0426
	2.0095	1	4.8667	1	10.333	1	9.5333	1	21	1	5	1
C3	**S1**	**NS1**	**S2**	**NS2**	**S3**	**NS3**	**S4**	**NS4**	**S5**	**NS5**	**NSUM**	**ASUM**
S1	1	0.4976	3	0.6164	7	0.4884	3	0.3913	5	0.2941	2.2879	0.4576
S2	1/3	0.1659	1	0.2055	3	0.2093	3	0.3913	5	0.2941	1.2661	0.2532
S3	1/7	0.0711	1/3	0.0685	1	0.0698	1/3	0.0435	3	0.1765	0.4293	0.0859
S4	1/3	0.1659	1/3	0.0685	3	0.2093	1	0.1304	3	0.1765	0.7506	0.1501
S5	1/5	0.0995	1/5	0.0411	1/3	0.0233	1/3	0.0435	1	0.0588	0.2662	0.0532
	2.0095	1	4.8667	1	14.333	1	7.6667	1	17	1	5	1

C4	S1	NS1	S2	NS2	S3	NS3	S4	NS4	S5	NS5	NSUM	ASUM
S1	1	0.533	3	0.6338	3	0.2432	5	0.5245	7	0.3333	2.2678	0.4536
S2	1/3	0.1777	1	0.2113	5	0.4054	3	0.3147	5	0.2381	1.3471	0.2694
S3	1/5	0.1066	1/5	0.0423	1	0.0811	1/3	0.035	3	0.1429	0.4078	0.0816
S4	1/5	0.1066	1/3	0.0704	3	0.2432	1	0.1049	5	0.2381	0.7633	0.1527
S5	1/7	0.0761	1/5	0.0423	1/3	0.027	1/5	0.021	1	0.0476	0.214	0.0428
	1.8762	1	4.7333	1	12.333	1	9.5333	1	21	1	5	1
C5	**S1**	**NS1**	**S2**	**NS2**	**S3**	**NS3**	**S4**	**NS4**	**S5**	**NS5**	**NSUM**	**ASUM**
S1	1	0.3659	3	0.2308	5	0.4225	1	0.385	5	0.3571	1.7609	0.3522
S2	1/3	0.122	1	0.0769	1/3	0.0282	1/5	0.077	1	0.0714	0.3754	0.0751
S3	1/5	0.0732	3	0.2308	1	0.0845	1/5	0.077	2	0.1429	0.6082	0.1216
S4	1	0.3659	5	0.3846	5	0.4225	1	0.385	5	0.3571	1.9148	0.383
S5	1/5	0.0732	1	0.0769	1/2	0.0423	1/5	0.077	1	0.0714	0.3407	0.0681
	2.7333	1	13	1	11.833	1	2.6	1	14	1	5	1
C6	**S1**	**NS1**	**S2**	**NS2**	**S3**	**NS3**	**S4**	**NS4**	**S5**	**NS5**	**NSUM**	**ASUM**
S1	1	0.5056	3	0.6164	3	0.2432	5	0.524	9	0.3913	2.2811	0.4562
S2	1/3	0.1685	1	0.2055	5	0.4054	3	0.315	5	0.2174	1.3115	0.2623
S3	1/5	0.1011	1/3	0.0685	1	0.0811	1/3	0.035	3	0.1304	0.4161	0.0832
S4	1/3	0.1685	1/3	0.0685	3	0.2432	1	0.105	5	0.2174	0.8026	0.1605
S5	1/9	0.0562	1/5	0.0411	1/3	0.027	1/5	0.021	1	0.0435	0.1888	0.0378
	1.9778	1	4.8667	1	12.333	1	9.5333	1	23	1	5	1
C7	**S1**	**NS1**	**S2**	**NS2**	**S3**	**NS3**	**S4**	**NS4**	**S5**	**NS5**	**NSUM**	**ASUM**
S1	1	0.4976	3	0.6164	5	0.4054	5	0.524	7	0.3333	2.3773	0.4755
S2	1/3	0.1659	1	0.2055	3	0.2432	3	0.315	5	0.2381	1.1674	0.2335
S3	1/5	0.0995	1/3	0.0685	1	0.0811	1/3	0.035	3	0.1429	0.4269	0.0854
S4	1/3	0.1659	1/3	0.0685	3	0.2432	1	0.105	5	0.2381	0.8206	0.1641
S5	1/7	0.0711	1/5	0.0411	1/3	0.027	0.2	0.021	1	0.0476	0.2078	0.0416
	2.0095	1	4.8667	1	12.333	1	9.5333	1	21	1	5	1

Annex 4- Sensitivity analysis matrix

	BW	C1-10	C1+10	C1-20	C1+20	C2-10	C2+10	C2-20	C2+20	C3-10	C3+10	C3-20	C3+20	C4-10	C4+10	C4-20	C4+20
S1	0.446	0.457	0.467	0.456	0.46	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.458	0.458
S2	0.22	0.226	0.228	0.227	0.222	0.224	0.225	0.224	0.226	0.224	0.225	0.224	0.226	0.224	0.225	0.224	0.226
S3	0.094	0.094	0.096	0.094	0.095	0.094	0.095	0.094	0.095	0.095	0.094	0.095	0.094	0.095	0.094	0.095	0.094
S4	0.189	0.167	0.168	0.168	0.165	0.166	0.166	0.166	0.166	0.166	0.166	0.167	0.165	0.166	0.166	0.166	0.166
S5	0.051	0.056	0.059	0.055	0.059	0.057	0.056	0.058	0.056	0.057	0.057	0.057	0.057	0.057	0.057	0.057	0.056

	C5-10	C5+10	C5-20	C5+20	C6-10	C6+10	C6-20	C6+20	C7-10	C7+10	C7-20	C7+20
S1	0.459	0.458	0.459	0.457	0.458	0.458	0.458	0.458	0.458	0.459	0.458	0.459
S2	0.225	0.224	0.226	0.223	0.224	0.223	0.224	0.224	0.225	0.223	0.225	0.223
S3	0.094	0.095	0.094	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095	0.095
S4	0.165	0.167	0.164	0.168	0.166	0.166	0.166	0.166	0.166	0.166	0.166	0.166
S5	0.057	0.057	0.057	0.057	0.057	0.058	0.057	0.057	0.057	0.058	0.057	0.058