ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

AFRICAN RAILWAY CENTER OF EXCELLENCE

Analysis of Signaling and Train Control System Interoperability in East Africa Railway Network

A Thesis in MSc. Railway Engineering (Traction and Train Control)

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DECLARATION

I certify that the "**Analysis of Signaling and Train Control System Interoperability in East Africa Railway Network**" research project is entirely original and hasn't been submitted to another institution for evaluation. Materials taken from other sources have been properly cited and credited.

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ABSTRACT

Interoperability of the train control and signal systems is required to realize safe, smooth, and efficient railway transport, particularly across borders such as those in the East African Region. The transition risk and interoperability issues are estimated for four main East Africa railway corridors with a systematic technical comparison methodology, Hazard identification analysis, and Fault Tree Analysis (FTA). Interoperability matrix is developed on the basis of Jaccard similarity as an initial analytical indicator in order to research cross-border running issues. The Jaccard index provided a baseline interoperability value for each pair-wise situation. Results indicate an average interoperability score of 41.11%, with significant inter-corridor gaps. The study reveals extensive inconsistencies in communication schemes and signaling standards, most importantly between Chinese CTCS and European ETCS implementations. A set of hazard logs and scenario FTAs for each transition determine primary paths of failure leading to unsafe operation, namely communication dropouts, driver misinterpretation, and inactivity of Automatic Train Operation (*ATP*). *To address these challenges, the study employs a multi-criteria decision-making (MCDM) approach on the basis of Analytic Hierarchy Process (AHP) to weight evaluation criterions, and Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS) to analyze possible solutions for enhancing cross-border interoperability. Five different alternative solutions were evaluated according to a range of technical and operational criteria, the relative weight of each being determined through AHP. Sensitivity analysis with ±10% and ±20% fluctuation in weights was employed to assess the validity or robustness of TOPSIS ranks. The findings highlight the utmost requirement for interoperable, standardized technologies and harmonized control strategies on East African rail networks. Ultimately, through the integrated synergies of Jaccard similarity for interoperability testing, technical hazard modeling and TOPSIS for solution ranking. The study concludes with strategic recommendations to achieve optimum regional interoperability as standard harmonization, collaborative communications infrastructure investment, and coordinating operating policies across the border.*

Keywords: Analytic Hierarchy Process (AHP), East African Rail Networks (EARN), Fault Tree Analysis (FTA), Interoperability, Jaccard Similarity, Multi-Criteria Decision-Making (MCDM), Technique for Order Preference by Similarity to the Ideal Solution (TOPSIS)

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ACRONYMS

ACE	Axle Counter Evaluator
ADPs	Advance Detection Points
AIHSRN	African Integrated High-Speed Railway Network
ATC	Automatic Train Control System
ATP	Automatic Train Protection
AHP	Analytic Hierarchy Process
AKH	Awash-Kombolcha-Haragebeya Railway
BTS	Base Transceiver Stations
CCCC	China Communications Construction Corporation
CCECC	China Railway Group and China Civil Engineering Construction Corporation
CCS	Control-Command and Signalling
CIECC	China International Engineering Consulting Corporation
CTC	Centralized Traffic Control
DMI	Driver-Machine Interfaces
EA	East African
EAC	East African Community
EARMP	East African Railways Master Plan
EDR	Ethio-Djibouti Railway
EARN	East Africa Railway Network
EMC	Electromagnetic Compatibility
ERP	Emergency Recovery Programme
ERTMS	European Rail Traffic Management System

ETCS	European Train Control System
FTA	Fault Tree Analysis
GSM-R	Global System for Mobile Communications - Railway
LEU	Lineside electronic unit
MA	Movement Authority
MCDM	Multiple Criteria Decision Analysis
MNR	Mombasa-Nairobi Railway
PTC	Positive Train Control
PIDA	Programme for Infrastructure Development in Africa
RBC	Radio block center systems
RRP	Railway Restructuring Programme
SGR	Standard Gauge Railway
STM	Specific Transmission Module
SIL	Safety Integrity Levels
SoS	System of Systems
TAZARA	Tanzania Zambia Railways Authority
TOPSIS	Technique for Order Preference by Similarity to the Ideal Solution
TMS	Traffic management system
TRC	Tanzania Railways Corporation
TSI	Technical Specification for Interoperability

CHAPTER ONE

1. INTRODUCTION

1.1 Background

The Africa rail sector had served as a cornerstone for facilitating trade, connecting the inland areas with seaports, and contributing to socio-economic growth. Practically all African rail networks dates back to the beginning of the twentieth century, when railways were constructed by European colonial powers to facilitate military mobility and transport commodities manufactured in large-scale farming or mining operations[1]. At the time when most infrastructure where built the focus was local and there where little concern related to effective logistical chains. However, the continent's railway infrastructure remains fragmented and under development, with significant differences in technical standards, signalling systems, and operational protocols. This lack of interoperability poses serious barriers to the unlimited movement of passengers and freight across borders, disappointing the expectations of regional integration offered by ventures like the African Integrated High-Speed Railway Network (AIHSRN) within the Programme for Infrastructure Development in Africa (PIDA)[2], [3].

The East African Community (EAC), has earmarked the railway sector to be at the core of its regional development strategy, to modernize and expand the railway system, with the aim of developing a new standard-gauge railway (SGR) network as outlined in the East African Railways Master Plan (EARMP) and subsequent improvement projects. EAC member states' end goal is to have one transport policy for all modes of transport, including rail. The strategy is meant to act as a guide in the process of shaping the transport sub-sector of railways within the time frame of the next 25 years [4]. However, interoperability issues due to variations in track gauges, signalling systems, and administrative structures, still remain a hindrance to the fully integrated network.

Generally, railway interoperability advances have been transformative in enabling successful and seamless transportation across countries. For instance, the European Union's use of Technical Specifications for Interoperability (TSI) has been instrumental in eliminating technical as well as operational barriers in its rail networks [5]. These innovations have encouraged increased connectivity, improved safety levels, and greater economic efficiency for rail transport. Such frameworks call emphasis on harmonization of different systems, from control and signaling to operating routines, to allow secure and efficient movement of trains between jurisdictional boundaries. Success in the initiatives provides a suitable model for replication in the East African region, where similar challenges occur because of the multiplicity of railway systems and administrative regimes.

Figure 1-1: Map of East African railway master plan [6]

Following such encounters, this thesis aims to explore the specific challenges and prospects for signalling and train control system interoperability in East Africa's railway corridors, namely for the Addis Ababa-Djibouti, Awash-Kombolcha-Haragebeya, Mombasa-Nairobi, and Dar es Salaam-Morogoro-Makutupora corridors. Such corridors apply heterogeneous signalling systems Chinese (CTCS Levels 0 and 2) variations and European (ETCS Levels 1 and 2) variations. The systems are diversified in movement authority logic, train detection techniques, interlocking schemes, onboard apparatus, and communication protocols. The technical difference between these systems results in significant operating, safety, and coordination problems most notably with changes of plane across corridors or national frontiers. The aim of this study is to review these signalling and train control subsystem in selected corridor with a perspective to identify and address interoperability challenges. The study employs Jaccard similarity in diversity measurement between different systems, and it presents a systematic method of measurement for commonality and variation. The primary interoperability barriers will be established through correlation or other statistical testing, providing data-driven insight into the most effective barriers.

According to the barriers identified, the research will propose efficient solutions for enhancing interoperability on technological, operational, and regulatory factors. To ensure a systematic decision-making process, a multi-criteria decision-making (MCDM) approach, i.e., Analytic Hierarchy Process (AHP) and Technique for Order Performance by Similarity to the Ideal Solution (TOPSIS) methods. The AHP takes into account the pairwise comparison of attributes to calculate their weight values, and the TOPSIS technique to evaluate and rank proposed solutions that enhance cross-border interoperability. Finally, the research will validate the effectiveness of the proposed solutions through sensitivity analysis to guarantee their applicability and robustness in real railway operations.

This study will be under initiatives to improve railway interoperability in the East African region by employing quantitative analysis, decision support approach, and validation methods. The outcome is expected to offer railway managers, policymakers, and infrastructure investors with informative data to support cross-border rail operation and system integration.

1.2 Statement of the Problem

As all over East African (EA) there are several railway signalling systems in use, so a train used in cross-border railway traffic must have communication capabilities for all the various systems. In order to standardize the Rail system, various railway signalling systems are in use, and a train used for cross-border railway traffic must have communication capabilities for all required systems. In order to standardize the Rail system, The East African Community (EAC), has earmarked the railway sector to be at the core of its regional development strategy, to modernize and expand the railway system, with the intention of enhancing continental trade and competition by establishing an interoperable high-speed rail network linking Africa's capital cities and important economic hubs.

East Africa Railway Network (EARN) is one of the priority infrastructure development projects for facilitating regional integration, trade, and economic linkage. Interoperability of signaling and train control systems across the network remains the major challenge. Even though railway technologies of new generations have been embraced in selected parts of the network, the region lacks harmonized standards and systems, hence the inefficiency, safety challenges, and tardiness in service delivery. This is exacerbated by the diversified legacy systems that are inherited from the colonial railways as well as varying stages of technological advancement in East Africa.

The Secure and effective operation of railway networks relies heavily on signaling and train control systems, which are an integral part of train movement control, collision prevention, and operational efficiency maintenance. Signaling and train control systems consist of many technical specifications, ranging from hardware interfaces and communication protocols to control algorithms and technology. Incompatibility among various technologies and proprietary solutions give rise to the fact that there can be several systems that act as interoperability barriers and become issues in offering seamless coordination and communication between infrastructure and trains.

Despite the rapid expansion of East African modern railways, there still remains a barrier to cross-border interoperability of train control and signaling systems. Several East African railway corridors i.e., the Addis Ababa-Djibouti, Awash-Kombolcha-Haragebeya, Mombasa-Nairobi, and Dar es Salaam-Morogoro-Makutupora lines are run with different technical and operational standards. Variation in standards of signaling systems, signaling levels, train detection systems, data transmission protocols, onboard and trackside equipment, and coverage of GSM-R are significant obstacles to interoperable railway operation. There are traditional mode mismatches, activation gaps for ATP, non-optimized driver-machine interfaces (DMI), and conflicting radio communication protocols when changing from CTCS and ETCS-based corridors. All these bring with them the possibility of delayed operation, miscommunication, and even unsafe movement of trains. A methodical strategy needs to be formulated for evaluating such interoperability gaps, determining key risks of transition points, and proposing technically and operationally feasible solutions.

Current research and implementation efforts have largely focused on standalone national systems with little room for integration and interoperability between the signaling and train control systems across borders. Poor interoperability has resulted in separated operations, increased costs, and reduced reliability of the railway infrastructure. Furthermore, the absence of a single universal framework for interoperability prevents realization of the entire potential of the EARN as an un-broken and efficient regional transport corridor.

The study seeks to analyze the challenges and opportunities that arise with achieving interoperability within train control systems and signaling systems in the East Africa Railway Network. By determining the technical barriers, this study seeks to give recommendations towards greater interoperability, safety, and overall network performance. The findings of this study will be applied in the development of a standardized framework that ensures sustainable growth and integration of the EARN, ultimately ensuring regional economic development and connectivity.

Despite efforts to stimulate cross-border rail connections, no uniform mechanism exists to calculate the degree of interoperability and periodically establish significant barriers. Existing decisions are predominantly qualitative and lacking in detail for specific identification of incompatibility locations. Likewise, there does not exist a systematic approach for selecting and sequencing solutions for greater interoperability to make decisions simplistic and comparative.

1.3 Objectives of the Study

1.3.1 General Objectives

The main objective of this research work is to comprehensively analyze the signaling and train control system interoperability across East African rail networks.

1.3.2 Specific Objectives

Here are the objectives of analyzing the interoperability of signaling and train control systems in East African railway networks:

- To identify technical specifications for interoperability of signaling and train control systems and reviewing the existing signaling and train control system infrastructures in East African.
- To identify and categorize hazards at transition points using the Hazard Log and Fault Tree Analysis (FTA).
- To assess the interoperability level between CTCS and ETCS-based systems and identify bottlenecks for interoperability in selected railway network.
- To propose and rank solutions for enhancing interoperability using the AHP and TOPSIS multi-criteria decision-making approach.
- To contribute recommendations for future standardization and system integration in East African cross-border rail corridors.

1.4 Research Questions

To address the research objectives, the following research questions shall be considered:

1. What are the technical specifications for interoperability of signaling and train control system?
2. What are the main technical challenges or barriers associated with the signaling and train control systems currently in use in the East African railway network?

3. How compatible are the existing systems across different railway corridors in East Africa?
4. What is the best technical approach and solutions to ensure interoperability of existing EARN?

1.5 Significance of the Study

Different rail networks, railway operators, and countries may use different signaling and train control systems. Signaling and train control system interoperability is the cornerstone for the safe, efficient, and seamless operation of modern railway systems, particularly in EARN, where multiple railways exist and systems of different vendors are running. Analyzing interoperability helps to ensures that trains from different systems can safely coexist on shared tracks, facilitate the cross-border movement of trains, reduces delays, increases the capacity of the network, and potentially leads to cost savings for both operators and passengers, mitigate risks associated with incompatible systems. It has the potential to transform rail operations and be an occasion of prosperity and wealth for areas it covers through rail transport.

Overall, interoperability analysis research of train control and signaling systems is crucial for safety, efficiency, and connectivity enhancement of rail transport. It has operational as well as regulatory implications for the railway industry and results in overall improvement of rail systems globally.

1.6 Scope of the study

In this Master's thesis, the railway systems within the East African region are considered, and particularly in Ethiopia, Kenya, and Tanzania railways. Focusing on three corridors operating different signaling levels:

- Addis Ababa-Djibouti (CTCS Level 0)
- Awash-Kombolcha-Haragebeya (ETCS Level 1)
- Mombasa-Nairobi (CTCS Level 2)
- Dar es Salaam-Morogoro-Makutupora (ETCS Level 2)

The study limits its analysis on technical aspects of signaling and train control systems. Broader interoperability issues such as rolling stock compatibility, variation in track gauge, and differences in power supply fall out of its scope.

1.7 Limitation of the study

The analysis will center on the interoperability of railway systems signaling and train control subsystems. It entails research on how these different countries' systems can harmonize to achieve safe and effective operation of railways. One of the main constraints encountered while doing the research was the difficulty of having complete and verifiable information about all the corridors. While systems like Awash-Kombolcha and Addis Ababa-Djibouti provided relatively accessible documentation, others, such as Mombasa-Nairobi and Dar es Salaam-Morogoro-Makutupora, lacked publicly available or standardized information, particularly in areas like data transmission protocols and subsystem configurations. This data scarcity impacted the comparative analysis depth required cautious interpretation of correlation results. Also, the study delimits its examination of interoperability issues to technical aspects, exclude in-depth analysis of regulatory and legal factors. Other active or emerging corridors in the region were not included due to this data availability constraints. Also, the study delimits its examination of interoperability issues to technical aspects, exclude in-depth analysis of regulatory and legal factors.

1.8 Definition of Key Terms

Trackside control-command and signalling: all of the equipment used to communicate (command and control) to the trains that are permitted to run on the railway network in order to further assure safety.

Onboard control-command and signalling: all the equipment that is located on board the train to maintain safety and effective communication in order to command and control the trains on the designated authorized network

Movement authority: is the authorization a train receives to proceed to a prearranged location.

Hazard: A condition that could lead to an accident.

Risk: is the likelihood that accidents and events may occur that cause harm (due to a hazard) and the extent of that harm.

1.9 Structure of the Thesis

This thesis is organized in five major chapters, and each chapter addresses a main issue of the research on interoperability between the signaling and train control systems of the East African railway network. The structure of the thesis is as follows:

The first chapter begins with an introduction highlighting the network's growth, significance of interoperability in railway networks and specifies the focus on the East Africa Railway Network. The chapter develops the problem statement, research objectives, research questions, scope, limitations, and study significance. The chapter concludes with the thesis outline.

The second chapter explores existing research and theoretical frameworks related to railway interoperability, some concepts required to understand the control command and signaling systems and railway interoperability; and overview of the development stages Railway network in East Africa and Analyzing Existing signaling and train control systems of EA Railway System. The chapter also identifies gaps in the literature.

In chapter 3, methodology of the research methodology on technical document analysis it develops the research approach, data collection methods, and analytical techniques employed in the study. It details the use of **Jaccard similarity** to measure interoperability, key challenges and barriers and the process of developing practical solutions.

The 4^{th} chapter explains briefly the findings on the current state of control command and signaling systems interoperability in East Africa followed by the discussion of the results.

Finally, Chapter 5 provides a summary of the key findings of the research and recommends how interoperability in the East African rail system can be improved. The chapter concludes by suggesting recommendations on areas of future research directions.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Introduction

This chapter delves into the literature on railway interoperability for signaling and train control subsystems in East African Railway Network. It deals with the historical evolution and significance of railway interoperability, investigates the function of signaling and train control subsystems in railways.

2.2 Railway Interoperability

A common definition of interoperability is the degree of technological unification in railway transport that allows trains to cross international borders (i.e., with different infrastructure managers) without having to switch traction vehicles (i.e., locomotives) or drivers, thus avoiding border stops [7]. The definition of interoperability: [26]

> *"The ability of a railway system to allow the safe and uninterrupted movement of trains on the characteristics appropriate for the given railway lines, depended on all the technical, legal and operational conditions which ensures fulfilling the essential requirements."*

The main objectives of interoperability are to create standardized African procedures for evaluating compliance with interoperability requirements, help gradually to create an open and competitive domestic market for the supply of railway systems and construction, renewal, restructuring, and operational services and simplify, improve, and develop international railway transport services. For this reason, defining a collection of platform components and subsystems and establishing their fundamental needs and interfaces through the creation of functional and technical specifications were crucial steps in achieving interoperability [8].

Railway interoperability ensures the smooth operation of trains on various rail networks, especially those in different nations that trains can run seamlessly on different rail networks. The various technical standards and legal parameters are being undertaken internationally to make this possible[9]. The primary technological differences between the states are found in the rail system, the power supply system, the control system, and the legislation governing train traffic[10].

2.2.1 Technical Specifications for Interoperability (TSIs)

The Technical Specifications for Interoperability (TSIs) define the technical and operational standards which must be met by each subsystem or part of subsystem in order to meet the essential requirements and ensure the interoperability of the railway system of the European Union[11]. The rail interoperability consists of a number of technical specifications for different kinds of the rail's subsystems[12].

The structural and functional subsystems that comprise the European Union's railway network are defined by Directive (EU) 2016/797. In order to satisfy the fundamental criteria for each of those subsystems, the technical specifications must be established, especially with regard to components and interfaces. Safety, dependability and accessibility, health, environmental preservation, technological compatibility, and accessibility may be summed up as the fundamental needs [13].

A. Subsystems of the Structural areas:

1. Infrastructure: consist of the track, points, engineering structures (bridges, tunnels, etc.), associated station infrastructure (platforms, zones of access, including the needs of persons with reduced mobility, etc.), safety and protective equipment.
2. Energy: includes the overhead lines and onboard components of the electric consumption measurement apparatus, as well as the electrification system.

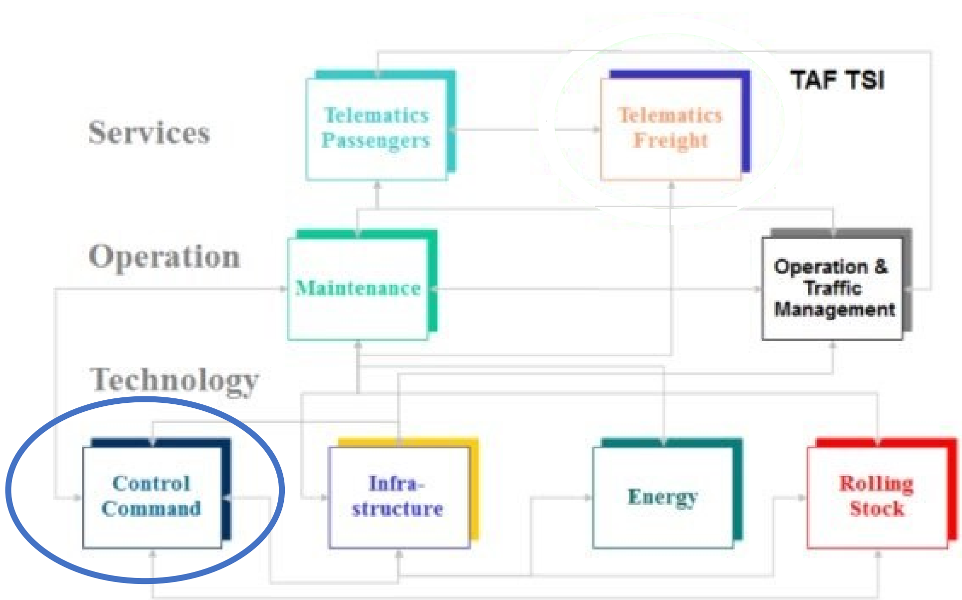

Figure 2-1: TSI´s structure for railway [12]

3. Rolling stock: all train equipment, including the defined structure, command and control system, traction and energy conversion units, current collection devices, braking, coupling, and running

gear (bogies, axles, etc.), suspension, doors, man/machine interfaces (driver, passengers, and on-board staff, including the needs of individuals with reduced mobility), passive or active safety devices, and requirements for the passengers' and on-board staff's health rolling stock.

4. Signalling and Train Control: consist of the all equipment necessary to ensure safety and to command control movements of trains authorized to travel on the network [11].

B. Subsystems of the operational areas [14]**:**

1. Traffic operation and management: the procedures and associated tools that allow the many structural subsystems to function coherently during both normal and impaired operation, particularly train driving, traffic planning, and management. the professional credentials that could be necessary in order to provide cross-border services.
2. Maintenance: in order to ensure the interoperability of the rail system and the necessary performance, the procedures, related equipment, maintenance logistics centers, and reserves enable the required corrective and preventative maintenance.
3. Telematics applications: this subsystem comprises two elements application for passenger and freight services. Passengers' applications include information, reservation, payment, luggage management, and connections between trains and other transport modes, while freight services applications include real-time monitoring and electronic document production.

2.2.2 Signaling and Train Control Subsystems

This TSI concerns the control command and signalling on-board and trackside subsystems. It applicable for both to control-command and signalling on-board subsystems of vehicles and control-command and signalling trackside subsystems of the rail network [15]. The signalling system is essential to train movement safety as well as train control and administration. An extremely complex and technological sector has emerged as a result of the evolution of several signalling and train control technologies throughout time [16]. Railway signaling systems are interconnected systems that that communicate information to train drivers and control centers, using signals like lights and audible warnings to convey track condition, train location, and other important information to train drivers. The primary purpose of signaling is to keep trains separated by providing enough distance to stop in case of failure. However, this distance should not be too long to prevent delays and increase headway between trains [16], [17].

There are a number of items within the larger category of signalling systems:

- Track circuits and signals aid in traffic management on the railway line to prevent collisions.

- Balises and radio-based systems allow the train control center to limit train movement,
- Interlocking systems and Radio Block Center systems (RBC) providing information to onboard signaling systems.
- Onboard signaling systems, composed of a centralized computer, process inputs and supervise train operations. Drivers interact with the onboard computer, and a juridical recorder record generated information.

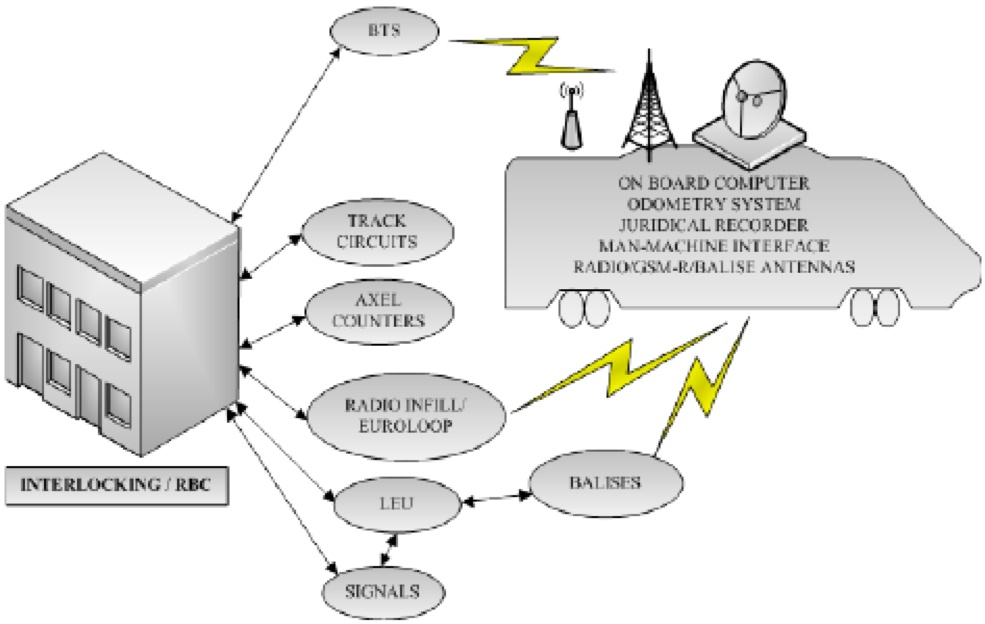

Figure 2-2: Different signalling subsystems and their interfaces [18]

Other systems, like GSM-R or radio infill, exchange information between wayside signaling and onboard signaling systems. Some auxiliary systems, like the Lineside electronic unit (LEU), do not depend on the interlocking system for information processing [10].

2.3 Railway Standards

Specific Special rules and standards must be fulfilled for safe, high-speed, punctual, and efficient train running. Railway standards are a set of guidelines, specifications, and regulations guaranteeing the security, interoperability, and efficiency of rail networks worldwide. Railway standards cover many areas, including track gauge, signaling, rolling stock, and operation. Therefore, it is essential for the national government to clearly indicate standards on safety conditions and so forth so that railways can satisfy a specific level of social requirements by meeting the standards. The most widely applied signaling standards in East Africa are the European Train Control Systems (ETCS) and the Chinese Train Control System (CTCS).

2.3.1 European train control Systems (ETCS)

The European Rail Traffic Management System (ERTMS) includes ETCS as a subsystem. It is occasionally referred to as ERTMS/ETCS. ETCS (Euro-cab), GSM-R (Euro-radio), Euro-balise, Euro-interlocking, and other components are included in ERTMS [19]. The European Rail Traffic Management System (ERTMS), has been specified to create to establish a uniform standard throughout Europe to address the technological barriers impeding the growth of rail transportation [20].

ERTMS aims to offer a harmonized European rail traffic management system for cross-border interoperability of train control throughout Europe. It seeks to lower the cost of train control systems as well as facilitate the transfer of trains across borders. The European Train Control System (ETCS) and the Global System for Mobile Communications-Railway (GSM-R), a radio-based system employed to enable communication between trains and control centers, form ERTMS.

ERTMS consists of two main components. The first is the ETCS, an Automatic Train Protection (ATP) system. Train movement is supervised by a system made up of track-side and onboard components. ETCS increases train management flexibility by giving controllers and drivers access to real-time information. There are different levels at which ETCS can be employed, defining how data is transferred between trains and infrastructure as well as determine whether side-track signals are still in operation. The second component of ERTMS is GSM-R, a railway-optimized mobile communications network. Additionally, railway-specific data and telephony services are offered on top of this network [21].

Communication is the exchange of information between the train and the track's equipment in the rail perspective. It is still feasible for some interfaces to display information to the driver differently. ETCS application ‘Levels ’specify the various ways that ETCS can be used as a train control system that can communicate continuously between the train and the radio block center (Level 2) or track to train (Level 1). While Level 1 gives the train safety information at specific points on the track connected to the signals ahead (thus offering "intermittent" automatic train protection), Level 2 can offer continuous automatic train protection because any change in the train's location or status is instantly communicated to the Block center, which can then radio the next train to be alerted and controlled.

Table 2-1: Levels of ETCS [8], [16], [22]

Levels	System Description
ETCS Level 0	No ERTMS equipment is installed on the trackside other than Eurobalises for level transitions or on a route that is still undergoing commissioning, such as when trackside ERTMS/ETCS infrastructure may exist but must be disregarded. Lineside optical signals give the movement authority, train borne equipment just keeps an eye on the train's maximum speed, and the only supervisory data shown on the DMI is the train's speed. In order to supervise temporary speed restrictions and enable level changeover, the onboard equipment reads the Eurobalises.
ETCS Level 1	Fixed block intermittent speed supervision system. The Eurobalise is used to facilitate communication between the train and the trackside. The Eurobalises which are installed on the track receive signalling data from the existing lineside signals via signal adapter and telegram encoder (LEU) together with the route data to the train. Movement Authorities through Eurobalise, Train integrity and position by track circuit.
ETCS Level 2	Trackside signals are no longer required can be retained to accommodate trains, trackside equipment consists of centralized Radio Block Centers (RBC) and distributed Eurobalises. Information on the status of the track occupancy is sent by the interlocking to the RBC. Based on this information and the train position information sent regularly by onboard ERTMS/ETCS, the RBC generates the correct movement authorities for the different trains in the section. Eurobalises are used to transmit fixed data such as train location, gradient, speed limit.
STM Level	Specific Transmission Module (STM) processes the data transmitted by the trackside national train protection system and converts it into a format that the onboard ERTMS/ETCS can understand. In STM lineside signals required depending on the implementation of the national train protection systems. This level can be utilized during the migration process in order to integrate the onboard ERTMS/ETCS with the current national train protection systems, along with any additional trackside infrastructure

	modifications. Depending on the national protection system, level STM offers varying degrees of supervision.
ETCS Level 3	Radio-based train control system. Lineside signals and the track occupancy detection are no longer required. The train location is determined by the RBC in co-operation with the train. Movement Authority (MA) is given by the track equipment and transmitted to the train by Euroradio. The Radio Block Centre, which sends out the data to the trains, knows exactly which vehicle is controlled by this system, through the ETCS train's identity, provided by its onboard equipment. Moving block system

2.3.2 Chinese Train Control Systems (CTCS)

The situation of the Chinese railway serves as the foundation for CTCS. Though it was derived from the European Train Control System (ETCS), it is different with ETCS. Given the many commonalities in Chinese Railways, CTCS and ETCS have many characteristics.

A train control system designed for China's mainline railways is called the Chinese Train Control System (CTCS). The state of the Chinese Railways serves as the foundation for CTCS. Though it was derived from the European Train Control System (ETCS), ETCS is distinct. Given the many parallels between Chinese and European railways in terms of their operational methods and signalling systems, CTCS and ETCS share many characteristics [19].

Chinese Railways adopt CTCS as the norm for signalling systems. The new signalling systems and the current signalling systems will work together. All signalling systems, whether they are manufactured domestically or imported, wayside or onboard, must adhere to the CTCS standardization in the future. In addition to interoperability, other factors taken into account includes safety and dependability, capacity growth, ease of maintenance, lower investment, open market, standardisation of interfaces between signalling systems, switching from current signalling to CTCS, and data transfer format between the subsystems are all aspects of CTCS functioning. CTCS will be separated into many tiers according to the current state of the Chinese Railway Network's signalling system. From level 0 to level 4, there are five distinct levels in CTCS.

Table 2-2: Levels of CTCS [19], [22]

Levels	System Description
CTCS Level 0	For the trains with maximum speed of 120km/hr. It includes the train operation supervision system, universal cab signalling (digital, microprocessor-based cab signalling), fixed blocking and track circuits. The primary signals are wayside signals, whereas the auxiliary signals are cab signals.
CTCS Level 1	For a train with speed between 120km/hr and 160km/hr. It consists of ATP system, transponders (also known as balises), and track circuits. Track Circuits detects track occupancy and transfer train control information continuously, Cab signaling provides the movement authority to driver when wayside signal aspect cannot be distinguished.
CTCS Level 2	Applicable for lines with maximum speed higher than 160 km/hr. It consists Fixed Block Track circuit, Eurobalise, Lineside Electronic Unit (LEU), Train Control Center (TCC), ATP system, Intermittent-Continuous ATP based on the information from the Track circuit plus Eurobalise. The distance to go control mode for ATP.
CTCS Level 3	Consists of Track circuit, Eurobalise, Lineside Electronic Unit (LEU), ATP system with GSM-R. Train control system based on GSM-R wireless Communication. Track circuit only detects track occupancy, Radio Block Center (RBC) provides movement authority. Fixed Block System.
CTCS Level 4	GSM-R is responsible for the information exchange between trains and wayside devices. track circuits are used only at stations. Train positions are filled via GSP/Balises. The system's maintenance costs are decreased by minimizing the number of wayside system. Moving block system.

2.4 Interoperability Challenges in East Africa Railways

East African railway interoperability is a key driver for the achievement of seamless regional connectivity, improved trade, and economic integration. However, technical challenges exist that limit the achievement of an entirely interoperable rail system within the region. These are due to infrastructure, signaling systems, rolling stock, and operational standards differences across countries.

The key technical challenges:

- **Different Signaling Systems:**
  - For instant the **Addis Ababa–Djibouti Railway** uses the **Chinese CTCS** system, while the **Awash–Weldiya Railway** operates on **ETCS/ERTMS Level 1,** a European standard. This requiring dual-system onboard equipment or operational handovers at transition points.
- **Communication Protocols:**
  - Inconsistent use of **GSM-R**, fiber optics, or microwave-based systems affects real-time coordination and cross-border command/control integration.
- **Training and Operational Management:**
  - Different signaling technologies demand distinct **training, procedures, and safety protocols**, complicating staff transfers across corridors.
- **Technical Standards and Vendors:**
  - Projects developed by **different countries (China, Turkey, Europe)** use **non-harmonized standards** for interlocking, balises, and onboard control, resulting in poor interoperability unless custom integration is implemented.

Many railways in East Africa rely on outdated signaling technologies such as analog systems, which do not have compatibility with more advanced digital systems. This makes integration of advanced communication-based train control (CBTC) systems impossible.

2.5 Systematic Literature Review

Signaling and train control system interoperability is essential to modern railway operation, allowing for seamless, secure, and efficient train movements across borders. This systematic literature review (SLR) aims to contribute to existing knowledge in the subject, identify research niches, and provide a foundation for an understanding of the challenges and opportunities unique to the East African railway system.

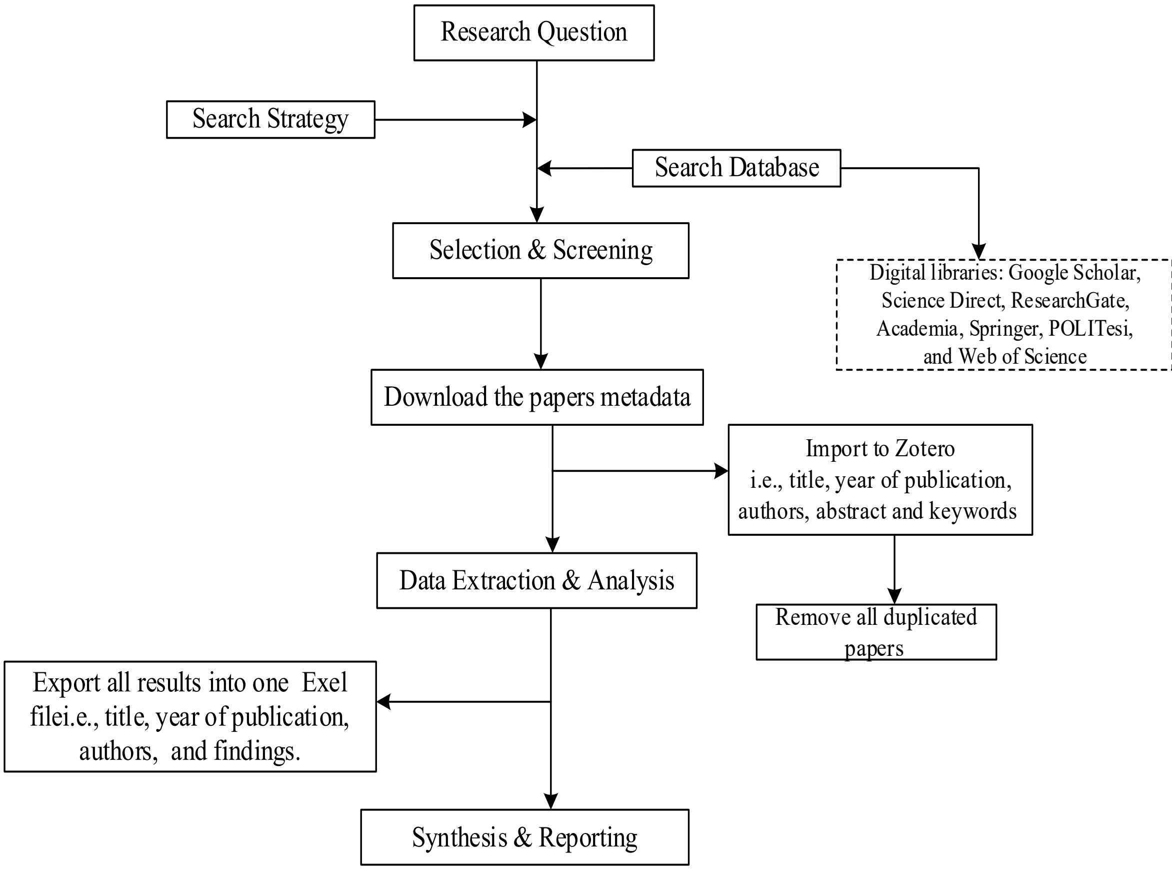

Figure 2-3: Detailed flow diagram for literature review

First, started by define questions that will guide and support the paper selections. Next, the selection and screening performed, i.e., relevant papers from the related literature were identified. To cover the overall relevant studies, documents were searched by querying digital libraries: Google Scholar, Science Direct, ResearchGate, Academia, Springer, POLITesi, and Web of Science. To do so, we download the papers metadata (i.e., title, year of publication, authors, abstract and keywords). After that, the data on the extracted paper analyzed to identify the relevant keywords, parameters, and technical specification for interoperability of signaling and train control subsystem.

2.6 Analysis of the Selected Papers

In this section, the comparison criteria are defined. Then the comparative analysis taking into account the established criteria come next.

2.6.1 Defining the comparison criteria

The first criterion that we consider in this analysis is evaluate how the papers address the need for **standardization** of signaling and train control systems across different rail networks to ensure interoperability. how the papers discuss the use of interoperability standards and best practices for signaling and train control systems, such as European Train Control System (ETCS), Positive Train Control (PTC), or other international standards, and their applicability across different railway systems.

The second criterion regards the **infrastructure compatibility**. Consider how the papers discuss infrastructure compatibility issues when integrating signaling and train control systems across different countries with varying track layouts, signaling equipment, and operational requirements.

The third criterion refers to the **cross-system communication**. Analyze the proposed approaches for enabling effective communication and data exchange between signaling and train control systems of different railway systems, including interoperability standards and protocols.

Technological solution is the fourth criterion, the technological solutions proposed in the papers for achieving interoperability between signaling and train control systems in diverse country contexts, considering factors such as communication protocols, data exchange formats, and system architectures.

The fifth comparison criterion concerns **case studies and best practices**. Looking for case studies or best practices presented in the papers that demonstrate successful implementations of interoperable signaling and train control systems in diverse railway systems, highlighting lessons learned and practical insights.

The sixth criterion that we considered in our analysis is **safety assessments**. Evaluate how the papers address the safety at cross boarder when implementing interoperable signaling and train control systems across diverse railway systems, including reliability, risk assessments, fail-safe mechanisms, and fault tolerance.

2.6.2 Analyzing the Selected Papers

According to [8] ERTMS program aims to create a standardized and interoperable command and control system for trains, known as ETCS (European Train Control System), and a communication system called GSM-R (Global System for Mobile Communications - Railway). The system has a number of levels that enhance the efficacy of train control and communication. Some of the key benefits of ERTMS include increased safety through constant speed monitoring, reduced costs with fewer physical signals, simplified access with rapid error recovery, and effective maintenance with standard networks. Through this manner, ERTMS is at the core of rail transport integration and development in Europe.

The paper [23] focuses on enhancing domestic train control systems and interoperability by examining the interface of wayside train control systems and onboard systems. Since train systems are safety-critical, the authors created a simulation platform to execute interoperability tests without endangering safety during site tests. The results confirm the Transmitting/Receiving data systems of the equipment for interoperability, gaining experience with the effectiveness of the systems in operation The author emphasizes the role simulation played in testing and optimization of train control systems to match global trends in development.

The article [24] explains why interoperability is required in train control systems that are vital to ensuring safe operation of trains. While computer codes are assuming a more pervasive role over the traditional mechanical and electrical control, various train control devices must communicate with each other effectively. The article notes that as interface protocols among these devices get standardized for wider interoperability, implementation in practice proves to be less effective with incomplete requirements, specification errors, and conformance testing limitations. Thus, separate interoperability tests need to be conducted to ensure the functioning of these systems before their implementation in real railway environments.

In paper [25] the implementation of interoperability in the railway transport system of the European Union in order to integrate various rail systems and provide safe, continuous train services across nations with various infrastructure managers. The study focuses on the key components of the railway system that rely most on interoperability, such as the power supply, operation systems, and control-command and signalling systems. In terms of rolling stock, infrastructure, energy, command control, and signal, it outlines the minimal criteria for interoperability. Jacyna and Szkopiński recommend creating a simulation model that takes into account the constraints, costs, and benefits of various stakeholders.

The article [26] analyzes non-technical and technical barriers to interoperability in rail freight from Europe to China, driven by expanding demand for rail freight traffic along the New Silk Route. Even though free flow of rail freight is a quicker and more reliable means of freight compared to sea freight, its movement is hindered by inefficient intermodal transport, technological specification incompatibility, and nationally specific legislative systems. More interoperability is being advocated for by combining norms and regulations, and the development of new rolling stock and infrastructure. Elimination of these hindrances is necessary to drive up the efficiency and capacity of railway operations, thereby improving economic growth in the two regions.

The paper[27] addresses the main theme of interoperability across the European rail network. It stresses that even if efforts are made to harmonize technical solutions, incompatibilities might still occur between subsystems that can make it difficult for interoperable rolling stock to move freely between railway lines. The authors refer to the Technical Specifications for Interoperability (TSI) that establish minimum requirements and procedures for achieving technical harmonization. The article further describes the integration testing by the Railway Research Institute for the purpose of ensuring conformity of on-board subsystems to trackside-systems specifications, with the necessity of serious testing as a major requirement for identification and correction of faults prior to certification. The outcome underlines the necessity of extensive integration tests to render railway trains licensable for safe operation in order to promote the development of a cohesive European rail space.

The paper [28] provides the importance of interoperability in the rail transport of Europe, primarily discusses the implementation of interoperability tests (IOP tests) within the context of the European Rail Traffic Management System (ERTMS) including the elements of the European Train Control System (ETCS) and Global System for Mobile Communications-Railways (GSMR). It emphasizes on the relevance of these tests with regard to ensuring interoperability between rolling stock and railway infrastructure, aiming at making it easier to prove compliance with ETCS specifications. The authors present practices in European countries, propose a model for carrying out IOP tests in Poland, and indicate the need for simulation methods for easing the testing process. The article also provides information about organizational needs and challenges of overcoming the obstacles in establishing IOP laboratories in Poland, ultimately suggesting an optimal and cheaper path towards interoperability testing for the railway industry. The article also examines the working models of EU labs, including Switzerland and Spain, and proposes conditions for interoperability testing in Poland considering pan-European procedures and experiences in foreign labs with the possibility of future implementation in the Polish railway system.

The paper [29] analyzes the specificity of railway and maritime transport modes and presents the results of a research questionnaire conducted with Lithuanian transport companies to identify the most important components of interoperability between maritime and railway transportation. The research findings prioritize the sequence of elements to ensure efficient interoperability between rail and maritime transport, emphasizing the importance of information exchange and the need for a joint database for planning the rail and sea movement of freight.

The paper [30], presents a system definition that explains the control-command and signalling system's definition in terms of safety standards. The document outlines the system risks and provides numerical safety specifications. The paper lists the System Hazards and presents quantitative safety requirements. It includes examples of tolerance rating from different countries and discusses the need for harmonization of THRs (Tolerable Hazard Rates). The document is mandatory for achieving harmonization until the THRs are harmonized. The paper also mentions the task of causal analysis in analyzing and evaluating the link between input and output interfaces within the defined System.

Another study aims to evaluate the technical interoperability of the European signalling system (ETCS) and the Chinese signalling system (CTCS) used in the Ethiopian railway system, identify potential technical solutions for interoperability issues, and assess the economic benefits of a uniform system [22]. This study also provided good insight into the interoperability question. The two systems' interoperability was examined by looking at their features and speaking with experts who had experience with them. Two potential technical solutions were identified: either implementing ERTMS as an overlay on top of the current CTCS level 0 or upgrading the Ethiopian-Djibouti railway line from CTCS level 0 to CTCS level 2. The viability of these ideas from a practical and financial standpoint must be evaluated.

In this paper, an analysis of the interoperability of signaling and train control systems in railways will be conducted to reduce the risk of accidents and incidents caused by miscommunication or incompatibility between systems. By addressing interoperability challenges, the analysis attempts to remove the barriers of cross-border transport of goods and passengers and eventually enhance trade and regional economic development.

Table 2-3: Summary of reviewed studies

SN	Publisher	Researcher	Title	Methodology	Findings	Gap
1	WIT Press	B. Ning, T. Tang, K. Qiu, C. Gao & Q. Wang	CTCS—Chinese train control system	Review of existing systems and proposed improvements	ETCS is incompatible with CTCS levels 0 &1. CTCS level 2 adds the balise, to be compatible with ETCS level 1. both CTCS level 3 and ETCS level 2 rely on track circuits, balises, fixed blocks, and GSM-R, they may work together.	The paper is largely theoretical and descriptive, lacking empirical data or case studies from the actual implementation of CTCS. This limits the ability to assess the practical effectiveness of CTCS in real-world scenarios.
2	Budapest University of Technology and Economics	Bessenyei György	Theoretical Principles for Quantitative Evaluation of Railway Interoperability	Compatibility matrix	The study proposes a universal index aimed at quantifying the level of railway market liberalization It highlights how crucial unique vehicle identification is for technical, operational, and legal reasons.	Lack of comprehensive analysis of technical parameters, suggesting that there remains significant potential for improvement in this area.
3	Transportation Research Record, Journal of the Transportation Research Board	Warren Walker, Andre van Velzen, Baarse, Järvi	Assessing Barriers to Improving Rail Interoperability in European Countries	Statistical approach	To enable a cross-country evaluation of obstacles, a Barrier Significance Score (BSS) was calculated for implementation conditions in each nation.	A reduced statistical strategy was necessary due to the complexity of the variables involved in order to guarantee clarity in data organization and link identification.
4	Archives of Transport	Janusz Szkopinski	The Certain Approach to the Assessment of Interoperability of Railway Lines	Systematic approach	The paper suggests developing a simulation model to assess railway lines for interoperability, prioritizing lines based on investment costs, benefits, and required changes.	Generally, consider the subsystem's without taking into account each component. Lack of empirical validation, and insufficient discussion technical challenges.

5	N/S	Miroslav Prokic, Branislav Zdravko Boskovic	Concept of Interoperability of the Railway System in Europe	Review of directives, regulations, and documents.	Interoperability is crucial for creating a single railway market in the EU, and all member states require to transpose EU directives into national law.	The paper does not provide empirical data on how interoperability affects the efficiency and competitiveness stakeholder perspectives, and the integration of emerging technologies.
6	14th International Conference on Evaluation of Novel Approaches to Software Engineering (ENASE)	Racem Bougacha, Abderrahim Ait Wakrime, et al..	A Model-based Approach for the Modeling and the Verification of Railway Signaling System	Graphical modeling of railway systems using UML class diagrams.	Proposed safety model supports the hierarchical organization of railway systems, allowing sub-organizations to inherit and modify safety rules.	Doesn't cover all safety aspects required by the railway system, necessitating the introduction of additional concepts such as "Mode" to address different operational circumstances.
7	Department of Electronics and Information Systems, Ghent University, Belgium	Juli´an Andr´es Rojas et al..	Leveraging Semantic Technologies in European Railway Domain	Knowledge Graph-based system design approach.	The architecture facilitates high flexibility for various use cases and allows for the integration of additional external data sources with significantly less effort compared to traditional relational data models	Identifies limitations related to the architectural approach, though specific details are not provided in the excerpts.

CHAPTER THREE

3. METHODOLOGY

3.1 Introduction

This chapter presents the approach taken to assess the interoperability between train control and signaling systems on four most important East African railway corridors: Addis Ababa-Djibouti, Awash-Kombolcha-Haragebeya, Mombasa-Nairobi, and Dar es Salaam-Morogoro-Makutupora. The corridors operate signaling technologies of Chinese-origin CTCS Level 0 up to European ETCS Level 2 system. The analysis is focused on identifying failure modes, high-risk conditions, and interoperability deficiencies at interfaces using a combination of hazard lists, fault tree analysis (FTA), interoperability scoring technique (Jaccard similarity), and decision-modeling methods.

3.2 Study Framework Overview

Analysis methods for study begin by conducting a comprehensive literature review to gather existing knowledge, research, challenges, and best practices related to signaling and train control interoperability. This helps establish a baseline understanding of the topic.

Figure *3-1* provides the proposed model; Begins with defining research questions and objectives, followed by a comprehensive literature review to gather existing knowledge, research, challenges and best practices. Next, technical specifications for interoperability are analyzed based on parameters that ensure interoperability. The relevant railway network is then selected, and information is collected and analyzed to conclude the present status of the train control and command Systems. The reliability of the collected data is evaluated. If the data is not reliable, the process loops back to data collection and analysis. If the data is reliable, a descriptive analysis of the CCS is conducted.

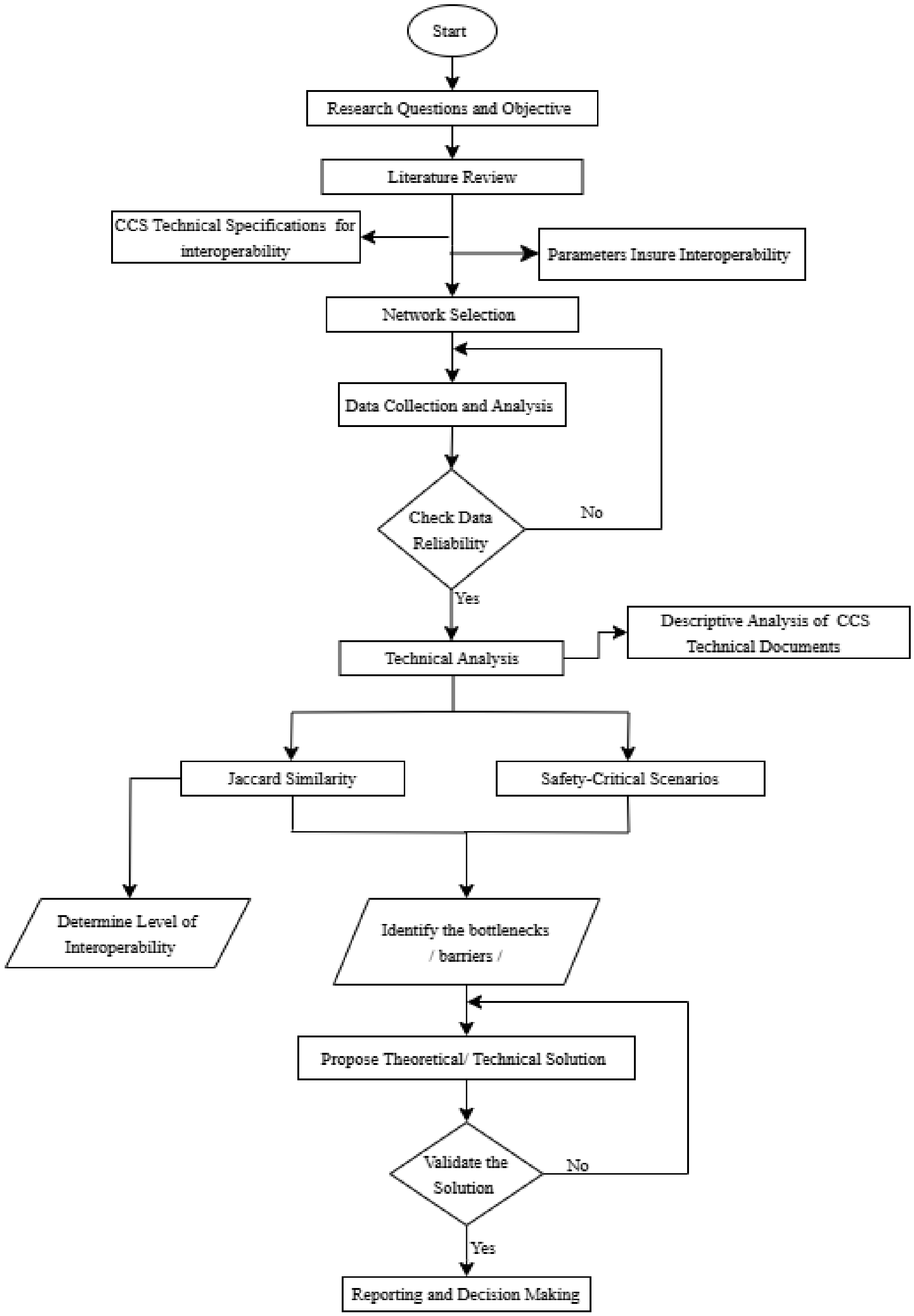

Figure 3-1: Designed study framework

This analysis is employed to determine the degree of interoperability at the current point and the bottlenecks. Based on the outcome, theoretical or technical solutions are proposed and validated. In case it is validated that the solution is not applicable, the loop returns to proposing alternative solutions. After successful validation of a solution, the results are returned, and decisions are made about how to address interoperability issues. This analytical approach ensures a thorough analysis and the development of effective solutions for enhancing interoperability in the East African Railway Network.

3.3 Data Collection

The data collection process for the study was designed to obtain comprehensive and reliable information of the signaling and train control systems applied across the East African Railway Network (EARN). Both primary and secondary sources of information were used for detailed information of the existing interoperability, technical standards, and operational issues.

- Primary data sources
  - asking peoples
- Secondary data sources
  - configuration documents and data
  - reviewing literatures

3.4 Essential Requirements for CCS

The control-command and signaling subsystems in railway systems have essential requirements to ensure safe and efficient train operations. These requirements need have various technical, operational, and safety aspects to enable trains to be run efficiently and safely from one country to another and from one region to another. The first six requirements that the subsystems and the interoperability constituents including interfaces meet the essential requirements set out according to Directive (EU) 2016/797.

Here are the essential requirements for the control-command and signaling subsystems:

1. **Safety:** the initial necessity is to ensure train operation, passenger, and railway personnel safety. This includes achieving safety integrity levels (SIL) for the signaling system, fail-safe design, and compliance with safety standards.
2. **Technical Compatibility:** include the features, interfaces, and outputs necessary to attain interoperability.
   - Standardizing interfaces between different control-command and signaling systems to ensure interoperability.
   - Using common formats of data and communication protocols, e.g., as defined by the European Train Control System (ETCS) and GSM-R standards

- Ensuring that hardware components from different suppliers can work together within the same system.

3. **Health:** care shall be taken to ensure that the materials used and the design of the Control-Command and Signalling Subsystems do not constitute a health hazard to persons having access to them [31].
4. **Reliability and Availability:** the control command and the signalling on-board and trackside subsystems share the objectives. The degree of danger posed by the deterioration and age of the components utilized in the subsystem will be tracked [31].
   - Designing systems to handle faults without leading to failures that impact railway operations.
   - Incorporating redundant components and systems to ensure continuous operation even in the event of a failure.
   - Establishing standardized maintenance procedures to ensure consistent system performance and quick recovery from faults.
5. **Environmental Protection:** The Control-Command and Signalling equipment shall not contain substances which may abnormally contaminate the environment during their normal use and shall not give rise to any unacceptable level of vibration that might endanger the infrastructure's stability [31].

3.5 Study Design and Corridor Selection

The study focuses on the East African Railway Network covering principal railway lines in Tanzania, Kenya, and Ethiopia. All three nations are members of the East African Community (EAC) and have railway networks that are of significant importance to regional trade, transport, and economic integration. The analysis covers the following railway corridors:

Table 3-1: Selected railway lines

Country	Railway Lines
Ethiopia	Addis Ababa- Djibouti
	Awash-Kombolcha-Haragebya
Kenya	Mombasa-Nairobi
Tanzania	Dar es Salaam-Makutupora

This study also focuses specifically on the following transition points to further analysis the interoperability gaps at common stations:

Transition 1: Addis Ababa–Djibouti to Awash-Kombolcha–Haragebeya (CTCS Level 0 → ETCS Level 1)

Transition 2: Addis Ababa–Djibouti to Mombasa–Nairobi (CTCS Level 0 → CTCS Level 2)

Transition 3: Mombasa–Nairobi to Dar es Salaam-Morogoro-Makutupora (CTCS Level 2 → ETCS Level 2)

Each pair represents a shift between different signaling systems with varying safety, communication, and control architectures. This study analyzes how transitions between signaling systems particularly where Movement Authority (MA), Automatic Train Protection (ATP), or communication protocols difference pose safety and operational risks.

3.6 Methods for Interoperability Assessment

Interoperability is the ability of different systems, devices, or applications to work together, exchange information, and make efficient use of the exchanged information. Interoperability may be measured using different approaches, which may include qualitative and quantitative methods. Each railway system is represented as a vector of its attributes. A quantitative matrix was developed to evaluate the compatibility of subsystems across both corridors. Interoperability between systems is quantified using the following mathematical formulations:

3.6.1 Jaccard Similarity Index

To quantify the interoperability of railway signaling and train control systems, the Jaccard Similarity Index is used. The index measures the proportion of common elements between railway corridors to their total unique elements.

It is mathematically expressed as [32]:

$$J(A, B) = \frac{|A \cup B|}{|A \cap B|} \tag{3.1}$$

where:

- $J(A, B)$ is Jaccard Similarity between two railway corridors A and B.
- $|A \cup B|$ is number of common features between the two corridors.

- $|A \cap B|$ is total number of unique features across both corridors.

The Jaccard Similarity value ranges from **0 to 1**:

- **J = 1** → Fully interoperable (identical systems).
- **J = 0** → Completely different systems (no shared features).
- **0 < J < 1** → Partial interoperability (some shared features).

A simple way to quantify interoperability across all railway corridors is by calculating the average Jaccard Similarity for all railway pairs. To obtain an overall interoperability score for the railway network, the average Jaccard Similarity across all railway pairs was calculated using [32]:

$$J_{avg} = \frac{\sum J(A, B)}{N} \tag{3.2}$$

where:

- N is total number of railway corridor pairs (6 in this case).
- $\sum J(A, B)$ is sum of all pairwise Jaccard Similarities.

The overall Jaccard Similarity results indicate the following interoperability classification:

Table 3-2: Overall Jaccard interoperability level

Jaccard Score	Interoperability Level
1.00	Interoperable ☑
0.50 – 0.79	Moderately Interoperable
0.30 – 0.49	Low Interoperability
0.00 – 0.29	Not Interoperable

3.6.2 Hazard identification at Transition Points

A hazard is a situation that has the potential to cause an accident. According to the Regulation (EU) No 402/2013, finding, listing, and characterizing dangers is the process of hazard identification [33].

Hazards were identified and categorized for each corridor and for transitions between corridors. This analysis enables targeted risk mitigation and prioritization of system upgrades and procedural adaptations. For every transition, a hazard log analysis has been performed. Lists of potential system risks, together with their sources, effects, classifications, and existing hazard treatments, are organized in the hazard log to make it easier to comprehend.

3.6.3 Fault Tree Analysis (FTA)

A Fault Tree Analysis is a logic diagram demonstrating the interdependence among system component failures that cause or contribute to an unwanted event. The study employed fault tree analysis to model potential failure modes at critical transition points between different signaling systems. A top-level fault event was defined for each transition. FTA enables scenario-based diagnosis of the manner in which specific events (like a collision between two trains) may occur, on the basis of stratified system failures.

In this study, FTA helps by:

- Complex interactions modeling: it shows how hardware (e.g., MA logic), software (e.g., ATP command), and human factors (e.g., driver behavior) interact during transitions.
- Root cause tracing: FTA breaks up high-level hazards (such as collisions or loss of MA) into failure paths, pinpointing precisely where there are shortcomings or weakening in safety barriers.
- Comparing transition severity: by applying the same scenario to all three transitions, FTA identifies which system interfaces are most at risk and why.

The fault tree is constructed deductively, starting with an undesirable incident and using fundamental events, which are made up of the various components that produce the fundamental events (such as component failure, human error, or other failures), resulting from it. The basic events are linked to gates, either AND or OR gates. An AND gate requires all of the basic events linked to the gate to occur in order for the fault tree to advance, while an OR gate requires at least one of the input events to occur in order for the fault tree to advance [34].

3.7 Technical Barriers impeding the interoperability

This study identify which technical mismatches (barriers) are statistically associated with high-risk hazards (Hazard log/Fault Tree). This helps prioritize the most impactful interoperability gaps. The technical barriers that affect the interoperability between train control and railway signaling systems are determined using Spearman's rank correlation analysis.

Spearman's Rank Correlation has been used in this book to determine correlation values for various parameters or factors influencing the interoperability of train control systems and signaling systems. Such parameters include such as signaling system standards, data transmission protocols, on-board and trackside equipment, and access to GSM-R. Ranking such characteristics based on their compatibility in various systems, Spearman's equation allows us to determine the correlation coefficient (ρ) of each of parameters.

The Spearman's Rank Correlation equation is given by [35]:

$$\rho = 1 - \frac{6\sum {d_i}^2}{n(n^2 - 1)} \tag{3.3}$$

Where:

- ρ is the correlation coefficient,
- d_i is the difference in ranks for each paired parameter,
- n is the number of pairs of attributes.

This correlation identifies whether a given attribute positively or negatively impacts interoperability.

- Parameters with a negative correlation indicate potential technical barriers
- Parameters with low or near-zero correlation have less impact on interoperability
- Parameters with a high positive correlation contribute positively to interoperability and should be considered for standardization efforts.

3.8 Technical Solution Evaluation Development Model

Ensuring interoperability in railway signaling and train control systems across the East African network presents significant technical and operational challenges. To resolve the aforementioned issues, this study compares different technical solutions and determines their performance based on a structured decision-making method. The Analytical Hierarchy Process (AHP) determines the preliminary weight values of the criterion and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method systematically ranks the proposed options against different criteria.

Optimizing interoperability in train control and railway signaling systems across the East African network is a very serious technical as well as operational issue. In order to find answers to such issues, this research evaluates a range of technical solutions and sets their feasibility in accordance with a structured decision-making process. AHP determines the preliminary weight values of the criterion and TOPSIS method ranks the solutions suggested systematically in accordance with different criteria.

3.8.1 Multiple Criteria Decision Analysis (MCDM)

The subfield of operations research known as multiple-criteria decision analysis (MCDA) or multiple-criteria decision making (MCDM) focuses on creating mathematical and computational tools that enable an individual or group of decision makers to subjectively evaluate a finite number of decision alternatives under a finite number of performance criteria [36]. A group of options is screened, prioritized, ranked, or chosen under often independent, incommensurate, or competing criteria. This process is known as MCDM. Finding the qualities is essential to MCDM as they are a major factor in the decision-making process. Many approaches have been put out to address related issues, but a significant challenge with MCDM is that various approaches may provide disparate outcomes for the same issue [37].

This research examines two significant MCDM techniques: TOPSIS and AHP. AHP is utilized to answer problems in the domains of science, business, engineering, and other disciplines and is considered the foundational method for decision-making. Due to its ease of use in analyzing problems in the form of hierarchical structure and finding the best solution through a straightforward comparison matrix approach, AHP is utilized in a wide range of applications. To determine the starting weight values of the criterion and to rank the best solution, TOPSIS method has been used.

3.8.2 Analytical Hierarchical Process (AHP)

The analytical hierarchy process (AHP) is a method for categorizing and analyzing decisions according to a number of criteria. This method addresses a challenging decision-making problem with several characteristics by modelling the unstructured situation under study into hierarchical forms of components.

Step-1: Create the Pairwise Comparison Matrix

A pairwise comparison matrix is created using the Saaty 1-9 preference scale (Table 3-3) to determine the degree of relative relevance of features at each level.

Table 3-3: Saaty's pairwise comparison scale [37]

Scale	Compare factor of i & j
1	Equally Important
3	Weakly Important
5	Strongly Important
7	Very strongly Important
9	Extremely Important
2,4,6,8	Intermediate value between adjacent scales
Reciprocals	Value for inverse comparison

Step-2: Normalize the Pairwise Comparison Matrix

Divide each element in a column by the total number of items in that column to normalize the matrix. This will make the columns sum to 1, allowing for comparison of the criteria on an equal scale.

Step-3: Compute Criteria Weights

After normalizing the pairwise comparison matrix, the average of every row must be calculated to obtain the weight of each criterion. The formula for the weight of a criterion i is [38]:

$$W_i = \frac{1}{n}\sum_{i=1}^{n} \hat{a}_{ij} \tag{3.4}$$

Where:

- W_i is the weight of criterion i
- $\hat{a}_{ij}$ is the normalized value for criterion i under comparison j,
- n is the total number

Step-4: Compute the Consistency Index (CI) and Consistency Ratio (CR): the consistency index (CI) assesses the decision maker's inconsistent comparisons [38].

$$CI = \lambda_{max} - n/n - 1 \tag{3.5}$$

The maximum eigenvalue of the judgment matrix is given by λ_{max} , and n is the order of the matrix. The maximum Eigenvalue is given by the sum of the products of each eigenvector element and the sum of the columns of the reciprocal matrix [37], [38].

$$CR = \frac{CI}{RI} \tag{3.6}$$

The consistency index of the randomly generated pairwise matrix, the random index (RI), is shown in Table 3-8 computed for n ≤10. The judgment results are consistent, if calculated value of CR results less than 0.10.

Table 3-4: Random consistency index table [37], [38]

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

3.8.3 A Technique for Order of Preference by Similarity to Ideal Solution

TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), developed by Hwang and Yoon [37], is an effective MCDM method due to the specific characteristics of this technique which make it a high consistent method with less effort for computation. Basically, the multi-response values are combined in this approach to provide a single performance response value [39].

The TOPSIS method seeks to achieve an order preference that is similar to the ideal solution, which is a hypothetical solution with the most benefits and the fewest costs of attributes or choices. The hypothetical negative ideal solution, on the other hand, would increase the expenses of the qualities or criteria while decreasing their benefits. Consequently, the optimal option which also acts as the issue's solution is the one that is farthest distant from the negative and closest to the ideal, positive answer. The Euclidean Distance/Geometric Distance and the ideal solution define these similarities or differences, and the negative ideal is analyzed based on the database's maximum and minimum values.

In all MCDM problems, an $m \times n$ decision matrix with m alternatives and n criteria is considered as below [39]:

$$X = \begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}_{m \times n} \tag{3.7}$$

The stepwise procedure of Hwang and Yoon [40] for implementing TOPSIS is presented as follows:

Step-1: Calculate the normalized decision matrix

$$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{j=1}^{J} x_{ij}^2}}, \qquad j = 1,2,3 \dots, J;\ i = 1,2,3 \dots, n \tag{3.8}$$

Where x_{ij} and r_{ij} are original and the normalized score of decision matrix respectively.

Step-2: Construct the weighted normalized decision matrix by multiplying the weights w_i of evaluation criteria with the normalized decision matrix r_{ij}.

$$v_{ij} = w_i * r_{ij}, \qquad j = 1,2,3 \dots, J;\ i = 1,2,3 \dots, n \tag{3.9}$$

Step-3: Determined the positive ideal solution (PIS) and negative ideal solution (NIS)

$$A^* = \{v_1^*, v_2^*, \dots, v_n^*\} \text{maximum values} \tag{3.10}$$

Where $v_i^* = \{\max(v_{ij}) \text{ if } j \in J; \min(v_{ij}) \text{ if } j \in J^-\}$

$$A^- = \{v_1^-, v_2^-, \dots \dots v_n^-\} \text{ minimum values} \tag{3.11}$$

Where $v^- = \{\min(v_{ij}) \text{ if } j = J; \max(v_{ij}) \text{ if } j \in J^-\}$

Step 4: Calculate the separation measures of each alternative from PIS and NIS

$$d_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_i^*\right)^2}, \qquad j = 1,2, \dots \dots J \tag{3.12}$$

$$d_i^* = \sqrt{\sum_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}, \qquad i = 1,2, \dots \dots J \tag{3.13}$$

Step 5: Calculate the relative closeness coefficient to the ideal solution of each alternative

$$CC_i = \frac{d_i^-}{d_i^* + d_i^-}, \qquad i = 1,2, \dots I \tag{3.14}$$

Step 6: Based on the decreasing values of closeness coefficient, alternatives are ranked from best to worst. The alternative with the highest coefficient of closeness is chosen.

CHAPTER FOUR

4. EAST AFRICAN RAILWAY NETWORKS

4.1 Introduction

Africa is the world's second-largest and most populous continent, following Asia. With Madagascar and the other nearby islands included, its total area exceeds 30 million km^2, which is three times larger than that of Europe [41]. Nearly all of Africa's rail networks date back to the early 20th century, European colonial powers constructed railway lines to facilitate military movements and transport goods produced from extensive farming or mining operations [1]. At the time when most infrastructure where built the focus was local and there where little concern related to effective logistical chains. Typically, the emphasis was on just one country and the particular commercial target for the railway investment (e.g., raw commodities). The agenda did not include topics like efficient border crossings, technical standardisation, or harmonization. Additionally, there was no emphasis on broader market orientation, commercial interoperability, and the use of railways as a tool for regional development in Africa.

The degree of development among African countries is low, yet due to their special colonial history, their rail building started early, even ahead of China. Looking back at the history of building and development and anticipating the future, the evolution of the African railway network can be categorized into three stages, with two upsurges, when tracing the history of building and development and looking to the future [42].

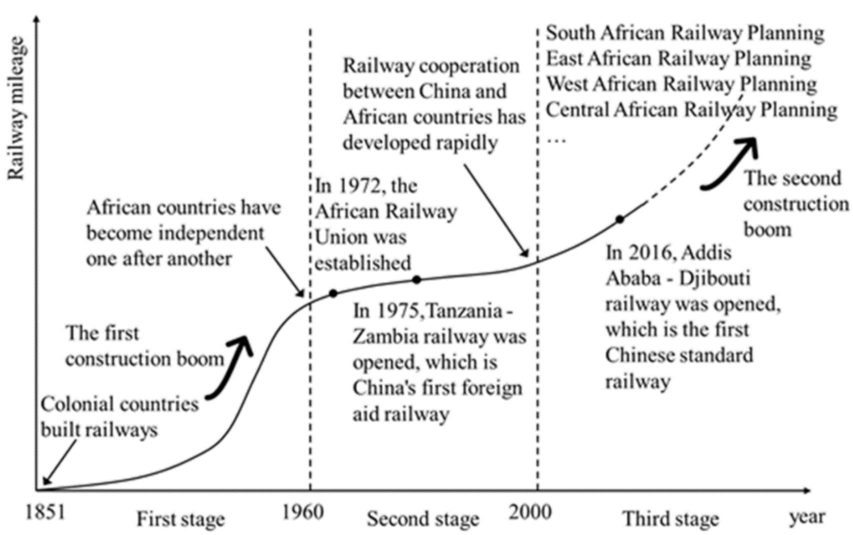

Figure 4-1: Development stage of African railway network [42]

In the beginning, European nations started constructing railroads across Africa. The basis of the present African Railway was established in 1851 when Britain constructed Egypt's first railway, sparking the first building boom of the early 20th century. The second phase, which started around mid of 20th century, saw the gradual independence of African nations. Rich resource nations attempted to build various infrastructure projects, including railways, for economic development. However, the development and construction of African railways happened slightly at a slow rate due to various factors such as lack of funds, geographical terrain, political unrest, geopolitics, and technological limitations.

By the beginning of the 21st century, most of Africa's old railways were in poor condition and the freight transportation cost remained high due to the long-term lack of construction and management. At the same time, the second upsurge was brought about the railway construction in Africa, which benefited from China-Africa collaboration [42].

As of 2005, the United Nations had reported Africa had a total railway network of 90,320 kilometers. 22% belonged to North Africa, while Central, Eastern and Western Africa together share of 35%, the rest of 43% belonged to the Southern Africa. Excluding the island nations, eleven countries in sub-Saharan Africa (mostly landlocked in central Africa) [43].

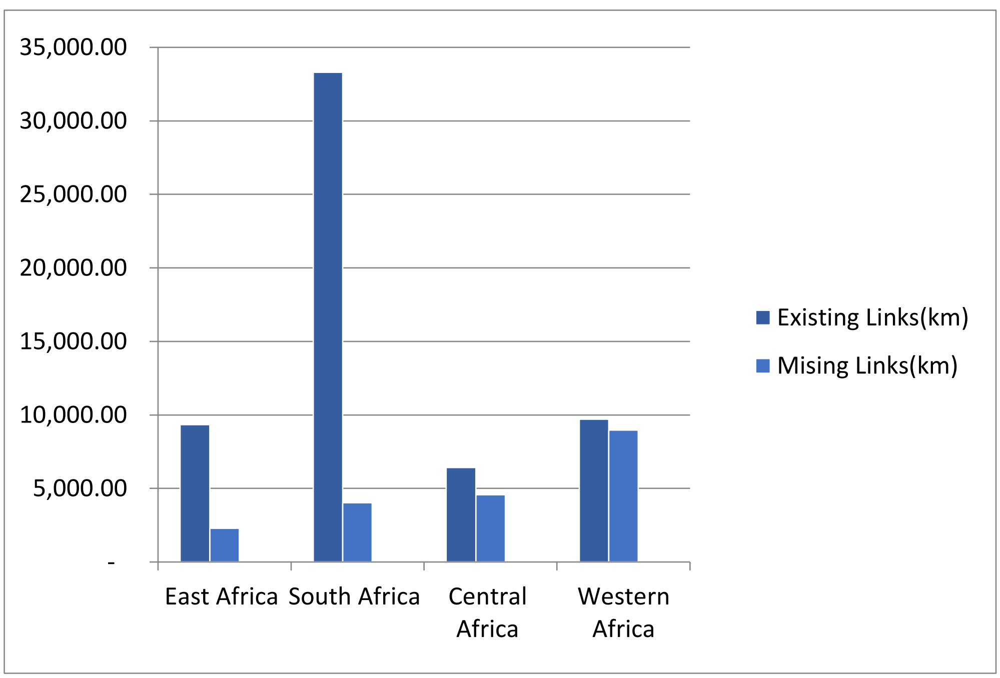

Figure 4-2: Existing and missing railway lines in Africa

4.2 Existing East Africa Railway Network

4.2.1 Ethiopian Railway System

Ethiopia's railways sector has been closely tied to the Ethio-Djibouti Railway (EDR) Company for over a century. This railroad is among the oldest in Sub-Saharan Africa and it has contributed a great deal to the development of Ethiopia. The 781 km long 1,000 mm gauge railway runs from Addis Ababa to the Port of Djibouti and has 681 km within Ethiopia and 100 km in Djibouti. The ownership is jointly held by the governments of Ethiopia and Djibouti.

The Ethiopian Railway Systems, also known as the Ethiopian Railway Corporation (ERC) is the state-owned railway of Ethiopia. It was established by regulation 141/2007 of the Federal Democratic Republic of Ethiopia Council of Ministers. ERC is not only the railway infrastructure manager but also the operator. The responsibilities of the corporation are: to build railway infrastructure, operate cargo railway transport services, operate passenger railway transport services, fulfill the other duties in its charter, and engage in other activities necessary for the attainment of its purpose. Since its formation in November 2007, the ERC has plan to develop around 5,000 km of railway alignments on eight corridors identified as necessary to enhance both the social and economic needs of the country [49] [50]. ERC achieved the one urban rail transit system and three electrified standard gauge railway lines:

1. Addis Ababa-Djibouti Railway
2. Awash-Weldiya Railway and
3. Weldiya-Mekelle Railway (under construction), there is also an urban light rail system in the country's capital, the Addis Ababa Light Rail, this paper focuses on the two completed national lines: the Addis-Djibouti line and the Awash-Weldiya Line.

4.2.1.1 Ethio-Djibouti Railway (EDR)

Ethio-Djibouti (Addis Ababa-Djibouti) railway project is envisaged as a major export and import connection linking land locked Ethiopia with Djibouti Port in the Red Sea's international shipping routes. There used to be an old railway line on almost the same corridor before the current Ethio-Djibouti railway line. It connects Ethiopia with Djibouti via Dire Dawa is a 780km meter-gauge[1] line with diesel traction

[1] a 1000 mm gauge and stretched for 756 km, 656 km in Ethiopia, and 100 km in Djibouti

opened in 1917. It is a single railway line that links landlocked Ethiopia with Djibouti Port, a significant cargo entrance point, has deteriorated due to poor management and maintenance [46].

The new standard gauge Addis Ababa-Djibouti railway is the first modern cross-border, electrified railway in Africa with the total length of 756km, (656km in Ethiopia section and 100km in Djibouti section), stretches from Addis Ababa (capital of Ethiopia), then runs along Adama, Dire Dawa (two big cities of Ethiopia), and ends in Djibouti port. The project, constructed by China Railway Group and China Civil Engineering Construction Corporation (CCECC). It was designed and constructed in compliance with Class II Chinese electrified railway standard at design speed of 120km/h. The line was formally inaugurated for passenger services in October 2016, providing landlocked Ethiopia with faster access to the port of Djibouti [46], [47].

Figure 4-3: Ethio-Djibouti railway line map [48]

A modern Chinese railway control system was added to the railway line for efficient and safe transport. Computer technology, network communication technology, and contemporary control technology are all integrated in Centralized Traffic Control (CTC), which uses intelligent decentralized and autonomous design concept, with the control of the train operation adjustment plan as its primary component. The technical apparatus that allows the dispatching center to directly coordinate and oversee train operations while centrally controlling the signal equipment in a dispatching section is known as a centralized dispatching control system (CTC). The main center for train dispatch along the entire line is the Lebu

Operation Control Centre (OCC). The entire Addis Ababa Djibouti Railway line has two dispatching centers: the Nagad dispatching subcenter and the Lebu dispatching center.

A modern Chinese railway control system was added to the railway line to ensure efficient and safe transportation. Centralized Traffic Control (CTC) employs the intelligent decentralized and autonomous design principle, integrates computer technology, communication via networks, and modern control technologies, and keeps the control of the train operation adjustment plan at the center of the system. The technical equipment that allows the dispatching center to directly monitor and oversee train operations while centrally controlling the signal equipment in a dispatching section is known as a centralized dispatching control system (CTC). The main center for train dispatch along the entire line is the Lebu Operation Control Centre (OCC). The entire Addis Ababa Djibouti Railway line has two dispatching centers: the Nagad dispatching subcenter and the Lebu dispatching center [47].

Signaling System Description

The Chinese signalling system is the basis for this project. The signalling system's design range includes a computer interlocking system, a block system, tools and instruments for maintenance, and the installation and commissioning of spare parts and equipment. The Ethio-Djibouti railway line uses CTCS level 0. CTCS level 0 is consists of:

Signal: in stations or sections, multi-lenses colour light signals are utilized. Short signals are used when placed on bridges or inside tunnels, whereas high signals are used for homes and distant locations. Generally speaking, shunting signals on the inlet of lead lines, special lines, or branch lines utilize high signals, whereas the others use short signals.

Block equipment: semiautomatic block is used between stations along the line. It is used for the information transmission channel with a semiautomatic block between stations.

- The double track section from Sebeta-Adama line is provided with jointless track circuits.
- The single-track section from Adama-Mieso of the line employs an automatic intersection block, and the axle counter checks the section. When the axle counter fails, the block type may be degraded to a semiautomatic block, as confirmed.

Interlocking system: all the stations of the line are installed with a cluster of computers interlocking. Each group of turnouts of the station in the interlocking zone is provided with a switch machine for switching the turnout, locking the turnout, and reflecting the turnout status.

Centralized traffic control (CTC): Each station has a self-operating control unit, and the center is located in Lebu. Every station and the center exchange information via the CTC communication channel. The dispatching center subsystem, station subsystem, and network subsystem make up the CTC system. Every station in Ethiopia is run by any station that has been given permission by the Lebu control center, which has integrated authority over all of them. Non-conventional station control is used in the event of a fault, meaning that each station regulates itself [49].

Track circuit in the track-side: 25Hz phase sensitive track circuit is employed in the station for the line to complete the check of unoccupied track sections [50]. Information is supplied to the onboard equipment via the track circuits of the track sections on the mainline receiving route in the single-track section station, receiving route, and mainline positive receiving departure route in the doubletrack section station. With movement authorization (MA) supplied by an automated block via a train control center (TCC), CTCS levels 0 use track circuits to send train control information.

4.2.1.2 Awash-Kombolcha-Hara Gebeya (Weldiya) Railway (AKH)

The Awash-Kombolcha-Hara Gebeya (AKH) Railway Project is located along the railway line that connects Addis Ababa and Djibouti, and is an extension project that connects the two countries. Turkish construction tycoon Yapi Merkezi, who had already fought Chinese builders for the SGR project in Tanzania, was awarded the contract. Chinese Communications Construction Company was also hired to complete the second section from Weldiya to Mekele (CCCC) [51], [52], [53].

The Awash-Weldiya Railway project, funded by Turk Exim-Bank, is a 392km air pollution-free railway line in Ethiopia. The project, which includes 10 substations, 12 caves, 52 bridges, 8 power control stations, 12 radio poles, and a main workshop(maintenance center), connects the northern and central parts of Ethiopia and can run at speeds up to 120 km/h [54]. The project consists of one workshop depot and ten stations in total. The three-block section has been allowed and managed by dividing all of the sections between the stations—aside from Kombolcha—into three intermediate block signals.[55].

i. Signaling System Description

Signalling system on this project will be based on the European rail traffic management system (ERTMS/ETCS) Level 1 based on Bombardier Interflo 250 which is a semiautomatic signalling system [55]. These systems are being used for the first time in Ethiopia with the execution of the Awash-Weldiya project.

- Conventional signalling system and internationally used ERTMS (European Railway Traffic Management System) Level 1 Automatic Train Control. The signal lights will be based on ETCS rules.
- Conventional signalling includes:
  - Driver uses trackside signals to determine
    - If the train can proceed forward (aspect)
    - The speed the train will travel at
  - 3-aspect signaling systems
  - The Location of the train is determined by Axle Counters
  - One block separation must be maintained between trains for safety
- Signalling Interlocking hardware will be designed according to IEC 61508 SIL-4 (Safety Integrity Level).

ii. Onboard and Trackside Assemblies

Signals: Signals are fail safe type, located beside the railway line to give information relating to the state of the line ahead and back of the train. Multi aspects, shunting and midget railway signals will be installed at conventional signalling system [56].

Axle Counters: This function allows to detect the presence of a train in a section of track and send the information to the interlocking logic. The axle counter system will provide also soft and hard reset functionalities for the system start-up and recovery from degraded operation mode. Axle counter systems will be used as train detection system, both for stations and for line. The right of way is separated into "blocks" with wheels (axles) being counted into and out of the block [56].

Interlocking: This functionality allows to safely operate all the eleven stations, the depot/workshop and the line between stations according to signalling rules. Several computers will receive as input the yard status and commands from dispatchers. Interlocking provides safe route settings, authorization to train movements, staff protection restricting train movements in zones with maintenance work.

Yard Interface: The interface between the interlocking logic and yard objects is managed by electronic boards (Object Controllers). Object controllers collect in a safe way the status from yard objects (signals, point machines, etc.) and send it to the interlocking logic by means of a software protocol [56].

Eurobalise: This is a spot transmission equipment which is based on a passive transponder installed in the track. The Eurobalise is used to send information to the onboard ERTMS/ETCS as the train pass over it.

- The Eurobalise is frequency by an electromagnetic field generated by an antenna fitted onboard the train. frequency of the magnetic field used to energize the Eurobalise is 27 MHz**.** The frequency of the telegrams from the Eurobalise is around 4 MHz, with a data rate of around 564 kbit/s.
- It fulfills the 'FFFIS Interface 'A' Balise Transmission Sub-System' and complies with 'FFFIS Coding strategy' and 'FFFIS Balise Transmission Sub-System', and preferably also complies with 'FFFIS Interface 'C' Balise Transmission Sub-System'. The interface between the Eurobalise and Eurobalise reader is known as the Form Fit Functional Interface Specification (FFFIS). This interface guarantees that systems from various vendors that satisfy this requirement can cooperate without the need for additional security measures [56].
- If the Balise is powered by the train, it does not transmit a locally stored telegram but the telegram from the LEU connected at the so-called interface "C".
- There are two different types of balises [56]:
    - Balises that are not connected to the interlocking and transmit a fixed Telegram information about the alignment.
    - Balises that receive the telegram to be transmitted are connected to the interlocking by the Balise Object Controller. If disconnected from the controller, sends a default telegram.

Object Controllers: In order to provide data transfer between signalling wayside equipment, object controllers will be installed along the route and operate in integration with the interlocking system.

Radio In-fill Unit (RIU): The RIU can be used to send the GSM-R Network the signalling information pertaining to the primary signal in the train's running direction. The GSM-R radio channel is then utilised to send the updated information to the train.

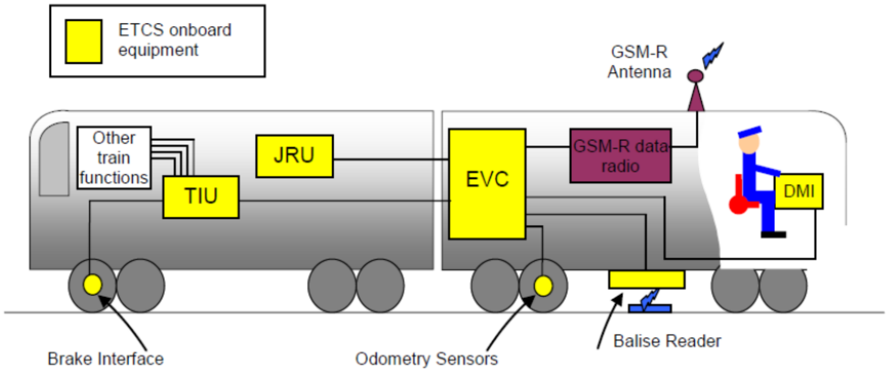

Figure 2: ETCS onboard equipment [57]

European Vital Computer (EVC): The onboard computer-based system, that elaborates the information about the train circulation and the movement authority.

iii. Automatic Train Protection (ATP):

ATP modules in the train-borne ETCS subsystem use pre-fed track description data, known train braking characteristics, and received ETCS data to determine a safe speed profile. The driver can view this information on a special screen in the cabin called the Driver Machine Interface (DMI). The core of this communication is GSM-R, a dedicated mobile network for railway transport. it provides both voice and data transmission services.

iv. Train control and operation

It involves non-continuous communication between the train and the trackside, usually via Eurobalises, and continuous supervision of train movement (i.e., the onboard computer continuously monitors the maximum allowed speed and calculates the braking curve to the location to which the train is permitted to proceed; the end of movement authority) [58].

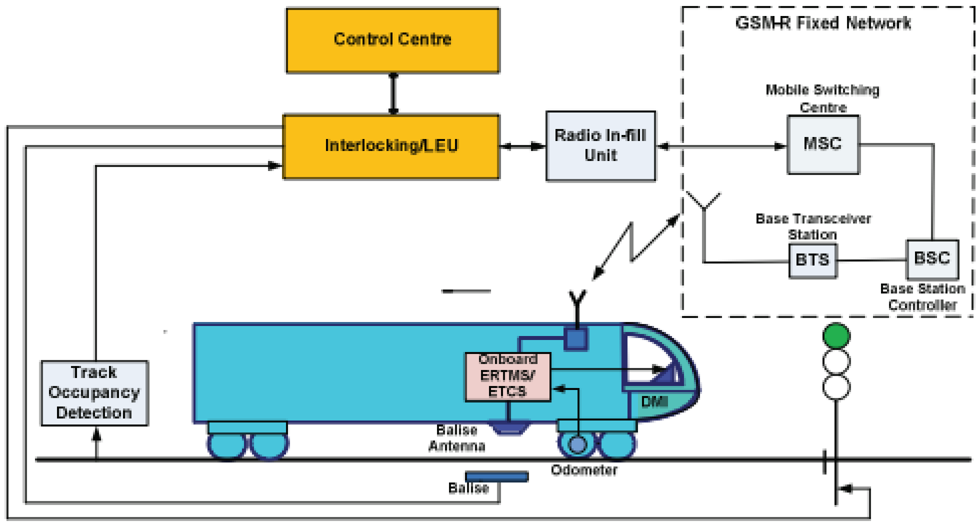

Figure 4-4: ETCS Level 1 (with infill balise group) [59]

4.2.2 Kenyan Railway System

The railway system in Kenya was initially developed during the British colonial period. The construction began in 1896 and was completed in 1901. The railway line was built between 1896 and 1901. The railway line connected Mombasa with Kisumu, facilitating the transportation of goods and people and the settlement and economic development of the region. After independence in 1963, the rail network continued to form an integral component of the national infrastructure, and Kenya established the Kenya Railways Corporation (KRC) as the operator of the railway. The state-owned Kenya Railways Corporation (KRC) is in charge of building and maintaining Kenya's railway network. It collaborates with a number of partners and manages significant railway projects.

The SGR construction was undertaken due to the requirement for high speeds, increased capacity, reliable and safe network. The MGR service, had deteriorated and did not meet the service level agreements. This poor service led to a high rail-road modal split that created a mess on the roads [47]. The SGR was designed to be faster and more efficient than the old meter gauge railway, and passenger trains will travel at a top speed of 120 km/h and freight trains will travel at a top speed of 80 km/h.

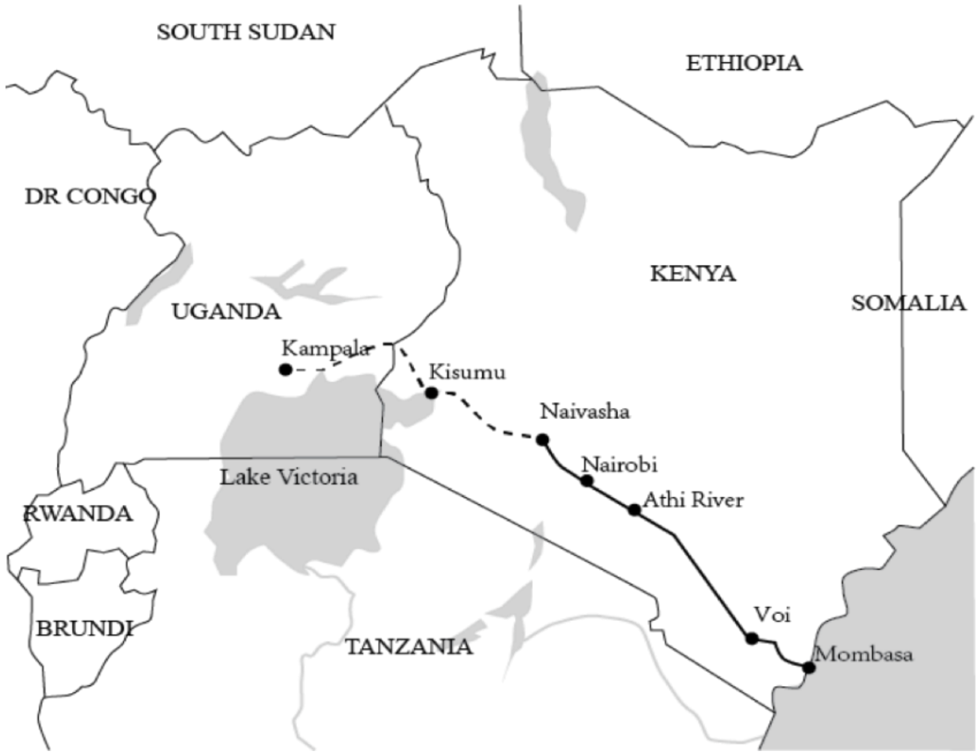

Figure 4-5: Kenyan SGR map [60]

The solid line represents the sections constructed between Mombasa and Naivasha, and the dashed line indicates sections planned between Naivasha and Kampala. Source: Zhengli Huang, 2022

Phase I of the SGR project linking the Port of Mombasa with Nairobi, the capital city of Kenya, was initiated in 2017 [4]. Phase II was divided into three sections: Nairobi–Naivasha, Naivasha–Kisumu, and Kisumu–Malaba (Uganda). SGR has total 592 kms of rail network in Kenya, 472 km from Mombasa to Nairobi and 120 km from Nairobi to Naivasha[61]. China Road and Bridge Corporation (CRBC), a subsidiary of China Communications Construction Company (CCCC), was also one of the key contractors in the development of the Standard Gauge Railway (SGR) project in Kenya. They constructed the Mombasa-Nairobi and Nairobi-Naivasha SGR lines [60], [61].

Train control system employs track circuits, balises, and wireless communication (GSM-R) to transmit information like movement authorities, speed restrictions, and route data between the ground and train. This data is crucial for safe operations in fixed block systems. Primary communication systems use balises and track circuits, while secondary systems use Lineside Electronic Units (LEU) and a Train Control Center (TCC) for managing and processing information related to train movements and safety. GSM-R provides a reliable, high-bandwidth radio link for continuous data exchange.

Signaling System Description

The Chinese Train Control System (CTCS) Level 2 serves as the foundation for the project's signalling system. Based on train operation permission messages sent by the transponder group and the rail circuit, the CTCS-2 train operation control system provides automatic train operation control.

Wayside and Onboard Configurations:

CTCS Level 2, a points-and-continuous control system consists of trackside continuous equipment ZPW2000 track circuits, point balises, and onboard automatic train protection (ATP).

Temporary speed limit server: is programmed to generate a temporary speed restriction command and send it after processing the received temporary speed limit directive.

Train control center: uses the carrier frequency low frequency coding information and is set up to produce an active transponder message and carrier frequency low frequency coding information based on the track segment state data provided by the track circuit and the temporary speed limit command. sending the active transponder message to the terrestrial electronic unit and sending it to the track circuit.

Track circuit: is employed to generate and transmit track segment status information for train occupancy checks, as well as to modulate received carrier frequency low frequency coded information to create and transmit a track circuit signal. With a similar architecture to the TVM-300, the track circuit is utilized for both movement authorization and train occupation detection. Intermittent trackside information is provided by the Balises and the track circuit, which also automatically protects cab equipment from trains.

Balise/ Transponders: is configured to transmit both the received active transponder message and the fixed transponder message when the transponder power signal is driven.

Balise transmission module (BTM): is designed to transmit the transponder power signal, and the transponder antenna is used to send fixed and active transponder messages to the transponder information receiving module.

Vital Computer (VC): is set up in accordance with the fixed transmission by the transponder group received by the transponder information receiving module and the track circuit signal transmitted by the track circuit received by the track circuit information receiving module. To keep an eye on train operations, the transponder message and the active transponder message create a goal distance continuous speed control curve.

Trackside radio communication network (GSM-R): This radio network, which is dispersed along railway tracks, facilitates bidirectional data flow between the RBC and the aboard. Additionally, drivers, maintainers, and track workers who utilize GSM-R handheld terminals can communicate verbally with the signals control center.

The onboard equipment consists of a station interlocking mechanism and a centralized dispatching system. A temporary speed limit command is generated by the scheduling system and transmitted to the server. Using track segment security data, the station interlocking device sets up routes. Additional onboard equipment consists of a speed sensor, a driver machine interface (DMI), a specific transmission module (STM), and a balises transmission module (BTM). A speed measuring ranging unit generates train actual speed and travel distance information. A human machine interface (DMI) displays the target distance and monitors train operation.

4.2.3 Tanzania Railway System

Tanzania has two railway lines: Tanzania Railways Corporation (TRC) runs on the central and northern corridor, while Tanzania Zambia Railways Authority (TAZARA) runs on the southern highland corridor [62]. From Dar es Salaam to the new Kapiri-Mposhi in Zambia, the TAZARA oversees a single 1,860-kilometer route that was constructed between 1970 and 1975. The Republic of Zambia and the United Republic of Tanzania jointly own the Railway [63].

The Tanzania Railways Corporation (TRC), spans 2,706 km and is regulated by the Railway Act supplement of 2017 and the Tanzania Railways Corporation Act of 1977. The network links Tanzania's major towns and cities, including Dar es Salaam, Tabora, Mpanda Kigoma, Mwanza, Tanga, Arusha, and Moshi [62].

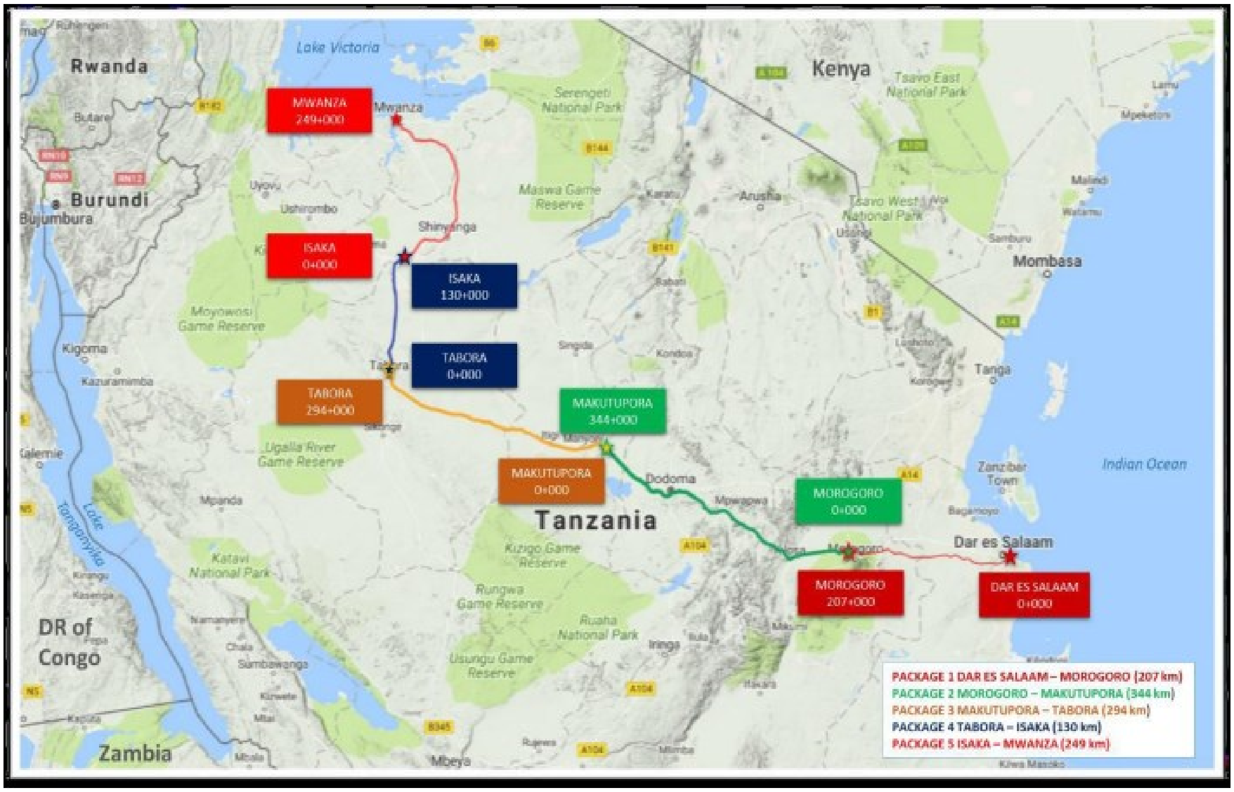

Figure 4-6: Tanzania SGR alignment [64]

As part of the East African Railway Master Plan, the Tanzania SGR serves Tanzania and connects it to its neighbor's, Rwanda, Uganda, and Burundi, and via these to the Democratic Republic of the Congo. It is currently under construction and partially operational. It is planned to replace the old meter-gauge railway system with the new, electrified standard gauge railway. The SGR is a wide railway corridor whose purpose is to connect Dar Es Salaam and Mwanza. The SGR corridor is divided into 5 sections for a total length of about 1.224 km and the SGR network line from the port of Tanga via Moshi and Arusha to Musoma of ~1028 km is feature planned phases.

Table 4-1: Tanzanian SGR networks [62], [65]

Railway Sections	Length	Phase
Dar es Salaam-Morogoro	270 km	Operational
Morogoro-Makutupora	344 km	Operational
Makutopora-Tabora	294 km	Under construction

Tabora-Isaka	130 km	Under construction
Isaka-Mwanza	249 km	Under construction
Tabora-Kigoma	506 km	Under construction
Tanga-Moshi-Arusha-Musoma	1028 km	planned phases
Kaliua-Karema	321 km	planned phases

Tanzania has one of the most advanced railway communication systems in the region. The network uses GSM-R base stations coupled with a continuous fibre optic infrastructure, and the system combines the European Train Control infrastructure (ETCS) and Centralised Traffic Control (CTC).

4.2.3.1 Dar es Salaam-Morogoro-Makutupora

The Dar es Salaam–Morogoro–Makutupora section is part of Tanzania's Standard Gauge Railway (SGR) project, which is being built in multiple phases to connect the port of Dar es Salaam with the country's central and western regions. Spanning approximately 722 km, built to a 1,435 mm standard gauge and electrified at 25 kV AC, the corridor is equipped with European Train Control System (ETCS) Level 2, computer-based interlocking, axle counter train detection, and GSM-R communications, enabling safe, high-speed passenger services of up to 160 km/h and efficient freight operations.

The overall railway operations can be controlled through a hierarchical arrangement of control rooms in the main Operation Control Centre (OCC) located at Dar es Salaam (DSM). In the event of failure of the main OCC, the controls will be switched to the recovery OCC located at Morogoro. All critical functions can be controlled in the recovery OCC located at Morogoro.

Signalling System Description:

The signalling system is based on the ERTMS/ETCS Level 2 for train spacing. ETCS L2 provides continuous speed supervision and it protects against overrunning the MA (Movement Authority). The system generates integrated signalling functions in the driver's cab and ensures assuring track-train bidirectional communication via the GSM-R system using its special BTS (Base Transceiver System) antennas located along the line and the dedicated GSM-R antennas located on the vehicles.

The interlocking system sets train routes according to the orders received from a Centralized Traffic Control (CTC) (Dar Es Salaam and Morogoro) and sends information to the RBC, which performs distance and speed monitoring and calculates the safest braking curve. ETCS L2 consists of two subsystems, the ETCS On-Board and the ETCS Trackside.

Trackside Equipment

- LED Signals: dwarf light signals will be used in secondary tracks, whereas high light signals will be used in the main tracks for visibility reasons.
- Point machines: The project uses traditional electro-mechanical point machines on main tracks and sidings, with the option for safe manual operation for maintenance and emergencies. Non-trailable machines will be used on running tracks, while accidentally trailable machines will be used on siding tracks.
- The Axle Counters System: compliant with the SIL4 CENELEC Standard, will be a multiple section axle counter typology. It includes magnetic sensors, ADPs, and Axle Counter Evaluator (ACE) devices. All equipment operates under an Uninterruptible Power Supply (UPS) system, with ACEs housed in Technical Buildings and interfaced with the interlocking system via a serial interface and safe communication protocol. ACEs and external ADPs can communicate through optical fiber networks or copper cables [64].
- Eurobalises: are fixed ETCS trackside installations used mainly for train position referencing. Each balise group will consist of a redundant fixed balises which transmit always the same ETCS messages. Different kinds of balise groups are used, depending on the functions that have to perform. Generally, all the balise groups included in the ETCS telegram transmitted to the train the ‘position report’. The train reads Eurobalises via the air-gap and sends its ‘position report’ to the RBC. The train receives MAs and ‘track description’ via Euroradio relating its position.
- Radio Block Center (RBC): hosted in the equipment room of the OCC at Dar Es Salaam and Morogoro. Using the Euroradio protocol and GSM-R connection, RBC provides track information and MAs to each train separately. The ETCS On-Board subsystem combines MA and track description with its own information to perform distance and speed monitoring and to calculate the safest braking curve.

Onboard Equipment

- European Vital Computer: The on-board system consists of an EVC, which can be based on a supplier-specific platform and uses a safety platform running SIL4 ETCS firmware. It connects to external and internal interfaces, including emergency brake, service brake, traction cut off, lower pantograph, open main switch, and passenger emergency brake output.
- Eurobalise Transmission Module (ETM) and Balise Antenna: the balise reader subsystem allows ETCS Onboard equipment to read track mounted Eurobalises, requiring cable routing and antenna placement location evaluation to prevent electromagnetic interference.
- GSM-R system: GSM-R System is responsible of data and voice communication through the air gap. Data communication provides critical information like movement authority to the EVC. GSM-R Voice communication provides voice communication with critical operators like dispatchers to the drivers. Therefore, the hand-held of the GSM-R Voice communication should be placed in arm's reach to the driver's seat.
- Driver Machine Interface (DMI): The driver machine interface features a touch screen providing crucial information like ERTMS level, mode, speedometer, target distance, brake indications, text messages, track conditions, profile, gradients, and time. It's recommended to install the DMI screen at the driver's desk's axis.
- Odometry (Tachogenerator & Doppler Radar): The odometry subsystem calculates train speed, acceleration, and position using Pulse Generators/speed sensors and Doppler radars. The principle of diversity minimizes common mode failures. Two Pulse Generators per ETCS equipment are installed in different bogies and sides of the train, providing two output signals. A Doppler Radar is mounted under the train, used as a speed and distance sensor. The train wiring must be less than 30m long and positioned on the track bed [64].

Train Detection

The track vacancy detection system for the line and stations of the SGR is based on the electronic axle counters. The Axle Counters System is compliant with the highest safety level (SIL4 CENELEC Standard) [64].

CHAPTER FIVE

5. TECHNICAL INTEROPERABILITY ANALYSIS

5.1 Introduction

This chapter presents the technical, operational, and risk-based analysis of signaling system transitions on three key East African railway corridors. The analysis seeks to identify failure mechanisms, interoperability gaps, and high-risk scenarios by using a combination of hazard logs, fault tree analysis (FTA), interoperability scoring, and decision-modeling techniques.

5.2 Technical Analysis of the Railways

This section defines and compares the four East African railway corridors involved in the interoperability analysis, focusing on their signaling and train control system architecture. Each system is compared with a set of operational, technical, and communications-related features.

The technical analysis highlights key differences in system components such as train detection, movement authority, data transmission, communication systems and train control and operation. These differences create interoperability barriers when trains cross between corridors with incompatible signaling systems. These are further evaluated in the following hazard and fault tree analysis sections.

5.2.1 Signaling System Principles

The signaling systems on the selected railway corridors exhibit broad divergence in their design principles that directly affects interoperability, operating efficiency, and safety performance. The Addis Ababa-Djibouti corridor, operating under CTCS Level 0, relies primarily on trackside signals and fixed block principles, with manual block clearance and no continuous cab signalling. This system is based on extensive driver observation and voice communication, which results in limited automation and low safety margins. In contrast, the Awash-Kombolcha-Haragebeya corridor employs ETCS Level 1, which introduces cab signalling and intermittent Automatic Train Protection (ATP) through balise transmission. While the system enhances safety and operating reliability compared to CTCS-0, its intermittent data updates create gaps in continuous supervision.

The Mombasa-Nairobi corridor utilizes CTCS Level 2, incorporating continuous GSM-R communication, cab signalling, and Radio Block Centre (RBC) control, enabling higher speeds, improved flexibility, and greater safety. The most advanced among the four, the Dar es Salaam-Makutupora corridor operates on ETCS Level 2, featuring continuous, communication-based train control, RBC management, and optional lineside signalling. This configuration delivers the highest safety integrity, operational flexibility, and interoperability potential, especially with other ETCS Level 2 systems in the region. The progressive shift from manual, fixed block operations toward advanced communication-based train control demonstrates a clear technological evolution, but also highlights the challenges of integrating disparate systems within the East African railway network.

Table 5-1: Signaling system principles comparison

Features	**Addis Ababa–Djibouti**	**Awash-Kombolcha-Haragebeya**	**Mombasa–Nairobi**	**Dar es Salaam-Makutupora**
Signaling principles	Trackside signalling with fixed block; manual driver observation; cab signalling	Fixed block with intermittent balise transmission; cab signalling; lineside signals	Moving block principles with continuous GSM-R communication to onboard units; cab signalling	Continuous communication-based signalling via GSM-R and RBC; cab signalling; lineside optional
Train Control Method	Manual block clearance via radio or telephone; driver relies on lineside signals	ATP with intermittent data updates from balises; driver supervision through DMI	Continuous ATP with real-time movement authority updates	Real-time movement authority from RBC; fully computer-based interlocking.
Flexibility	Low, not adaptable to mixed traffic; interoperability requires	Medium, compatible with other ETCS lines	Medium to High	High, fully interoperable with other ETCS systems
Safety	Medium	High, SIL-4 safety integrity	Medium	High, SIL-4 safety integrity
Interoperability Preparedness	Low	High	Medium	Medium-High

5.2.2 Track Detection and Movement Authority

Addis Ababa–Djibouti (CTCS-0**):** relies on track circuits for occupancy detection. In order to send train control information, CTCS levels 0 use track circuits for occupancy detection. An automatic block via a train control centre (TCC) provides movement authority (MA).

Awash–Kombolcha (ETCS-1**):** employs axle counters and Eurobalises for train detection. When a train enters a piece of track, axle counters identify it and notify the interlocking logic. Both for stations and lines, axle counter devices are employed as train detection systems. Wheels (axles) are counted into and out of the "blocks" that make up the right of way.

Mombasa–Nairobi (CTCS-2**):** integrates balises with ZPW-2000 track circuits for more frequent and accurate updates. When the transponder power signal is driven, the track circuit is set up to transmit both the received active transponder message and the fixed transponder message. Location, gradient, and speed limit spot transmissions are provided by balises. Intermittent trackside information and automatic train protection for cab equipment are provided by the Balises and the track circuit.

- Movement Authority: Shifts from trackside signals to cab-based control via the DMI. The system enforces speed profiles and movement authorities automatically, reducing driver workload and human error.

Dar es Salaam-Makutupora (ETCS-2**):** applies axle counter-based train detection integrated with the RBC to issue movement authorities dynamically and continuously, optimizing line capacity and ensuring high safety integrity by eliminating reliance on lineside signals.

- Movement Authority: The operator at OCC sets the route required for a specific train; the route request is sent to the relevant interlocking that processes it according to the status of the trackside equipment. Once the route is locked, the RBC issues a Movement Authority to the train via GSM-R, allowing it to move up to the next virtual signal in Full Supervision mode under the control of the train-borne equipment.

Table 5-2: Train Detection Technique and Train Movement Authority Analysis

Features	**Addis Ababa–Djibouti** (CTCS-0)	**Awash-Kombolcha-Haragebeya** (ETCS-1)	**Mombasa–Nairobi** (CTCS-2)	**Dar es Salaam-Makutupora** (ETCS-2)
Train Detection and positioning	Track circuits	Axle counters, Eurobalises, Euroloop,	Track circuits, Balises, GSM-R for position reporting	Axle counters and Eurobalises
Detection Principle	Electrical circuit completion and Human intervention	Spot detection	Leaky coaxial cable/ Microwave detection, Radio communication	Spot detection
Continuous or Intermittent	Intermittent	Intermittent	Continuous	Continuous
Movement Authority	Fixed block, Manual, visual signal-based	Continuous supervision, Balise-based automatic	Continuous supervision, Radio-based (GSM-R)	Continuous supervision, RBC-based (Euroradio)
Human-Machine Interface (HMI)	Track side signals, Cab signaling	Driver displays, Central control	Speed control display, Cab signaling	Driver displays, Central control

5.2.3 Communication and Data Transmission

Addis Ababa–Djibouti (CTCS-0)**:** trains use traditional trackside/wayside signals for data transfer, with digital signal processing for cab signals and track circuits for fixed block occupation signals. Train drivers basically use trackside signals, and cab signals, which use data from track circuits, serve as a backup.

- GSM-R technology can improve information transfer between trains and roadside equipment. The communication network provides connectivity along the rail line, carrying vital information like command, voice/dispatching, train control, and monitoring information. The radio communication provides communication between trains/drivers in motion and stations in the vicinity for exchange of control information. The GSM-R uses 450 MHZ spectrum. duplex spacing of 450MHz is 10MHz. Uplink and downlink frequency spacing is 450-460 MHz and 460-470 MHz, respectively.

- Voice communication systems, including radios and telephones, are the primary means of contact between train operators and dispatchers. The line uses synchronous digital hierarchy (SDH) technology, with trunk and access layers. The managed service provider access layer transmission system uses SDH 2.5GHz and SDH 622MHz. Fiber optic cable serves as the transmission medium.

Awash–Kombolcha (ETCS-1**):** relies on Eurobalises, trackside transponders, for data transmission. These transponders transmit information about the train's speed and movement authority via a 27MHz electromagnetic field. The balises respond at 4 MHz, with a data rate of approximately 564 kbit/s. To improve operational efficiency, infill systems like Euroloop or radio-based systems can provide continuous or semi-continuous data transmission. The train's on-board unit (OBU) receives and processes the data from the balises, continuously monitoring the train's speed and comparing it to the permitted speed. ETCS Level 1 introduces continuous supervision of train movement by the onboard computer, which calculates braking curves based on the received data.

Mombasa–Nairobi (CTCS-2**):** Data transmission for train control involves both trackside and onboard equipment, using track circuits, balises, and wireless communication (GSM-R) to exchange information like movement authorities, speed restrictions, and route data. CTCS-2 employs a dual communication strategy, using GSM-R for voice communication, redundancy, and intermittent data exchange and the CTCS-3/LCM system for continuous data transmission. Lineside Electronic Units (LEU) and a Train Control Center (TCC) manage and process train movement and safety information. GSM-R provides a reliable, high-bandwidth radio link, while LCM system facilitates continuous data transmission along the railway line.

Dar es Salaam-Makutupora (ETCS-2**):** ETCS-2 utilizes GSM-R for data communication, allowing two-way communication between the trains and the RBC via a radio link. This connection-oriented, wireless system ensures real-time updates and precise control of train movement. Line Side signals are optional, as train’s movement authorities are received directly via the radio link from the RBC. GSM-R backbone is supported by SDH STM-16 infrastructure for low latency and high availability for mission-critical traffic.

- The on-board train computer (EVC), also facilitated by GSM-R, processes this data to manage train movement and ensure safe operation, facilitating continuous supervision of train movements.

Table 5-3: Communication methods and Data transmission Protocol

Features	**Addis Ababa–Djibouti** (CTCS-0)	**Awash-Kombolcha-Haragebeya** (ETCS-1)	**Mombasa–Nairobi** (CTCS-2)	**Dar es Salaam-Makutupora** (ETCS-2)
Primary Communication	GSM-R	GSM-R + Euroradio	CTCS-3/LCM + GSM-R (Ref. from the standard)	GSM-R + Euroradio
Backup Method	-	Radio infill	GSM-R	-
Frequency Band	Trunk layer SDH 2.5GHz and SDH 622MHz access layer	27 MHz	900 MHz (GSM-R), 1.8 GHz to 2.4 GHz (LCX), 5/7 GHz (MW) (Ref. from the standard)	900 MHz
Data Rate	SDH 622Mb/s access layer	564 kbit/s	9.6-64 kbps (GSM-R), 2 Mbps (LCX), 10 Mbps (MW), (Ref. from the standard)	9.6 kbit/s
Data transmission	Voice communication, synchronous digital hierarchy technology (SDH)	Standardized, Eurobalise transmission protocol	Continuous data transmission	Continuous, bi-directional wireless
Protocol type	Proprietary	Standardized	Proprietary & Standardized	Standardized

Transmitted data type	Train position	Movement authority, speed limits, track conditions	Information about the speed limit, the track segment security, line parameters, and train control commands	Track data and Position report
Type of Data Transmission	Semicontinuous	Spot (Semicontinuous), Unidirectional (from track to train)	Bidirectional data transmission	Spot detection

5.2.4 Train Control and Operation

Ethio-Djibouti railway line: relies on conventional trackside signalling. uses conventional trackside signals. The primary signals that train drivers follow are trackside signals, with cab signals serving as a backup. Through the use of digital signal processing, the universal cab signal displays train fixed block occupation signals that are received from track circuits. The purpose of the train operating service unit (Train Operation Supervision, TOSU and Recording Device, LKJ) is to monitor speed limitations; it is only capable of providing train drivers with braking curve advice. The primary responsibility for ensuring train speed protection rests on the drivers.

Awash–Kombolcha (ETCS-1**):** consists of non-continuous communication between the train and the trackside, usually via Eurobalises, and continuous supervision of train movement (i.e., the onboard computer continuously monitors the maximum allowed speed and calculates the braking curve to the location to which the train is permitted to proceed (the end of movement authority) [58].

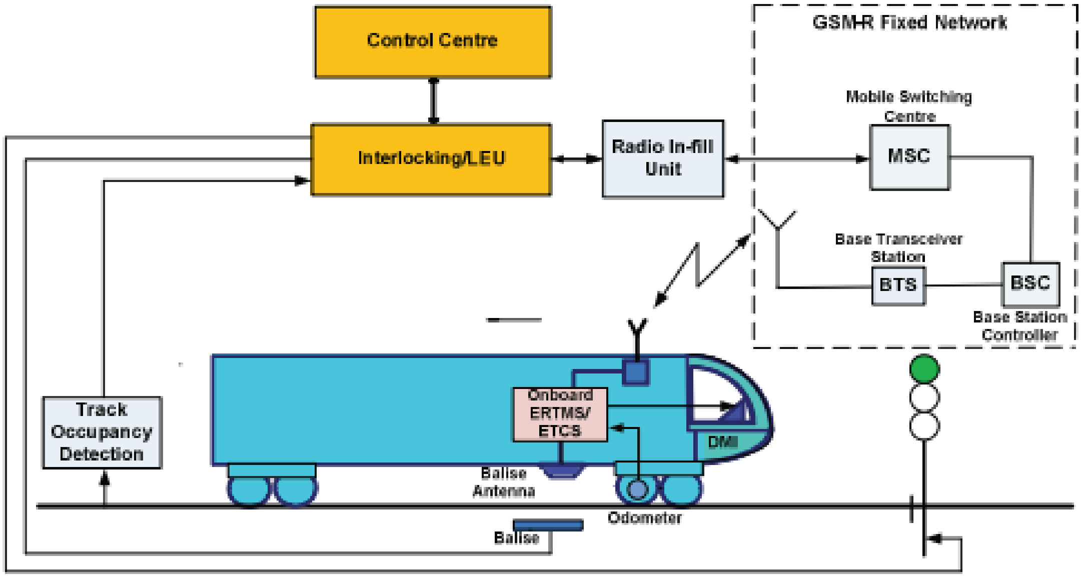

Figure 5-1: ETCS level 1 (with infill balise group) [59]

Mombasa–Nairobi (CTCS-2**):** The onboard equipment includes a station interlocking device and a dispatching centralized system. The server receives a temporary speed limit directive generated by the scheduling system. The station interlocking equipment establishes routes based on track segment security information. A speed sensor, driver machine interface (DMI), Balise transmission module (BTM), and Specific Transmission Module (STM) are also included in the onboard device. Train actual speed and trip distance data are produced by a speed measuring ranging equipment. A human machine interface (DMI) displays the target distance and monitors train operation.

Dar es Salaam-Makutupora (ETCS-2**):** to create movement authorities for various trains in a section based on train location data from the interlocking and track occupancy. The Eurobalise is replaced with the GSM-R, for information transmission to the train. Eurobalises are used to send fixed data, such as the position of the train and the speed limit, and to initialize and recalibrate the onboard odometer. To choose and send a serial message to the GSM-R radio, the RBC programmers integrate variable information from the interlocking with fixed infrastructure information. The train can attain its top speed while keeping a safe braking distance factor because to this constant data stream.

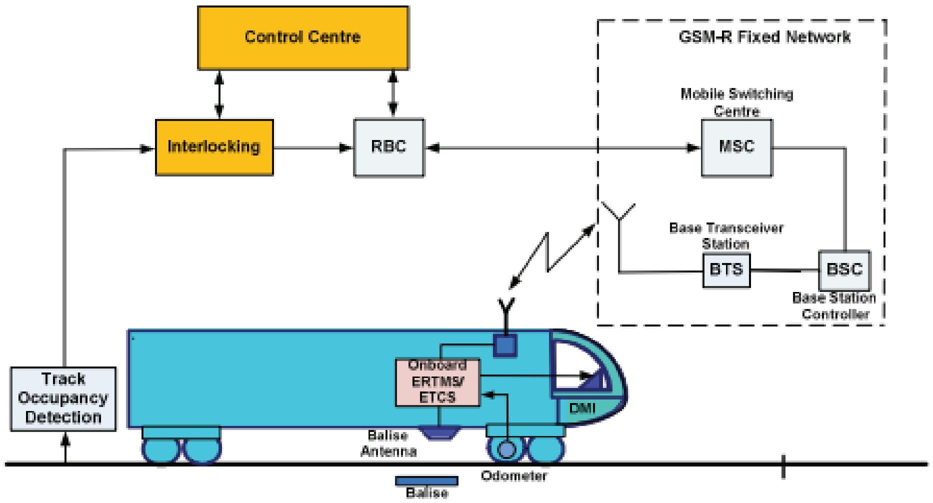

Figure 5-2: ETCS/ERTMS Level 2 [59]

- The train can attain its maximum or ideal speed while still keeping a safe braking distance factor due to a constant stream of data that updates the driver on line-specific information and signals status on the upcoming path. The signalling control and train describer functions can access real-time information about train positions and speeds since GSM-R offers bidirectional (duplex) data transmission.

5.3 Hazard Identification at Transition Points

Hazards were identified and classified by comparing sequential corridors' subsystem features and operation procedures. This type of analysis allows for effective risk reduction and system and procedural upgrade priority setting.

Identification of the hazards in this study was conducted systematically in a way that can expose potential operational and safety risks that might be encountered in changes of railway corridors with different signaling and train control systems. The approach used was the Hazard Log approach and Fault Tree Analysis (FTA) as well, thus conforming to international railway safety risk requirements.

The process began with a comparison of subsystem configurations such as train detection methods, communication systems, interlocking logic, movement authority systems, and onboard equipment for each transition corridor pair. Differences were used to identify functional incompatibilities and potential failure points at each interface. Hazards were then created for each transition on the basis of reported failure cases, expert assumptions, and reasonable operational deviations. Each hazard entry was then classified with:

- A unique hazard ID
- Short description
- Technical or procedural root cause
- Potential operational or safety effects
- Dominant type of safety barrier

This official logging allowed hazards to be ranked according to seriousness and frequency, which formed the foundation of later risk modeling (FTA), statistical barrier comparison, and solution ranking (AHP–TOPSIS).

Transition 1: Addis Ababa–Djibouti to Awash–Kombolcha (CTCS 0 to ETCS 1)

This transition involves a manual-to-automated shift. CTCS Level 0 relies on driver observation and dispatcher instructions. The absence of ATP in CTCS0 makes this transition extremely vulnerable to human error and lack of protection if the driver fails to engage ETCS mode. Most of the failure paths here are due to procedural gaps, equipment incompatibility, and communications loss.

Table 5-4: Hazard Log for Transition 1: Addis Ababa-Djibouti to Awash-Kombolcha-Haragebeya (CTCS Level 0 → ETCS Level 2)

Hazard ID	Description	Cause	Consequence
H1-01	Movement Authority (MA) not issued at system boundary	No ETCS activation; transition from CTCS Level 0 to ETCS Level 1	Train halted or proceeds without valid MA
H1-02	No ATP active in CTCS corridor	ATP only installed on ETCS side	No automatic speed control or braking
H1-03	Communication loss in GSM-R zone	GSM-R dropout, antenna failure, Radio interference /infrastructure	Loss of data link, Delayed MA updates

H1-04	Different train detection logics	CTCS uses track circuit + axle; ETCS uses axle counter only	Conflicting train presence information
H1-05	Eurobalise transmission failure	Balise misalignment /power loss or onboard BTM error	No position update; Incorrect speed limits, MA interruption

Transition 2: Addis Ababa-Djibouti → Mombasa-Nairobi (CTCS 0 → CTCS 2)

Both systems belong to the CTCS family, but the leap from Level 0 (manual) to Level 2 (automated ATP and MA) introduces a technology and responsibility gap. While not as risky as Transition 1, this scenario still hinges on driver actions and dispatcher coordination. Major threats come from incomplete handovers, lack of real-time supervision, and delayed driver input.

This warrants the priority technical upgrade, procedural training, or policy harmonization to enable safe and interoperable operations on East African rail corridors.

Table 5-5: Hazard Log for Transition 2: Addis Ababa-Djibouti to Mombasa-Nairobi (CTCS Level 0 → CTCS Level 2)

Hazard ID	Hazard Description	Cause	Consequence
H2-01	MA conflict during handover	Manual MA vs. radio-based MA mismatch	Train proceeds without valid authority
H2-02	STM module failure (legacy compatibility)	Software incompatibility	Loss of track circuit data interpretation
H2-03	Onboard DMI misalignment	Inconsistent cab signal adoption	Conflicting speed commands
H2-04	GSM-R latency in TCC communication	Network congestion	Communication gap or delay speed restrictions
H2-05	ATP override at transition	Driver fails to engage CTCS2 ATP	No braking supervision

Transition 3: Mombasa-Nairobi → Dar es Salaam Makutupora (CTCS 2 → ETCS 2)

Despite both systems being highly automated with ATP, their differing origins (Chinese vs. European) introduce software-level incompatibilities, particularly in how MA is formatted, interpreted, and enforced. Hazards here are mostly technical rather than procedural, requiring middleware, protocol converters, or hybrid onboard units. The risks are less visible but harder to detect, making this transition the most software-critical.

Table 5-6: Hazard Log – Transition 3: Mombasa–Nairobi to Dar es Salaam–Kigoma (CTCS Level 2 → ETCS Level 2)

Hazard ID	Hazard Description	Cause	Consequence
H3-01	Protocol mismatch	Chinese CTCS vs. European ETCS encoding	MA cannot be interpreted
H3-02	ATP failure in transition zone	Balise unreadable or out of sync	Train loses position tracking
H3-03	Driver confusion during auto mode-switch	Different UI, lack of harmonized training	Late or failed response
H3-04	GSM-R packet collision or delay	Uncoordinated RBC handover	MA delay or data loss
H3-05	Control center coordination failure	Different interlocking protocols	Unsynchronized route release

The above hazard log identifies and classifies risks related to the lack of interoperability across selected corridors. Each hazard is tied to specific infrastructure or procedural mismatches, with mitigation measures linked to the type of safety barrier. This supports the prioritization of technical upgrades, procedural training, or policy harmonization to enable safe and interoperable operations across East African rail corridors.

5.4 Fault Tree Analysis

Separate FTAs were developed for high-risk interface points, including: Addis Ababa–Awash, Addis

Ababa- Nairobi, and Mombasa- Dar es Salaam. To demonstrate system behavior under a high-risk condition and to compare how CTCS Level 0 and ETCS Level 1 respond to identical dangers, a scenario-based evaluation was introduced.

Top Event for FTA

To analyze the underlying causes of major hazards at corridor transition points, a scenario-based Fault Tree Analysis (FTA) was conducted for each transition. The FTA approach visually maps the sequence of faults that may lead to an undesirable top-level event.

For each transition, A top-level fault event was defined as: "Train collision or unsafe movement due to train control and signaling systems at transition failure."

Scenario Definition: This failure could result in unsafe train movement, unexpected stops, or loss of train control. The FTAs provide a structured diagnosis of system incompatibilities and help identify critical points where safety barriers must intervene. This scenario simulates the most severe outcome caused by signaling failure, human error, or loss of Movement Authority.

This scenario is triggered during or near the transitions, particularly where Movement Authority (MA) must be handed over or re-calculated.

The scenario was selected because:

- It reflects a critical interoperability hazard with high potential impact.
- It highlights differences in how the two systems handle MA and emergency response.
- Similar scenarios have occurred during real-world ETCS test phases in Europe.

Separate FTAs were developed for key transition points including Addis Ababa–Awash, Djibouti - Nairobi and Nairobi - Dar es Salaam. Each FTA diagram breaks down the top event (collision) into basic failure causes via logical gates (OR/AND), allowing identification of root vulnerabilities and failure combinations unique to each corridor interface.

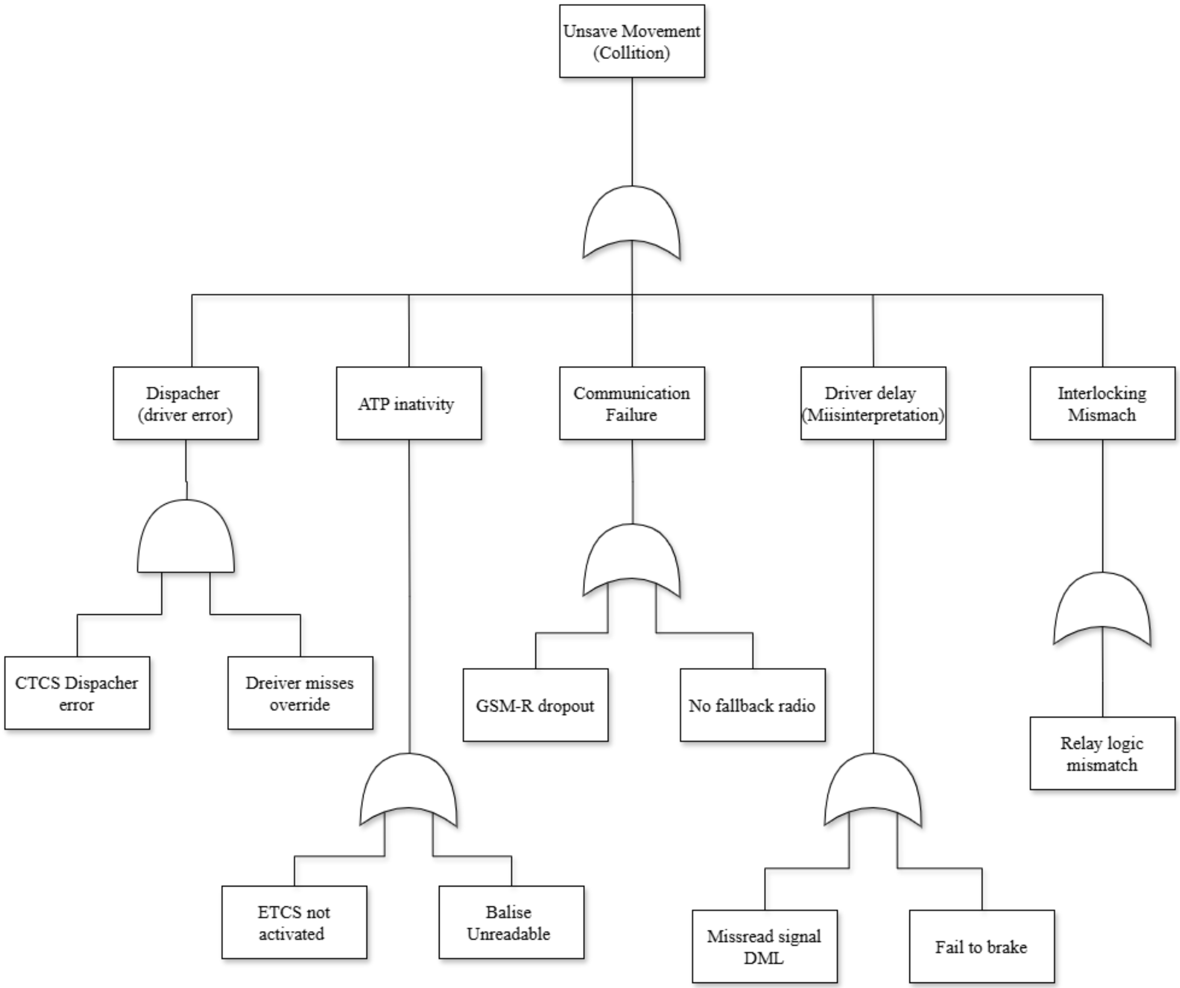

Figure 5-3: Fault Tree Analysis for Addis Ababa-Djibouti to Awash-Kombolcha-Haragebeya

This fault tree models the top event of a collision caused by failure to issue or interpret Movement Authority (MA) during transition from the manual CTCS Level 0 system to the semi-automated ETCS Level 1 system. Contributing factors include driver inaction, absence of ATP in CTCS-0, train detection mismatch, and interlocking incompatibility.

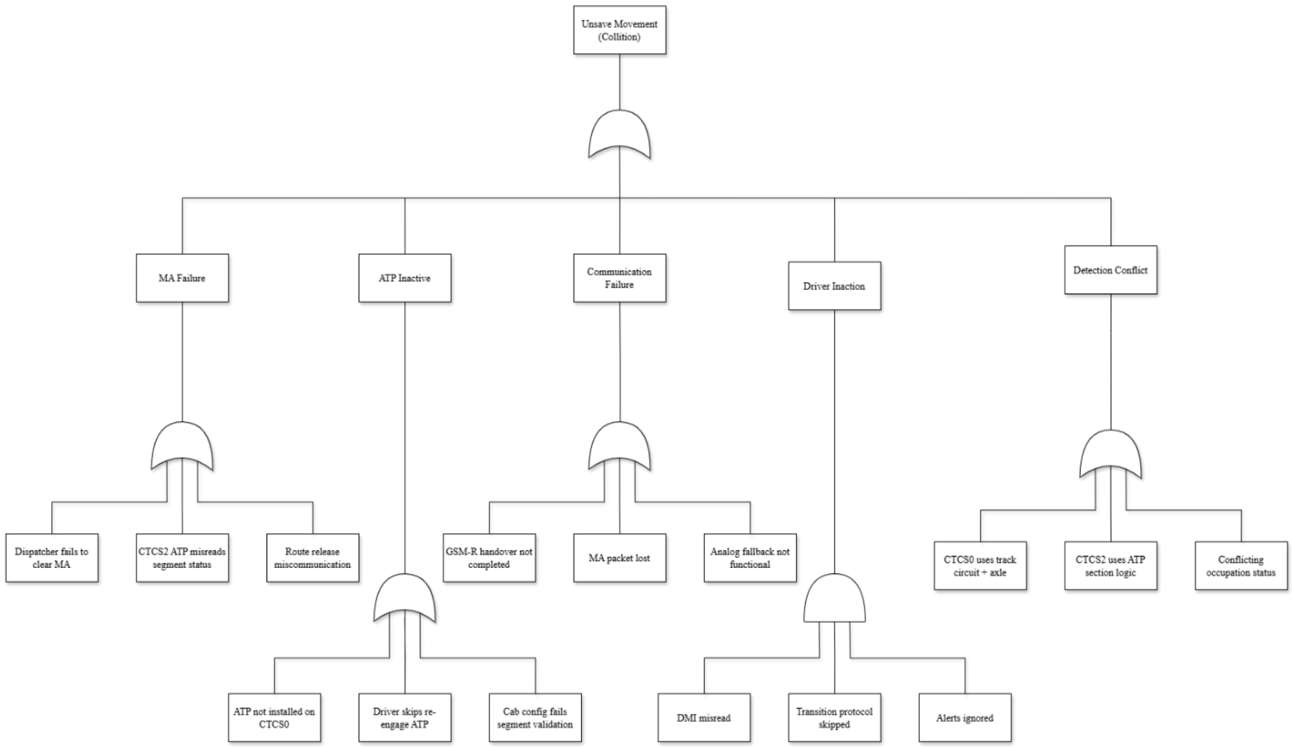

Figure 5-4: Fault Tree Analysis for Addis Ababa-Djibouti to Mombasa-Nairobi

This fault tree illustrates how procedural gaps, dispatcher errors, and ATP override during the shift from CTCS Level 0 to Level 2 can lead to a safety-critical event. The tree highlights failure paths rooted in manual MA conflict, GSM-R dropout, and driver failure to switch modes.

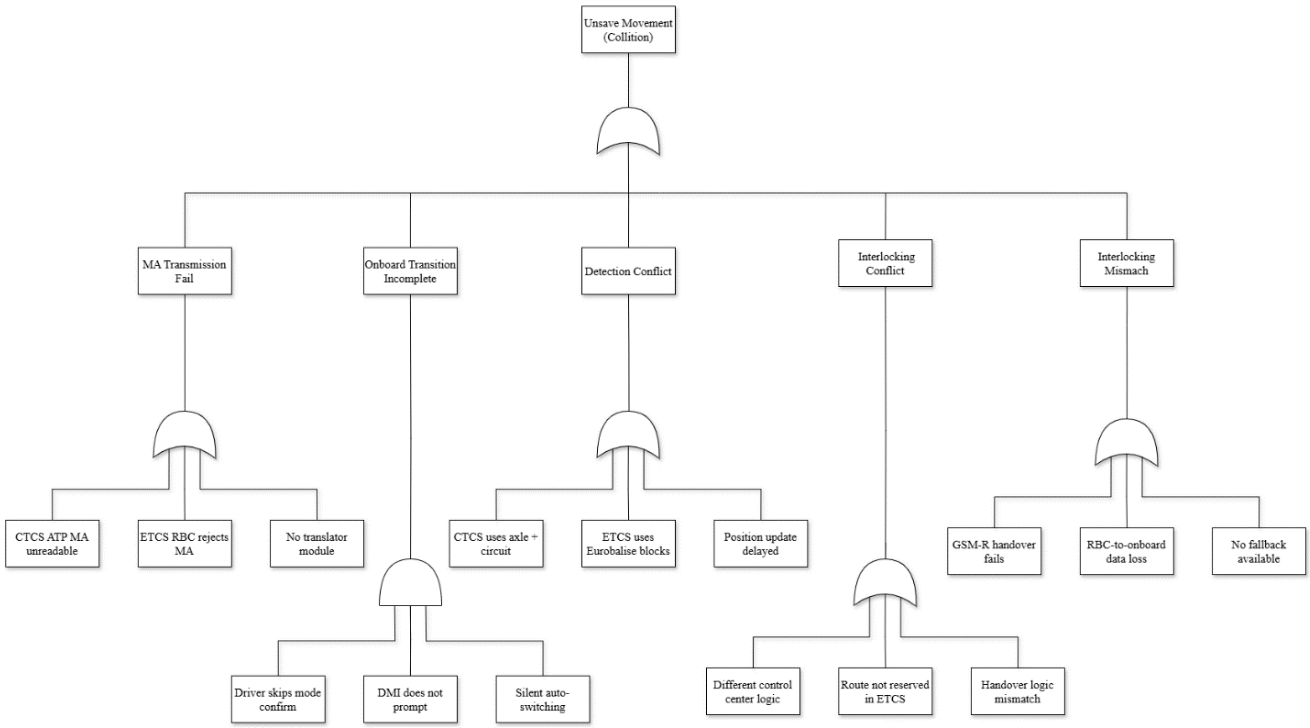

Figure 5-5: Fault Tree Analysis for Mombasa-Nairobi to Dar es Salaam-Makutupora

This diagram evaluates the software and protocol-related hazards that may result in loss of MA or incorrect train positioning when transitioning from Chinese CTCS Level 2 to European ETCS Level 2. Key branches include onboard decoding failure, communication loss between RBC and ATP, and lack of a middleware interface.

5.5 Combined Hazard Risk Score Heatmap

To evaluate and compare the safety-critical hazards of each of the three signaling system modifications, a combined hazard risk score heatmap was developed. Every hazard that was identified was assigned a Risk Score, the result of its consequence severity and likelihood of occurrence. This numerical score is an estimation for the relative criticality of each hazard. These ratings are represented on a heatmap by the transitions CTCS Level 0 to ETCS Level 1, CTCS Level 0 to CTCS Level 2, and CTCS Level 2 to ETCS Level 2. The x-axis of the heat map represents each transition interface, and the y-axis shows the IDs of hazards. The intensity of color reflects the size of the risk, where darker values corresponding to higher scores for risk. This graphic enables immediate comparison of high-risk cells and determination of priorities for mitigation. Special interest, the risks Movement Authority failure (H1-01) and Protocol mismatch (H3-01) emerged as highest-ranked risks due to their high probability and impact, calling for priority attention in any future cross-system integration planning. Each cell is a Risk Score for a given hazard in a specific transition, equal to a Consequence Severity × Likelihood. Darker cells indicate higher risk exposure. The heatmap highlights the most critical hazards such as H1-01 requiring urgent mitigation during signaling system transitions in East African railway corridors.

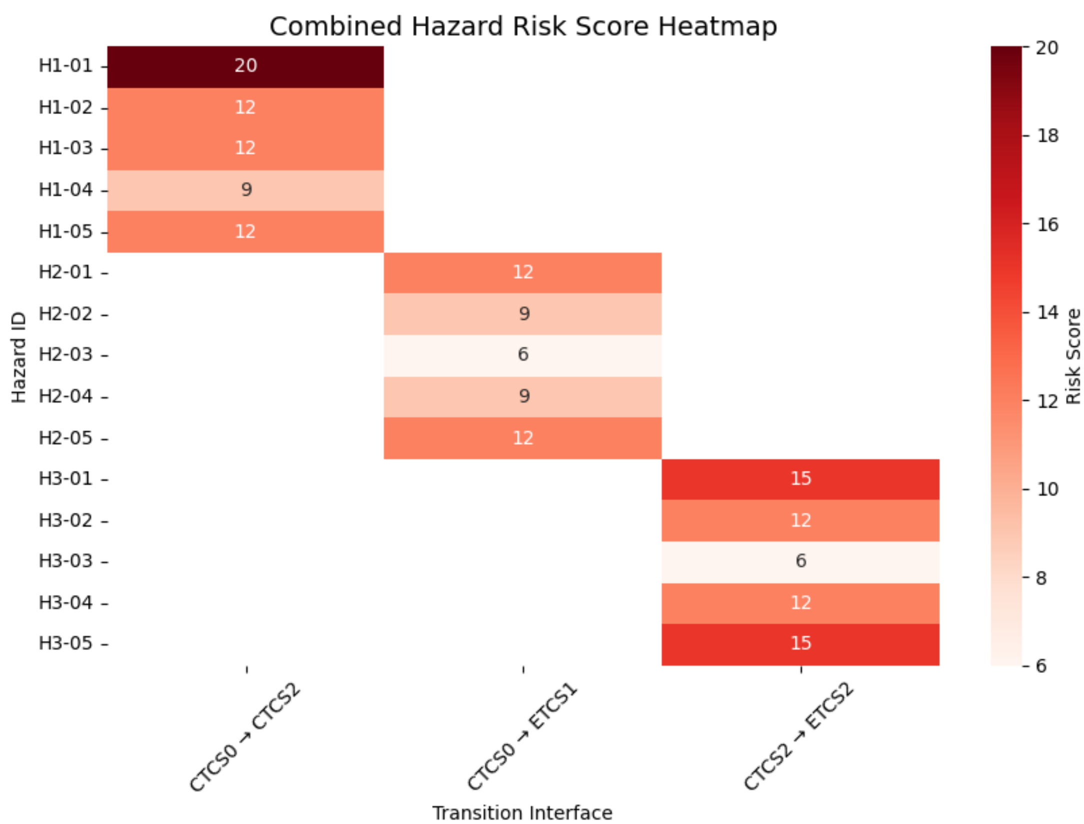

Figure 5-6: Combined hazard risk score heatmap for all three transitions

- Transition 1:

This transition between the Addis Ababa-Djibouti corridor and the Awash-Kombolcha-Haragebeya corridor exhibits the highest overall risk, particularly due to fundamental differences in system architecture:

- H1-01 (Risk Score: 20) represents the most critical hazard: failure to issue Movement Authority (MA) at the system boundary, stemming from lack of ETCS activation.

- Other hazards such as ATP inactivity(H1-02), communication loss in GSM-R zone (H1-03) and balise misalignment (H1-05) further highlight the technical gap between the manual CTCS Level 0 and the ETCS Level 1 systems.
- This transition suffers from both technical incompatibility and lack of fallback procedures, indicating a significant interoperability challenge.

- Transition 2:

Connecting Addis Ababa-Djibouti to Mombasa-Nairobi, this transition shows moderate hazard levels, primarily associated with human factors and signaling logic mismatches:

- H2-01 (Score: 12) reflects the risk of conflicting MA handovers, due to mixed manual and radio-based control.
- Failure to engage ATP (H2-05) indicate human-dependency risks in transition zones.

Although both systems follow CTCS architecture, the evolution from Level 0 to Level 2 introduces complexity in driver-machine interfaces and communication protocols, explaining the observed risk scores.

- Transition 3:

The transition from Mombasa-Nairobi to Dar es Salaam-Makutupora shows more balanced and manageable risks:

- H3-01 and H3-05 (Scores: 15) represent the highest risks related to protocol mismatch and control center coordination.
- Hazards like GSM-R delay and mode-switch confusion are present but scored lower (6–12), suggesting manageable technical interventions.

This transition benefits from architectural similarity (both systems use ATP, GSM-R, and digital block control), leading to lower average risk severity compared to Transition 1 and Transition 2. The heatmap confirms that Transition 1 is the most critical in terms of interoperability risks, followed by Transition 2, while Transition 3 is relatively safer.

CHAPTER SIX

6. RESULT AND DISCUSSION

This chapter interprets and discusses the results of the technical and scenario-based analyses presented in Chapter 4. It focuses on understanding how system incompatibilities, hazard patterns, and transition fault paths affect the overall interoperability of East African railway corridors. The chapter also draws strategic insights from fault tree analyses, hazard rankings, and compatibility scores to support decision-making.

6.1 Interoperability Score of Selected EARN Lines

The interoperability between the selected corridors was quantified using the Jaccard Similarity Index, which compares shared technical parameters relative to the total parameters considered between two corridors. Figure *6-1* illustrates the interoperability matrix between the four railway lines based on the Jaccard similarity index, which measures the extent of shared technical parameters between any two networks.

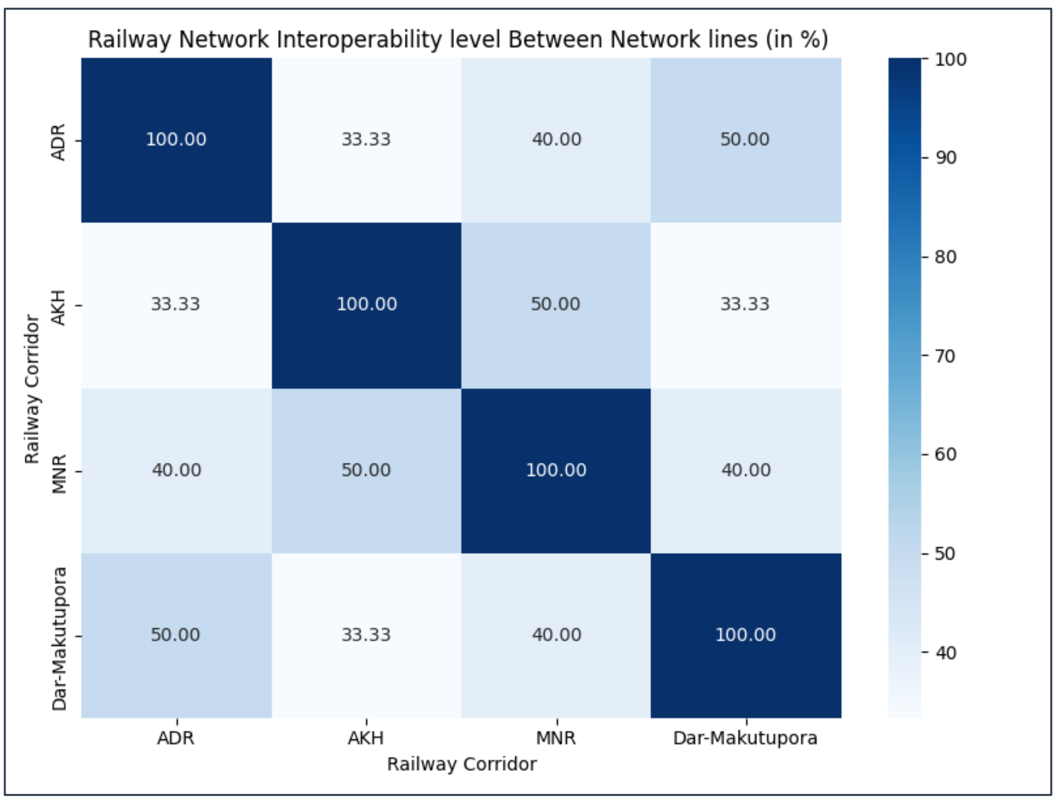

Figure 6-1: Interoperability score matrix

- The lowest score (33.33%) is observed between Addis Ababa-Djibouti and Awash-Weldiya-Haragebeya, showing significant technical incompatibilities in signaling and control subsystems.
- Mombasa-Nairobi shows moderate compatibility (40–50%) with other corridors, suggesting partial standard alignment, especially in interlocking and communication interfaces.

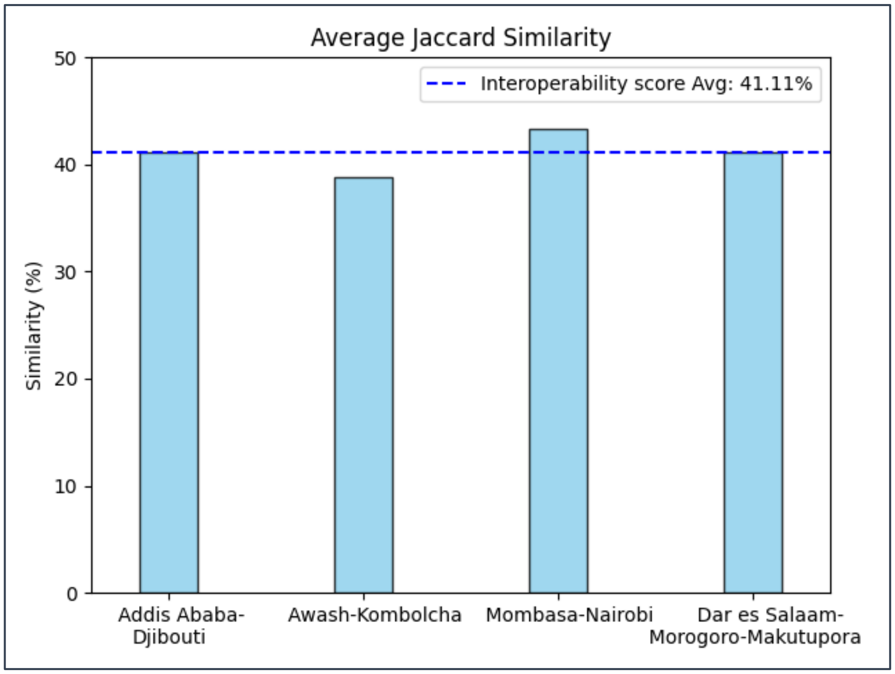

Figure 6-2: Average interoperability score

The average interoperability score among the four networks, as visualized in Figure *6-2*, is 41.11%, based on Jaccard similarity coefficients. This moderate value reveals a partial level of alignment among railway networks in East Africa, but also emphasizes the lack of harmonized signaling and control system architectures across borders. While some of these pairings (e.g., Awash-Weldiya-Haragebeya and Dar es Salaam-Makutupora and Mombasa-Nairobi and Awash-Weldiya-Haragebeya) are relatively more congruent, others are evidently fragmented, creating operational and technical challenges for cross-corridor consolidation.

This score is reflecting the reality that the majority of the rail networks in the region were constructed independently, with suppliers, standards, and technologies often decided by numerous international partners. Therefore, interoperability in the region is unimaginable except through deliberate efforts at harmonization, especially where signaling protocols, detection systems, and communications platforms are concerned.

6.2 Transition Compatibility Ranking

This section evaluates the degree of technical and operational interoperability across the three defined transitions using a technical compatibility scoring framework. It encompasses past hazard logs, fault tree analysis results, and the Jaccard index to rank the ease or difficulty of shifting from one signaling system to another. Compatibility was assessed using a combination of technical feature matching (e.g., ATP, train detection, interlocking), communication protocol alignment, hazard frequency, and barrier severity scores derived from earlier sections.

Based on the given feature sets, the pairwise Jaccard Similarity (Compatibility Score) values are:

Table 6-1: Pairwise Jaccard similarity values

Transition	Jaccard Similarity (Compatibility Score)
Addis Ababa-Djibouti → Awash-Kombolcha-Haragebeya	0.33
Addis Ababa-Djibouti → Mombasa-Nairobi	0.4
Mombasa-Nairobi → Dar es Salaam-Makutupora	0.5

- The transition from Mombasa-Nairobi to Dar es Salaam-Makutupora (CTCS Level 2 to ETCS Level 2) representing some similar conformity in modern system design, protocol modularity, and onboard automation.
- The transition Addis Ababa-Djibouti → Mombasa-Nairobi (CTCS Level 0 to CTCS Level 2) was moderately compatible by virtue of common signaling but nevertheless limited by communication and interlocking mismatches.
- The least compatible transition was Addis Ababa-Djibouti → Awash-Kombolcha-Haragebeya (CTCS Level 0 to ETCS Level 1), primarily due to the absence of ATP, extreme reliance on manual MA logic, and deep-seated architectural discrepancies in detection and control logic. Priority is determined based on these rankings where East African rail interoperability needs technical enhancements, harmonized protocol, or fallback configurations most urgently.

Notably, even within Ethiopia, EDR and AKH exhibit low compatibility (33.33%), revealing the lack of standardization across national infrastructure. These results highlight an overall fragmented interoperability landscape, where no corridor pair exceeds 50% compatibility, limiting seamless regional rail operations. The CTCS 2 → ETCS 2 transition has the highest compatibility but faces issues with protocol alignment and onboard data interpretation. The CTCS 0 → CTCS 2 transition follows, both systems share similar Chinese technology origins and use GSM-R communication. CTCS 0 → ETCS 1 is the least compatible due to the fundamental differences between manual operations in CTCS Level 0 and the digital automation in ETCS Level 1.

6.3 Impact of Hazard Identification and FTA

The structured hazard logs and FTAs offered clear visibility into the specific technical subsystems that fail during transitions.

- In the EDR → AKH transition (CTCS0 → ETCS1) the absence of ATP and reliance on visual signal interpretation created critical safety risks. This transition showed that failure to switch modes and lack of balise recognition led to unissued MA and potential collisions.
- In the EDR→ MNR transition (CTCS0 → CTCS2) emphases ATP override and dispatcher miscommunication as high-risk failure paths.
- In the MNR → DRM-Makutupora transition (CTCS2 → ETCS2) most hazards were mitigated by shared protocol converters, although GSM-R collision risks remained. FTA for CTCS2 → ETCS2 illustrated protocol mismatches and RBC-to-ATP incompatibility as dominant hazards.

6.4 Summary of Observed Interoperability Challenges

The hazard logs and fault trees reveal the cascading failures that can result from interoperability gaps at system transition points. Transition 1 poses high safety risks due to lack of ATP and automated MA. Transition 2 is procedurally vulnerable, especially in dispatcher handovers. Transition 3 has deeper protocol-level barriers requiring middleware or translator modules. These models support risk prioritization and mitigation in subsequent analysis.

- Addis Ababa–Djibouti shows missing or weak alignment in many modern control features, such as BTM, Signaling Level, and Interlocking System. Requires major upgrades to align with modern interoperability standards.

- Awash–Kombolcha appears more aligned with modern systems, showing higher correlation across critical fields thus presenting fewer barriers to integration. Highly interoperable with modern systems like ETCS Level 1/2.
- Mombasa–Nairobi has reasonable alignment in data and detection systems, but diverges in standardization, notably Balise, Radio Block systems, and inconsistent communication protocols.
- Dar es Salaam-Makutupora has the most inconsistent profile, with negative or low correlations in communication and human-machine interface systems this corridor poses the greatest interoperability challenge. Missing protocol converters for interoperability with CTCS corridors.

Correlation analysis reveals significant technical interoperability gaps among the railway corridors under investigation. None of the pairs of corridors are entirely interoperable, as they possess a certain degree of technical incompatibility. Among the noted pairs, it is identified that the Dar es Salaam-Makutupora corridor is the least compatible and exhibits numerous key critical mismatches between critical signaling and control parameters. Such differences throw light on the demands for standard harmonization especially in signal equipment, communication interfaces, and onboard control technologies with a view to diminishing technical barriers. In an effort to increase cross-border railway traffic, interoperability activities in future action will focus on aligning standards in the railway system, equipment specifications, and communication standards along the East African railway corridor.

6.5 Interoperability Solutions and Evaluation

In this chapter the interoperability barriers are identified and strategic solutions proposed to address those barriers also identified in the preceding chapters Based on the hazard logs, fault tree analysis, and transition rankings, this chapter formulates targeted interventions in technical, operational, and regulatory realms. It also employs a Multi-Criteria Decision-Making (MCDM) using the Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to rank and compare the proposed solutions.

6.5.1 Identification of Key Interoperability Barriers

A Spearman rank-order correlation test was conducted in an attempt to determine specific areas that can be specifically tackled to enhance the overall interoperability of the railways on four railway lines: Addis Ababa-Djibouti, Awash-Kombolcha, Mombasa-Nairobi, and Dar es Salaam-Kigoma. The analysis was used to ascertain what parameter is most directly associated with interoperability performance. The Spearman correlation coefficients (ρ) for the various parameters are presented in Figure *6-3*. The coefficients indicate the strength and direction of the monotonic relationship between every parameter and the interoperability.

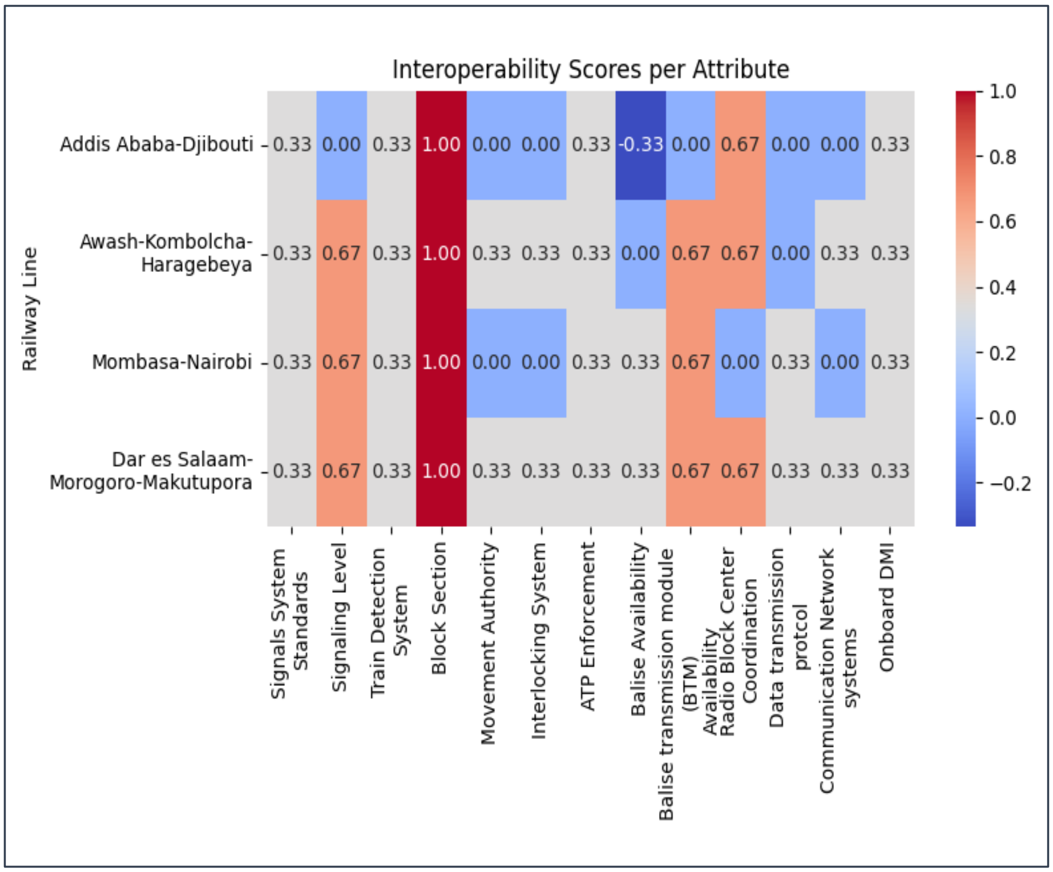

Figure 6-3: Correlation Coefficients Signaling Train Control Parameters

Main Findings on Technical Barriers

- The Signaling System Standard shows very low correlation (0.0–0.333), meaning there is no uniform standard across the networks. This is a major interoperability barrier, as signaling standards dictate compatibility of both onboard and trackside systems.

- Signaling Level, BTM Availability, Radio Block Center Coordination, and Balise Availability show clear variability. These are critical factors in determining compatibility and performance differences between systems.
- Parameters like Movement Authority, Interlocking System, Data Transmission Protocol, and Communication Network Systems have low or mixed values, indicating partial implementations or missing functionalities in some scenarios. This may contribute to reduced interoperability or increased complexity during transitions.
- Block Section have a correlation coefficient of 1.0 across all corridors. This indicates that are not significant technical barriers.

6.5.2 Multi-Criteria Decision Analysis for Interoperability Solutions

To address the identified interoperability challenges in the East African railway network, a two-step multi-criteria decision-making approach was implemented using the Analytical Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). This ensured a rational, data-driven evaluation of proposed technical solutions based on multiple critical performance factors.

6.5.2.1 Proposed Interoperability Solutions

Once technical barriers are identified using Spearman correlation analysis and the hazard logs and fault trees analysis, the next step is to address the interoperability challenges identified in East Africa's railway network. Practical technical solutions must be developed based on hypothesis-driven analysis and real-world case studies. This section outlines significant technical interventions applied to enhance system compatibility, safety, and operation efficiency. The following solutions are derived from the most recurrent failure modes and transition incompatibilities:

Table 6-2: Proposed interoperability solutions

	Solutions	Description
S1	Deploy ETCS-compatible equipment across all networks to unify signaling protocols	Reduces risk in CTCS L0 → CTCS L2/ETCS L1 transitions

S2	Development of a common rail control center	Handles Human Error (Driver Error) and authorization
S3	Standardization of signaling and train control systems	Harmonization of operational rules and bridges organizational gaps at border points
S4	Install Protocol Conversion Middleware	Ensures MA transmission between CTCS and ETCS systems
S5	Introduce Redundant GSM-R or fallback radio	Resolves MA data loss across communication zones

6.5.2.2 Criteria for Evaluation

Each solution is evaluated using eight critical decision criteria (C1–C8), encompassing safety, technical compatibility, operational efficiency, cost-effectiveness, reliability, accessibility, health impact, Cross-Border Applicability, and environmental protection. This multi-criteria evaluation ensures recommendations are robust, appropriate to the situation, and aligned with regional railway integration strategic goals. The evaluation of each proposed solution is based on eight critical criteria.

Table 6-3: Eight Critical Evaluation criteria's

No.	Criteria	Description
C1	Safety	The extent to which the solution enhances operational safety.
C2	Technical Compatibility	The ability of the solution to integrate with existing systems and to mitigates or eliminates identified hazards and failure modes.
C3	Operational Efficiency	The impact of the solution on train operations and human performance.
C4	Cost-effectiveness	The balance between implementation costs and benefits.
C5	Reliability and Availability	Ensuring continuous and fail-safe operations.
C6	Cross-Border Applicability	The ability of the solution to be applied across multiple national corridors and signaling system combinations.
C7	Healthy	The effect on workforce and public health.

C8	Environmental Protection	The sustainability of the solution.

6.5.2.3 Analytical Hierarchy Process (AHP)

The AHP method was used to derive the relative importance (weights) of each decision criterion based on expert judgment or pairwise comparisons. Figure 6-4 indicate that Safety (weight = 0.317) is the most important criterion, followed by Technical Compatibility and Operational Efficiency. Other relevant factors include Cost-effectiveness, Reliability & Availability, Cross-border Applicability, Health, and Environmental Protection.

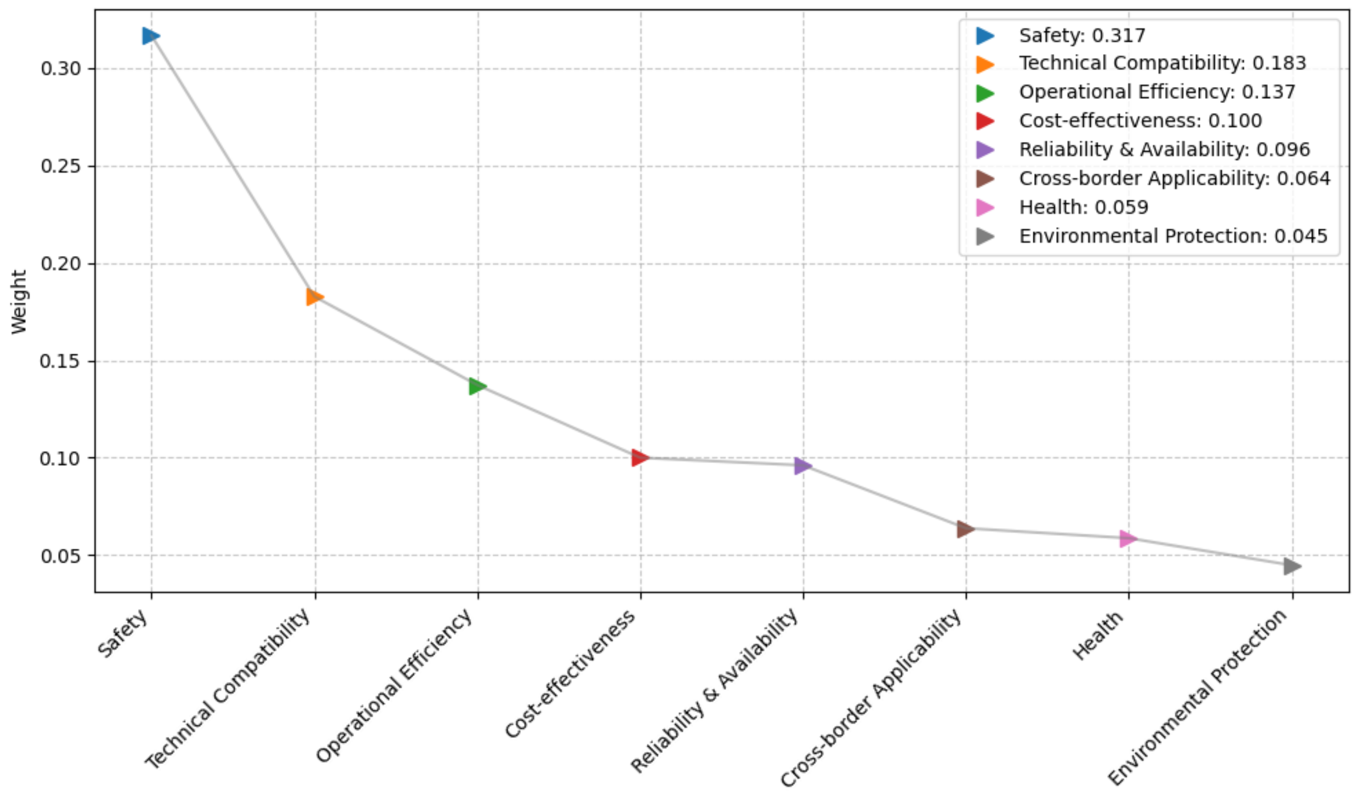

Figure 6-4: Weight of Criteria's

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}} = \frac{0.0789}{1.41} = 0.0560$$

To ensure the logical consistency of the pairwise comparisons, the Consistency Index (CI) was calculated to be 0.0789. Since the CR is less than 0.10, the judgments are considered consistent.

6.5.2.4 Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

Based on the AHP-derived weights, the TOPSIS method was applied to rank five proposed technical solutions according to their closeness to an ideal solution. The final scores, known as the Relative Closeness to Ideal Solution, are as follows:

Table 6-4: Relative Closeness to Ideal Solution

Rank	Solution	Relative Closeness(C)
1	Standardization of signaling and train control systems	0.824336
2	Deploy ETCS-compatible equipment	0. 604378
3	Development of a common rail control center	0.400616
4	Install Protocol Conversion Middleware	0.341335
5	Introduce Redundant GSM-R or fallback radio	0.138905

A higher closeness value indicates that a solution is more desirable when all decision criteria are considered collectively. The results of this analysis are presented below:

Ranking of Solutions using TOPSIS

TOPSIS highlight the most effective strategies for improving interoperability across East Africa's railway corridors. as visualized in Figure 6-5, standardization of signaling and train control systems is the most preferred solution, with a relative closeness score of 35.7%. This indicates strong alignment with critical evaluation criteria, particularly in ensuring safety, technical compatibility, and system-wide coherence. Standardization is essential to eliminate disparities in protocols and equipment that currently hinder seamless cross-border railway operations.

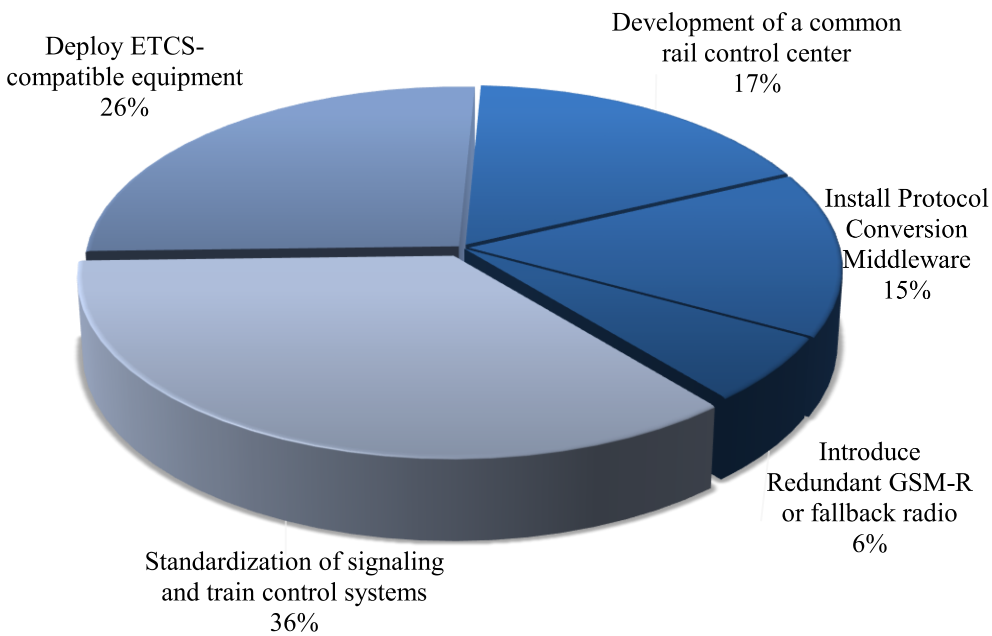

Figure 6-5: Technical solution rank

The deployment of ETCS-compatible equipment ranks second with 26.2%, reflecting its role in promoting uniformity through the adoption of internationally recognized standards. ETCS compatibility supports interoperability by enabling trains and infrastructure to communicate effectively, regardless of national boundaries.

The third most favored option is the development of a common rail control center, which accounts for 17.3% of the solution preference. This approach facilitates centralized coordination and real-time management of train operations in various corridors, thus enhancing operational efficiency and responsiveness. Collectively, these top three solutions comprise nearly 80% of the total relative closeness scores, underscoring their strategic importance. The ranking emphasizes that harmonization of standards, upgrading of equipment, and centralized operation coordination are essential pillars for addressing interoperability problems in the East African railway network.

The integrated AHP-TOPSIS approach demonstrates that addressing technical fragmentation through standardization is the top priority for achieving railway network interoperability. The prioritization aligns with earlier correlation findings, where key compatibility issues in signaling systems and communication interfaces were identified as dominant barriers. This ranking can guide policymakers and infrastructure developers to allocate resources and investments in the most impactful way.

6.6 Validation of Results: Sensitivity Analysis

Sensitivity analysis was carried out to test the stability and robustness of the TOPSIS-based ranking of interoperability solutions with various criterion weights. The weights of each criterion were manipulated desperately by ±10% and ±20%, and the changes induced in TOPSIS scores were monitored. The objective was to see how these perturbations affect the ranking and score of every alternative solution.

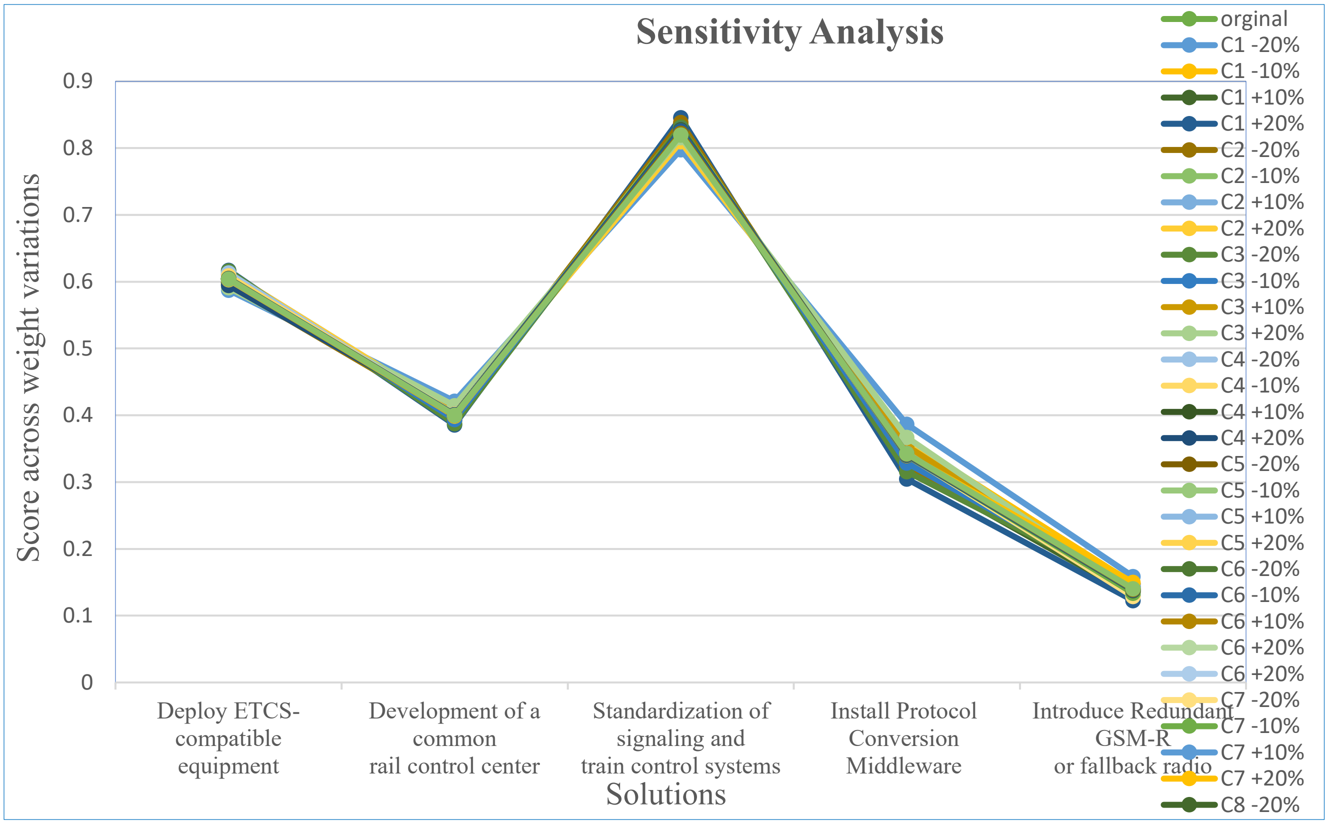

Figure 6-6: Sensitivity analysis solutions for variation of weights criteria's

The above graph (Figure 6-6) shows the fluctuation in the score of a solution due to weight changes in a specific criterion. The X-axis shows the five alternative solutions, and the Y-axis displays the corresponding TOPSIS scores under all variations, including the base case.

- Standardization of signaling and train control systems consistently maintained the highest TOPSIS score across all variations, indicating its robustness and stability as the top-ranked solution.

- Deploy ETCS-compatible equipment exhibited the lowest sensitivity in terms of score fluctuation, but its rank remained lower across all scenarios, suggesting that its evaluation is less influenced by weight changes.
- Development of a common rail control center had moderate variability, indicating relatively stable but somewhat weight-sensitive positions.
- Install Protocol Conversion Middleware and Introduce Redundant GSM-R or fallback radio showed high sensitivity, with noticeable fluctuations in its score. This implies that its performance and suitability as a solution are strongly dependent on the weights assigned to specific criteria like technical compatibility and cost-effectiveness.

Table 6-5: Summary of Result for the weight of criteria with ±10% and ±20%

Solution	Average Score	Score Range	Sensitivity Level	Remark
Standardization of signaling and train control systems	0.824	0.797 – 0.845	Low	Consistently top performer, stable
Deploy ETCS-compatible equipment	0.604	0.587 – 0.617	Low	Stable but slight variation with weight change
Development of a common rail control center	0.401	0.385– 0.421	Medium	Minor fluctuations, relatively stable
Install Protocol Conversion Middleware	0.342	0.304 – 0.386	High	Highest fluctuation, least robust
Introduce Redundant GSM-R or fallback radio	0.14	0.122 – 0.158	High	Sensitive to changes, low ranking

The sensitivity analysis validates that the initial TOPSIS results are robust and stable, especially for the top-ranked solution. While some alternatives show moderate to high sensitivity to criteria weighting, the overall ranking does not drastically change. This confirms the soundness and reliability of the decision model and supports the recommendation to prioritize "Standardization of signaling and train control systems" for improving interoperability in the East African railway network.

CHAPTER SEVEN

7. CONCLUSION AND RECOMMENDATION

This research examined the interoperability challenges of signaling and train control systems across key East African railway corridors, focusing on transitions between CTCS and ETCS levels. Through comparative system definitions, hazard identification, fault tree analysis, and multi-criteria decision-making, the study covered gaps at transition interfaces that hinder seamless operations.

7.1 Conclusion

Interoperability between systems and specially rail systems allow an evolution of infrastructure and facilitate mobility. The study analyzed the interoperability challenges of signaling and train control systems across key East African railway corridors, focusing on three critical transition scenarios:

1. Addis Ababa–Djibouti to Awash–Kombolcha Haragebeya (CTCS Level 0 → ETCS Level1)
2. Addis Ababa–Djibouti to Mombasa–Nairobi (CTCS Level 0 → CTCS Level 2)
3. Mombasa–Nairobi to Dar es Salaam-Makutupora (CTCS Level 2 → ETCS Level 2)

The Jaccard similarity result confirmed a generally low level of interoperability, with a 41.11% average similarity rate, indicating fragmented and non-standardized systems between corridor pairs. Further investigation using correlation coefficients helped in establishing specific technical barriers, and it identified differences in signaling system standards, balise types, onboard equipment availability, and communication protocols. Dar es Salaam-Makutupora was found to be the highly interoperable with other ETCS systems, and it pointed out that the other corridor needs urgent technical harmonization for interoperability.

Through a combination of hazard logging, Fault Tree Analysis (FTA), and transition compatibility scoring, the research identified systemic mismatches in communication protocols, ATP availability, movement authority logic, and train detection subsystems. The analysis revealed that:

- CTCS Level 0 corridors (e.g., Addis Ababa–Djibouti) lack upgrade trackside equipment, onboard automation, and high reliance on manual operation which makes integration with ETCS1 and CTCS2 systems highly vulnerable.
- GSM-R handover problems, interlocking incompatibilities, and manual MA overrides were recurrent fault sources.

- Corridors with ETCS Level 1 and Level 2 demonstrates better compatibility, supported by shared features like onboard ATP, balise-based detection, and GSM-R radio systems.

To address such issues, an AHP-TOPSIS-based multi-criteria decision-making method was used. The AHP process determined Safety (0.317) and Technical Compatibility (0.183) as the most significant criteria. TOPSIS analysis, based on these weights, determined "Standardization of signaling and train control systems" as the most suitable solution, followed by equipping with ETCS-compatible equipment and establishing a common rail control center. Finally, the sensitivity analysis confirmed the stability of the top-ranked solution under alternative weight scenarios, re-establishing standardization as a priority foundation in enhancing interoperability in railway networks in East Africa.

7.2 Recommendation

- Initiate regional standardization programs for signaling and train control systems, with emphasis on the introduction of interoperable standards such as ETCS and standardizing equipment and protocols across borders.
- Deploy ETCS-compatible equipment, especially on cross-border corridors, to improve real-time communication, security, and system reliability.
- Establish a regional control center for coordinated railway operations and monitoring, supporting coordinated traffic responses, emergency response, and system disturbances.
- Implement protocol translation gateways in the short term to allow legacy systems to interoperate during times of transition.
- Invest in technical training and capacity building of rail staff to allow for smooth installation and operation of new systems.
- Facilitate cross-border policy congruence by joint governance structures and regulatory convergence to ensure sustainable interoperability.

7.3 Future Work

Studies could extend this methodology to incorporate:

- Expand the scope of interoperability assessment by including more railway lines within and beyond East Africa, particularly those under development through the African Union's continental railway initiatives.
- Integrate real-time train operation data to validate hazard frequencies, communication failures, and MA issuance delays.
- Study how regulatory alignment and institutional cooperation affect the pace and quality of cross-border signaling interoperability.
- Apply simulation-based validation models to test the operational effectiveness of proposed solutions under varying traffic, infrastructure, and emergency scenarios.
- Explore economic impact modeling of interoperability improvements to support investment planning and stakeholder engagement.

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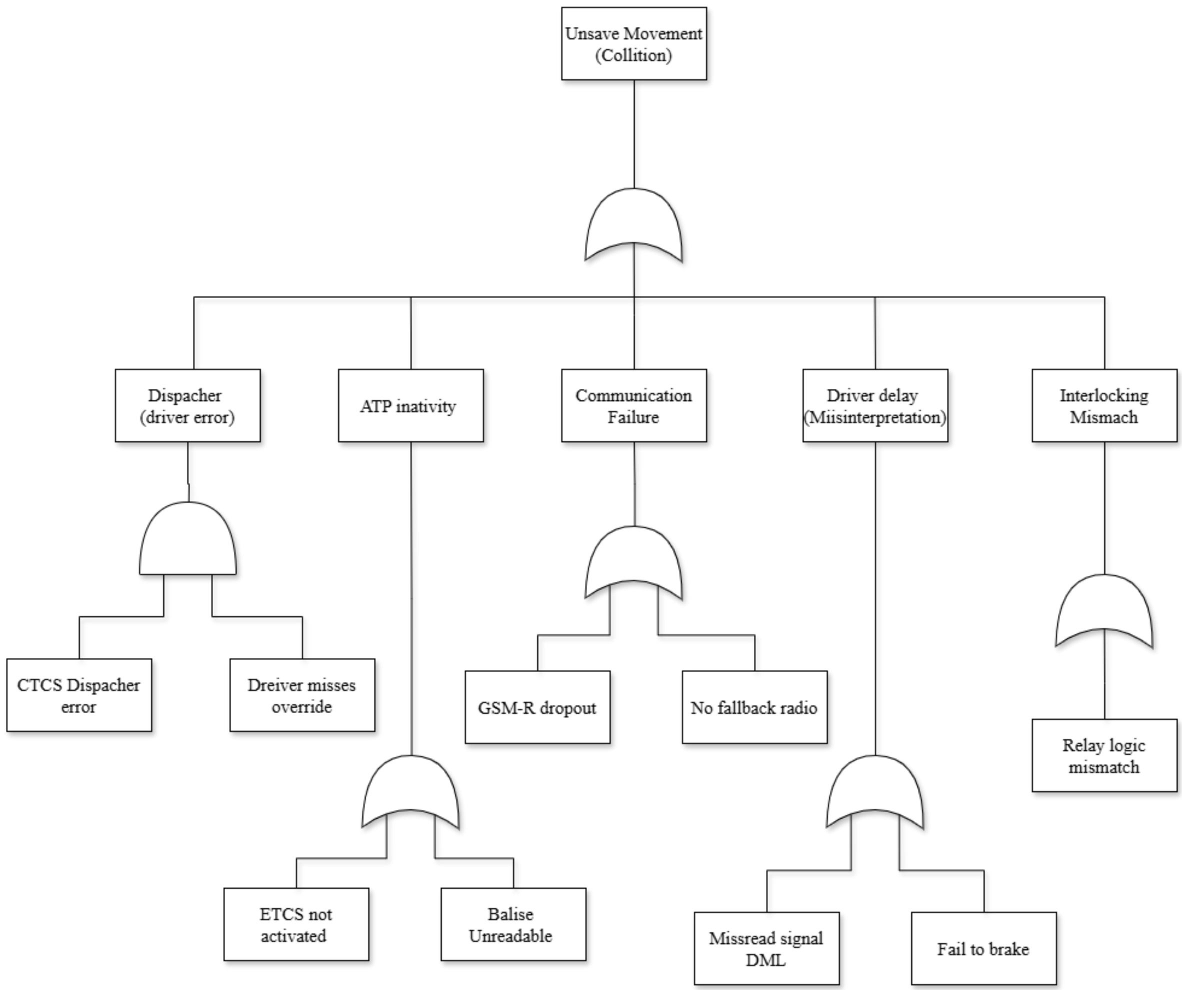
9. AP P E N D I X

Table 0-1: Summary of basic differences between the four projects signalling systems

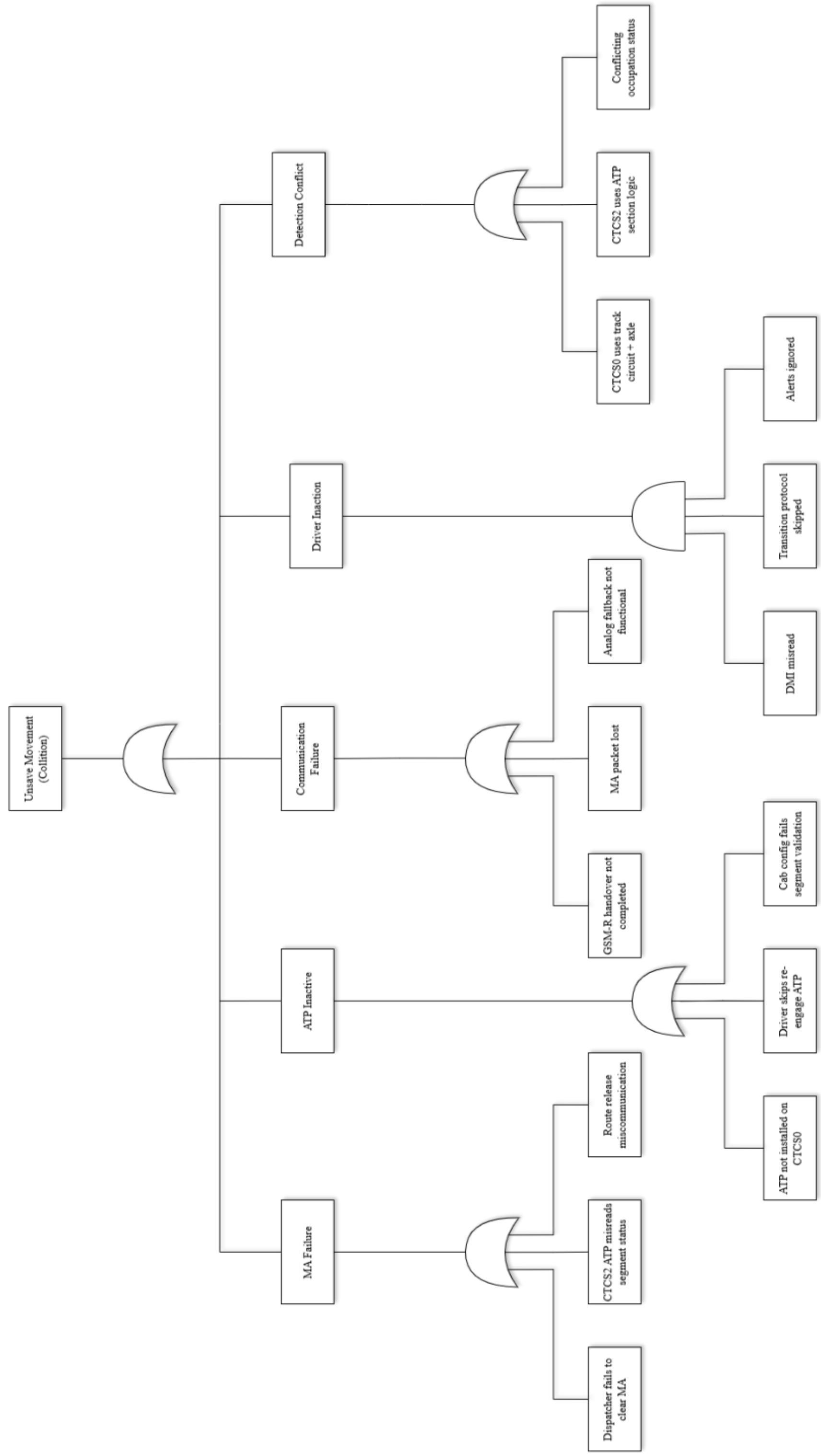
Railway	Addis Ababa- Djibouti (Ethiopia to Djibouti)	Awash-Kombolcha-Haragebya (Ethiopia)	Mombasa-Nairobi (Kenya)	Dar es Salaam- Makutupora (Tanzania)
Stage	Operational	Ready for testing/operation	Operational	Operational
Total Length	756 km	392km	472 km	611 Km
Max. speed of passenger trains	120km/hr	120km/hr	120km/hr	160 km/hr
Max. speed of freight trains	80km/hr	120km/hr	80km/hr	120 km/hr
Traction type	Electrified - Overhead 25 kV AC / 50 Hz	Electrified - Overhead 27.5 kV AC / 50 Hz	Diesel-electric with provisions for future electrification.	Electrified - Overhead 2x25 kV AC Autotransformer
Signalling Type	Chinese based signalling system with 3-aspect, colour light signaling, Semi-automatic blocking system	European based signalling system with 3-aspect, colour light signaling, Automatic Block System (ABS) and Semiautomatic	Chinese signalling system and Automatic Block System (ABS)	European signalling system ETCS/ERTMS based systems,
Traffic Management	Centralized Traffic Control (CTC)	Centralized Traffic Control (CTC)	-	Centralized Traffic Control (CTC)
Train Control/Train Protection	CTCS Level 0	ETCS Level 1	CTCS Level 2	ETCS Level 2
Number of Block section between stations	1 (station to station)	3	-	-

Block Section	Fixed block	Fixed block	Fixed block	Fixed block
Train Vacancy Detection	Track circuit	Axle counter	Track circuit	Axle counter
Control of train position and train integrity	Track circuit +Axle counter	Eurobalise	Eurobalise	Eurobalise
Interlocking Systems Type	Computer-based interlockings	Electronic interlockings	Electronic interlockings	Computer Based Interlocking
Automatic Train Operation (ATO)	N/A	Available	N/A	Available
Automatic Train Protection (ATP) Availability	Continuous ATP	Intermittent ATP	Intermittent ATP	Continuous ATP
On-board Configurations	Universal Cab-signalling, Driver Machine Interface (DMI), Train Operation Supervision, Recording Device (LKJ)	onboard ATP, Vital Computer (VC), Track circuit information receiving unit (TCR), Balise transmission module (BTM), Data recording unit (DRU) and Driver machine interface (DMI)	Vital Computer (VC), Specific Transmission Module (STM, receiving track circuit telegram), BTM, DMI, Speed Detection Unit (SDU), Recording unit	European Vital Computer (EVC), Driver Machine Interface (DMI),
Interlocking Systems Type	Relay-based interlockings	Electronic interlockings	Electronic interlockings	Computer-based interlocking
Speed Control	multivalued automatic locomotive signaling (ALS) onboard equipment	Eurobalise s+ ETCS onboard devices	Track Balises + multivalued automatic locomotive signaling (ALS) onboard equipment	GSM-R +Eurobalise + ETCS onboard devices
Standardized interfaces for communication with control centers and field devices	Fiberoptic	Fiberoptic	Fiberoptic	Fiberoptic

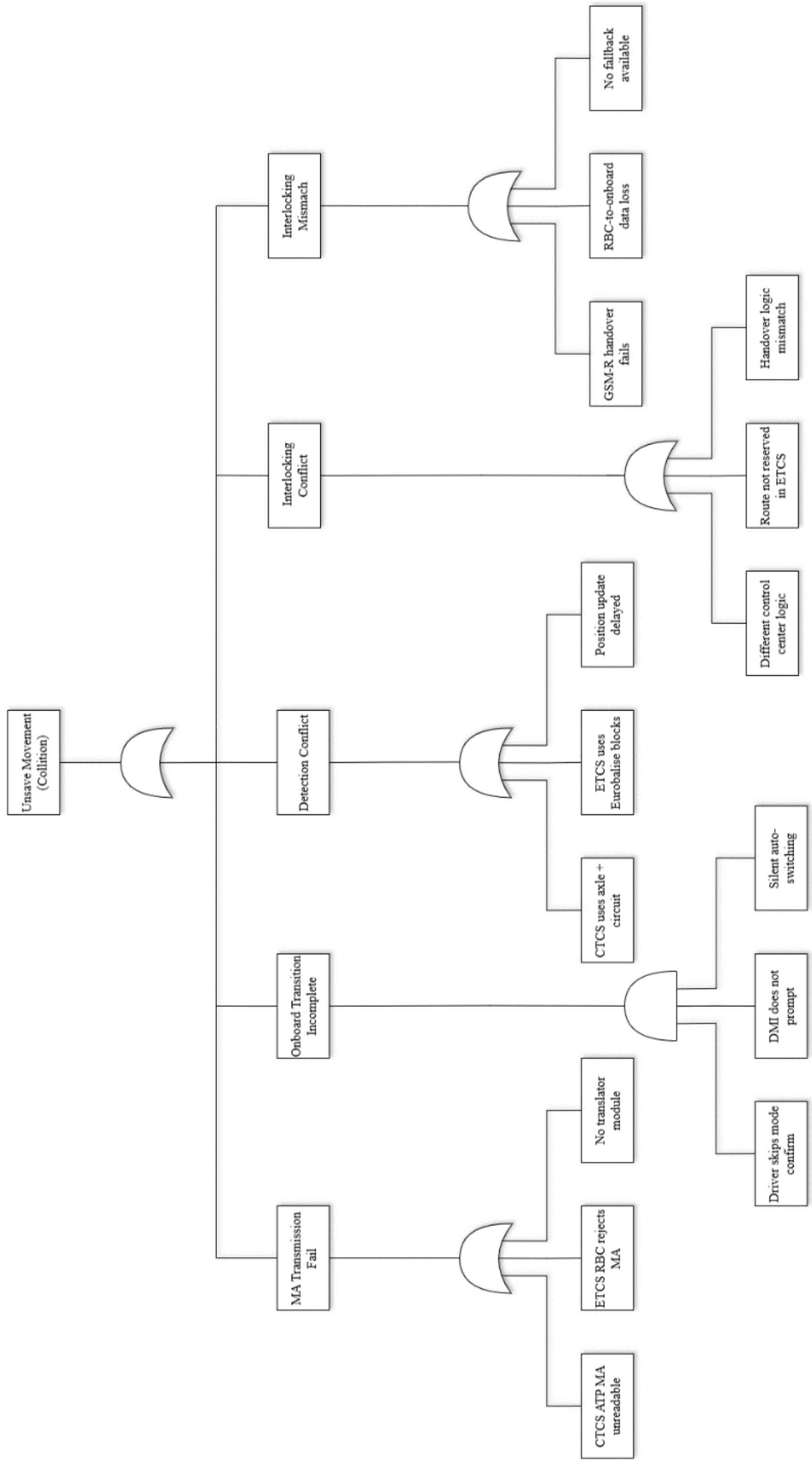
Communication Network Type	Fiber optic based; Fixed Line and mobile telephones	GSM-R	GSM-R Microwave backbone	Railway (GSM-R) base stations and Signaling system with continuous Fiber Optic system
Data Transmission Protocol	-	Standardized	Proprietary & Standardized	Standardized
Type of Data Transmission	Semicontinuous	Spot (Semicontinuous), Unidirectional (from track to train)	Continuous Bidirectional	Continuous Bidirectional Track-to-train
Transmitted data types	Train position	Train position, maximum allowed speed, and the next safe allowable train position	Information about the speed limit, the track segment security, line parameters, and train control commands	Track data and Position report
Vital information is transmitted through	Track circuit	Eurobalise Transmission Protocol + Radio Infill and Lineside signals	CTCS-3/LCM protocols, GSM-R protocols	Radio communication via GSM-R
Train movement authority through	Trackside signals + Cab Signals	Eurobalise	Track circuit and Eurobalises	GSM-R and Euroradio
Interoperability Readiness	Low	High	Moderate	High



Fault Tree Analysis for Addis Ababa-Djibouti to Awash-Kombolcha-Haragebeya



Fault Tree Analysis for Addis Ababa-Djibouti to Mombasa-Nairobi



Fault Tree Analysis for Mombasa-Nairobi to Dar es Salaam-Makutupora