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COLLEGE OF TECHNOLOGY AND BUILT ENVIRONMENT

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INTEROPERABILITY ANALYSIS OF ROLLING STOCK SUBSYSTEMS IN THE EAST AFRICAN RAILWAY NETWORK

A Thesis in Railway Engineering Rolling Stock Stream

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A Thesis

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Approval Page

This is to certify that the thesis prepared by **Miss. Bethel Lemma Bizuneh** entitled "**Interoperability Analysis of Rolling Stock Subsystems in the East African Railway Network**" and submitted as a partial fulfillment for the award of the Degree of Master of Science in Railway Engineering (Rolling Stock), complies with the regulations of the university and meets the accepted standards with respect to originality, content, and quality.

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Declaration

I hereby declare that this thesis entitled **"Interoperability Analysis of Rolling Stock Subsystems in the East African Railway Network"** was prepared by me, with the guidance of my advisor. The work contained herein is my own except where explicitly stated otherwise in the text, and this work has not been submitted, in whole or in part, for any other degree or professional qualification. Parts of this work have been published in [state previous publication].

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Abstract

With the ongoing expansion and modernization of the East African railway infrastructure, ensuring seamless transportation is crucial for the network's efficiency and success. However, studies carried out on interoperability in East Africa are hardly seen specifically, lacks equivalent engineering analysis in the East African context. Additionally, instead of building railways that match the regional networks, railway infrastructure projects are driven by the preferences and funding of foreign suppliers. For that reason, this thesis aims to assess the current state of railway interoperability in East Africa using the Weight Sum multicriteria decision-making model, which exhibited that the region significantly lags behind the 2007 regional railway master plan targets, indicating poor interoperability across East Africa. Subsequently, to guide the verdict of stakeholders by evaluating the impact of the rolling stock subsystem on interoperability, Buckley FUZZY Analytical Hierarchy Process (F-AHP) multicriteria decision-making model is used. Consequently, the parameter criteria with physical barriers having 58% higher impact, followed by safety, technical conversion, and operational disruption. For the main parameters like track gauge %, axle load 18%, wheel-rail interface 10%, and the like are ranked accordingly. From all parameters listed, the axle load, an engineering analysis was conducted to assess the mechanical compatibility using static structural simulation with ANSYS Workbench, which demonstrated operating the Ethiopian-Djibouti railway wheel (capacity of 25t) on the Tanzania-Zambia Railway track (design capacity 20t). The material change used to represent the TAZARA rail track is much softer than EDR; therefore, the results show that, as load varies by 20%, stress varies by 42.58%, indicating higher stress with increased load. Deformation exhibits the same pattern, at 43.07% indicate that the rolling stock subsystem parameters have their own contribution. Therefore, strengthening subsystem coordination, harmonizing axle load standards, and considering parameter-wise can improve connectivity. It is recommended that East African railway authorities analyze at a more engineering level and consider an overall compatibility check to promote safe, seamless, and sustainable cross-border railway operations.

Keywords: Interoperability, Rolling Stock, East Africa, axle load variation

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Abbreviations and Acronyms

AAR	**Association of American Railroads**
AfCFTA	African Continental Free Trade Area
AREMA	American Railway Engineering and Maintenance-of-Way Association
BIM	Building Information Modeling
BNSF	Burlington Northern Santa Fe
BRI	Belt and Road Initiative
CAD	Computer-Aided Design software
CCECC	China Civil Engineering Construction
CCS	Control-Command and Signaling
CEF	Connecting Europe Facility
COTIF	Conversion concerning international carriage by Rail
CREC	China Railway Engineering Corporation
CRRC	China Railway Rolling Stock Corporation
CRS	Chinese Railway Standards
CSU	Central South University
CTP	Common Transport Policy
DC	Direct Current
DFH	Dong Fang Hong
EAC	East African Community
EDR	Ethiopia-Djibouti Railway
EMU	Electric Multiple Unit
ERCE	Ethiopian Railway Corporation
ERTMS	European Rail Traffic Management System
ESCAP	Economic and Social Commission for Asia and the Pacific
ETCS	European Train Control System
EU	European Union
FEA	Finite Element Analysis
FRA	Federal Railroad Administration
FSA	Functional System Architecture
GIS	Geographic Information System
HSR	High Speed Railway
INSTC	International North–South Transport Corridor
IPA	Instrument for Pre-Accession Assistance
LEAP	Leading Engineering Application Provider
LICs	Low-Income Country

MCDA	Multi-Criteria Analysis
MEC	Mobile Edge Computing
MENA	Middle East and North Africa
NATO	North Atlantic Treaty Organization
NOEMIE	Noise Emission Measurements for High-Speed Interoperability in Europe
OEMC	Orient/East Med Corridor
OPE	Operation and Traffic Management
OSJD	Organization for Co-operation between Railways
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QGIS	Quantum Geographic Information System
RAM	Reducing traffic and massive transportation liability, Availability, and Maintainability
RTS	Rail Technical Strategy
SCTC	South Caucasian Transport Corridor
SERA	Single European Railway Area
SM	Strategic Modes
SMGS	Surface Movement Guidance and Control
SOA	Service-Oriented architecture
STEEPLE	Social, Technological, Economic, Environmental, Political, Legal, and Ethical factors
SWOT	Strengths, Weaknesses, Opportunities, and Threats
	Trans-Maghreb Multimodal
TAZARA	Tanzania- Zambia Railway Authority
TENT	Trans-European Transport Network
TIC	Technological Innovation Capabilities
TMC	Trans-Maghreb Multimodal
TSI	Technical Specifications for Interoperability
UIC	International Union of Railways
WAG	Freight Wagons TSIs
WSM	Weight Sum Method

Nomenclatures

Symbol	Description	Unit
AR	Aspect Ratio	-
$\wedge D$	Distance Reduction	km
$D_{Existing\ railway}$	Total distances of Existing Railway	km
$D_{New\ railway}$	Total distances of the New Railway	km
F	Applied load Vector	N
J_r	Jacobian Ratio	-
K	Global Stiffness Matrix	-
Qo	Orthogonal Quality	-
S_k	Element Skewness	-
$\wedge T$	Time Reduction	hr.
$T_{Existing\ railway}$	Total Time of the Existing Railway	hr.
$T_{New\ railway}$	Total Time of the New Railway	hr.
U	Nodal Displacement	m
U_x	Nodal Displacement in X-direction	m
U_y	Nodal Displacement in Y-direction	m
U_z	Nodal Displacement in Z-direction	m
M	Coefficient of Friction	-

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Chapter 1 Introduction

1.1 Background

The railway industry has played a vital role in serving customers for over a decade by transporting passengers and goods nationwide, contributing significantly to the global economy through cost-effective transportation[1], while also alleviating traffic congestion and facilitating large-scale transportation. The railway industry mainly contains three major parts: infrastructure, rolling stock, and traction. The term rolling stock (railway vehicle) in the rail transport industry refers to the moving part that is guided by the track [1], [2], including power or unpowered vehicles like freight, locomotives, and passenger cars. The rolling stock provides quality service to passengers, which is highly dependent upon the efficient movement of rolling stock required per trip between the provided rolling stock capacity and the passengers' demand for transportation[3]. Hence, the availability of rolling stock for operation with the existing line can determine how well the railway transportation system is being effectively used. Moreover, as countries evolve to modernization, they expand their communication to their neighbouring countries, and the need for movement across different nations arises.

Hence, realized from experience, if this industry is restricted to one country, it will not go hand in hand with the rapid expansion and modernization of the global industry, to further extension and interconnectivity of countries, leading to the concept of interoperability. The developed countries reap the benefits by clearly defining [4], [5], [6], [7], [8], [9], and allowing their trains to be accessible to any part of the network, promoting market openness and integration of rail transport systems [10], [11] which was looked at by the European Community [12]. For that reason, the European Union has introduced safety and interoperability directives to ensure that rail systems are safe and do not disrupt train operations across different countries [13], [14]. Harmonizing specifications of rolling stock, signaling, command, and control systems will help to reduce operating costs and enhance efficiency [15] leading to the use of the railway industry to its full capacity.

However, across developing countries in Africa, the progress of the concept of interoperability, especially in East Africa, is very little. The first railway in Africa was opened in 1853 in Egypt [16] and, in the majority of the countries in Africa, railway was introduced by colonization [17] to transport agricultural products, slaves, minerals, and many more items. In March 1899, Cecil Rhodes (British colonialist) met Wilhelm II (German emperor) in Berlin to discuss ideas for a telegraph and railway across Africa, his personal 'Cape-to-Cairo' [18] interconnecting the southern part to the northern part of Africa [19], showing how deep-rooted the concept of interoperability is. Moreover, East Africa's railway lines were constructed at the turn of the 19th century when European powers were embroiled in a "scramble for Africa". Despite the harsh reality by which the railway industry was introduced, many countries strive to carry on the railway transportation system by enhancing its efficiency [20] because of its benefits like cost-effectiveness, environmental friendliness, reliability, safety, and being ideal for both goods and passenger transportation on land, regarding reducing traffic and massive transportation. New investments in infrastructure are making possible routes and modes of connectivity that were initially imagined and planned when East Africa was under German and British rule [21]. Following that, the East African community introduced its own master plan, leading to the interconnectivity aspect in 2007 [22], with the main purpose of strengthening regional cooperation, infrastructure, and development via full political, economic, and cultural integration of the member states. The East African railway master plan, prepared by the East African community, consists of eight countries: Tanzania, Kenya, Uganda, Rwanda, Burundi, and also a later step that would expand the railway network to South Sudan, Ethiopia, and the Democratic Republic of the Congo, as shown in the Appendix A illustrating both the proposed line and the existing one. Their main objective is to work seamlessly throughout the master plan, aiming for good interoperability, leading to standardizing the gauge and coming to an agreement to make the East African railway network safe, efficient, and effective.

Additionally, most existing academic and technical studies on railway interoperability in Africa approach the subject from a macro-level or policy-oriented perspective [23][24]. While they provide a limited analysis of rolling stock subsystem compatibility, which plays a role in mechanical, structural, and operational interoperability. In contrast, the European technical specification for interoperability (TSI) emphasizes that rolling stock must meet a wide range of subsystem-level requirements, including axle load, braking performance, wheel/rail interface geometry, traction characteristics, and communication systems to ensure safe and efficient cross-network operations [25]. Despite this, comprehensive subsystem-level analysis has hardly been conducted for the East African railway, resulting in a significant knowledge gap in understanding how technical mismatches influence safety, maintenance cycles, asset lifespan, and operational continuity.

Thus, this thesis builds upon an international framework by identifying the current interoperability status of East African railways and extracting the rolling stock subsystem from the TSI framework as a reference model. It employs an impact ranking using the Buckley FUZZY Analytical Hierarchical Process(F-AHP) approach to evaluate each subsystem's relative importance to the others. Subsequently, the thesis focuses on axle load, which is chosen as a key structural link between rolling stock and track infrastructure, directly influencing track degradation, structural stress, and asset life [26]. According to European and international railway engineering, subsystems have interdependence, such as rolling stock being dependent on the track characteristics of a given corridor [27][1]. and conducts a static structural analysis using ANSYS to examine compatibility between rolling stock designed for the Ethiopia-Djibouti standard-gauge railway (25-ton axle load limit) and the TAZARA meter-gauge track (20-ton axle load).

1.2 Problem Statement

Despite a decline in market share in 1960, the European railway system underwent significant reforms in three phases, culminating in the introduction of open access for freight and the establishment of safety requirements and certification directives[13]. All of these measures had a profound impact on the industry, improving regional trade and logistics, facilitating the transportation of large loads, and unlocking corridor potential [28]. Later, East Africa set its own goal to elevate the railway industry [29], along with the East African master plan [30], aiming for better interoperability. However, during this process, many obstacles remained because of the lack of research in this area, particularly regarding subsystem interoperability, which lacks equivalent engineering analysis despite European standards emphasizing the central role of rolling stock subsystems in achieving interoperability [29][31]. Specifically, technical barriers of rolling stock, such as axle load variation, tunnel clearance, and train length, significantly affect railway interoperability [32]. There is also concern that railway infrastructure projects are often driven more by international suppliers' preferences and financing rather than tailored to meet the needs of regional networks [33]. Due to insufficient focus on customized technological choices and data-driven approaches in East African countries [34], interoperability faces major challenges, especially regarding axle load compatibility between rolling stock and track infrastructure. Thus, taking the two most interoperability connections that are the Ethiopia-Djibouti railway (EDR) and the Tanzania-Zambia railway (TAZARA), which operate under different infrastructure design specifications, especially in terms of axle load capacity. This difference raises concerns regarding infrastructure safety and long-term performance of the railway track if the rolling stock designed for higher axle loads operates on infrastructure with lower design capacity. However, despite the importance of this issue, limited studies have quantitatively evaluated the mechanical interaction between wheel and rail in different axle load scenarios in the context of East African railway interoperability.

Hence, this thesis analyzes the structural response of the wheel-rail contact system when an EDR wheel operates on the TAZARA design load(20t) and a higher loading scenario(25t). If not properly examined through engineering simulation, this gap complicates assessments by railway authorities and policymakers concerning the impacts of subsystem incompatibility on safety, asset durability, and operational reliability. Lastly, without subsystem-level engineering analysis and scientifically based route evaluation methods, East African railway planners, policymakers, and operators lack the empirical data needed to design effective interoperability systems, select compatible rolling stock, and modernize legacy corridors. The rolling stock subsystem is interconnected with other systems, such as the track, which greatly influences overall performance [27][1]. Therefore, this thesis addresses the knowledge gap and the lack of technical subsystem analysis of rolling stock interoperability in East Africa, with a particular focus on axle load compatibility and its structural implications.

1.3 Significance of the Thesis

This thesis is significant because it offers a clear and structured assessment of the degree of rolling stock interoperability within the East African railway network, an area that has received limited academic and technical attention. It will show as the starting point before making a billion-dollar railway investment. Moreover, by examining how well rolling stock systems across the region can operate together. The findings contribute directly to improving regional railway planning, coordination, and decision-making by identifying compatibility challenges and areas where harmonization is needed. In addition, the information can be useds to fill the dataset and be a foundation for future research.

1.3.1 Research Question

This is the research question of the overall thesis:

1. What are the existing practices of interoperability in the East African railway network & how to analyze them?
2. Which rolling stock subsystem parameter most critically influences interoperability?
3. What is the impact of the axle load variation of the rolling subsystem parameter on the interoperability of the East African railway?

1.4 Objective of the Thesis

1.4.1 General Objective

The main objective of the thesis is to analyze the interoperability of rolling stock subsystems in the East African Railway Network and to suggest solutions to enhance rolling stock cross-border operations and technical compatibility.

1.4.2 Specific Objectives

The thesis addresses the following specific objectives:

1. To analyze the existing practice of interoperability in the East African railway network.
2. To evaluate the rolling subsystem parameter impact on the interoperability.
3. To the effect of axle-load variation under the scenario of the Ethio–Djibouti Railway (EDR) wheel operating on the Tanzina-Zambia railway TAZARA track.

1.5 Scope and Limitation of the Thesis

While the thesis aims to analyze the interoperability of rolling stock subsystems for the East Africa Railway Network, it is important to recognize certain delimitations that define its scope and boundaries, such as Geographical Focus, which primarily concentrates on the East Africa region, specifically the member countries of the East African master plan candidate. Also does not include the technical and operational interoperability aspect of the East African railway systems issue, such as signaling technology, communication protocol, traction performance, scheduling, or real-time operational coordination. These delimitations guide the thesis process and ensure that it remains focused and manageable within the specified scope. Although these boundaries provide clarity, they also acknowledge that there are broader considerations.

1.6 Organization of the Study

This thesis consists of five chapters. Chapter one is the introductory part, which presents the overall study and basic information, including background, problem statement, research objectives, scope, and limitations. Chapter two is the literature review, discussing various literature, books, articles, and academic papers related to railway interoperability. After reviewing these, the gaps in the literature are highlighted. Chapter three details the research methodology used to analyze the study's objectives. It provides an overview of the research design, data sources, tools, and techniques, and explains how the study aims to fill these gaps. Chapter four presents the analysis and results of the research, including graphs and tables with their implications. Finally, chapter five summarizes the conclusions and recommendations, along with areas for future research.

Chapter 2 Literature Reviews

2.1 Overview

The literature review aims to provide an overview of previous studies related to interoperability. This section begins with a definition of interoperability and its implementation in different countries, including some railway subsystems that influence it. These considerations will help offer a comprehensive understanding of the importance of interoperability and the challenges involved. Consequently, relevant thesis papers were identified through searches using keywords such as ("interoperability" OR "compatibility") AND (Railway* OR "rolling stock" OR "rail vehicle" OR "locomotive" OR "wagon" OR "railcar") AND ("track gauge" OR "coupling system" OR "braking system" OR “axle load”) AND ("East Africa" OR "Africa" OR "Kenya" OR "Ethiopia" OR "Tanzania" OR "Uganda" OR "Rwanda" OR "Sudan"). By manipulating these keywords and constructing search queries, relevant literature was found on Google Scholar. Additionally, only articles and journals written in English were selected for review. The exclusion criteria included publications from 2019 to 2025 E.C.

Therefore, the total number of papers from the database is 343, where duplicates and research that are not related to this thesis concept are excluded; finally, 53 papers are reviewed and summarized in a professional manner according to Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) 2020, shown in Figure 2.1. Overall, the literature review is divided into three parts: the first discusses papers obtained using a systematic approach to the concept of interoperability, the second covers traditional approaches without timeline restrictions, and the final section provides an overall summary and identifies gaps from the comprehensive review of the papers.

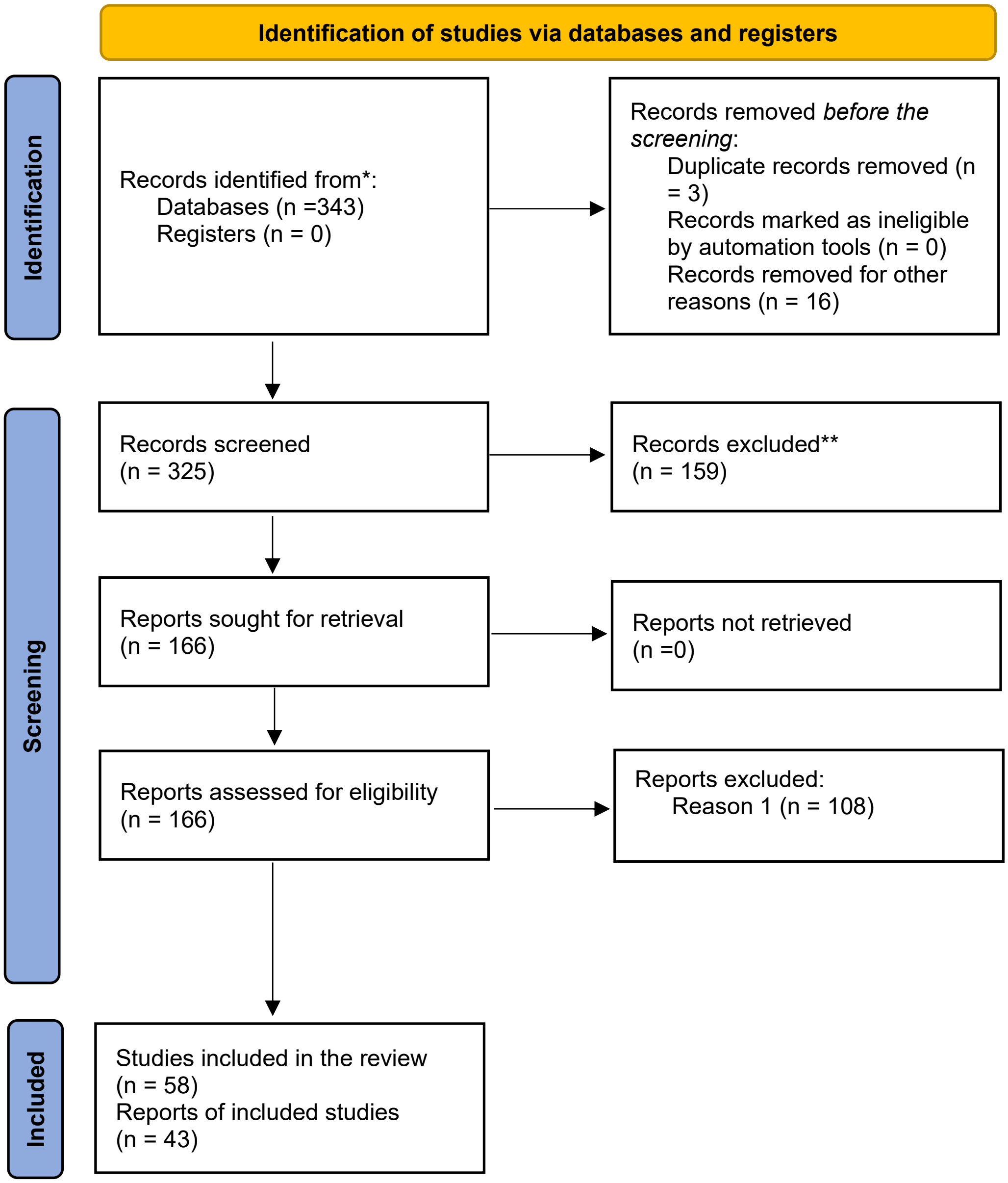

Figure 2.1. PRSIMA Flowchart (Autor)

2.2 Systematic Approach to Interoperability of Railway

2.2.1 Introduction to interoperability

As the world unifies, the global transportation industry is shifting toward sustainable energy solutions. A report combines data analysis from international transport agencies, case studies, and policy reviews to assess the feasibility of various energy transition pathways. The most popular option today is electric vehicles on the road, while the rail and maritime sectors require greater investment in producing green hydrogen and electrifying infrastructure [35]. Yet, the electrical railway transportation system is becoming a sustainable and efficient mobility solution worldwide. There is advancement in electrical technology, including regenerative braking, smart grid integration, and renewable energy adoption in railway networks. Thus, it employs a comparative analysis of different electrification systems, such as AC and DC supply models, evaluating their applicability based on geographic, operational, and economic factors. Results indicate that optimized electrification design can significantly reduce lifecycle costs and carbon emissions, enhancing system reliability and operational efficiency. The paper concludes by recommending the harmonization of technical standards, investment in renewable-powered traction networks, and digital monitoring tools to improve energy management and cross-border interoperability in rail transport [36]. These insights are particularly relevant for countries aiming to modernize or expand their railway networks while aligning with decarbonization goals. Thus, the expansion of the network led to the need for harmonized global standards, targeted funding mechanisms, and coordinated public-private partnerships to accelerate this transition. The harmonization leads to the idea of interoperability, fostering cross-border collaboration in the transport system[35].

Thus, interoperability is defined as [37] "The technical compatibility between the railway rolling stock or track equipment of different countries or industries, allowing the safe and uninterrupted movement of trains, while accomplishing the required levels of performance.". Having three connected layers: technical, operational, and legal [37][38]. Following its definition, the challenge and opportunity is a concept studied by many from different corridors and countries' perspectives, having some similarities and differences. For example, railway infrastructure in the Middle East and North Africa (MENA) region encounters fragmented standards and a lack of regional coordination, political volatility, a lack of standardized technical frameworks, and unequal investment capacities[39]. Additionally, the Asia Pacific region in the Belt and Road Initiative came across uneven infrastructure development, financing gaps, and regulatory differences among participating countries, which obstruct efficient cross-border movement[40]. Moreover, identifying the problem of fragmented legal systems, diverse technical standards, and infrastructural mismatches (e.g., gauge differences, traction power supply) as major gaps limiting cross-border efficiency[41]. Also, having mixed traffic (HSR trains and conventional trains) reduces the capacity of the line because of the big differences in the speed of trains, and it also reduces safety[42], which can be a greater obstacle to seamless connection.

Additionally, in a cross-country railway system, security can be a major issue because of its open-access nature, high passenger density, and extensive infrastructure. Thus, thought examines international case experiences, particularly from Europe, Asia, and North America, examining security policies, technological interventions, and organizational practices. Resulting in a gap in accordance with balancing security with passenger convenience, and in harmonizing international standards, even when there is advancement in surveillance technologies, intelligence coordination, and crisis management [43]. More on the Addis Ababa Light Rail Transit and Addis–Djibouti railway corridor, Ethiopia's railway sector has particularly encountered growing cyber security risks. Following that, a study identified a problem that existing international frameworks like ISO 27001 and NIST SP 800-30, as well as Ethiopia's national cyber security standard, are too generic and do not account for railway-specific safety and operational requirements. Using a design science research approach, the author developed an integrated Cyber Security Risk Assessment (CSRA) framework tailored to Ethiopia's railways, combining thematic analysis of data from Ethiopian Railways Corporation and the Information Network Security Agency with standards such as ISO 27001 and NIST. As a result, the framework incorporates strategic, tactical, and operational levels of risk assessment and outlines 13 core components, including cyber security awareness, asset identification, vulnerability and threat assessment, intrusion detection, likelihood and impact analysis, risk evaluation, and continuous updates validated by conducting scenario-based testing and expert reviews[44].

Finally, a study highlights significant interoperability barriers such as gauge differences, inconsistent signaling systems, and inefficient customs procedures investigated in the South Caucasian Transport Corridor (SCTC) that connects Europe and Asia. As well, logistical inefficiencies like poor terminal performance and a lack of digitalization were observed. The paper proposes coordinated infrastructure investment, regulatory harmonization, and adoption of variable gauge systems and ICT tools to enhance corridor efficiency. Ultimately, it recommends regional cooperation and international support to unlock the corridor's full potential in facilitating seamless, sustainable rail transport across borders[28]. Hence, for logistic efficiency, an analysis of their performance among the APEC member states, addressing the problem of the uneven development and weak transport-logistic integration despite regional cooperation, is conducted by using the World Bank Logistics Performance Index (LPI) as a benchmark. The result shows digitalization being the key enabler of logistics efficiency[45]. Despite the challenges encountered, it is witnessed that the rail development is being empowered as an instrument of soft power and infrastructural diplomacy[39].

2.2.2 Interoperability and the developed countries

The Economic and Social Commission for Asia and the Pacific (ESCAP) report [38] provides a comprehensive framework for understanding and improving interoperability in international railway transport systems, especially within the Asian region. It stresses that interoperability is not just a technical issue but also a governance challenge that requires strong cooperation between countries and institutions. The paper outlines various models of border crossings (Mode 1–3) and levels of interoperability (A–C), offering practical insights for corridor planning. Although this methodology focuses on Asia, it provides scalable strategies for developing railway networks in Africa. For East African nations, the recommendation is to start with harmonized corridors and gradually develop regional standards, mirroring Europe's slow but steady approach to interoperability over decades. The report ends by proposing pragmatic, step-by-step investment plans, strong government coordination, and alignment with international organizations like the Organisation for Co-operation between Railways (OSJD) or the International Union of Railways (UIC).

Besides, different countries have studied interoperability, especially the developed countries like Spain [46], Uzbekistan [47], Kazakhstan [48], Ukraine [49], the Balkans [50], and Poland[51]. First, starting from Spain, they invested an average €7 billion per year to transform a degrading railway network into an advanced and environmentally sustainable system. Notably, the network achieved a reduction in CO_2 emissions by over 12.9 million tons and 2.6 million tons of oil saved. Additionally, through strategic integration with European interoperability standards such as the European Rail Traffic Management System (ERTMS), Spain implemented rolling stock with variable gauge systems, advanced signaling, and high-speed infrastructure adapted to mountainous terrain [46]. Uzbekistan is a landlocked country that highly depends on its railway network for economic development. Thus, they made a strategic move by modernizing their railway system to meet global standards, which helps enhance regional trade and logistics. Specifically, they adopted international railway terminology to ensure communicational efficiency, safety, and operational effectiveness across their global network. If not, the consequences of the lack of standardized terminology can lead to an obstacle in communication, an unsafe environment, limited international collaboration, training challenges, and a lag in technological adoption. Organizations like the International Union of Railways (UIC) play a crucial role in promoting standardization that encourages interoperability and creates a unified standard for railways worldwide. Taking a real-world example from Europe, Japan, India, and South Africa shows that standardization can reduce delay, lower accident rates, and attract foreign investment[47].

Next, Kazakhstan [48] invested in upgrading the infrastructure, border efficiency, and intercountry coordination along paths like the Trans-Caspian and China-Europe corridors by standardizing the axle load, expanding terminal volume, and deploying a break of gauge as a solution to operationalize the regional interoperability for its 1520mm network. On top of that, incorporating a modern logistics hub and customer harmonization reduced delay and improved the nation. On the left side of Kazakhstan on the map, there is Ukraine[49], having an 85 mm gauge disproportion against Europe, where both technical and policy-oriented solutions are proposed. The solution includes flexible vehicle design, finding the optimum way to reuse assets, adopting the European Union (EU) service quality standard, usage of dual gauge track and variable gauge axles, with a long-term goal to align operational standards through collaborative governance. Moreover, countries like Poland, positioned between Western Europe and Eastern NATO, can serve not only civilian but also military. The rail shown makes sure faster, more secure troop and gear movement compared to road transport, especially for heavy loads. They emphasize the need for harmonized technical standards, investment in dual-use infrastructure, and enhanced cooperation between civilian railway operators and NATO military logistics. The findings suggest that strengthening Poland's rail capacity is essential for NATO's operational readiness, with future recommendations including digital tracking integration, corridor prioritization, and cross-border interoperability agreements[51].

Overall, the European Union (EU) within the Trans-European Transport Network (TENT) has over nine corridors, where one of them is the Orient/East Med Corridor (OEMC) studied on focusing on the Balkan portion by identifying the challenges in the infrastructure and operation, especially in rail transport. Aside from geography and static importance, it is witnessed that they have outdated rail, different gauge and signaling, lack a unified technical standard, and slow project implementation and funding constraints. Thus, to modernize their network, EU co-financed projects, particularly through Instrument for Pre-Accession Assistance (IPA) and Connecting Europe Facility (CEF), were considered. Due to bureaucratic delay, the absence of coordination among countries, and inconsistent application of interoperability standards such as ERTMS, track gauge unification (1435mm), and train length standardization (>740m). The study observes the potential for interoperability improvement through the use of the EU standard, investment, and the enhancement of multimodal transport and regional logistics hubs[50]. And the other TENT designed is the Mediterranean corridor, which spans 3,500 kilometers and includes six countries (Spain, France, Italy, Slovenia, Croatia, and Hungary), intending to achieve two key objectives: interoperability and an intermodal transport system through collaborative efforts and projects [52].

2.2.3 The relation between interoperability and the intermodal transportation system

Intermodal transportation, rail freight, is widely recognized as a foundational mode with a significant impact[53]. A study tackles current interoperability, efficiency, and automation within the rail freight industry, noting that although passenger rail has advanced significantly technologically, freight systems are mainly constrained by diverse operating rules, manual operations, and a lack of standardized automation interfaces. Thus, developing a Functional System Architecture (FSA) that is modular, scalable, and compatible with different freight operator strategies aims to automate both mechanical and digital connections and align the automation strategy with the EU standard (ERTMS) [54]. Additionally, another study analyzes the complex framework shaping rail freight operation, focusing on the interplay of technical, legal, and organizational barriers that affect competitiveness in international markets. The method combines literature review with policy and regulatory analysis of EU directives, international conventions (COTIF, SMGS), and case examples from Poland's eastern border, where interoperability challenges are most visible. Results are presented through three models of freight transport organization (classic, carrier–subcontractor, and single-carrier), demonstrating how contractual and operational frameworks evolve under different legal and technical conditions, alongside specific case technologies such as multi-system locomotives, SUW variable-gauge systems, and IT-based freight management[41].

On the other hand, in the intermodal connectivity of the Baltic Adriatic TENT corridor and its integration with core maritime ports in Gdynia (Poland) and Koper (Slovenia), [55] identifies a mismatch and coordination gap between the rail and port systems, which acts as a barrier. As a result, the paper highlighted that shared standards and synchronized infrastructure planning are essential for successful corridor development. In addition, at the International North–South Transport Corridor (INSTC), covering India, Iran, Russia, and Europe, efforts to improve intermodal connectivity were studied, highlighting key bottlenecks such as inconsistent regulations, border delays, and a lack of interoperable digital systems. Using comparative and statistical analysis, the examination demonstrates that improvements in policy coordination and digital infrastructure greatly enhance corridor efficiency, and they conclude that soft infrastructure is just as crucial as physical construction for attaining the strategic and economic profits of intercontinental corridors[56].

Coming back to [7], the Mediterranean Corridor already has the only Spanish port that is fully interoperable and already connected to Europe, which is the Port of Barcelona. This shows that not only the railway system but also other modes of transportation can be connected, linking a continental route between Africa and Europe by combining the Corridor with the Mediterranean Corridor. The Africa corridor, which is the Trans-Maghreb Multimodal (TMC), involves three main nations (Algeria, Morocco, and Tunisia) plus Mauritania as a minor participant, and aims to connect more than just railway infrastructure, including roads, ports, and airports. Therefore, this integration spans three different scales: regional (Alboran Sea), bilateral (Spain-Morocco), and Euro-Mediterranean (EU Maghreb). This integration emphasizes the vital role of railways within multimodal transportation networks, focusing on interoperability, competitiveness, and environmental sustainability. Morocco and Spain are a significant player in TMC and in the Mediterranean respectively, benefit from the fact that most items are compatible with railway transport, making the route crucial for capturing and distributing goods in the market. This is pursued through infrastructure and service standards such as a standard track gauge (1435 mm), train length >740 m, 25 kV electrification, ERTMS signaling, axle loads ≥22.5 tons, and strong rail port integration, showing how the railway is important for both freight and passenger transport as a sustainable and effective transport mode. Thus, these developed countries, like Europe and Asia, have a transport corridor strategy mainly focusing on regional integration and global logistics planning. A study offers a scenario-based analysis of current and emerging Eurasian corridors by integrating tools like SWOT and STEEPLE analyses to assess corridors' strength, weaknesses, and their geopolitical and economic context. Concluding the corridor, the competitiveness and sustainability of Eurasian transport corridors rely on coordinated infrastructure development, harmonized regulations, and strategic investment in multimodal logistics. It highlights that policy alignment and regional cooperation are essential for boosting efficiency and resilience[57].

2.2.4 The impact of China on the interoperability of other countries

The Belt and Road Initiative (BRI), sponsored by the Chinese government, positions itself as part of a larger goal to be achieved [52]. A study examines it as a strategic framework to improve seamless connectivity and sustainable development in the Asia Pacific region. It has a role in enhancing infrastructure networks, promoting trade, and fostering economic integration via investments in transportation, energy, and communication systems. Thus, methodologically, it employs a policy and regional development analysis, integrating case studies of BRI projects to assess their socioeconomic and environmental impacts. Results indicate that the BRI has significantly enhanced transport corridors, reduced logistics costs, and supported regional value chains, though sustainability concerns such as environmental protection and debt risks remain critical. The paper concludes that coordinated policies, standardized infrastructure norms, and inclusive governance are essential for maximizing the BRI's benefits [40]. It is also restructuring the railway development by focusing on Africa. The study claims that while China offers investment for the infrastructure, it often introduces high-speed, standard gauge that do not align with the legacy system, such as metre-gauge rail[58].

Additionally, a study [59] explores whether China's funding of Africa follows the same pattern as a European colonization-era rail project, which often prioritized resource extraction. Thus, the analysis of this spatial distribution of the funds from China and the European colonial powers has some similarities and differences. They are similar in terms of controlling strategic corridors; however, it is seen that the projects are often initiated or cofounded with the African government, making it a more complex interaction of mutual interest. Moreover, in the case of Lao PDR [58], a 414km standard gauge rail line with Chinese support is presented as a successful example of BRI infrastructure transforming a landlocked nation into a land-linked logistics hub. Similarly, another study [60] emphasizes that China's infrastructure investment tends to balance rather than compete with those of traditional benefactors. However, the [58] author warns that poor transparency, misaligned national strategies, and the absence of cross-border trade facilitation can undermine the long-term success of such projects. Similarly, [61] analyses the role of China in African countries' railway development, taking East, West, and Southern Africa as a case study; therefore, the author suggests that while China's investment has enabled aspiring rail projects, leading to interoperability challenges due to fragmented infrastructure, lack of shared standards, and uneven integration. Thus, the African leadership and strategy organization coordination has an important place to make sure the new railway infrastructures function within national and continental interests rather than geopolitical leverage [61]. Also, another study [62] showed a measurable increase in China's footprint in SDOs and 5G contributions (select technical wins such as polar coding for the 5G control channel alongside notable failures), widespread BRI agreements (e.g., reported cooperation accords and translation/registry efforts), and state mechanisms that socialize risk and mobilize resources to favor Chinese solutions abroad. The authors argue that this state-centric variant accelerates external adoption of Chinese norms and creates dependencies that may fragment markets and politicize standard setting; strengths of the paper include its systematic mixed-methods design and institutional detail, while limitations acknowledged by the authors are restricted case selection (two sectors), challenges of generalization, and the need for negotiation-level or broader comparative work.

However, from all the planned railways in Africa, there is the Ethiopia-Djibouti rail line that was also built by the Chinese government. According to a study made via ethnographic method and infrastructure analysis, the author stated that the project has become a tool for asserting sovereign developmental agendas while also embedding dependencies through financial, operational, and institutional arrangements that remain uncertain or risky. Thus, Ethiopia's case is symbolic of broader infrastructure governance problems in African contexts, where visions of modernity and development meet the uncertainties of financing models, maintenance planning, institutional continuity, and geopolitical influence[63]. Similarly, focusing on the low-income countries' (Sub-Saharan Africa and South Asia) interoperability, their railway systems have been driven by external forces, often by foreign suppliers, which leads to being unaligned with national needs and regional interoperability goals. The study emphasizes the importance of customized technological choice and calls for data-driven planning and harmonized technical direction, particularly in subsystems such as gauge, axle loads, and rolling stock compatibility. Its major contribution is the introduction of the six-theme framework adopted from Europe's rail technical strategy (RTS), which includes control and communication, energy, infrastructure, rolling stock, information systems, and customer experience[34]. Another study [64] suggested that African countries should adopt a continental standard based on the European Rail Traffic Management System (ERTMS) due to its recognized global interoperability, openness, and supplier compatibility to meet the longer vision.

On the contrary, Ethiopia's recently built Addis Ababa light rail can be taken as an example, as its stations were designed largely using foreign standards, generating a copy-paste problem, which is not tailored to the national needs. It leads to inadequate platform width, poor pedestrian flow management, insufficient accessibility for people with disabilities, safety hazards at crossings, and a lack of integration with other urban transport modes [65]. Therefore, one should consider the national and customer needs when adopting other standards. Hence, a study shows an insightful contribution to subsystem adaptation on redesigning existing technology to suit the local railway. Methodologically, the study identifies technical incompatibilities between Chinese-manufactured Dong Fang Hong (DFH) locomotive speedometers for compatibility with South African diesel electric locomotives, particularly concerning input signals, calibration, and reliability under local operating conditions. The redesign involved re-engineering the sensor interface, recalibrating gear ratios, and modifying electronic circuitry to ensure accurate speed detection and robust integration with locomotive control systems. Testing included laboratory validation of the redesigned speedometer against reference standards, followed by field trials on operational locomotives. Findings demonstrate that the redesigned system achieved improved accuracy, durability, and cost efficiency compared to importing new systems, while also enhancing local capacity for maintenance and technological adaptation[66].

From a different perspective, the Middle East and North Africa (MENA) region, which is also influenced by BRI, especially in Egypt and Iran, sees Chinese investment aligning rail development with global trade corridors [39]. In the same way,[67] investigated the influence of BRI in the Middle East, findings reveal that while BRI investments have fostered positive spillover effects, such as enhanced connectivity, foreign direct investment, and economic growth in nations like Serbia and Bangladesh. Limitations persist due to financial unsustainability, infrastructure heterogeneity, and geopolitical frictions in countries such as Pakistan, Sri Lanka, and India. Therefore, highlights BRI's dual role: enabling underdeveloped nations to access global trade networks while simultaneously creating risks of debt dependency and undermining local industries.

Likewise, the impact of the BRI on key Eurasian transit countries [68] is examined using international relations theory and regional economic integration frameworks. From both economic and geopolitical perspectives, Russia leverages BRI to support the goal of economic union; Kazakhstan views it as a way to modernize and diversify; and Belarus benefits from its strategic transit position despite limited bargaining power. Therefore, it can be concluded that while the BRI projects improve infrastructure connectivity and transit capacity, they also strengthen China's dominant role in regional trade networks, raising concerns about asymmetric dependency. Consequently, China's influence in the railway industry has been greatly witnessed, for that its universities have their own contribution regarding high-speed technology by supporting the country's ambitions. One of the universities is Central South University (CSU), which has been instrumental in revolutionizing engineering innovations that enhance rail safety, efficiency, and resilience. It also contributes to aerodynamic testing, seismic and wind resilience, crash safety, track material innovation, and infrastructure durability, paving the way for future-ready railway systems [69].

2.2.5 A change due to the interoperability of the railway system

Generally, throughout the connectivity, port operation becomes increasingly complex. Thus, a case study [70] introduces a structured methodology for optimizing capacity in ports, combining process modeling, simulation, and stakeholder-based evaluation, applying it to the port of Trieste. The modeled railway operates using BPMN and simulates various "what if" scenarios through BpSim to identify bottlenecks and evaluate resource needs. The use of multi-actor, multi-criteria analysis (MCDA), precisely the AHP method, enables ranking interferences based on the priorities of terminal operators, port authorities, and shunting operators. Results indicated that the availability of tracks and shunting locomotives significantly affects throughput, while organizational changes alone provide limited gains. The study's integrated approach is a valuable reference for designing scalable, interoperable rail port systems in capacity-constrained settings, particularly in developing countries seeking to modernize their freight corridors.

On the other hand, manufacturing companies also have to compete to survive; the industry has seen consolidation, restructuring, and foreign acquisitions, with some legacy firms failing while others adapted through modernization and international collaboration. Poland's rolling stock industry has emerged in the European rail manufacturing sector by meeting the interoperability standard, exporting to foreign markets, and contributing to technological advancements such as multi-voltage locomotives and modernized passenger coaches[71]. Not to forget the country currently moving to influence the railway industry, which is China, a study investigated how its companies are evolving in economies, and particularly the China Railway Rolling Stock Corporation (CRRC). The study identifies a key problem: latecomers face mismatches between their strategic modes (SM) and technological innovation capabilities (TIC), making catch-up difficult. Using an exploratory embedded case study on CRRC's electric multiple unit (EMU) development, the authors develop a framework showing that industrial policies act as triggers that enable firms to evolve from absorptive capacity to integration and eventually continuous innovation capacity. Methodologically, the study relies on interviews with CRRC managers and experts, analysis of policy documents, reports, and technical data, triangulated to ensure validity. Results show that CRRC's catch-up progressed in three stages: exploration (internal innovation with limited capacity), localization (cooperative innovation with foreign firms enhancing integration capacity), and standardization (independent innovation strengthening continuous innovation). The discussion emphasizes that strategic path transformation is an evolutionary process of mismatches and rematches between SM and TIC, with industrial policy acting as a decisive trigger[72].

2.2.6 Railway Subsystems

Learning from past mistakes made in Britain’s 19th century, called “gauge war”, where private companies, particularly the Great Western Railway’s (7 ft) broad gauge, went head-to-head with the national trend, which is standard gauge (1435mm), resulted in significant logistical disruptions and delays. Despite trying to solve it by using a break gauge station and gauge convertible rolling stock, it only stretched the cost. Thus, taking it as a warning for long-term infrastructure strategy to avoid repeating the same mistake that the technical interoperability should be backed with institutional coordination[73]. The world gauge difference seen in Figure 2.2 makes it a sensitive subsystem. Another study also stated about subsystem impact on interoperability as [32]“Gauge width is potentially the most significant constraint to interconnect railway networks, but other aspects such as electrification, communications systems, maximum axle load, train length, or tunnel clearances are also factors on many networks.”

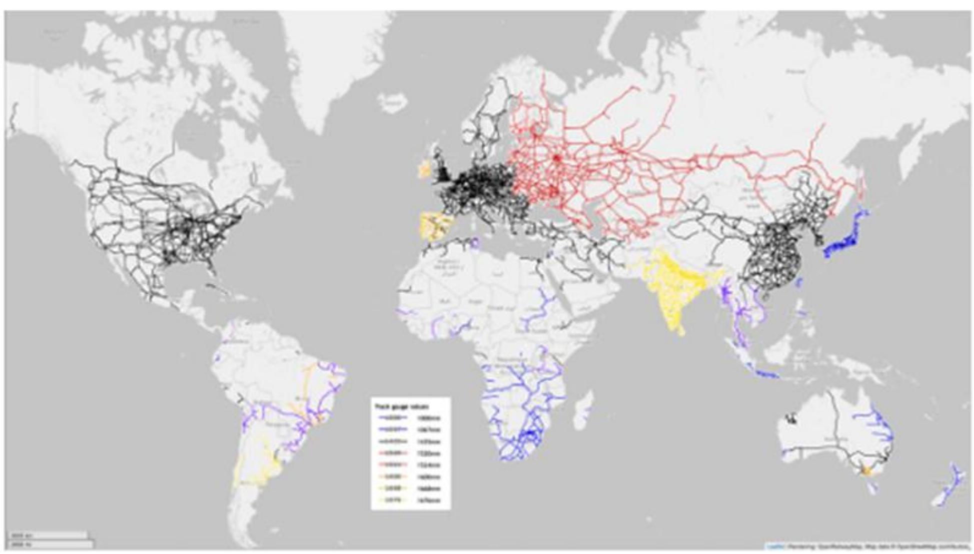

Figure 2.2. The World Railroad Gauge Map[73]

Thus, the international railway corridors' major technical barrier is the break of gauge, where a study systematically reviewed the accessible technologies for addressing the issue by identifying three solutions. These three solutions are transhipment operations for a medium-term solution, removable bogies for a long-term solution, and, finally, the variable gauge axles to help enhance the productivity and competitiveness of international railway corridors, reduce logistics costs, and improve the viability of rail as a freight transport mode, particularly in regions with gauge diversity like Africa or Central Asia [74]. Nevertheless, the solution comes with a high cost[73].

In the railway,[75] highlights the interdependence of subsystems, track, rolling stock, signaling, communication, and energy supply, and the necessity of harmonized standards to ensure cross-border interoperability, particularly within the EU. The analysis underscores the Institute's strength in combining certification, risk assessment, and conformity evaluation, though the study is primarily descriptive and institution-specific, limiting its direct applicability outside Europe. A study of one of the subsystems, which is rolling stock were a study provided an overview of its technology by focusing on the design principles, operational requirements, and engineering challenges. A synthesis of technical standards, engineering practices, and comparative analysis across vehicle types, including locomotives, passenger coaches, and freight wagons, is the methodology used. Resulting in the interdependence of vehicle design with track infrastructure, showing how factors such as suspension systems, wheel–rail interaction, and braking technology directly influence stability, ride quality, and energy efficiency[76].

What is more, interoperability depends on rail subsystems; therefore, a comparative analysis of elastic rail fastening systems used in European railway infrastructure, particularly in Poland, identifies it as a vital component. Using laboratory testing in line with European standards PN-EN 13481 and EN 13146, evaluated static and dynamic stiffness, longitudinal and torsional resistance, clamping force, and impact load suppression for both systems. According to the findings, the SB system has lower vertical stiffness but higher longitudinal resistance, which benefits load distribution and ballast protection, whereas the W14 system has superior torsional resistance, is easier to install, and is more adaptable for track gauge regulation. It shows the trade-offs between stiffness, resistance, and maintainability, thereby informing infrastructure managers and designers in selecting fastening systems for reliable and interoperable rail track construction [77].

On the other hand, an investigation of obstacle detection in a railway environment aiming to address safety gaps left by existing European Rail Traffic Management System (ERTMS) and European Train Control System (ETCS), which is one of the railway subsystems in the communication categories. In doing so, a prototype on-board detection system was combining a 77 GHz automotive radar, RGB and thermal cameras, a high-precision GNSS module, and open-source railway maps was developed and tested, with sensor data fused through a C++/Q_t interface to filter out non-track obstacles using geographic track curvature. Experiments conducted along a road-based testbed showed reliable detections up to 200 m, but also revealed insufficient range for full emergency braking distances of typical trains, highlighting both the promise and current limitations of such systems. Thus, the valuable technical framework for integrating obstacle detection into interoperability railway safety systems, informing future development toward long-range, all-weather detection solutions needed for safe, cross-border rolling stock operations in the evolving on usage of the control and management systems[78].

2.3 Traditional Approach to Interoperability of Railway

2.3.1 African Railway

Rail transportation in Africa is one of the oldest systems, mostly built during the colonial era, to transport goods from sources to ports [79]. The first railway was constructed in Egypt by Britain in 1851[80]. Mainly under European colonial rule, the railway network, starting from Cape Town, gradually expanded to other settlements [81], [82]. British missionaries were the first to cross Africa by train in 1897 [83]. Although networks were rarely connected across countries, the southern African network extended from South Africa to the Democratic Republic of Congo. Several landlocked countries in sub-Saharan Africa, such as Niger, Chad, and the Central African Republic, have no rail network at all [84]. A study analyzed the railway transportation system in West Africa and proposed strategies for developing an efficient and interoperable system. The findings highlighted challenges such as deteriorated infrastructure, outdated technologies, and limited connectivity. The proposed strategies aim to improve interconnectivity and boost economic growth and trade in the region[33].
Since the railways were constructed over 100 years ago, which was at the end of the colonial era, the network is also outdated; only 80% of them are operable as of 2009 due to poor maintenance and damage during the civil war. And also, the African railway network today is not much different from its state towards the end of the colonial era, with many countries sharing similar experiences of initial track construction from interior mines or trading hubs toward the main port, followed by branch lines. The network is almost all non-electrified, with manual signaling systems and narrower gauges than the rest of the world. The network has faced stiff competition from steadily improving and increasingly liberalized road networks, leading to a decline in the market share of rail transport [84].
The African railway network faces several challenges, including aging tracks, rail wear, deteriorating earthworks, poor civil works, obsolete signaling and telecommunications equipment, and scarcity of spare parts. A huge disincentive to tackling these challenges relates to the lack of commercial viability

of most of these rails, as traffic volumes are inadequate to break even, even if prices were liberalized. The lack of scale and low traffic volumes are major drawbacks for African railways, with African rail networks having a density of fewer than 1 million traffic units, compared to European systems, which average 2-5 million traffic units [85]. The current state of railway infrastructure in Africa is a mix of progress and challenges. While there is a renewed interest in railway infrastructure development, implementation has been slow and hampered by factors such as the historical colonial legacy, high costs, and lack of commercial viability[85], [86]. With disparate gauges and signaling systems throughout the continent, the African railway network is fragmented and unconnected[86]. The Northern Corridor Railway network comprises the Meter Gauge Railway and the Standard Gauge Railway (SGR), with a total length of 8,206 km in the Northern Corridor. The SGR line is 120 km from Nairobi to Naivasha, and there are plans to extend the SGR mainline from Mombasa to Kampala to join the line from Kigali-Kampala on the Northern Corridor, while the Isaka- Kigali line will be the mainline on the Central Corridor. The Kigali-Rubavu branch line will link Rwanda to the DRC [87]. Legally speaking, a study on the EAC's existing legal and institutional frameworks weak and unclear legal framework, fragmented institutional capacity, lack of enforceable rights/obligations, and inconsistent national laws form the core reasons behind stalled cross-border railway development. Which leads to soft infrastructure and a bottleneck of largely ignorance [88].

2.3.2 East African Railway

In East Africa, there are two networks: Tanzania, Kenya, Uganda, and Ethiopia (Addis Ababa) to Djibouti. Where the railway network consists of both passenger and freight transport, mostly the railway lines are single tracks running from inland destinations to coastal areas with little interconnectivity. The Uganda Railway, built between Mombasa and Lake Victoria between 1896 and 1903, is considered the beginning of East African railway connectivity [89].

The following are the East African countries history of their railway

- **Sudan Railway** opened in the 1870s, which is paralleling the River Nile for about 54km south of Wadi Halfa. Initially intended as a trade route, it was taken over for war purposes and twice extended, but abandoned in 1905. The first military railway in Sudan was constructed in the 1890s between Wadi Halfa and Abu Hamad, sharing the 3ft 6in (1067mm) gauge of the earlier line. It was later extended to Atbarah, Khartoum, and eventually formed the basis of the present-day network[90]. The Sudan railway network suffered losses in the early 1970s, and the losses were attributed to various factors, including inflation, the lack of spare parts, the company's headquarters being located in Atbara rather than in Khartoum, and the continuation of certain lines having only light traffic[81].

- **Kenya Railway:** was first built in 1896, connecting the Indian Ocean port of Mombasa to the port of Kisumu at Lake Victoria[80]. The railway also had a significant impact on the development of Kenya's towns and cities, with many major towns situated along its course. The railway helped to define the location of towns like Mombasa, Nairobi, and Kisumu, and it played a role in the rise of the rich white landowning class in Kenya. In recent years, the railway has faced challenges, including competition from road transport and a lack of investment in infrastructure. However, efforts are underway to modernize and expand the railway network in Kenya, including the construction of a new standard-gauge railway from Mombasa to Nairobi, which was completed in 2019[80][81][84].
- **Uganda Railway** was built to facilitate trade and export opportunities in the region, and to connect Uganda to the outside world. The line was completed in 1901, and it had a profound impact on Kenyan society, facilitating trade and economic growth in the region. The railway also played a role in decreasing slavery in East Africa, as it was cheaper and faster to transport cargo on a train rather than on a slave porter's shoulders[81][84]. In 1926, the name of the railway was changed from the Uganda Railway to the Kenya and Uganda Railway. The railway continued to play an important role in the region's economy, and by the end of the first year of full public operation, it had earned a profit over its working expenses. [80][81][84].
- **Rwanda Railway** history is limited to three industrial railways, but they were severely damaged during the Rwandan Civil War and the Rwandan genocide. Since the turn of the 21st century, there have been several proposals for a railway between Rwanda and neighboring countries. [80].
- **Tanzania Railway:** was constructed between 1896 and 1903, and it was a major undertaking, with 406 steam locomotives remaining against 56 diesels at the time of its completion[91].
- **Ethiopian Railway:** was first constructed by the French in 1917. It played a significant role in the political relationship between the Empire and Western powers. The Ethiopian government in 2010 proposed a new railway network. Where most of the proposed new railway lines were already planned decades before the meter gauge[92]. In 2016, a new 760km

standard-gauge electrified railway was built from Addis Ababa to Djibouti. Replace the meter gauge railway, where about 660km are within Ethiopia[91].

Overall, the East African Railway Master Plan candidate countries are planning to revitalize the railways currently in use in Tanzania, Kenya, and Uganda, and eventually expand them to Rwanda, Burundi, and South Sudan, including Ethiopia too. By improving performance and speed on each national railway network, lowering the cost of cargo transportation, and connecting to ports on the Indian Ocean coast, it offers strategies for improving the infrastructure and better managing the infrastructure and better managing the services better. It will also present business cases that would draw private sector investments in the sector and establish economic development. However, due to difficulties, East African Railways' actual level and condition are not as anticipated. Deteriorating infrastructure, including old rail and track degradation, is one of the numerous causes [93]. Another issue is that different nations have different signaling systems. For example, Tanzania and Zambia utilize ERTMS, Kenya uses Chinese, and Ethiopia has a combination of Chinese and ERTMS, which makes cross-border operations difficult [94]. Additionally, some nations, like Rwanda, rely mostly on road transit because they lack a railway system [95].

2.4 Summary of Literature Reviewed and Research Gap

Following globalization, with the expansion of a network for sustainable and efficient mobility, leading to the advancement of an electrified railway system, and the harmonization idea for cross-border collaboration [35] [36]. This cross-border collaboration or interoperability starts from its definition, which is operational and technical compatibility of the railway subsystem to get a seamless cross-border transportation service while accomplishing the desired performance level[37]. The challenges in reaching the seamless level are legal, technical[40][41][42], operational[39][28][45], and political[38]. Additionally, having many challenges such as a fragmented standard and legal system, a lack of regional coordination, lack of a technical standard framework[39][41], political volatility[38], unequal investment capacities, uneven infrastructure development[45], financing gaps, and regulatory differences among participating countries[40], and infrastructure mismatch[41]. Moreover, mixed traffic (HSR and conventional trains) [42], gauge difference [28][32][41] [73] [74] [75] [76], an inconsistent signalling system, inefficient customs procedures, and logistic inefficiencies[28], and difficulty in balancing passenger convenience with security[43]. Despite the encounter of an advantage in enhancing regional trade and logistics, specifically dealing with freight rail to transport massive loads of product from connected counties. Also, the railway's connectivity unlocks corridor potential [28] and is regarded as infrastructure diplomacy and soft power. Therefore, many developed continents have worked on their connectivity, like Europe and Asia [46][47][48][49][50][51] [52][54] [55] [56].

Specifically, China, who have a major influence throughout the world, like the Middle East [39][67], especially in Africa, is clearly seen in a controversial way. Some state a shared goal while balancing interests on both sides, claiming their aim differs from that of European colonists[60], who pursued the same idea of connecting Africa from Cape Town to Cairo, primarily to transport resources and raw materials[59]. Conversely, the majority warns not to overlook China's involvement by saying that it increases the risk of dependency, resulting in uneven integration, poor transparency, and misaligned national strategies[58][61][62]. Additionally, witnessed in the Ethiopian railway, the copy-paste problem is evident[63][65], where low-income countries' railways often end up being driven by external forces [25]. Therefore, African leaders and institutions play a crucial role in ensuring that rail infrastructure becomes a national and continental priority rather than a tool of geopolitical leverage, suggesting the adoption of a continental standard based[64]. Additionally, beyond country involvement, technical subsystems significantly impact the challenge of seamless transportation and railway interoperability, such as vehicle design[76], rail fastening[77], and object detection systems[78], gauge differences, etc. Gauge difference is often seen as the main obstacle to connectivity. However, the track system is interdependent with other subsystems, like the rolling stock [75]. Therefore, of the papers reviewed systematically, only 13.37% were mainly about railway and interoperability-related topics, specifically African railway interoperability, at 3.49%, indicating the scarcity of research in this area, even when traditional approaches are employed (4.46%). Additionally, taking the railway interoperability as a major problem, the interdependency with other subsystems, such as rolling stock, is noted. Combining these two perspectives makes it an underexplored idea that can greatly benefit low-income countries, such as those in East Africa.

Chapter 3 Methodology

3.1 Overview of the Methodology

The thesis adopts a pragmatic philosophy, concerned with finding effective solutions and generating useful knowledge applicable to real-world situations. The philosophy employs mixed-methods research to address the research questions and objectives [96]. Therefore, the thesis employs a mixed-methods (quantitative and qualitative) research approach to analyze the current state of interoperability in East African railway and rolling stock compatibility. The questionnaires are analyzed using statistical techniques for quantitative data and thematic analysis for qualitative data. The thesis was carried out in three phases. The Weight Sum multi-criteria decision-making (MCDM) model, the FUZZY AHP model, and SOLIDWORK (for modeling) with ANSYS analysis were the primary tools employed. This thesis employed the MCDV model to evaluate the current state of railway interoperability in East Africa. After assessing the railway status, the analysis focused on one of the railway subsystems, the rolling stock, where the parameter of interest was compared using the FUZZY AHP [96], as interoperability involves multiple technical parameters, the subjective judgment from experts involves its own uncertainty response, and it is more reliable than the classical AHP[96] model aiming to determine where investors and stakeholders should invest more. Next, after determining where to prioritize where to capitalize, showcasing a specific rolling stock subsystem impact by analyzing the static structure made according to the selected subsystem element as axle load, using SOLIDWORK to model and ANSYS software to perform the analysis. At last, the results are discussed to draw conclusions and provide recommendations based on the study's findings.

Data collection:

To achieve the thesis's research objectives, both primary and secondary data are employed, including journal articles, literature reviews, the official websites of the railway companies in the East African railway industry, and the technical specification for interoperability (TSI) document from the EU. Moreover, in order to validate the thesis content validity, experts who were well-informed opinions were used. A formal survey instrument was given to a chosen group of railway professionals, which included university researchers, train operators, and practitioners from infrastructure organizations. Respondents were asked to rank the relative significance of three indicators: (1) the existence of a cross-border physical track, and its operational status, (2) the criteria that can be used to compare the subsystem impact on interoperability, and (3) the rolling stock subsystems parameters with their impact on interoperability. Each indication was given a 5/6-point rating, and respondents were asked to justify their scores using operational experience and technical factors. The general workflow of this thesis is illustrated in Figure 3.1, starting from the literature review, which was conducted in both traditional and systematic approaches, were problems and gaps were identified. Additionally, three objectives are extracted that are resolved by the use of the scientific method.

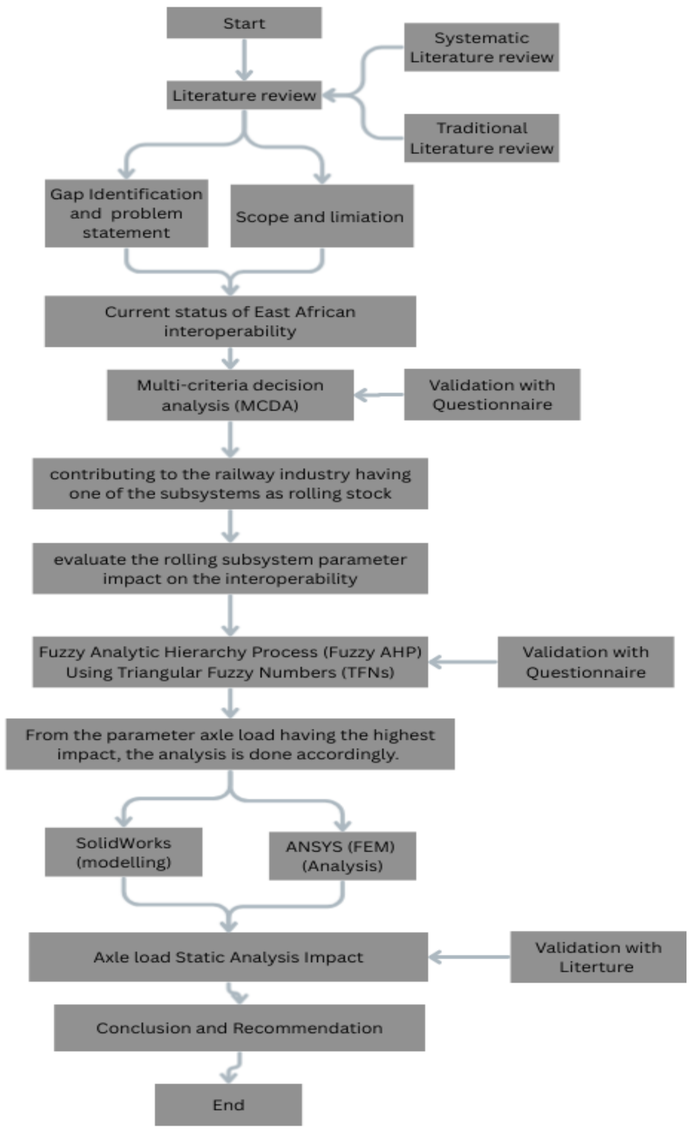

Figure 3.1.Flow chart of the Methodology of the Thesis (Author)

3.2 Current Status of Interoperability on East African Railway

Assessing the interoperability of East African railways begins by listing the member states, as defined by the East African Community (EAC). This foundational step is essential because the railway's success hinges on seamless integration and clear involvement by the nations when analyzing existing infrastructure, technical standards, and operational procedures. This helps identify disparities or challenges in achieving interoperability, which are essential to efficient cross-border rail transport. Only then can the project move on to its implementation phase. However, different platforms report different state numbers, such as the African Development Bank Group[97], which lists 13 countries in the region, while the East African Community partner count is 8[98]. Thus, from a different perspective, the list of countries to be considered for this thesis is drawn from the master plan[30], as shown in Appendix B, and includes Ethiopia, Kenya, Sudan, Uganda, Congo, Rwanda, Burundi, Tanzania, and Zambia. The overall approach is clearly illustrated in the Figure 3.2, where the final aim, that is, the current status of their connectivity and operability following the selected nation, is listed in result section of Table 4.1. This information was gathered from the East African official website and the master plan in Appendix B.

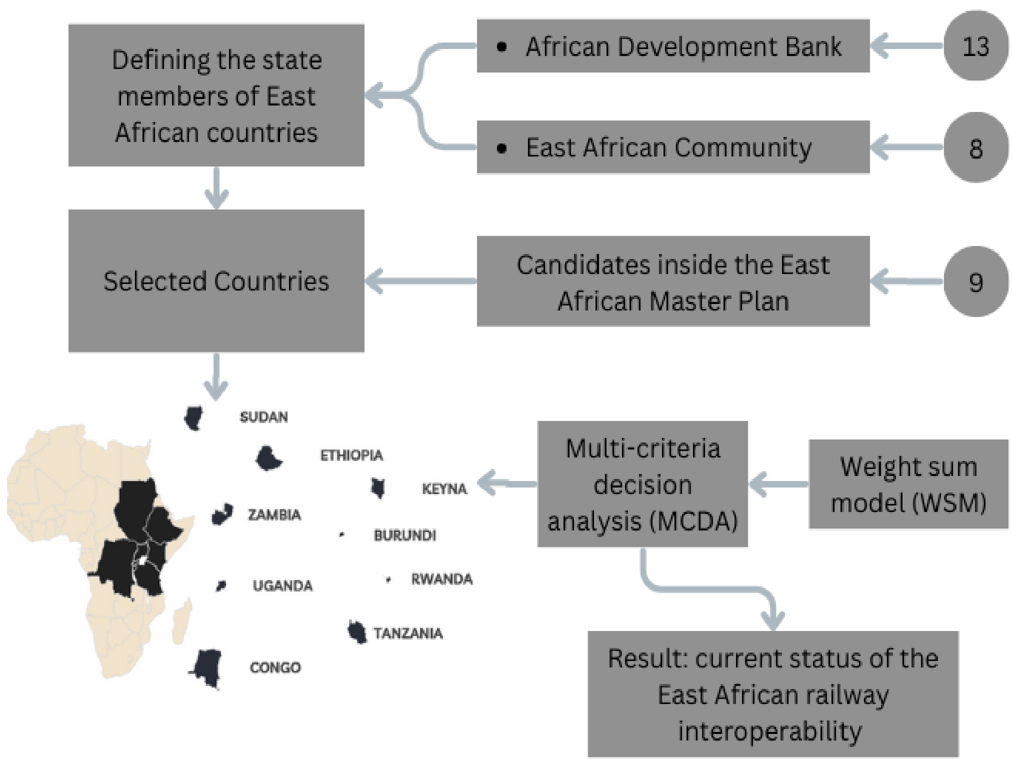

Figure 3.2 Research frame for analysis of the current Status of Interoperability on the East African Railway

Thus, for the numerical evaluation of the standing of interoperability in East Africa, a scientific method called multi-criteria decision analysis (MCDA) is used. Multi-criteria Decision analysis (MCDA) is defined as " a systematic approach to evaluating complex decision problems that involve multiple, and often conflicting, criteria."[99]. In the recent decade, the use of MCDA in the transport sector has grown significantly[100]. Additionally, it is frequently used in engineering and management research to assess and analyze. Among the several families of MCDA methods developed, the weight-sum model is the simplest and most widely applied technique [101]. Therefore, the following steps are used to analyze the status of interoperability on the East African Railway using WSM.

- Step one: Determining the existing, planned connectivity, and operability of the East African countries.
- Step two: Convert the qualitative data to quantitative (binary/binary coding) as shown in Table 4.1.

  Where: Yes = 1,

  No = 0
- Step three: Apply the WSM method.

$$\text{Pair Score} = (\text{Connected } \times \text{Connected Weight}) + (\text{Operating} \times \text{operating Weight}) + (\text{Planned } \times \text{Planned Weight}) \quad (3.1)$$

The connectivity of the railway (physical connectivity link), as stated in several policies and reports, is essential to enabling cross-border rail flow [102]. International frameworks emphasize that operational interoperability determines whether a physical link offers transport value. Studies that evaluate cross-border potential clearly separate the removal of operational limitations from technological obstacles, since both must be addressed to achieve traffic[103]. Therefore, the weight score value for connective and operability rates the largest share. As the main aim is to assess the current state of East African interoperability, the planned connectivity is taken as an additional or bonus, so the value is lower than the connectivity and operability.

Where:

Connected Weight= 0.5

Operating Weight= 0.5

Planned Weight= 0.25

$$\text{Pair Score} = (\text{Connected} \times 0.5) + (\text{Operating} \times 0.50) + (\text{Planned} \times 0.25) \qquad (3.2)$$

- Step Four: Calculate the total Score to determine the East African connectivity

$$\text{Total Score} = \sum(\text{Criterion Score} \times \text{Criterion Weight}) \qquad (3.3)$$

After all the above steps, the current status of the East African railway interoperability was determined and presented with a visual representation in the results and discussion section.

3.3 Rolling Stock subsystem impact on interoperability

After knowing which countries have both connectivity and operability in railway systems, the next part is to dive into the moving vehicle parameters. Since, the rolling stock subsystem can be used as an assessment tool to determine if a railway is interoperable; in doing so, one can utilize a framework that classifies the degree of impact as high, medium, or low. On the research design and approach, starting from the different design and manufacturing companies that produce rail vehicles with various material properties and dimensions, which affect compatibility across diverse track designs, also have their own influence. Therefore, this thesis evaluates the impacts of rolling stock subsystems listed in Table 3.1 on seamless transportation by referencing developed countries and incorporating scholarly opinions through questionnaires. Additionally, a static structural analysis is performed considering only the axle load limit and material differences for EDR and TAZARA, mimicking a scenario “what happens if rolling stock of EDR is placed in TAZARA rail track” because that is the first thing that actually is done when there is a path connecting these two interoperable countries. Static structural analysis was chosen for its robustness, computational efficiency, and suitability in representing the actual load transfer mechanism in railway wheel–rail systems. Dynamic or transient effects such as vibration and impact loading were not considered in this stage, as the focus was to explore the physical barrier and structural safety and evaluate steady-state mechanical behaviour under the specified axle load. Overall, the research framework is illustrated in Figure 3.3.

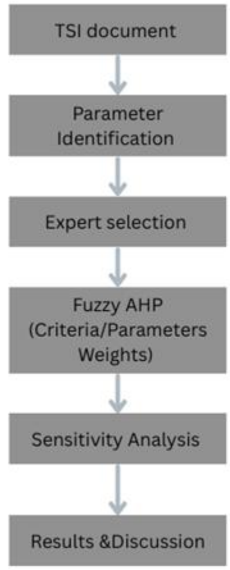

Figure 3.3 Research framework to identify the rolling stock parameter on interoperability

Thus, the procedure began by extracting the subsystems from reputable organizations like the European Union (EU) that introduced the technical specification for interoperability (TSI). The complete map of TSI categories is shown in Figure 3.4, illustrating the overall solid line to understand the interoperability criteria.

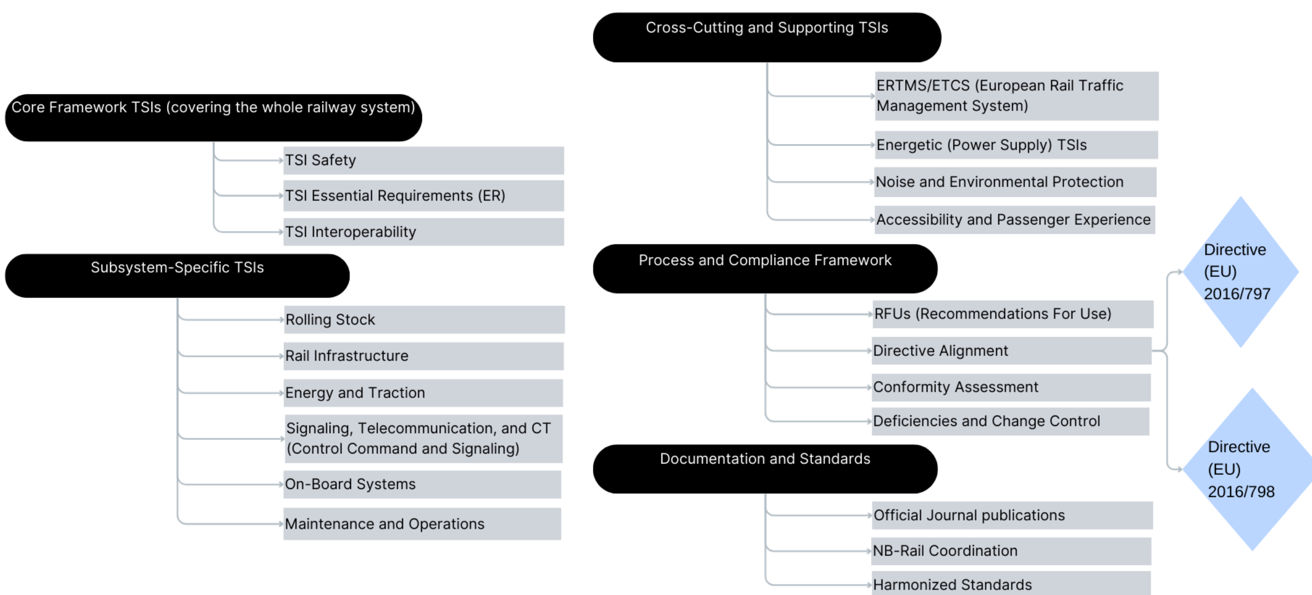

Figure 3.4. General mapping of TSIs (Autor)

This map contains the general safety rules for the entire EU rail system, an essential requirement that must be covered, and interoperability guidelines. Along with the cross-cutting and supporting

TSIs, which address elements that span different subsystems, it also displayed the subsystems considered in the interoperability. The process and compliance framework covers how the rules are enforced and aligned across the EU, which is documented to ensure consistency. Moreover, the Directive (EU) 2016/797, which is precisely established by the European Union agency, aims to improve and develop rail transport services by building a single European railway area with a higher level of technical harmonization. The directive uses Technical Specifications for Interoperability (TSIs) to detail the specific requirements for each railway subsystem, including Interoperability constituents, Infrastructure, Energy, Vehicles (Rolling stock and other mobile components), Control-Command and Signalling (CCS) systems, Telematics applications, and Accessibility for persons with reduced mobility. Accordingly, the applicable TSI to rolling stock documents is listed as follows;

- ✓ Locomotive and Passenger Rolling Stocks [104]
- ✓ Freight Wagons TSIs (WAG) [105]
- ✓ Noise [106]
- ✓ Compatibility with other subsystems

The subsystem's component or parameter was compiled from the above-mentioned documents, and the impact level was determined as indicated in Table 3.1. Three levels are assigned to the values: low (comfort, environment, or inclusivity; significant but not crucial for physical connectivity), medium (restrictions or additional costs, but not absolute barriers), and high (directly prevents or enables interoperability). On this first layer of filtering, a questionnaire (Appendix B) was distributed to rank the parameters on the considered impact levels.

Table 3.1. Interoperability Impact of the Rolling Stock Subsystem Extracted from the TSI

Subsystem	Parts/types	Interoperability impact
Traction and energy system	Traction type (diesel/ electric/ hybrid)	High
	Installed traction power	High
	Maximum operation speed	High
	Acceleration performance	High
	Electrification system compatibility (voltage and frequency)	High

	Pantograph geometry and contact strip	High
	On-board energy measurement system	Medium
Vehicle geometry & gauging	Vehicle Geometry (length, width, height)	High
	Loading gauge / kinematic envelope (EN 15273)	High
	Clearance compatibility (tunnels, bridges)	High
	Platform interface compatibility	Medium
Running gear & track interaction	Wheel profile & equivalent conicity	High
	Wheelsets	High
	Bogie geometry	High
	Gauge compatibility	High
	Axle load/ unsprung mass	High
	Track force performance	High
Coupling & mechanical interfaces	Automatic coupler	Medium
	Rescue coupler compatibility	Medium
	Buffers & draft gear	Medium
	Digital automatic coupler (DAC) compatibility	Medium
	Train-to-train interface	Medium
Braking system	Braking system type	High
	Brake medium (air/vacuum)	High
	Service brake performance	High
	Emergency brake performance	High
	Wheel slide protection	Medium
	Parking brake	High
Driver interface & control	Driver machine interface (DMI)	Medium
	Cab ergonomics and visibility	Medium
	Control system integration	Medium
	Structural strength	High
	Crashworthiness	High

Safety & structural integrity	Fire safety	High
	Emergency evacuation system	High
Accessibility	PRM accessibility compliance	Medium
	Door geometry & boarding step	Low
Noise performance (TSI Noise)	Pass-by noise	Low
	Interior noise	Low
	Aerodynamic noise	Low
	Stationary noise	Low
	Braking noise	Low
Signalling & train control	Onboard ETCS/ERTMS level compatibility	High
	Train detection compatibility (axle counters/ track circuits)	High
	GSM-R/FRMCS radio compatibility	High
	Odometry integrity	Medium
	Event recorder (JRU/OTMR)	Low

After the first layer of categorizing the parameters, a Fuzzy AHP model is used to evaluate and rank rolling stock subsystem parameters based on their relative impact on cross-border railway interoperability. This method is selected due to data scarcity, the field's under-explored nature, and the technical judgment required. Additionally, Fuzzy AHP replaces exact numbers with Triangular Fuzzy Number (TFN), given the inherent subjectivity and uncertainty associated with expert evaluation of interoperability barriers, a Fuzzy AHP model was employed while considering linguistic ambiguity in pairwise comparisons. Thus, the criteria to evaluate the selected parameter are as follows:

1. Physical compatibility barrier (C1): The element is qualified as a primary determinant criterion because interoperability begins with infrastructure-vehicle interface compatibility[107], [108], [109].
2. Technical conversion difficulty(C2): because interoperability is not only technical but also techno-economic, the complexity, cost, and engineering effort required to modify a parameter to achieve compatibility lead to great retrofit difficulty act as structural barriers to harmonization[110][103].

3. Operational disruption(C3): This parameter evaluates the performance-based interoperability determinant, specifically the extent to which incompatibility disrupts scheduling, service continuity, or cross-border operations [111].
4. Safety Criticality(C4): This variable evaluates the degree of unsafe operational condition across the network; that is to say, rolling stock interoperability cannot exist if safety integrity is compromised[112].

After selecting the criteria, the next step is to list out the parameters of rolling stock, which are extracted from the document that is published in the technical specification of interoperability (TSI). Following that, the next stage is where the parameters are structured using a questionnaire distributed to experts with a background in the rolling stock department, mechanical engineers, and other safety specialists with a minimum of 2 to 20 years of experience. From all the parameters, the high and some selected medium-impact ones, which are preliminary and qualitatively filtered, total 27 + 4 parameters. To use 31 parameters in the FUZZY model, the matrix is paired 31 x 31, with a total of 456 comparisons. Thus, the parameter count is systematically reduced by merging parameters into a system, aggregating those with similar functional roles to avoid redundancy and reduce the pairwise comparison burden, while preserving interoperability critical dimensions. Thus, they are reduced to 20 parameters. That is the second layer of filtering, still resulting in a 20 by 20 matrix for each criterion. Additionally, under each criterion, the parameters being compared must be consistent. Therefore, group the list of variables into their compatibility criteria, such as physical compatibility, which is all about the harmony between the rolling stock and infrastructure. Thus, elements like gauge compatibility, axle load, and other parameters listed in the Table 3.2 are grouped together, as they all affect dimensional, mechanical, or load-transfer interactions between the rail and the track. Next is the technical conversion difficulty, which includes variables that affect the techno-economic difficulty of the railway, such as traction type, installed traction power, and so on. The third criterion, operational disruption, is very much related to energy source and performance; thus, variables like operating speed and train detection system are grouped under. Finally, for the last criterion, safety elements are selected based on their relation to hazard characteristics, such as braking system, emergency evacuation compliance, and the likes. Overall, after grouping the parameters into their consistent places for comparison (seen on table 3.2), FUZZY AHP is used to assess their impact on interoperability.

Table 3.2 Parameters filtering for the FUZZY analysis

Second Layer of grouping/filtering the parameters	
Traction type	Gauge compatibility
Installed traction power	Vehicle-infrastructure geometric compatibility
Maximum operation speed	ETCS/ERTMS compatibility
Acceleration performance	Train detection compatibility
Electrification system compatibility	GSM-R/FRMCS compatibility
Pantograph geometry	Axle load
Braking system compatibility	Coupler compatibility
Structural & fire safety compliance	Emergency evacuation compliance
Wheel/rail interface compatibility	Driver-machine interface compatibility
Infrastructure load compatibility	Energy measurement system compliance
Third layer of grouping/filtering the parameters	
Criteria 1: Physical compatibility barrier	
Gauge compatibility	Vehicle-infrastructure geometric compatibility
Axle load	Wheel/rail interface compatibility
Infrastructure load compatibility	Coupler compatibility
Criteria 2: Technical conversion difficulty	
Traction type	Pantograph geometry
Installed traction power	ETCS/ERTMS compatibility
Electrification system compatibility	GSM-R/FRMCS compatibility
Criteria 3: Operational disruption	
Maximum operation speed	Train detection compatibility
Acceleration performance	Driver-machine interface compatibility
ETCS/ERTMS compatibility	Energy measurement system compliance
Criteria 4: Safety Criticality	
Braking system compatibility	Emergency evacuation compliance
Structural & fire safety compliance	Axle load
Wheel/rail interface	

After clearly stating the parameters for each criterion, the FUZZY analysis will follow after the collection of the survey (questionnaire to evaluate the impact of rolling stock subsystem on interoperability) from selected experts. Before computing the variables defining the fuzzy analysis has six major steps listed[96], [113], [114], [115], [116].

Step one: Collect the data from the expert using a linguistic approach where the expert judgment is represented by Triangular Fuzzy Numbers (TFNs).

Table 3.3Representation of expert judgment using Triangular Fuzzy Numbers

Linguistic term	Triangular Fuzzy Numbers (TFNs)		
	Low(l)	Medium(m)	Upper(u)
Equal importance	1	1	1
Slightly more important	1	2	3
Moderate more importance	2	3	4
Strong more importance	4	5	6
Very strong importance	5	6	7
Extremely more important	7	8	9

Step two: constructing an individual fuzzy pair-wise matrix

$$A = \begin{pmatrix} (1,1,1) & a_{12} & a_{1n} \\ \vdots & \ddots & \vdots \\ a_{n1} & \dots & (1,1,1) \end{pmatrix}$$

Where:

A= individual fuzzy pair-wise matrix

a_{ij}= the combined matrix comparison value

(1,1,1) = diagonal element

Lower triangular element = reciprocals of the upper triangular value

Reciprocal values are also defined as[117]:

$$(l, m, u) = \left(\frac{1}{u}, \frac{1}{m}, \frac{1}{l}\right)$$

Step two: combine it into a single value using the aggregated fuzzy value after the geometric mean across the expert answers, as defined by Equation 3.4.

$$\widetilde{a_{ij}} = \left(\prod l_e\right)^{1/n}, \left(\prod m_e\right)^{1/n}, \left(\prod u_e\right)^{1/n} \tag{3.4}$$

Where:

a_{ij}= the combined matrix comparison value from experts

l_e= Experts low linguistic term

m_e= Expert medium linguistic term

u_e= Expert upper linguistic term

n= the number of expert participants in the analysis

Step three: compute the Buckley geometric mean method of the pairwise matrix by referring to Equation 3.5.

$$r_i = \left(\prod_{j=1}^{n} a_{ij}\right)^{1/n} \tag{3.5}$$

Where:

r_i= row-wise Buckley geometric mean

n= the number of expert participants in the analysis

Step four: Normalize fuzzy weights to ensure $\sum w_i = 1$

$$w_i = r_i * \left(\sum_{i=1}^{n} r_i\right)^{-1} \tag{3.6}$$

Where:

w_i= row-wise normalized fuzzy weight

$\sum_{i=1}^{n} r_i = (\sum l_i, \sum m_i, \sum u_i)$

Step five: Defuzzification

$$W_i = \frac{l_i + m_i + u_i}{3} \tag{3.7}$$

Where:

W_i= row-wise defuzzied fuzzy weights

Step six: Final normalization to ensure the concluding sum is one, followed by ranking the parameters according to their corresponding criteria.

$$W_i^* = \frac{W_i}{\sum_{k=1}^{n} W_k} \tag{3.8}$$

Where:

W_i^*= final normalized weight of criteria

W_k= total sum of W_i

Consistency and sensitivity analysis

On the decision-making framework that implements pairwise comparisons to derive priorities, because human judgments in these comparisons can be inconsistent, so verifying the involvement of calculation using Equation 3.10. Thus, if the consistency ratio (CR) is less than 10%, the matrix is considered acceptably consistent; otherwise, revisions may be needed.

$$CI = \frac{\lambda_{max} - n}{n - 1} \qquad (3.9)$$

Where:

CI= consistency index

λ_{max}= the principal eigenvalue (maximum eigenvalue) of the pairwise comparison matrix

$$\lambda_{max} = \frac{\sum_{i=1}^{n} \lambda_i}{n} - - - - - - - - \rightarrow \lambda_i = \frac{(A * w_i)}{w_i}$$

n= the number of parameters (size of the square matrix)

$$CR = \frac{CI}{RI} \qquad (3.10)$$

Where:

CR= consistency ratio (used for normalizing CI against random inconsistencies)

RI= the random index, which is dependent upon the generated matrix size n, as the standard RI values include:

n = 3: RI = 0.58

n = 4: RI = 0.90

n = 5: RI = 1.12

n = 6: RI = 1.24

For the sensitivity analysis, to know at what Percentage change of the variables becomes sensitive, for the change Equation 3.11 is used.

$$Y2 = (1 - Y1)(\frac{W2}{W2 + W3 + W4}) \qquad (3.11)$$

Where:

Y1 = the original weight of the criteria

Y2= new Weight for criterion 2

W2= Weight of criterion 2

W3= Weight of criterion 3

W4= Weight of criterion 4s

Thus, the analysis for the impact on interoperability is conducted and presented on te result section.

3.4 Axle load static structural analysis

Even though some parts of the rolling stock have a stronger influence than others, the bigger picture is that all components are designed and manufactured to be compatible with the track, power, and signalling systems, which makes it highly dependent on the railway subsystem. Moreover, in the EU, interoperability is built around subsystems (infrastructure, energy, control-command/ signalling, rolling stock, operations) [118] as the rail vehicles' design choice is constrained by infrastructure and energy, not the other way around. This means that when designing a railway vehicle (locomotive, trainset, wagon, etc.), the designer should take into account the officially published infrastructure capability information (including track gauge, axle load limits, curve radius, platform height, electrification type, signalling systems, etc.). If the vehicle is designed with these infrastructure limits in mind, it becomes easier to carry out the compatibility checks required before allowing the vehicle to operate on a route. These checks must be done according to the TSI OPE (Operation and Traffic Management TSI), Appendix D.1, which provides the procedure for verifying whether a vehicle can run safely and effectively on a given EU railway line.

Furthermore, the outcomes of the design parameters are clearly evident in the manufacturing stage, where major companies in the rail industry contribute by producing different designs and parts. Thus, the global railway establishments shown in Figure 3.5, which are all currently in service, demonstrate how diverse they are. In African countries, only two, South Africa and Egypt, are counted as manufacturers. Heavy industrial production comes from the big players, leading to a focus on assembly, refurbishment, or regional coach/wagon manufacturing, making them dependent as well. Interoperability is not only technical; it is also institutional and economic. Knowing which companies dominate where (e.g., CRRC in Kenya/Ethiopia, Hyundai Rotem in Tanzania, Alstom in Morocco/South Africa) shows how Africa’s interoperability challenges are also tied to supplier dependency and a lack of coordination.

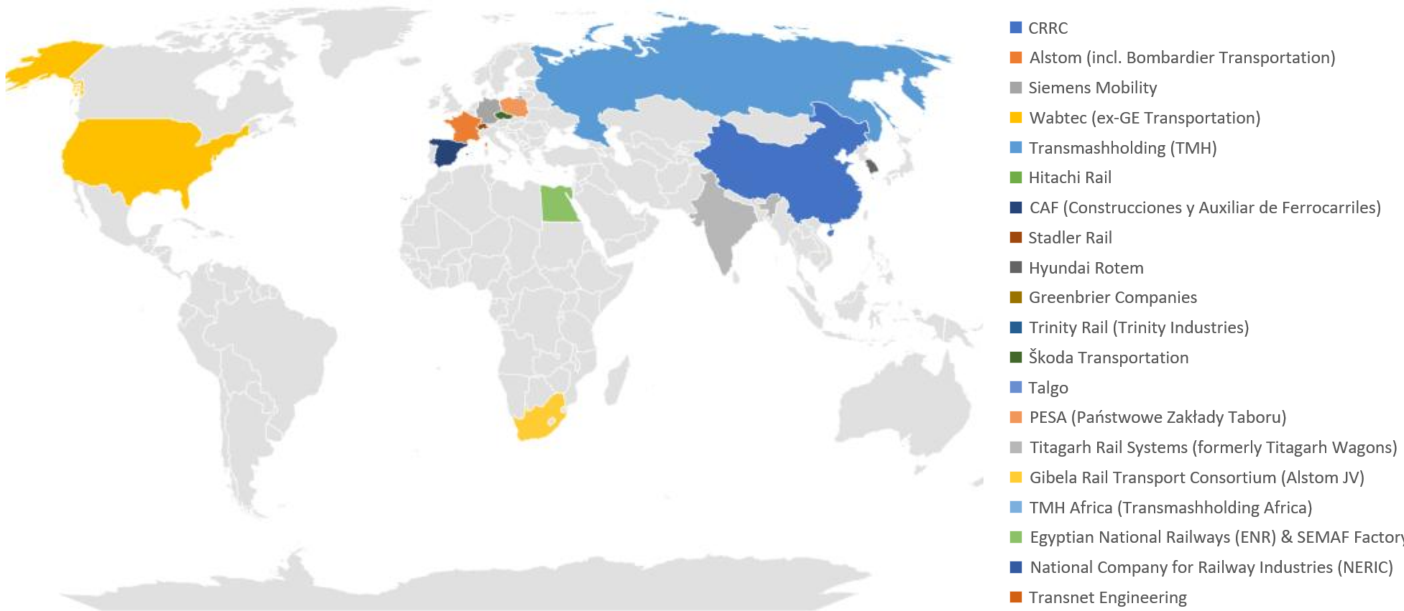

Figure 3.5. Manufacture and Assembly of Rolling Stock Companies in the World (Autor)

However, the operating rail line in East Africa, which is Ethio-Djibouti (EDR) and TAZARA, was constructed by China Railway Engineering Corporation (CREC) + China Civil Engineering Construction Corporation (CCECC) (joint contractors)[119] and China Railway Engineering Corps (CREC) [120] company respectively. Although a similar company built both countries' railway systems, they ended up having different subsystems, which may lead to an unknown outcome. Therefore, this thesis has analysed a scenario where the EDR wheel, having an axle load limit of 25 tonnes, is placed on the TAZARA rail track, with an axle load limit of 20 tonnes. Testing TAZARA on the EDR is not necessary because it does not exceed the axle load limit. Overall, these cases are constructed to answer the question" what would happen if the rolling stock of EDR is placed on the TAZARA track?". Therefore, the first scenario shows when the rolling stock of EDR is placed on the TAZARA track with its full axle load pressing vertically downward. Finally, case 2 is there to show what if we try to operate according to the track axle load limit by reducing the EDR rolling stock. Hence, taking only the three cases shown in Table 3.4 is enough to measure the percentage changes and understand the real impact on interoperability due to the selected variables.

Table 3.4. Scenario Matrix of the Analysis

Case	Wheel (fixed)	Track (varies)	Load (N)
1	EDR	TAZARA	F_Z = 122,625 N

2	EDR	TAZARA	F_Z = 98,100 N

Now, having established the baseline, the next step is to dive into the analysis. The ANSYS Workbench is adopted as the primary simulation environment for conducting static structural analysis on the wheel/rail system. The choice is based on its extensive industrial use, academic credibility, and advanced capabilities in modelling contact, nonlinearity, and material behaviour. It is also widely recognized in the railway industry for its strength and trustworthiness in simulating real-world engineering problems. Major rail companies and manufacturers employ ANSYS to validate design performance, optimize safety, and comply with international standards. For instance, Burlington Northern Santa Fe (BNSF) Logistics, one of North America's largest freight operators, utilizes ANSYS Workbench to perform finite element stress analyses on railcar structures to meet Association of American Railroads (AAR) design requirements. The company reports that ANSYS allows rapid conversion of CAD models into validated finite element analysis (FEA) models for various static and dynamic load cases, ensuring regulatory compliance and structural efficiency [121]. Similarly, Leading Engineering Application Providers (LEAP) Australia, in partnership with Knorr-Bremse Rail Systems, applies ANSYS structural mechanics tools for analysing braking systems, fatigue life of bolted joints, and static and dynamic responses of critical railway components [122]. These applications demonstrate ANSYS's acceptance as a trusted solution in railway component design and validation.

Beyond industrial practice, ANSYS is also validated in academic and experimental railway research. A Case study published in Construction Materials employed ANSYS R2 2023 to simulate the structural performance of welded and bolted rail joints under static loads, comparing numerical results to laboratory tests and achieving close correlation between measured and simulated stress distributions [123]. Such studies reinforce ANSYS's ability to replicate complex contact and loading conditions accurately in the railway domain. In addition, ANSYS's adoption extends across other transportation sectors such as aerospace and automotive, including agencies like NASA, Airbus, and Boeing, which rely on the same platform for structural and multi-physics analyses. NASA's official site states, "NASA has awarded ANSYS Inc., located in Canonsburg, Pennsylvania, a contract to provide a suite of modelling and simulation tools with capabilities in disciplines such as structures, crash, thermal, fluids, photonics, semiconductors, electromagnetics, materials, mission, test, evaluation, and orbit determination." This cross-industry trust underscores the software's reliability, numerical precision, and adaptability to demanding engineering applications. ANSYS Workbench is selected for this thesis, in which the 3-D model, exported from SolidWorks in the ".STEP" format, is shown in Figure 3.6.

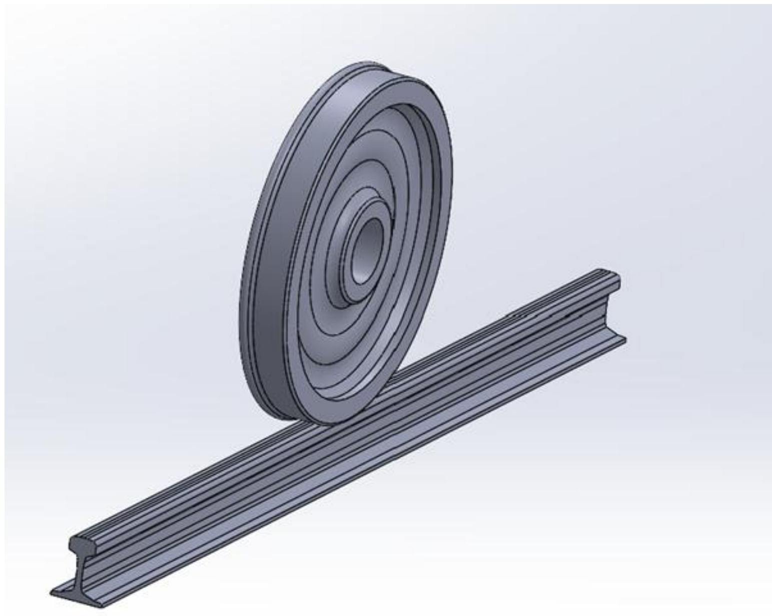

Figure 3.6 3D Models of the wheel/rail

Accordingly, a static structural analysis was carried out using ANSYS Workbench to determine the stress distribution and deformation between the wheel and rail interface under applied axle loads. The static structural module in ANSYS is designed to compute the response of structures subjected to steady loading conditions, assuming that loads are applied slowly and remain constant over time. This type of analysis is particularly suitable for railway applications where quasi-static conditions prevail, such as the vertical wheel load transmitted from a stationary or slowly moving axle to the rail. It allows accurate estimation of stress concentration and deformation within the elastic range of the materials involved.

The governing relationship for static structural analysis follows the fundamental equilibrium equation 3.12[124]:

$$\{F\} = [k(\{u\})] * \{u\} \tag{3.12}$$

Where:

F = the applied load vector

K = the global stiffness matrix, and

u = the nodal displacement vector

- ✓ After calculating nodal displacements, the solver uses these displacements to determine strains and stresses. To precisely mimic the actual contact circumstances, frictional interfaces are used in the study to account for the contact behaviour between the wheel and rail, aiming to build a model contributing to the nonlinearity of geometry and material. The coefficient of friction was assumed based on published literature and experimental data from similar wheel–rail contact studies [125][126] [127]. By analysing the large deformation, it takes into account the nonlinearity of the geometry of the wheel and rail model.

To ensure computational efficiency without compromising physical accuracy, the following simplifications were made:

- ✓ Mesh refinement: Contact surface as an additional fine mesh.
- ✓ Material homogeneity: Wheel and rail modelled as isotropic materials (elastic).
- ✓ Neglect of fasteners/sleeper: Only the rail block is represented; sleeper and ballast effects are represented through fixed support boundary conditions.
- ✓ Static loading assumption: Dynamic and rolling effects are neglected in this stage; only vertical static loading is applied to study elastic deformation.

These assumptions align with established practices in railway contact FEA modelling[125][127]. Before proceeding to meshing and loading, the imported geometry was verified in ANSYS for parameters like geometric integrity (no gaps or intersections), contact surface alignment, correct scale (units in millimetres), and compatibility of shared topology are checked. The accuracy of an FEA depends largely on the mesh quality and refinement, especially in regions with steep stress gradients such as the wheel–rail contact zone. In this thesis, meshing was performed in ANSYS Workbench (Static Structural Module) using high-quality tetrahedral solid elements with local refinement at the contact interface.

The geometry of the wheel–rail model was discretized using Solid187 elements, which are 10-node tetrahedral elements capable of quadratic displacement behaviour. The mesh was generated using a multi-zone automatic method in ANSYS, ensuring smooth transitions between fine and coarse regions. Element Type: Solid187 (3D 10-node tetrahedral); Mesh Method: Multi-zone (Automatic); Contact Type: Frictional ($\mu = 0.3$); Refinement Region: Wheel–rail contact interface;

Global Element Size: 6 mm; Local Element Size (Contact Patch): 0.5–1 mm. Next, to ensure numerical reliability, key mesh quality indicators were evaluated using the ANSYS Statistics tool. The average quality values are shown in Table 3.5. All metrics fall within acceptable limits for high-quality static structural analyses [127][125].

Table 3.5. Mesh Quality Metrics

Quality Metric Symbol	Acceptable Range	Average Value	Remarks
Element Skewness (S_k)	< 0.90	0.35	Excellent
Aspect Ratio (AR)	< 5	2.1	Good
Jacobian Ratio (J_r)	< 10	1.3	Excellent
Orthogonal Quality (Qo)	> 0.15	0.85	Excellent
No. of Nodes	-	198,762	-
No. of Elements	-	143,890	-

Hence, to ensure mesh independence, a convergence study was performed by progressively refining the mesh in the contact region while monitoring the maximum von Mises stress and total deformation reaching the finest mesh level. After the fine mesh, the variation in maximum stress dropped below 2%, indicating mesh convergence and confirming that further refinement would not significantly alter the results. Therefore, the fine mesh (0.05 mm in the contact region) was used for the final simulation. A local mesh control was applied on both the wheel tread and rail head surfaces, assigning them as contact and target sides as shown in Figure 3.7.

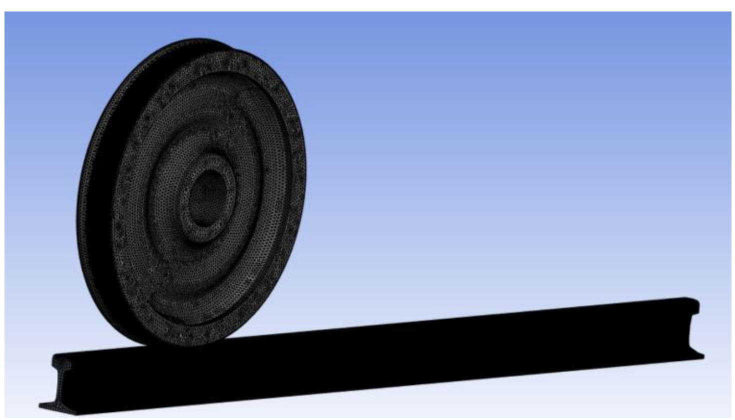

Figure 3.7. Finite Element Mesh of the Wheel–Rail Assembly Showing Refinement Near the Contact Interface (Autor)

Finally, verification of mesh accuracy is made by visual inspection for irregular elements and intersections, mesh statistics (skewness, Jacobian, and orthogonal quality) are checked in the ANSYS statistics tab, and trial runs with lower load steps are performed to confirm solver convergence without element distortion. After finishing the meshing, the next thing to do is to set the boundary conditions and loading.

3.4.1Boundary condition for the analysis

The boundary conditions define how the model interacts with its environment and how loads are transmitted through the structure. In this thesis, appropriate supports, loads, and contact interfaces were assigned in ANSYS Workbench (Static Structural) to accurately simulate the wheel–rail interaction under vertical static load. Thus, both support and constraint conditions are made as follows:

Fixed Support (Bottom Surface):

- ✓ The bottom face of the rail block was fully constrained in all translational directions ($U_x = U_y = U_z = 0$) to simulate the stiffness contribution of sleepers and ballast layers[128].

Lateral Constraints:
To prevent rigid body motion while allowing realistic stress distribution, symmetry planes were applied on the sides of the quarter model:

- ✓ XZ-plane symmetry: Prevents lateral movement in the Y direction.
- ✓ YZ-plane symmetry: Restricts longitudinal movement but allows vertical deformation.

Following the support and constraints, a load is applied representing the axle load limit. The analysis is made by changing just a couple of key variables, like axle load and material differences, while keeping everything else constant. The axle load is the force that the wheel/rail contact must support, and it is the parameter that determines how much stress, bending, and deformation the track structure must resist. Hence, for each wheel on the axle, it carries half the load, where the calculation is as shown below.

$$Wheel\ load = \frac{Axle\ load}{2} \quad (3.5)$$

$$Wheel\ load_{EDR} = \frac{(25000\ Kg.*9.81)}{2} = 122{,}625\ Newton \quad (3.5a)$$

$$Wheel\ load_{TAZARA} = \frac{(20000\ Kg.*9.81)}{2} = 98{,}100\ Newton \quad (3.5b)$$

This load was applied vertically downward on the wheel hub surface as a remote force to ensure uniform load transfer and to replicate the effect of the axle load distributed through the wheel web. And the other variable considered for the change to represent the TAZARA rail track is the material. The material properties of EDR[129] and TAZARA[130], [131] are shown in Table 3.6. Remember, all materials are assumed to be isotropic, homogeneous, and linearly elastic within the stress range considered. Temperature effects and residual stresses are neglected.

Table 3.6. Material Properties of EDR and TAZARA

Material property	EDR wheel	EDR track	TAZARA track
Density (kg/m)	7800	7800	7870
Young’s modulus (Gpa)	207	207	190
Possion ratio	0.3	0.3	0.3
Tensile Ultimate strength (Mpa)	900	940	780-1000
Yield strength (Mpa)	580	520	350-400

Thus, three primary cases are shown in Table 3.3, the first of which is the EDR wheel and rail taken with the axle load limit of 25 tonnes applied vertically downward. In the second case, the axle load limit of 25 tonnes is imposed vertically downward on the EDR wheel with the TAZARA rail track. The axle load limit of 20 tonnes is applied to the third case, which involves the EDR wheel with TAZARA rail track. The combination of cases 1 and 2 illustrates the percentage change when the material of the rail varies, whereas case 2&3 shows the load variation. These settings were refined through preliminary runs to achieve consistent convergence with minimal element distortion and acceptable CPU time. All analyses were performed on a workstation with the following specifications, as shown in Table 3.7.

Table 3.7. Spec of the Working Laptop Where the Analysis was Made Using ANSYS

Parameter	Specification
Processor	Intel® Core™ i7-6500U CPU @2.50
RAM	16 GB/available 10 GB
Software	ANSYS Workbench 2023 R1
Operating System	Windows 11 (64-bit)

Chapter 4 Results and Discussion

4.1 Overview of Collected Data

This section presents the current status of the East African railway interoperability, rolling stock compatibility, and static structural analysis. Primary and secondary data analysis of results compiled and analyzed in summarized tables and graphical illustrations. Moreover, the sets of stages for detailed subsystem and scoring analysis provide the empirical foundation of compatibility across the region.

4.2 Regional Connectivity and Cross-Border Analysis

Depending on the pattern of the results, they are subdivided into three sections. Section one states that Tanzania, Uganda, and Zambia have relatively interoperable railways, as shown in Table 4.1. Burundi, Congo, and Kenya are depicted in Section 2 as shown in Table 4.2, where they have ties to no more than one East African country. Section three is about the rest of the country selected from the master plan, where not even a single connection is witnessed.

Table 4.1 relatively interoperable railways across East Africa

	Connectivity/ operability		Planned connectivity	Score
	Track connecting the two countries	Operating track		
Tanzania to Other East African Countries				
Tanzania-Ugandan	1	1	1	1.25
Tanzania-Sudan	0	0	1	0.25
Tanzania-Rwanda	0	0	1	0.25
Tanzania-Burundi	1	0	1	0.85
Tanzania-Congo	0	0	1	0.25
Tanzania-Ethiopia	0	0	1	0.25
Tanzania-Kenya	0	0	1	0.25
Tanzania-Zambia	1	1	1	1.25
	3	2	8	
Ugandan to Other East African Countries				
Tanzania-Ugandan	1	1	1	1.25
Ugandan-Sudan	0	0	1	0.25
Ugandan-Rwanda	0	0	1	0.25
Ugandan-Burundi	0	0	1	0.25
Ugandan-Congo	0	0	1	0.25
Ugandan-Ethiopia	0	0	1	0.25
Ugandan-Kenya	1	1	1	1.25
Ugandan-Zambia	0	0	1	0.25

	2	2	8	
Zambia to Other East African Countries				
Tanzania-Zambia	1	1	1	1.25
Ugandan-Zambia	0	0	1	0.25
South Sudan-Zambia	0	0	1	0.25
Rwanda-Zambia	0	0	1	0.25
Burundi-Zambia	0	0	1	0.25
Congo-Zambia	1	1	1	1.25
Ethiopia-Zambia	0	0	1	0.25
Kenya-Zambia	0	0	1	0.25
	2	2	8	

Table 4.2. Burundi, Kenya, and Congo Connectivity/Operability and Planned Connectivity

	Connectivity/ operability		Planned connectivity	Score
	Track connecting the two countries	Operating track		
Kenya to Other East African Countries				
Tanzania-Kenya	0	0	1	0.25
Ugandan-Kenya	1	1	1	1.25
South Sudan-Kenya	0	0	1	0.25
Rwanda-Kenya	0	0	1	0.25
Burundi-Kenya	0	0	1	0.25
Congo-Kenya	0	0	1	0.25
Ethiopia-Kenya	0	0	1	0.25
Kenya-Zambia	0	0	1	0.25
	1	1	8	
Ugandan to Other East African Countries				
Tanzania-Burundi	1	0	1	0.85
Ugandan-Burundi	0	0	1	0.25
South Sudan-Burundi	0	0	1	0.25
Rwanda-Burundi	0	0	1	0.25
Burundi-Congo	0	0	1	0.25
Burundi-Ethiopia	0	0	1	0.25
Burundi-Kenya	0	0	1	0.25
Burundi-Zambia	0	0	1	0.25
	1	0	8	
Congo to Other East African Countries				
Tanzania-Congo	0	0	1	0.25
Ugandan-Congo	0	0	1	0.25
South Sudan-Congo	0	0	1	0.25
Rwanda-Congo	0	0	1	0.25
Burundi-Congo	0	0	1	0.25
Congo-Ethiopia	0	0	1	0.25
Congo-Kenya	0	0	1	0.25

Congo-Zambia	1	1	1	1.25
	1	1	8	

Table 4.3. Sudan, Rwanda, & Ethiopia Connectivity/Operability

	Connectivity/ operability		Planned connectivity	Score
	Track connecting the two countries	Operating track		
Sudan to Other East African Countries				
Tanzania-Sudan	0	0	1	0.25
Ugandan-Sudan	0	0	1	0.25
South Sudan-Rwanda	0	0	1	0.25
South Sudan-Burundi	0	0	1	0.25
South Sudan-Congo	0	0	1	0.25
South Sudan-Ethiopia	0	0	1	0.25
South Sudan-Kenya	0	0	1	0.25
South Sudan-Zambia	0	0	1	0.25
	0	0	8	
Rwanda to Other East African Countries				
Tanzania-Rwanda	0	0	1	0.25
Ugandan-Rwanda	0	0	1	0.25
South Sudan-Rwanda	0	0	1	0.25
Rwanda-Burundi	0	0	1	0.25
Rwanda-Congo	0	0	1	0.25
Rwanda-Ethiopia	0	0	1	0.25
Rwanda-Kenya	0	0	1	0.25
Rwanda-Zambia	0	0	1	0.25
	0	0	8	
Ethiopia to Other East African Countries				
Tanzania-Ethiopia	0	0	1	0.25
Ugandan-Ethiopia	0	0	1	0.25
South Sudan-Ethiopia	0	0	1	0.25
Rwanda-Ethiopia	0	0	1	0.25
Burundi-Ethiopia	0	0	1	0.25
Congo-Ethiopia	0	0	1	0.25
Ethiopia-Kenya	0	0	1	0.25
Ethiopia-Zambia	0	0	1	0.25
	0	0	8	

If all the states in East African Countries were interconnected by railway, there would have been 36 railway routes. Nevertheless, only five railway connections exist, namely Tanzania to Uganda, Tanzania to Zambia, Tanzania to Burundi, Uganda to Kenya, and Congo to Zambia. Of these five, four are currently operating, with the exception of the Tanzania-Burundi route (excluding Ethiopia-Djibouti). The WSM method was applied to determine the percentage of connectivity among East African countries. As shown in Figures 4.1, 4.2, and 4.3, Tanzania, Uganda, and Zambia score 30%, 20%, and 20%, respectively, while Burundi, Kenya, and Congo score 10%. Other East African countries score 0%. This indicates that Tanzania is connected to Uganda and Zambia, and that Burundi and Zambia are connected, but the Tanzania-Burundi link is not currently operational. Overall, Tanzania is connected to three countries, Uganda and Zambia to two, and Congo, Burundi, and Kenya to one, while the rest of the countries are not connected by train. However, according to the master plan, all East African countries were scheduled to connect via railway.

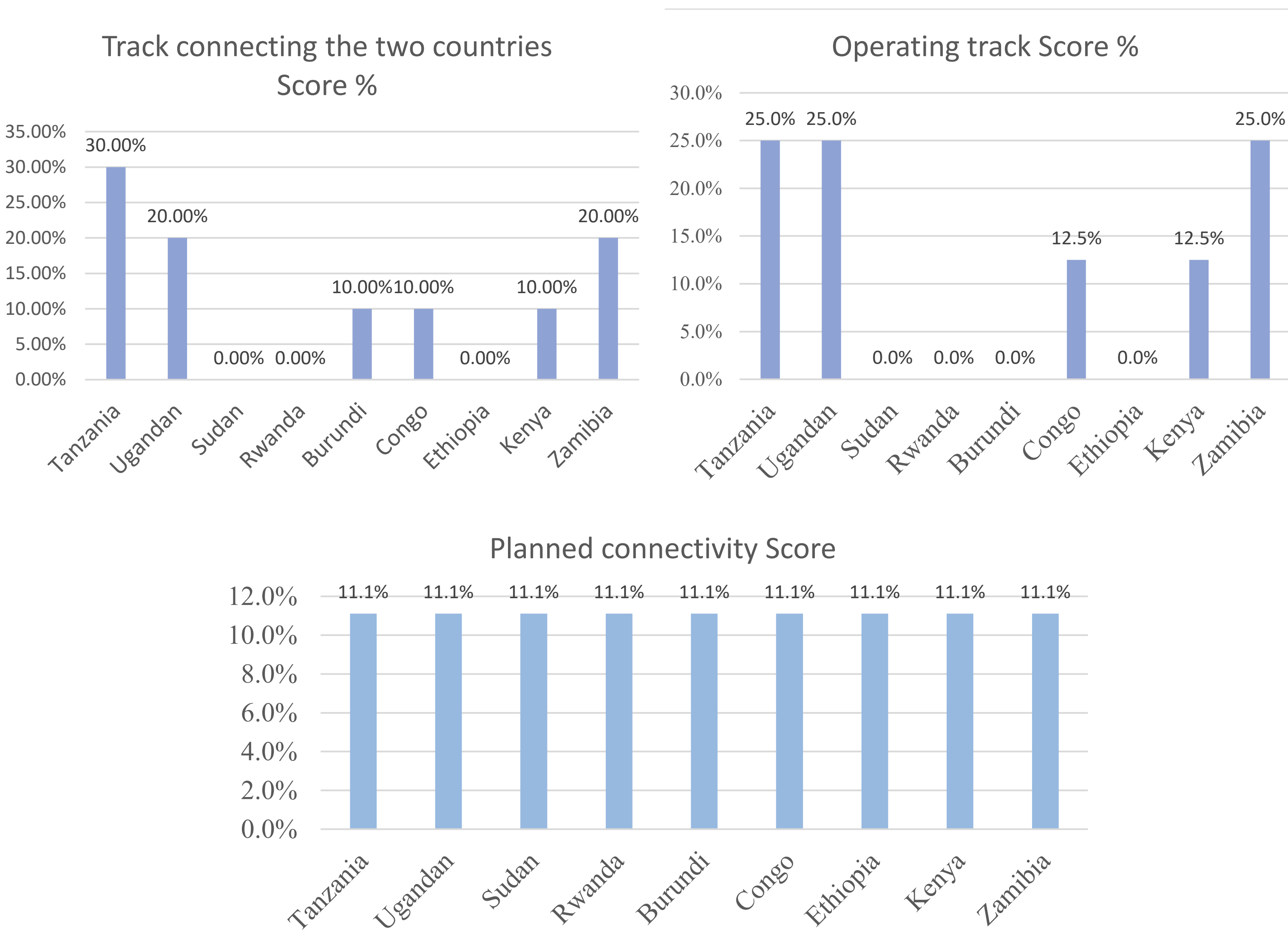

Figure 4.1. East African Countries' Connectivity, Operability, and Planned Connectivity (Author)

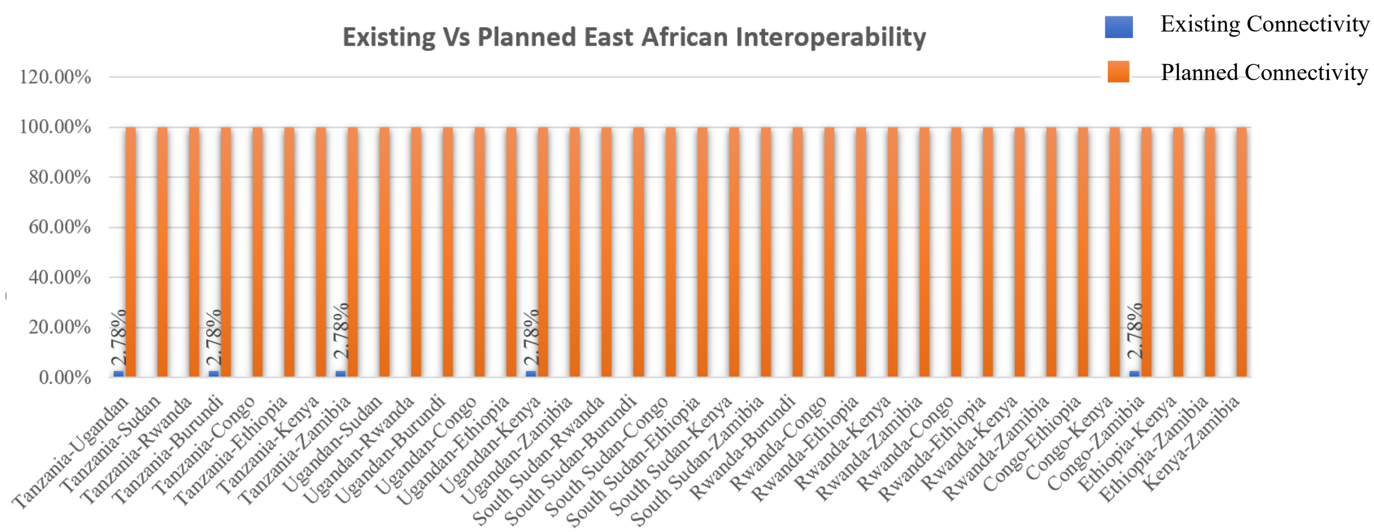

Figure 4.2. Existing Vs Planned East African Interoperability (Author)

Thus, the planned connectivity score for all East African countries is 11.1% as illustrated in Figure 4.1. The master plan has three sequential implementation and construction phases. Phase one (2007-2012) is for restoration and restoration of the existing railway networks, phase two (2013-2017) for the construction and upgrading of key corridors, including links to Rwanda and Burundi, and phase three (2018-2027) for the completion of new lines, modernization, and network expansion across all member states with 2030 serving as the long-term evaluation and traffic growth target year. However, currently being in the year 2025 and evaluating the plan vs the existing railway interoperability percentage progress is 0.375%, as shown in Figure 4.2 (excluding the Ethio-Djibouti rail line). Overall, this indicates that interoperability in East Africa is very poor. Moreover, validating the claim through questionnaires were collected and presented in Figure 4.3 of the qualified respondents and Figure 4.4 of their scholarly opponents.

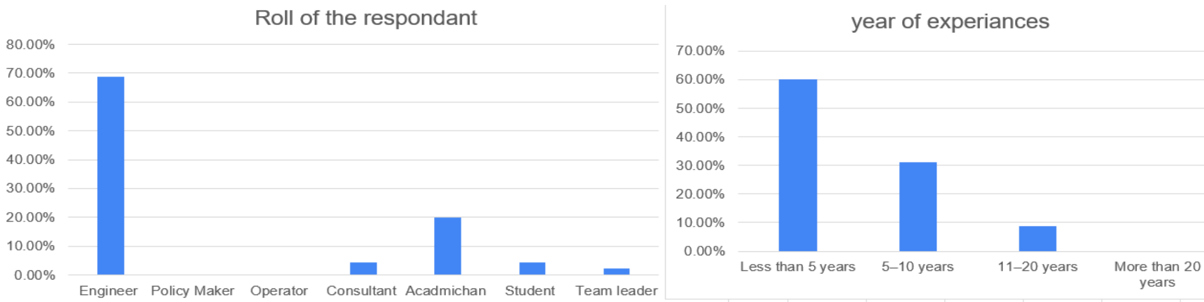

Figure 4.3. Roll and Experiences of the Respondent (Author)

As shown in Figure 4.3, of all the respondents, 68.9% engineers, 20% academicians, 4.4% students, 4.4% consultants, and 2.2% were team leaders. And 60% of the total have less than 5 years of experience, 31.1% have 5-10 years of experience, and 8.9% have 11- 20 years of experience, screening all the respondents who are qualified scholars living in Ethiopia.

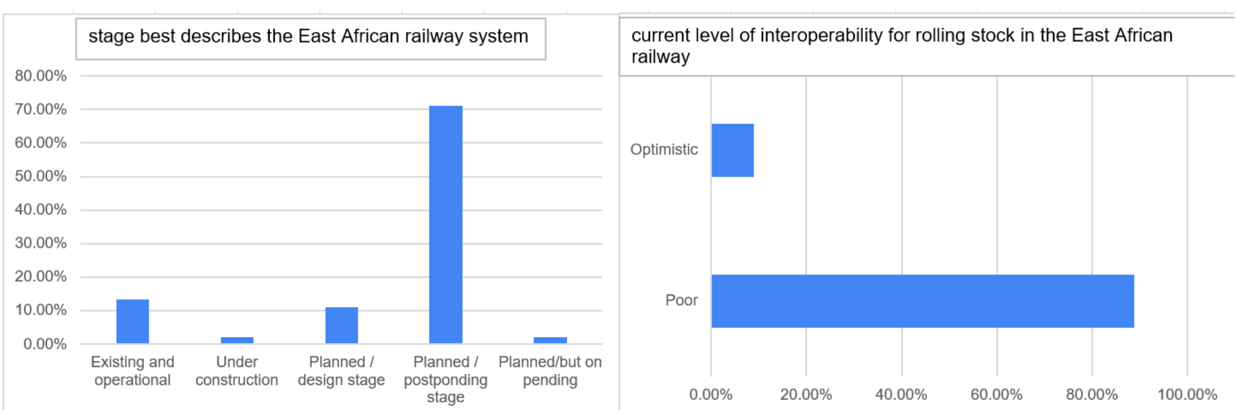

Figure 4.4. Current Status of East African Railway (Autor)

As shown in Figure 4.4, about 70% respond that the current stage that describes East African railway is planned and postponed, 13.3% existing and operating, 11.1% planned/design stage, and the other 2.2% planned but pending. For the level of interoperability, 88.9% responded poor and 8.9% responded optimistic; thus, the statement of the status of East African interoperability is concluded as poor.

Following that, for the rolling stock subsystem, the results indicate a strong consensus among respondents regarding the identified parameters affecting interoperability. Out of the 24 parameters analyzed, they were categorized based on their level of impact: high, medium, and low. The findings show that an overwhelming 99% of respondents agreed on the significance of these parameters in influencing interoperability. This high level of agreement demonstrates the reliability and validity of the classification, suggesting that the selected parameters accurately capture the critical factors that affect interoperability performance within the system. It also reinforces that the stakeholders share a common understanding of the challenges and enablers of interoperability, which is essential for developing effective strategies to improve integration and coordination across subsystems.

4.3 Rolling stock subsystem impact analysis result

A total of 48 parameters from the TSI document are filtered with a sequence of strategic steps, as shown in Figure 3.2. The first phase is classifying the overall parameters within three categories: high, medium, and low, which is used as a base for pairwise parameter comparison. Thus, on this level, the variable's impact value is validated through a survey were 97.8% support the result that indicated the wheelsets, bogie geometry, gauge compatibility, axle load/ unsprung mass, track force performance, traction type, and others as high impact, followed by parameter like automatic coupler, rescue coupler compatibility, buffers & draft gear, digital automatic coupler (DAC) compatibility as a medium, and lastly, noise performance, and event recorded as low impact parameters. Next, reducing the number of parameters to a manageable size by combining variables with similar characteristics, resulting in 20 parameters. Therefore, the final criteria and the parameters are evaluated using the FUZZT AHP analysis, which is conducted following every six steps as stated in the methodology section, starting from evaluating the criteria. Figure 4.5 shows that the analysis demonstrates the physical compatibility achieved the highest weight of 58%, indicating it plays the most significant role in determining rolling stock interoperability. Followed by safety criticality (25%), and technical conversion (11%), while operational disruption (6%) received the lowest priority weight among the evaluated factors, illustrated in Figure 4.5. Subsequently, categorizing the parameter under each criterion for further evaluation.

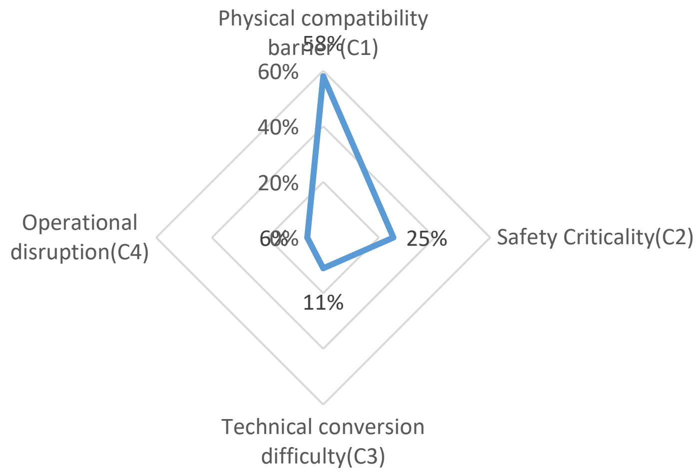

Figure 4.5 The ranking for the criteria to evaluate the parameter of rolling stock influence on interoperability

The parameter analysis provides deeper insight into the factors influencing interoperability within each criterion, as the results reveal that certain parameters dominate within respective categories, as shown in Figure 4.6. Thus, within criteria, one gauge compatibility (43%) takes the highest priority, followed by axle load (18%), showing how influential a factor they are in affecting interoperability.

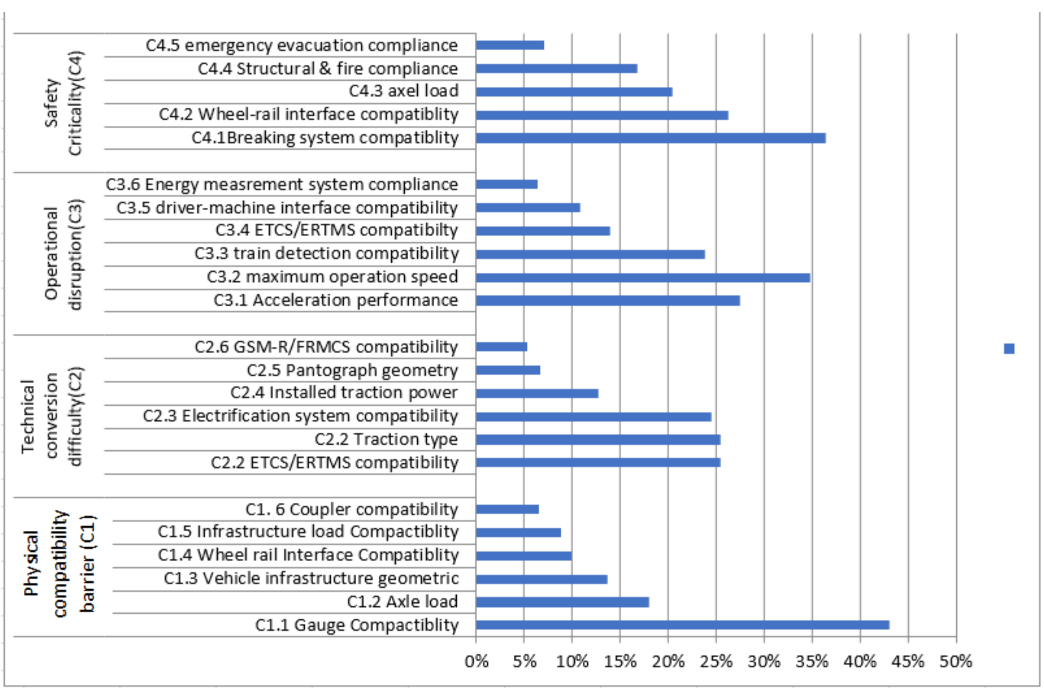

Figure 4.6. Rolling Stock Subsystem Impact

Consistency verification and sensitivity analysis

As shown in Figure 4.7, the sensitivity variation among the criteria exceeds 10%, this shows that a change in the weight of one factor has a limited influence on the other elements; therefore, the criteria indicate a relatively low level of interdependency, and the overall result can be considered as stable and reliable. Additionally, the reply from the scholar has shown consistency where it is analysis by taking a sample as the lowest triangular pairwise linguistic to show the consistency recorded as 9% where the range is interpreted a s long as the result is under 10% it shows the outcome are logical coherent.

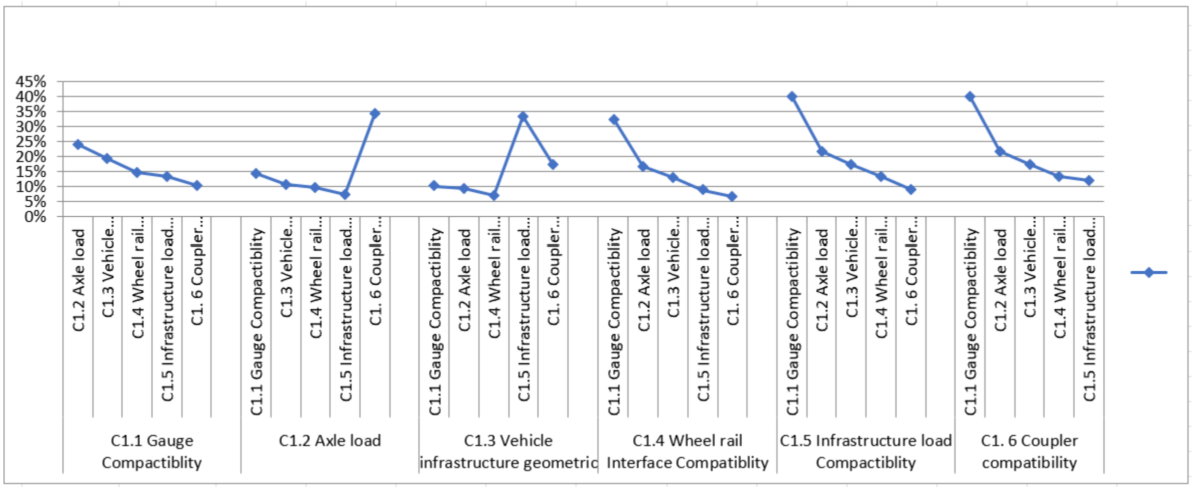

Figure 4.7 sensitivity analysis for the selected criteria

4.3.1 Discussion of the parameter impact on interoperability ranking

The result shows that the physical compatibility takes a vital role when evaluating interoperability, showing first that the railway system has to be connected and also have the ability to operate, entertaining the idea of its criticality by showing the physical alignment needed. Even when physically aligned, rolling stock that fails to meet safety standards cannot be permitted to operate within another railway system. With these strict authorities enforced, this element also becomes necessary before considering to cross-border to another network. However, unlike physical incompatibility, technical conversion challenges do not always prevent interoperability. Where rolling stock can be upgraded, or maintenance to meet the standard involves a significant amount of cost and effort, representing a significant barrier but less restrictive than fundamental physical capability constraints, lastly, operational disruption, which is ranked at the lowest, making it the least influential criterion among the four evaluated factors. This variable reflects the challenges affecting train scheduling, maintenance activity, and border operations. Thus, it affects the efficiency of the railway network service rather than the fundamental feasibility of interoperability.

From all four criteria, starting from the highest ranking, which is the physical compatibility barrier shown in the figure, it can be witnessed that gauge is the vital parameter overall, followed by axle load. The axle load is the vertical force that the track senses on the first connection with the rail vehicle, making it the second most important parameter on which the interoperability depends. Next, the vehicle infrastructure geometry, which is about the height, length, and width of the rolling stock, is influenced by the infrastructure built, like a tunnel, which makes it difficult to operate. Which close ranking with wheel rail interface that a connection that comes after the axle load force is applied, forming a contact which looks like an elliptical shape, thus, this parameter, where this small contact controls the energy consumption, wearing and tearing, and even can help predict the failure of the component due to poor lubrication. Hence, ranking fourth makes it the next important parameter to look out for when the vehicle starts moving. Lastly, the coupler that connected the rolling stock comes as the preceding element that contributes the least amount, as it facilitates a logical bridge between networks.

Secondly, under the criteria of safety, the important element to consider is the braking system. The braking system is a way to stop the moving rail vehicle by controlling the train speed in the desired range to load or unload passengers or freight, which may result in the most dangerous and uncontrollable machine accident. Subsequently, wheel/rail interface and axle load are the component which directly related to the structural safety of the wheel and the rail through the force and the contact. Lastly, in case of an accident already happen the element like fire, emergency exits are the necessary variables to consider to make the overall cross-border experience. The third criterion, which is about the technical conversion difficulty, compares six parameters result in traction type being the highest score, because changing the vehicle type is so expensive, considering diesel with electrified railway needing full investment. While the electrification system, which is also similar to the ETCS/ERTMS, pantograph, and GSRM. The fourths criteria being operational disruption, the first thing that comes to mind is the maximum operating speed, which is the primary input for building a timetable, leading to interrupted operations due to being late or unscheduled delay, making it unreliable and uneven train distribution of train movement. The same goes for the acceleration performance, too. Consequently, the train detects the digital communication, and the driver- machine interface, including the energy measuring system, facilitates their own fair share for better operation.

4.4 Ethio–Djibouti (EDR) to TAZARA Static Analysis

This section presents and interprets the results obtained from the static structural finite element analysis (FEA) using ANSYS Workbench 2023 R1, as shown in Table 4.4. The results include total deformation to assess rail bending, equivalent (von Mises) stress distribution to evaluate structural safety, fatigue life to assess long-term durability, and biaxiality to indicate the stress state under different axle load conditions. Recalling three primary cases, which are simulated:

- Case 1: EDR wheel on TAZARA rail, 25 t axle load (≈ 122 kN per wheel).
- Case 2: EDR wheel on TAZARA rail, 20 t axle load (≈ 98 kN per wheel).

The finite element analysis of the wheel/rail of EDR to TAZARA is used to evaluate the result of a question where the TAZARA track infrastructure can safely accommodate EDR rail vehicles. This assessment contributes to interoperability within the East Africa network by incorporating engineering analysis to enhance scholars' knowledge, demonstrating how a variation in a single variable can produce a change. Thus, Figure 4.8 shows the total static structure deformation, indicating the displacement of the rail under applied vertical load. The maximum deflection occurs beneath, and the vertical force is also gradually distributed from the wheel to the track. Hence, the two load variation increments are 20%, with the maximum total static deformation recorded for 98 kN being 1.1275e3 and for 122 kN being 1.9e^3. This shows that the greater the force applied, the more the rail bends, indicating the risk of rail damage.

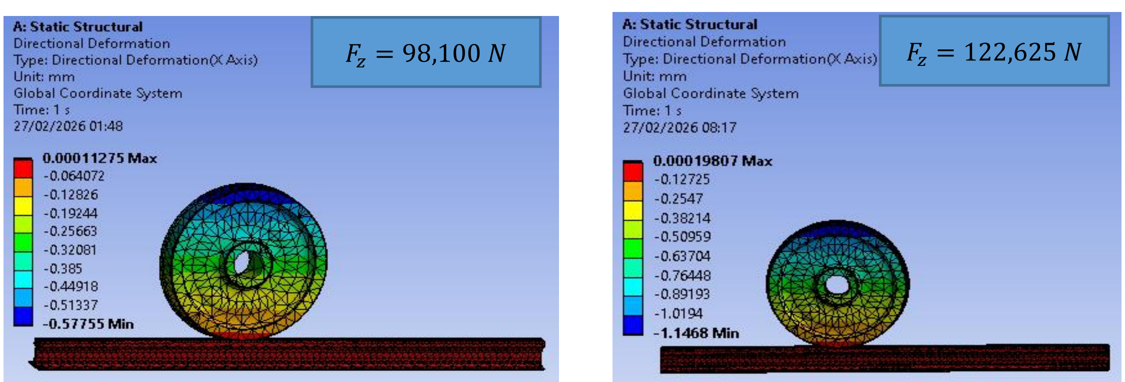

Figure 4.8 The total Static structural deformation analysis results of axle loads

Von Mises stress is an important measure that combines normal and shear stresses (in X, Y, and Z directions) into a single value; thus, this value can be used to determine whether the material fails. Because material fails when combined stresses reach a critical value, the von Mises stress is analysed in Figure 4.9. At a load of 98 kN, the stress is 19.7 MPa, whereas the material's yield strength is 580 MPa; at a load of 122 kN, the stress is 34.32 MPa. These values remain significantly low, indicating that structural failure is not imminent. Thus, in real time, the result indicates that when EDR is placed on the TAZARA rail, it does not cause structural yielding of the rail, even when it exceeds the nominal 20 t axle load capacity.

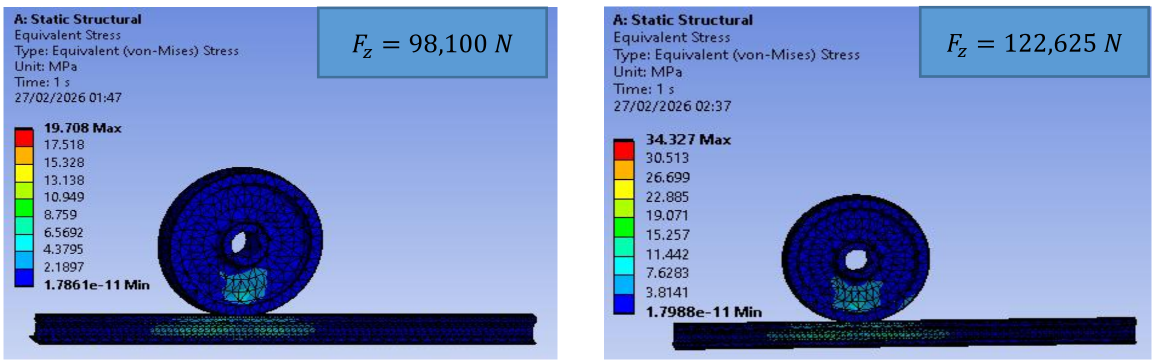

Figure 4.9Static structure analysis Equivalent (von-Mises) Stress results of axle load over TAZARA track

The fatigue safety provides insight into repeated loading environments shown in Figure 4.10, where for the first loading condition of 98kN, corresponding to 20t, a minimum fatigue safety factor was found to be 12.685, with a maximum value reaching up to 15, indicating that the rail structure operates with a very high margin of safety under the nominal axle load. In contrast, with the increment load of 122kN, the minimum fatigue safety factor decreased significantly to 2.51. Although this value is also above the critical limit, it shows fatigue failure is unlikely. However, the reduction in the safety factor suggests that fatigue loading on the rail structure is increasing in the real world, as the TAZARA rail continues to support the higher axle load of the EDR wheel. Therefore, increasing the loading may accelerate fatigue degradation over longer-term operation.

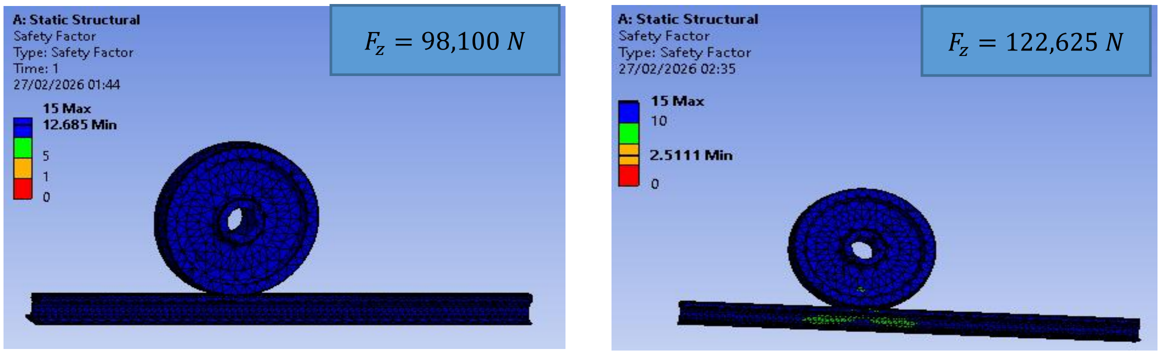

Figure 4.10 Contour Plots of Fatigue Safety Factors of TAZARA track by axle loads.

Biaxiality is defined as the ratio of the maximum principal stress to the second principal stress, with a value between -1 and 1. Uniaxial stress is represented by a biaxiality of zero, 0.5 moderate biaxial stress, and 1 perfect biaxial stress. Uniaxial stress means that the stress is in one direction, where the contact patch between wheel/rail behaves in one surface direction. Whereas for biaxiality, the surface has two directions behaving as Hertzian contact, where the stress spreads into two surface directions. In this thesis as shown in Figure 4.11 where the load representing the 20t have a value of 0.9902 approximately to 1 showing that the wheel/rial contact area experience almost equal stress of two directions (nearly pure biaxial stress)> for the incremented 25t the value became 0.984 where it slightly shows decrease meaning more shear component are appearing due to higher contact pressure. Additionally, see Figure 4.12, where most of the object sections of this model show both pure shear and almost pure biaxiality. In contrast, the remainder of the model is subject to pure uniaxial stress. A site of mostly uniaxial stress is where the most damage occurs, as can be observed when utilizing the biaxiality plot in conjunction with the safety factor plot above.

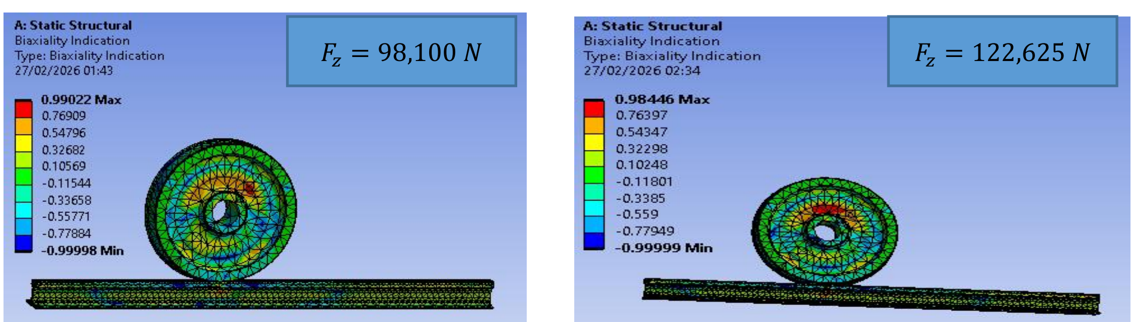

Figure 4.11Contour Plot of Biaxiality Indication axle load over the TAZARA track

Table 4.4. The Ethio–Djibouti (EDR) to TAZARA Static Analysis Result

Parameter	Case one	Case two
Axle load (KN)	98	122
E(Gpa)	190-207	190-207
Yield (Mpa)	350-400	350-400
Max von Misses stress (Mpa)	19.708	34.327
Deformation (mm)	0.00011275	0.00019807
Biaxiality indication	0.99022	0.98446

Overall, across the cases analysed, the material change used to represent the TAZARA rail track is much softer than EDR; therefore, the results show that, as load varies by 20%, stress varies by 42.58%, indicating higher stress with increased load. Deformation exhibits the same pattern, at 43.07%. Finally, the results are validated by comparison with prior studies. [132], following the analysis workflow. The general analysis is constrained to account for changes due to axle load; thus, the actual stress requires defining the frictional contact over a small patch connecting the wheel and track. Although all simulated cases remain within the elastic range under static loading, in practice, when a train moves, the static wheel load constitutes only part of the total load experienced by the rail. Dynamic effects such as impacts from track irregularities, speed, and suspension stiffness can increase the effective load by a factor called the Dynamic Load Factor (DLF) [133]. Therefore, in real railway operation, the combined influence of additional dynamic factors will significantly amplify these effects over time.

Chapter 5 Conclusion and Recommendation

5.1 Conclusion

This thesis assessed the current interoperability of the East African railway network, which is in a poor state, using Multi-criteria analysis (MCDA). Additionally, evaluating the rolling stock subsystem and assessing its impact level based on stakeholders' feedback helps determine where to focus standardization efforts when interconnecting the railway. Overall, this thesis demonstrated that the physical barrier is the primary constraint where the infrastructure compatibility parameters, with axle load, track gauge, wheel-rail, and the like, emerge as the critical factors. Thus, addressing these variables during the design, procurement, and railway planning of rolling stock is important for achieving seamless cross-network railway operations throughout East Africa. Moreover, the static structural finite element analysis (FEA) of the wheel–rail interaction using ANSYS Workbench 2023 R1 provided crucial insights into the mechanical compatibility of railway rolling stock operating under different axle loads for three conditions. Hence, three cases: (1) the EDR wheel on the TAZARA track at the same 25-ton load, and (2) the EDR wheel on the TAZARA track at 20t load. Results showed that the EDR wheel is operating on the TAZARA track; it does not exceed its limit but approaches the yield point. This indicates that a single variable makes its own contribution, and that direct interchange of rolling stock without axle-load harmonization risks long-term rail degradation. Overall, this study concludes that achieving this technical interoperability in East Africa requires engineering-level assessment of rolling stock subsystems, yielding evidence-based insights to inform infrastructure planning, procurement decisions, and harmonization strategies across the region.

5.2 Recommendation

- Establishing a regional interoperability framework through the East African Communities and the African Union that starts by defining the candidate country for a clear, harmonized railway standard.
- Develop national regulatory guidelines requiring engineering simulations, for example, multibody dynamics, before cross-network railway rolling stock deployment.
- Build a shared regional rolling stock database including axle load, brake type, coupler type, power systems, communication, etc.

- Strengthen the maintenance region by adopting predictive maintenance models based on axle load stress data.

Further research area,

- Exceeding the study by performing dynamic analysis and fatigue life prediction to understand the long-term effects of axle load mismatch.
- Conduct additional subsystem-level engineering assessments, like brake system, coupler, traction, etc.

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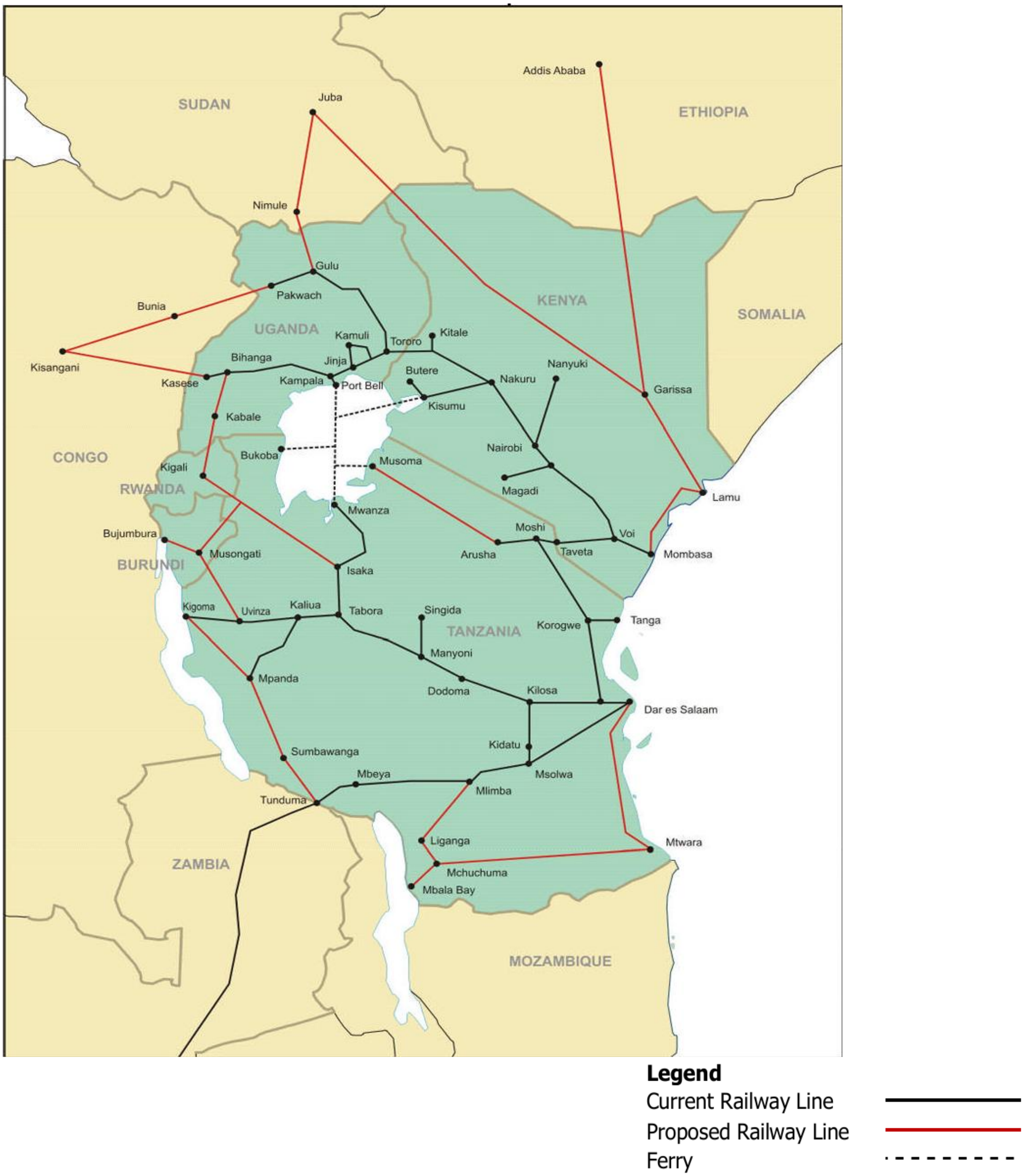
Appendix A: East Africa Master Plan Map of Railway



Appendix B: Questionnaires

Survey on the East African Railway: Current status of Interoperability and its Challenges (Rolling Stock and Infrastructure Dependencies)

This survey is part of an academic research study for a master's thesis on "Analysis of the Interoperability for Rolling Stock Subsystems in the East African Railway Network and Development of Strategy."

The purpose of this questionnaire is to identify the challenges affecting interoperability in East Africa, with a special focus on the dependency of rolling stock on track, power, and signaling systems, as well as the influence on railway design.

Your participation is voluntary, and your responses will remain strictly confidential. The data will only be used for academic purposes.

Instructions:
Most questions use a Likert scale (1 = Strongly Disagree, 5 = Strongly Agree).
Please answer all questions honestly based on your professional knowledge or experience.

Thank you for your valuable contribution.

What is your current role in the railway industry?

- ◯ Engineer
- ◯ Policy Maker
- ◯ Operator
- ◯ Consultant
- ◯ Acadmichan
- ◯ Other: ____________

How many years of experience do you have in the railway sector?

- ◯ Less than 5 years
- ◯ 5–10 years
- ◯ 11–20 years
- ◯ More than 20 years

In which region do you primarily operate?

- ◯ Ethiopia
- ◯ Kenya
- ◯ Tanzania
- ◯ Uganda
- ◯ Rwanda
- ◯ Burundi
- ◯ South Sudan
- ◯ Other: ____________

Current State of East African Interoperability

Please indicate the extent to which you
agree or disagree with the following statements regarding the impact of rolling stock compatibility issues on railway interoperability. Use the scale below: (Use a **Likert scale:** 1 = Strongly Disagree, 2 =
Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree)

Which stage best describes the East African railway system?

- ◯ Existing and operational
- ◯ Under construction
- ◯ Planned / design stage
- ◯ Planned / postponding stage
- ◯ Other: ____________________

The current level of interoperability for rolling stock in the East African railway network is very poor

- ◯ Yes
- ◯ No
- ◯ Other: ____________________

The following table shows the rolling stock subsystem parameters with their impact on interoperability. Do you agree on the assigned values? Mark "yes"; if not, mark "other" and state your reason.

No.	Subsystem	parts/ types	Interopearbility Impact
1	Traction and Energy	Diesel, Electrical, Hybrid, Pantograph geometry & contact strips & contact Strip	High
2	Traction and Energy	On-board energy measurement system	Medium
3	Vehicle Dimensions	clearance in tunnels/bridges and Vehicle geometry	High
4	Running gear & gauging	Wheel profile & equivalent conicity, Wheelsets, Bogies geometry, and Gauge Compatibility	High
5	Running gear & gauging	Axle load/ unsprung mass and Loading gauge/ kinematic envelope (EN 15273)	High
6	Couplers	Automatic Coupler, Rescue couplers, and Buffers/ draft gear	Medium

◯ Yes

◯ Other: ____________________

No.	Subsystem	parts/ types	Interopearbility Impact
7	Couplers	Train to Train interface	High
8	Braking systems	Brake medium (air vs vacuum), Service Brake, and Emergency brake	High
9	Braking systems	Wheel slide protection	Medium
10	Braking systems	braking control and Parking	High
11	Driver's CAB/ Control interfaces	Visibility, ergonomics and Driver Machine Interface (DMI)	Medium
12	Structural safety	Fire Safety, evacuation, emergency light, Carbody strength, and Crashworthiness	Medium

◯ Yes

◯ Other: ____________________

No.	Subsystem	Parts/ types	Interopearbility Impact
13	Accessibility (PRM)	Accessibility for all,	Medium
14	Accessibility (PRM)	Doors, Boarding step geometry	Low
15	Wheel profile		High
16	Wagon bogies & axle load		High
17	Freight Couplers	Digital Automatic Coupler (DAC)	High
18	Buffer and draft gear		High

◯ Yes

◯ Other: ____________________

No.	Subsystem	Parts/ types	Interopearbility Impact
19	Brake Standardization/ type	cast iron vs composite	High
20	Noise of Freight Wagons		Low
21	Rolling stock noise	Wheel/ rail noise, Aerodynaimic noise (Pantographs, high speed bodies, tunnel), Stationary noise (compressor, fans), Starting noise, Braking noise, Pass-by noise, Interior noise (passenger coaches),	Low
22	Signalling & Train control	Onboard ETCS/ERTMS (levels, STMs), Train detection compatibility (axle counters / track circuits)	High
23	Communications	GSM-R / FRMCS radios & DMI integration	High
24	Train Control	Odometry integrity & event recorder (JRU/OTMR)	Medium

◯ Yes

◯ Other: ____________________

Please indicate the extent to which you agree or disagree with the following statements regarding the railway subsystem dependency in the aspect of interoperability and East African track line design. Use the scale below: (Use a **Likert scale:** 1 = Strongly Disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree)

Rolling stock design is highly dependent on track geometry and alignment

- [ ] Strongly agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly disagree
- [ ] Other: ______________________

The performance and design of rolling stock are determined by the available power supply system (diesel, electric, or hybrid).

- [ ] Strongly agree
- [ ] Agree
- [ ] Neutral
- [ ] Disagree
- [ ] Strongly disagree
- [ ] Other: ______________________

When designing the track path for the East Africa railway project, the major parameters taken are social, economic, and geographic.

- ☐ Strongly agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly Disagree

Scientific principles and optimization methods are consistently applied when designing the track path for the East Africa railway project.

- ☐ Strongly agree
- ☐ Agree
- ☐ Neutral
- ☐ Disagree
- ☐ Strongly disagree
- ☐ Other: ____________________