ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

AFRICAN RAILWAY CENTER OF EXCELLENCE

TECHNO-ECONOMIC ANALYSIS OF DEPLOYING COMMUNICATION BASED TRAIN CONTROL SYSTEM (CBTC): IN CASE OF ETHIO-DJIBOUTI RAILWAY LINE

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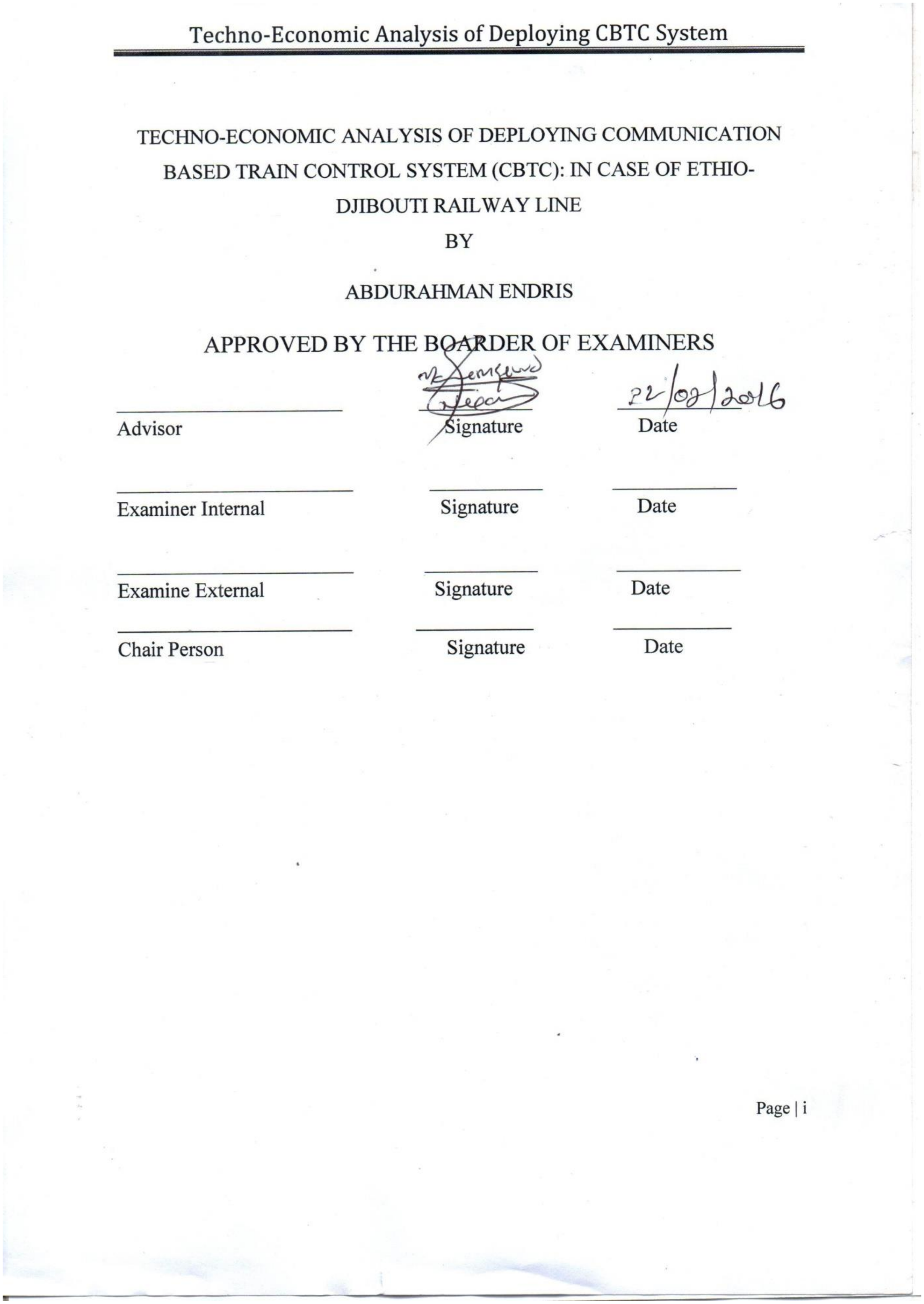

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APPROVED BY THE BOARDER OF EXAMINERS

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Examine External ______ Signature ______ Date ______

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DECLARATION

I, Abdurahman Endris, the undersigned person declare that the thesis entitled “Techno-Economic Analysis of Deploying CBTC system: In case of Ethio- Djibouti Railway line’’, Addis Ababa university at Addis Ababa hasn’t been presented for the award of any other degree. Under this study, the fellowship of other similar titles of any other university or institution of all sources of material used for the study has been appropriately acknowledged and noticed.

Abdurahman Endris	____________	______________
Candidate	Signature	Date

ABSTRACT

The techno-economic analysis is a technique to evaluate a technology's economic performance. It measures a technology's entire significance, enabling analysts to objectively assess benefits and expenses. It is crucial to conduct a techno-economic study of any new technology or product at the research and development stage before commercializing it for use in a significant industrial process. Due to the train control system's rapid growth, studies recommended a new communication control system called communication-based train control system. It improves line capacity and minimizes trackside equipment by safely reducing the separation (headway) between trains operating on the same line. The acceptability and economic viability of a new technology can't be demonstrated via implementation or adoption without a comprehensive technical and economic feasibility assessment. Therefore, we were motivated to investigate the techno-economic analysis of adopting CBTC for the Ethio- Djibouti railway line. For this study's techno-economic analysis, we utilized capital expenditure, operating expenditure, and total costs of ownership. We have analyzed the coming five consecutive years of revenue and cost data. We also used one year's signal and control data in the Ethio- Djibouti railway. In this study, using techno-economic analyses including net present value, internal rate of return, and payback period as economic indicators, we assessed the overall economic assessment of CBTC technology adoption. Finally, as the results of the study show, adopting CBTC technology on Ethio- Djibouti Railway allows the organization to increase competitiveness and economic returns. In addition to this, the study suggests that the use of CBTC on the railway can improve the safety of the train and faster train operation performance by increasing the ability of railroad lines, particularly in local and regional markets.

Keywords: CapEx, CBTC, Cost-Benefit Analysis, Ethio Djibouti, OpeEx, Rail transportation

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TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

LIST OF ABBREVIATION

3G	Third Generations
4G	Fourth Generations
5G	Fifth Generations
ARCE	Africa Railway Center of Excellence
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
BSC	Base Station Controller
BTM	Balise Transmission Module
CapEx	Capital Expenditure
CBA	Cost-Benefit Analysis
CBI	Computer Interlocking
CBTC	Communication Based Train Control System
CC	Carborne Controller
CCECC	Civil Engineering Construction Corporation
CCFE	Companies Des Chains De Fer Ethiopians
CPN	Coloured Petri Net
C-RAN	Cloud radio access network
CREC	China Railway Engineering Corporation
DCF	Discounted Cash Flow

DFROR	Discounted Cash Flow Rate Of Return
D-RAN	Distributed radio access network
E2E	End to End
EDR	Ethio Djibouti Railway
ER	Event Record
ERC	Ethiopian Railway Corporation
ERTMS	European Rail Traffic Management System
ETCS	European Train Control System
FACP	Fully Absorbed Cost of Production
F-RAN	Fog computing based Radio Access Network
FRMCS	Future Railway Mobile Communication System
GMSK	Gaussian Minimum-Shift Keying
GPRS	General Packet Radio Service
GPS	Global Position System
GSM-R	Global System for Mobile Communications Railway
GUI	Graphical User Interfaces
HLR	Home Location Register
HSR	High-Speed Railway
IASTED	International Association Science and Technology Development
IDS	Information Display System
IEEE	Institute of Electrical and Electronic Engineering
IRR	Internal Rate of Return
IRSE	Institution of Railway Signal Engineers

LMA	Limit of Movement Authority
LTE	Long-Term Evolution
MA	Movement Authority
MAPL	Maximum allowable path loss
MRU	Mobile Radio Unit
MSC	Mobile Switching Center
MSS	Mobile Switching Subsystems
MSTP	Multi-Service Transfer Platform
NFV	Network Function Virtualization
NPV	Net Present Value
NYCT	New York City Transit
OBC	Onboard Controller
OBCU	Onboard Control Unit
OCC	Operation Control Centre
OFDMA	Orthogonal Frequency-Division Multiple Access
OpeEx	Operational Expenses
PBP	Payback Period
PIDS	Passenger Information Display System
PIS	Passenger Information System
PSD	Platform Screen Doors
QoS	Quality of System
RNPO	Radio network planning and optimization

ROI	Return on Investment
RSRP	Reference signal received power
RSRQ	Reference signal received quality
SEPTA	Southeastern Pennsylvania Transportation Authority
SYC	Single Year Costing
T2I	Train to Infrastructure
T2T	Train to Train
TCN	Train Communication Network
TCO	Total costs of ownership
TEA	Techno-economic assessment
TOD	Train Operator Display
TWC	Train to Way side Communication
UTO	Unattended Train Operation
VLR	Visitor Location Register
VOBC	Vehicle On-Board Controller/Computer
WLAN	Wireless Local Networks
WRU	Way Side Radio Unit
ZC	Zone Controller

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

A well-functioning train control system is essential for the effective transportation of goods and services[1]. Railways, especially high-speed rail, play a crucial role in promoting economic growth and development[2]. However, without a properly set up train control system, there is an increased risk of accidents, which can lead to the loss of lives and property[3]. To ensure the safety and accuracy of train operations, it is important to develop new techniques that can support and enhance the existing train control system.

The currently used track-based train control system on the Ethio-Djibouti railway line has certain limitations that need to be addressed. These include reduced line capacity, lack of knowledge of specific train locations, and increased gaps between trains. These issues can lead to inefficient and ineffective use of the railway infrastructure and can have negative impacts on the company's economy and customer satisfaction[4]. To overcome these challenges, it is recommended to replace the existing system with an axel counter to create a fixed block system. Alternatively, a communication-based train control system (CBTC) can be implemented, utilizing wireless communication to achieve continuous bidirectional train-to-wayside communications. CBTC offers advantages such as shorter departure intervals, improved operational efficiency, safe train separation, and accurate train position information[5]. The implementation of a CBTC system would require a thorough techno-economic evaluation to assess its feasibility and economic benefits.

A techno-economic analysis is a crucial step in determining the feasibility and economic viability of implementing a communication-based train control system (CBTC) on the Ethio-Djibouti railway line [6]. The analysis involves assessing both the technological aspects and economic factors associated with CBTC implementation. It includes technological assessment which involves understanding the technical requirements and functionalities of CBTC, including train positioning, communication interfaces, signaling system integration, and hardware/software components [5]. The second one is assessing the current condition of the railway infrastructure and evaluates its compatibility with CBTC requirements. Determine the necessary upgrades or modifications needed for seamless integration. The third component includes the Cost-Benefit Analysis: Estimates the total cost of implementing CBTC, including system design, equipment procurement, installation, testing, and training [7]. Compare these costs against the expected benefits to ascertain the economic feasibility. In addition, it needs to assess the potential operational gains such as increased line capacity, shorter headways, reduced journey times, and improved train reliability. Finally, Calculate the financial returns that can be achieved through increased revenue, higher ridership, improved operational efficiency, and potential cost savings over the system's lifespan.

1.2 Statement of the Problem

The current Ethio-Djibouti railway line faces issues due to its fixed block system with an axel counter, resulting on ineffective communication. To address these problems, scholars propose adopting a communication-based train control system (CBTC). CBTC offers continuous and precise train positioning, dynamic control of train movements, enhanced safety features, improved maintenance capabilities, and higher operational efficiency. Implementing CBTC on the railway line would address the limitations of the current system and provide a safer, more efficient and reliable transportation system.

The Ethio-Djibouti railway Line Company is exploring the benefits of implementing a new communication-based train control system. However, before making any decisions, it is important to conduct a techno-economic analysis (TEA) to evaluate the economic performance and overall value of the technology.

Studying Techno-Economic Analysis (TEA) on CBTC is essential for several reasons. Firstly, CBTC implementation in rail networks requires a significant investment of financial resources. Conducting a thorough TEA allows decision-makers to understand the costs involved in procuring and installing hardware and software, integrating the system, and ensuring ongoing operational maintenance. Without a comprehensive understanding of these costs, it becomes challenging to assess the economic feasibility of CBTC projects and make informed decision

Secondly, TEA helps in quantifying the potential benefits of CBTC implementation. These benefits may include improvements in operational efficiency, increased capacity, enhanced safety, and reduced maintenance costs. By quantifying these benefits in monetary terms, decision-makers can compare them against the costs incurred to determine the potential return on investment and overall financial viability of CBTC projects.

Moreover, studying TEA on CBTC allows for a thorough assessment of the financial viability of such projects. Financial metrics such as payback period, net present value, and internal rate of return can be used to evaluate the return on investment and determine the feasibility of funding CBTC initiatives.

Additionally, TEA enables decision-makers to conduct a comprehensive risk assessment. By identifying potential financial or operational risks associated with CBTC implementation, mitigation strategies can be developed to ensure the successful and sustainable implementation of the technology.

Finally, sensitivity analysis is a crucial aspect of TEA as it helps decision-makers understand the impact of changes in key variables on the economic viability of CBTC projects. This analysis allows for more robust and flexible decision-making, taking into account potential uncertainties and fluctuations in costs, benefits, interest rates, and market conditions.

Overall, studying TEA on CBTC is vital to gaining a comprehensive understanding of the economic feasibility, potential risks, and benefits associated with implementing this advanced train control technology. It provides decision-makers with the necessary information and insights to make informed choices and optimize the return on investment in CBTC projects. At the end of this study, we will answer the following research questions:

1.3 Research Questions

1. What is the financial feasibility and expected return on investment of deploying a communication-based train control system on the Ethio Djibouti railway line?
2. What are the expected operational and maintenance costs, initial capital expenditures, and total cost of ownership associated with the system?
3. What are the potential risks and impacts, both positive and negative, of implementing the system?

1.4 Objectives of the Study

1.4.1 General Objective

The general objective of the study is to analyze the techno-economic analysis of CBTC implementation on the Ethio Djibouti railway line including various financial metrics to determine the feasibility of this technology to make an informed decision on investing in CBTC deployment or not.

1.4.2 Specific Objectives

Here are the objectives of conducting a techno-economic analysis for a communication-based train control system in the Ethio Djibouti railway line:

- To evaluate the financial feasibility of implementing a communication-based train control system on the railway line.
- To estimate the expected return on investment from the implementation of the system.
- To identify expected operational and maintenance costs associated with the system.
- To determine initial capital expenditures needed to implement the system.
- To estimate the total cost of ownership of the system over its expected lifetime.

1.5 Significance of the study

The significance of researching and conducting a techno-economic analysis of deploying a communication-based train control system on the Ethio Djibouti railway line are:

- **Improved Safety:** One of the most significant benefits of implementing a communication-based train control system is improved safety. By automating control of trains and ensuring better communication between trains and control rooms, the likelihood of accidents decreases and the safety of passengers as well as employees improve.
- **Increased Efficiency:** A communication-based train control system will make it possible to enhance daily train frequencies by reducing the headway time. This will increase network capacity and reduce operating costs due to efficient use of resources.
- **Financial feasibility:** The financial viability of implementing the communication-based train control system on the Ethio-Djibouti railway line will be determined by a techno-economic analysis. It will help decision-makers understand the expected costs and benefits associated with the system and determine whether it is a worthwhile investment for the railway line.
- **Improved decision-making:** Conducting techno-economic analysis will provide decision-makers with the necessary information both quantitative and qualitative, to make well-informed decisions. The analysis will also help question assumptions and

identify potential risks and unintended consequences that need to be taken into account during the decision-making process.

- **Enhanced stakeholder engagement:** The techno-economic analysis will help in identifying the potential impacts of the communication-based train control system on different stakeholders such as railway employees, passengers, and the community. This understanding will help in involving stakeholders in the decision-making process and addressing their concerns.
- **Realization of national plans:** Implementing a communication-based train control system on the Ethio Djibouti railway line is aligned with Ethiopia's national plans for development and modernizing existing infrastructure. The techno-economic analysis will provide valuable information to support national initiatives towards sustainable development.

1.6 Scope and Limitations

The scope of a techno-economic analysis of deploying a CBTC on the Ethio Djibouti railway line would include the following:

- Identification and analysis of the proposed CBTC system, including the specific technology and equipment required and its expected performance standards.
- Estimation of the financial feasibility of the proposed CBTC system including the expected return on investment, operational and maintenance costs, total cost of ownership, and initial capital expenditures.
- Assessment of the potential risks and impacts associated with the implementation of the CBTC system on the Ethio Djibouti railway line including its effects on safety, efficiency, and reliability.

The following are the **limitations** of the techno-economic analysis of installing a CBTC system on the Ethio Djibouti railway line:

- **Cost:** CBTC systems are expensive to implement and require significant infrastructure changes and upgrades. This can be a significant challenge for railways operating on tight budgets.
- **Lack of supporting infrastructure:** CBTC systems require reliable and robust communication networks, including wireless, fiber optic, and satellite systems. These

networks may not be readily available in remote or rural areas such as along the Ethiopia-Djibouti railway line.

- **Implementation timeframe:** CBTC systems require significant planning, design, and implementation time. This can be a challenge in areas with tight schedules such as railways that need to keep up with high demand cross border operations.
- **Coordination with neighboring countries:** CBTC systems may require coordination with neighboring countries, such as Djibouti and other countries along the Ethiopia-Djibouti railway line, to ensure seamless cross-border operations. This can be complicated due to the different technical systems and regulations in each country.
- **Cultural differences:** CBTC systems may require changes in organizational culture and work practices, which can be challenging to implement in areas with long-standing traditions and practices.

1.7 Contributions

The contributions of a techno-economic analysis of deploying a CBTC on the Ethio Djibouti railway line would involve identifying the costs and benefits of implementing the system on the railway line assessing its financial feasibility, evaluating potential risks and impacts, identifying key assumptions and their impact on the viability of the system and providing recommendations on how to optimize the benefits of the CBTC while minimizing costs and risks. In summary, a techno-economic analysis provides decision-makers with objective data and information to make informed decisions on investing in and implementing the CBTC system allowing them to assess the system's viability, benefits, and potential risks.

1.8 Thesis Report Outline

The research study is structured in five chapters. Chapter one presents the introduction part of the study. It quotes the statement of the problem, the objective of the study, the scope, and the limitation of the thesis. Chapter 2 covers a literature review of related work. Chapter 3 presents the methods of how this paper will achieve its objective. The fourth chapter presents results and discussion about the thesis using different data sizes and the last chapter settles the study by concluding remarks on overall research and gives insight for future works.

CHAPTER TWO

LITERATURE REVIEW

2.1 History and development of Ethio Djibouti railway line

During the reign of Emperor Menelik II in the late 19th century, railway lines first began to be built in Ethiopia. The first railway line, known as the Franco-Ethiopian line was built in 1894 to link Ethiopia's capital city, Addis Ababa, with the port city of Djibouti. To facilitate trade and cargo movement between Ethiopia and the Red Sea, the French company Companies des chains de Fer Ethiopians (CCFE) built the railway line[8]. The construction of the railway line was a significant feat as it involved building a railway line across rugged terrain and through mountainous regions.

However, the railway line faced several challenges including frequent attacks by Somali and Ethiopian rebels, lack of adequate maintenance, and the outbreak of World War II, which disrupted transportation and led to the closure of the railway line. After the war, the railway line was reopened and remained in operation until the 1970s when it was closed due to the political instability and civil war in Ethiopia. It failed until 2006 when Ethiopia started building the Addis Ababa-Djibouti Railway, a new standard gauge railroad route. The railway line which covers a distance of 759 km was built by Chinese companies and was completed in 2016[8]. The railway has significantly improved transportation and trade between Ethiopia and Djibouti leading to the growth of the economy and the creation of employment opportunities. Ethiopia has since embarked on the construction of new railway lines including the Awash-Weldiya and the Weldiya-Mekelle railway lines which are expected to facilitate transportation and contribute to the development of Ethiopia's economy.

The construction stages or revolution of the railway line from Ethiopia to Djibouti can be divided into four distinct phases.

Phase 1: Initial Planning and Construction (2006-2011)

In 2006, Ethiopia signed an agreement with China to commence the construction of a new standard gauge railway line, which would be 759 km long and run from Addis Ababa to Djibouti. The initial phase involved conducting feasibility studies, planning the route, and acquiring land for the construction of the railway line.

Phase 2: Major Construction Works (2012-2015)

The second phase of the construction involved major works such as building bridges, constructing tunnels, and laying tracks. China Railway Engineering Corporation (CREC) served as the project's primary contractor, and China Civil Engineering Construction Corporation (CCECC) was in control of energizing the railway. This stage also involved the construction of several stations along the railway line, including Addis Ababa, Adama, Awash, and Dire Dawa.

Phase 3: Testing and Commissioning (2016)

After the construction was completed the railway line went through a testing phase to ensure that it was functioning correctly. The first test run was conducted in October 2015 and the line was officially commissioned in October 2016.

Phase 4: Post-Construction Activities (2017 present)

The final stage of the development of the railway line involved post-construction activities such as hiring personnel, training staff, and promoting the railway to potential customers. This phase also saw the opening of additional railway stations such as Mieso and Nagad.

Overall, the construction of the railway line from Ethiopia to Djibouti represented a significant development for both countries. The railway has facilitated the transportation of goods, reduced travel time, and improved economic activity[9]. The railway line also represents a significant milestone in Ethiopia's ambition to become a middle-income country by 2025.

The Ethio-Djibouti railway line was constructed using modern technology including standard gauge tracks, electrification, and computerized systems. The railway line is double track and powered by electricity with a top speed of 120 km/h. The railway line features modern signaling and communication systems, as well as safety and security measures that comply with international standards. The railway line's locomotives and wagons were supplied by Chinese manufacturers, specifically the CRRC Corporation. The locomotives are designed to operate in harsh environments and have a load capacity of 4,000 tons. Additionally, the railway line is equipped with a Global Position System (GPS) based location system which enables the railway authorities to track trains' positions in real-time and manage railway operations effectively.

The Ethio-Djibouti railway line was constructed using modern technology but it does not use the CBTC system which is common in European countries. The CBTC system is a sophisticated signaling system that uses wireless communication between trains and control centers enabling precise control of train movement and safety. Compared to the CBTC system the Ethio-Djibouti railway line's signaling system may have some drawbacks, such as:

Limited capacity: The signaling system used in the Ethio-Djibouti railway line may have a limited capacity compared to the CBTC system which can accommodate more trains on the same track.

Reduced efficiency: The signaling system used in the Ethio-Djibouti railway line may not be as efficient as the CBTC system which enables trains to operate at higher speeds and reduce travel time.

Maintenance requirements: The signaling system used in the Ethio-Djibouti railway line may require more maintenance than the CBTC system, which is automated and operates with fewer physical components.

However, it is essential to note that the CBTC system is more expensive to install and operate than traditional signaling systems and its adoption may not be practical in all situations. The Ethio-Djibouti railway line's signaling system meets international safety standards.

2.2 Current System of Ethio Djibouti railway line

The traditional signaling system with line-side signals and periodic automatic train protection was found to be the current train control and signaling solution for the Ethio Djibouti railway line network. The study's conclusions indicate that the optimum technological choice or clarification is a balise-based system that complies with the European Rail Traffic Management System (ERTMS) Level 2 and has no indication of line signals[10].

2.2.1 Methods of Train Control by Ethio Djibouti Railway

It is recognized that numerous techniques are required to control the passage of a train between two specific sites, such as two stations, to ensure that only one train can enter the block section at a time under the space interval strategy.

2.2.2 BiLOCK Computer-based Interlocking Systems

BiLOCK system， has been accredited with both Generic Application and Generic Product SIL Certificates (BiLOCK is the first product has obtained these two certificates at the same time in China). BiLOCK inherited the advanced and safe concepts from Europe, and uses diversified techniques, independent real time safe diagnosis technology BIST, dynamic and static read back techniques, code acquisition techniques etc., to control the interlocking station safely. BiLOCK Interlocking is the fundamental safe guard for train operation[11].

Figure 2.1: BiLOCK system [12]

BiLOCK system carries out these functions:

- Implement the locking of switch, signal and sections, and ensure the proper interlocking relationship.
- Automatically select sections with overlaps and lock the sections as required.
- Automatically set Fleeting Route and Cycle Route.
- The switch being moved through route setting and the lock functions; also can be moved and lock manually.

BiLOCK system receives route control command by operator or from ATS/CTC, and acquires the status of the signaling equipment on site, then calculates the interlocking to achieve control signaling equipment on site. At the same time, it can acquire on site signaling equipment's status, send the field status to HMI/ATS/CTC. Due to project's requirement, BiLOCK system can interface with other systems. BiLOCK system has five subsystems as below:

- BiLOCK Interlocking Logical Calculation subsystem (ILC)
- BiLOCK Human-Machine Interface (HMI)
- BiLOCK System Diagnosis Maintenance (SDM)

- BiLOCK Redundant Network (RNET)
- BiLOCK Redundant Power (RPWR).

2.2.3 Absolute Block System

The block section refers to the distance between two stations, which is often 6 km or more. In this case, entry into the block section was efficiently arranged by the Ethio Djibouti Railway using two station masters as human agencies. A train may only leave the station once the block section is clear of other trains and line clearance has been looked for in advance from the station. The Ethio Djibouti railway uses multiple-aspect color light signaling, with 180 meters being considered to be a proper block overlap distance[12]. It features system settings for line clear on double lines that include block overlap is defined as the first stop signal plus a suitable distance. Up until the first stop signal and block overlap, the line is clear. The line is clear until the first block and stop signal overlap. Up to the first stop signal and up to a sufficient distance, often referred to as block overlap, for trains traveling in the opposite direction, a single line must be clear of trains traveling in the same direction.

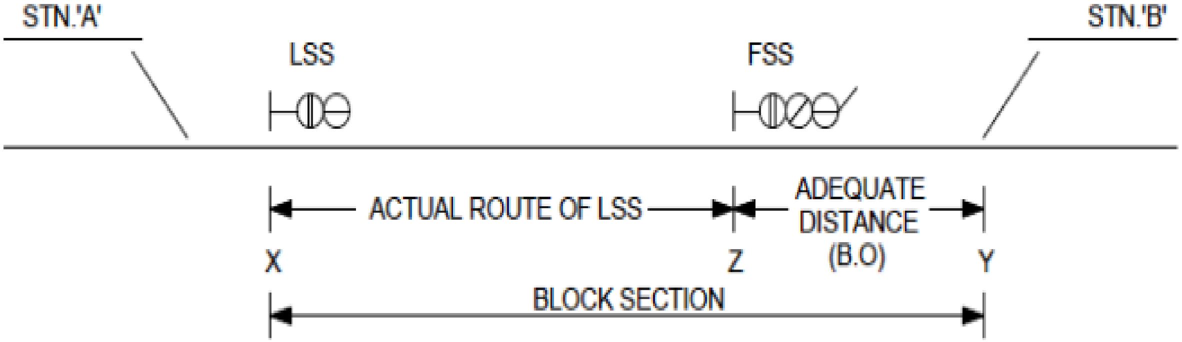


Figure 2.2: Absolute block system[13]

Although additional trains might operate in the block portion of the system, this study's analysis shows that only one train could run simultaneously in each direction. It demonstrates how fixed and restricted this approach is. Where the absolute block section is long (12-14 km) and train frequency is higher, an intermediate block signaling system may be used.

2.2.4 Intermediate Block Signaling System

An IBS arrangement divides a long block section into two sections known as the rear section and the advance section by installing an IBS signal at the point where that running line splits regarding the specified direction of traffic. To improve the section capacity on a double-line section, this design is employed.

Because of the introduction of the IBS system, this system can manage a maximum of two trains on a lengthy double-line block segment on each designated operational line. As was already said, this system has several disadvantages as well. An automatic block system is a better one that allows for the dealing of more than two trains.

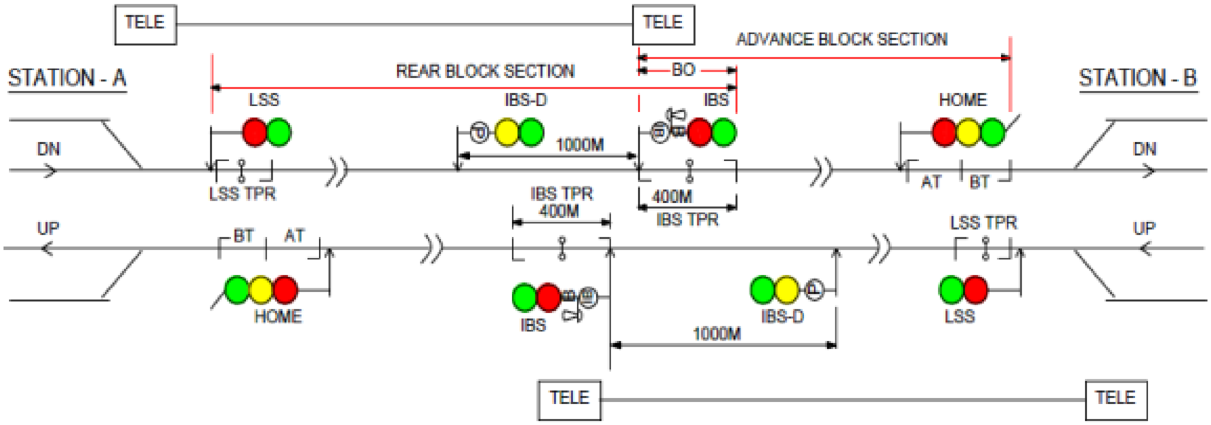


Figure 2.3: Intermediate Block Signalling System [5]

2.2.5 Automatic Block Signaling System (ABS)

In this system, axle counters or continuous track circuits are installed on the line connecting two stations. This system's "automatic block signaling section" separates the line between two stations into numerous segments.

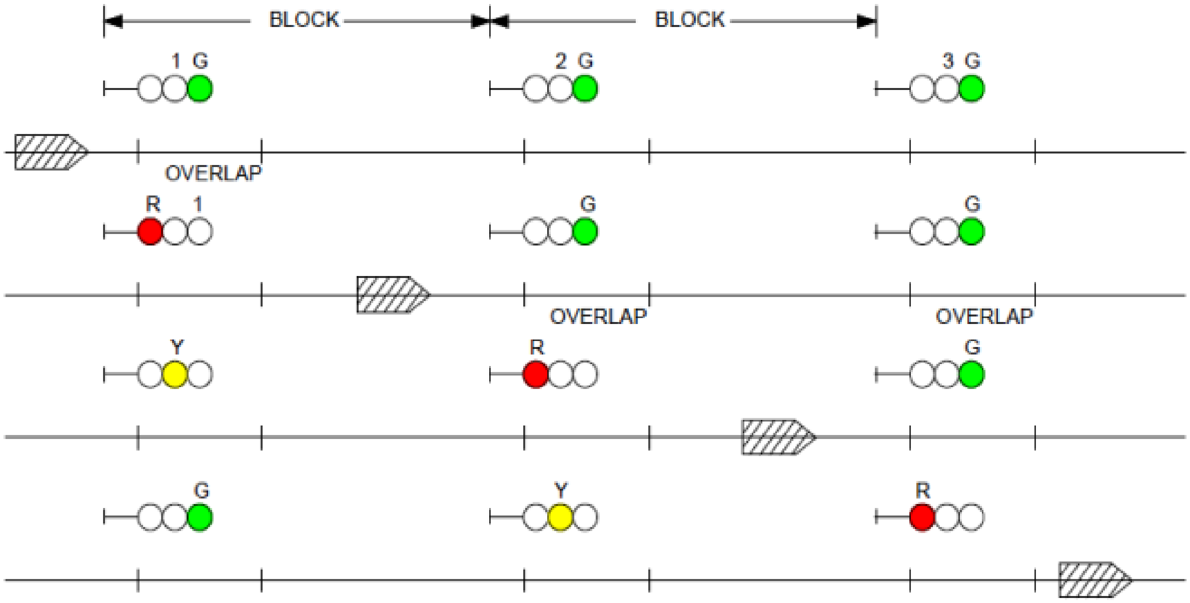


Figure 2.4: Automatic block signaling system [13]

The distance between these automatic block signaling sections is usually equal to the braking distance following the section's established allowed speed. A color light multiple aspect stop signal acts as a barrier at the entry to each automatic block signaling area system. The "OFF" function cannot be displayed until the line is clear enough beyond the next stop signal as well as up to it. At least 120 meters must separate the current overlap from the previous appropriate distance [9]. Signal 1 should be regulated by track circuits or axle counters so that it can presume the Yellow - line is clear for one block and one overlap. Even though the automatic block signaling system can handle more trains than the first two systems, full capacity deployment has not yet been achieved, as shown in the following Figure 2.5.

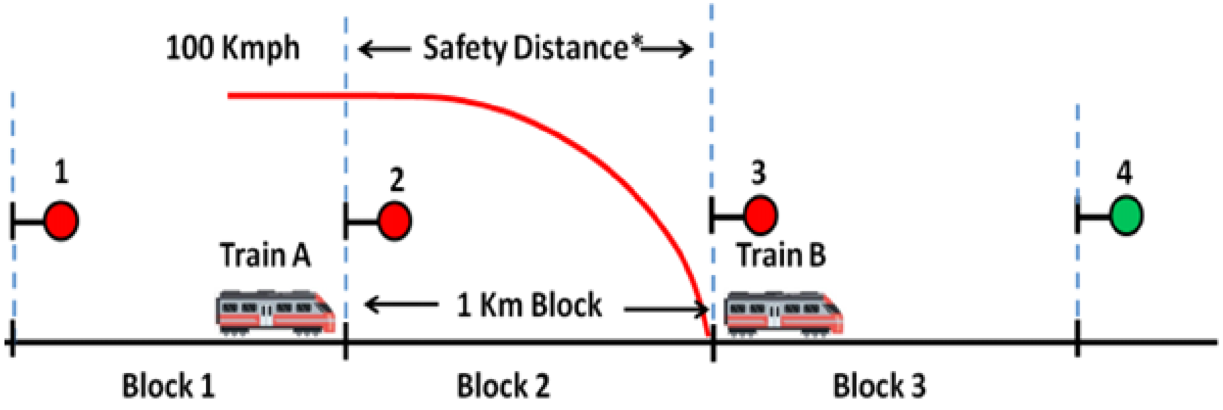


Figure 2.5: Keeping a safe distance or using the ABS emergency brakes [7]

The image to the right shows that, with train B occupying block 3, the block between the two trains must be at least 1 km long to meet safety standards if train A is traveling at 100 mph and needs that distance to stop using emergency brakes if it runs past signal No. 2 at hazard. Even if an imaginary distance between trains A and B is established, this system is ineffective because train A can still maintain a safe stopping distance by slowly approaching train B. The fixed blocks continue to prevent Train A from moving, though the trains can get closer as Train B advances deeper inside Block 3. A train must maintain the block separation designed for its speed if it is traveling at a slower pace, such as 60 mph. The signaling system is unable to adjust the safety distance to the speed of the trains due to static construction. This study preferred the development of the CBTC system as a result.

2.2.6 ATS Equipment

In Addis Ababa, wayside equipment for automatic train supervision (ATS) has been installed. It must carry out the tasks of identifying, following, and displaying trains. It offers manual and automatic route-setting options. To keep the operating schedule in place, it controls train movements.

2.2.7 Wayside Equipment

It has a network of central/wayside-installed processor-based wayside controllers. It has improved interfaces for ATS, external interlocking, and train-borne equipment. It will determine the movement authority based on the tracking of both CBTC-equipped and non-CBTC trains. Wayside equipment handles automatic train operation, automatic train braking, and automatic train protection. It consists of the track-based tools required to give train-borne tools like Balise a precise absolute positioning reference.

2.2.8 Balise

A module inside the ETCS onboard equipment for periodic transfer from track to train is the balise transmission module (BTM), which tests signals received from the onboard antenna and extracts data messages from a Eurobalise [14]. Eurobalise communicates trackside data to train movement authorities and stores infrastructure data as pre-formatted "telegrams" (position reference, speed restrictions, line gradient, works on the line, etc.) when powered by the train's antenna.

2.2.9 Way Side Radio Unit (WRU)

The WRUs are connected in a ring topology, and this ring is linked to the untrusted support ring via inter-ring shifts that follow a ring coupling redundancy protocol. In terms of coverage, the design is designed to provide overlap between WRUs, preventing performance degradation from a single radio failure. WRUs are purposefully placed at predetermined intervals, allowing the MRUs to communicate with at least two WRUs at any given location along the guide way. With the help of this design, full treatment is ensured to continue even if all other WRUs are lost, an optical fiber connection is severed, and the power source is switched off.

2.2.10 Controller On Board

It is made up of an onboard controller (OBC), a controller powered by a CPU. The installation of two OBCs in a hot standby configuration, one at either end of each train, allows for a high level of availability. It is the primary component on board the critical train control. Combining ATP and ATO capabilities, such as safe train automated or manually driven travel, driverless turn back and accurate station stopping automatic door operation, and protection, makes driverless train operation conceivable. Transponder tags, which are fixed along the running tracks and offer train relocation references, are used by the OBC.

2.2.11 Mobile Radio Unit

The Mobile Radio Unit (MRU), a CBTC component, connects the OBC to the ZC and the ATS. At each end of the train, there is an MRU. Each device on the network has its address. A mobile radio, a network switch, and a security device comprise the MRU. To connect with the wayside, MRUs are positioned at both ends of the train. If one of the radios fails or there is a loss of radio signal to a wayside radio unit at one of the trains, the system is still completely functional by maintaining communication with a wayside utilizing one radio unit.

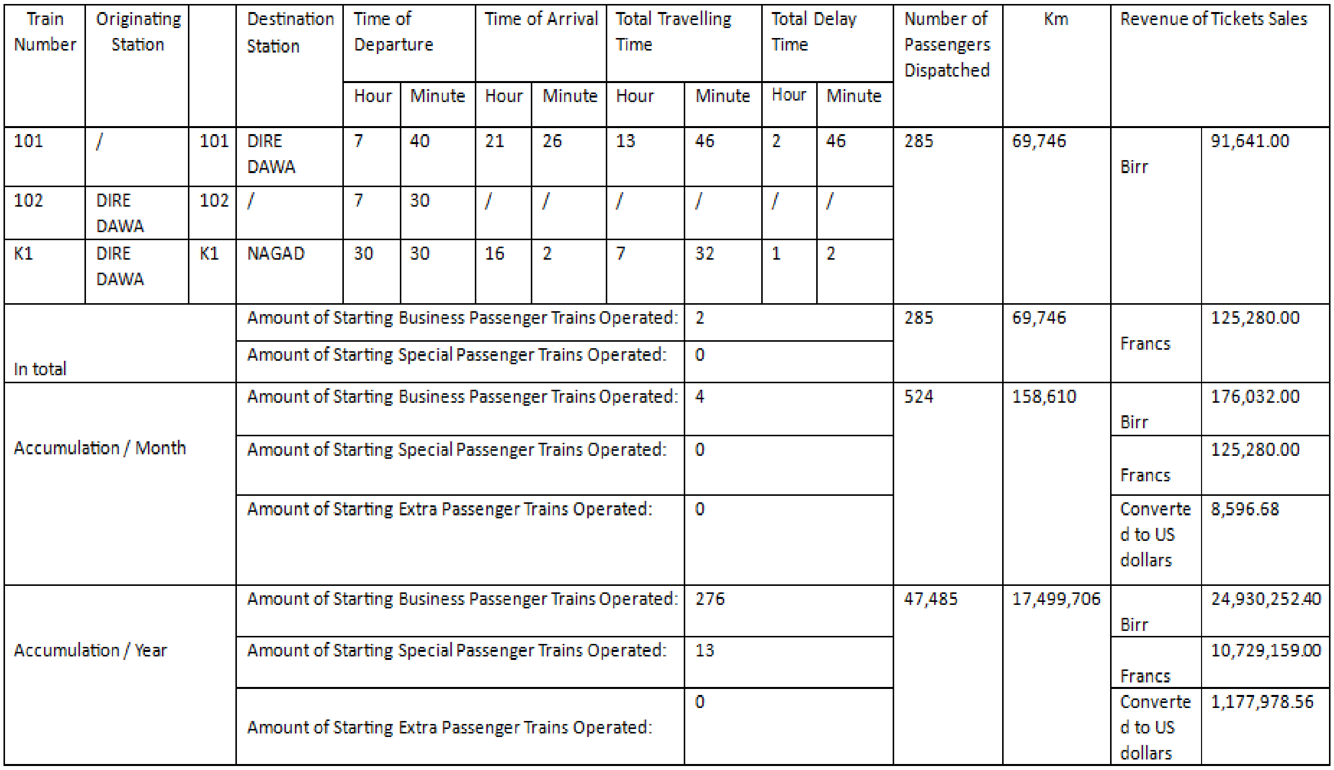
2.3 Technical Economic Analysis of a Technology

Wide-ranging technical economic analyses of technology are the result of a collaborative effort by skilled engineer project management and finance experts and analysts. The deployment potential of current technology into new markets can also be examined using this kind of analysis. Current technologies that openly compete with the technology being evaluated must be taken into consideration including evaluating their future developments in declining costs and illuminating performance. Because of the increased advantages of current technology, non-economic barriers to market share have been created including well-known infrastructure, suppliers, corporations with local communities, and long-term clients and contracts. The market barriers may be lifted or removed, allowing the unique technology to compete on a purely economic basis if the innovative technology can be maintained or licensed by established businesses. Emerging technology is subjected to sustainability analysis to determine whether it can tolerate use over time without disrupting environmental balances. To safely satisfy this increase in demand and traffic capacity, railway technology must develop and update its signaling systems[14]. By carefully minimizing the time interval (movement) between trains passing along the line, the CBTC signaling system aims to increase capacity. CBTC regularly uses communications between train equipment and railway track equipment.

2.3.1 Daily Operation Report of Ethio-Djibouti Railway

The Ethiopian minister stated that the 752.7kilometer Ethiopia-Djibouti standard gauge railway, also known as the Addis Ababa-Djibouti railway, is a landmark railway line connecting Ethiopia and Djibouti, a flagship project under China's proposed Belt and Road Initiative, and an important early harvest of China-Africa cooperation. The railway has played an essential part in Ethiopia's economic and social growth, as well as in raising people's living conditions. Since the railway's formal commercial launch in January 2018, it has carried about 530,900 passengers and 6,133 cargo trains carrying around 7,328,500 tons of cargo. The railway's total operating revenue has also maintained an average annual growth rate of more than 35 percent, vividly illustrating the high quality of jointly building the Belt and Road Initiative [15].

Table 2.1: Daily Operation Report of Ethio-Djibouti Railway



Train Number	Originating Station		Destination Station	Time of Departure		Time of Arrival		Total Travelling Time		Total Delay Time		Number of Passengers Dispatched	Km	Revenue of Tickets Sales	
				Hour	Minute	Hour	Minute	Hour	Minute	Hour	Minute				
101	/	101	DIRE DAWA	7	40	21	26	13	46	2	46	285	69,746	Birr	91,641.00
102	DIRE DAWA	102	/	7	30	/	/	/	/	/	/				
K1	DIRE DAWA	K1	NAGAD	30	30	16	2	7	32	1	2				
In total			Amount of Starting Business Passenger Trains Operated:						2			285	69,746	Francs	125,280.00
			Amount of Starting Special Passenger Trains Operated:						0						
Accumulation / Month			Amount of Starting Business Passenger Trains Operated:						4			524	158,610	Birr	176,032.00
			Amount of Starting Special Passenger Trains Operated:						0					Francs	125,280.00
			Amount of Starting Extra Passenger Trains Operated:						0					Converted to US dollars	8,596.68
Accumulation / Year			Amount of Starting Business Passenger Trains Operated:						276			47,485	17,499,706	Birr	24,930,252.40
			Amount of Starting Special Passenger Trains Operated:						13					Francs	10,729,159.00
			Amount of Starting Extra Passenger Trains Operated:						0					Converted to US dollars	1,177,978.56

Source: Ethio-Djibouti Railway sample monthly report, 2023

2.3.2 Income Generate by Ethio-Djibouti Railway

Addis Ababa, 14 August 2021 Ethio-Djibouti Railway reported 1.264 million US dollars in transportation income in the first seven months of 2021. It saw 722 freight trains run on the railway, with a freight volume of roughly 989,000 tons and a fright turnover of 770 million tonne-kilometres. Meanwhile, the freight service contributed more than 45 million US dollars, bringing the seven-month total transport revenue to 46.903 million US dollars. In contrast, as evidence of its position as a "livelihood protector," the Ethio-Djibouti Railway conveyed 225,000 tonnes of imported fertilizers, a 191 percent increase year on year. The railway connects industrial parks as the first of its kind "Eastern Industrial Park Trackless Station." Higher efficiency and better services will stimulate the economy and usher in a new development stage characterized by a close interaction of the railway and the parks. Ethio-Djibouti Railway will soon offer high-quality unimodal container transport services to small and medium-sized businesses.

Table 2.2: Income Generate by Ethio-Djibouti Railway

<table>
<tr><td rowspan="7">Operation of Trains</td><td colspan="3">Type/Category</td><td colspan="2">Trains in Diagram</td><td>Trains Operated</td><td colspan="2">Implementation Rate</td><td>On-Schedule Rate</td><td colspan="2">Volume</td><td colspan="2">Revenue of Passenger (Freight) Tickets Sales</td></tr>
<tr><td rowspan="3">Passenger Trains</td><td colspan="2">Business Passenger Trains</td><td colspan="2">60</td><td>56</td><td colspan="2">93%</td><td>0%</td><td>Person-Time</td><td>8,442</td><td>Birr</td><td>3,016,001.00</td></tr>
<tr><td colspan="2">Special Passenger Trains</td><td colspan="2">/</td><td>6</td><td colspan="2">/</td><td>/</td><td rowspan="2">Passenger Person-kilometers:</td><td rowspan="2">2,722,714</td><td>Francs</td><td>1,830,460.00</td></tr>
<tr><td colspan="2">Extra Passenger Trains</td><td colspan="2">/</td><td>/</td><td colspan="2">/</td><td>/</td><td>Converted to US dollars</td><td>145,508.81</td></tr>
<tr><td rowspan="3">Analysis of passenger transport efficiency</td><td>Planned ticket windows</td><td>472</td><td>Actual ticket windows</td><td>472</td><td>Ticket window utilization rate</td><td>100.00%</td><td>Train full seats</td><td>13850</td><td>Actual passenger number</td><td>8,442</td><td>Train seat occupancy rate</td><td>60.95%</td></tr>
<tr><td colspan="12">Statement for train seat occupancy rate and cancellation of train</td></tr>
<tr><td colspan="12">1, June.10. Train No.102 was cancelled due to OCS failure.
2, June.18. Train No. K1 was cancelled due to OCS failure between Dire Dawa and Arawa station.
3, June.19. Train No. K2 was cancelled due to OCS failure between Dire Dawa and Arawa station.
4, June.20. Train No. K1 was cancelled due to OCS failure between Dire Dawa and Arawa station.</td></tr>
</table>

Source: Income Generated by Ethio-Djibouti Railway

2.4 Over view of Communication-Based Train Control System

A multi-agent CBTC system for the Indian railway was developed by[16] using the methodology of software agent engineering. The behavioral study of the built system includes some operating scenarios that take place during a training run, which helps in understanding how the system reacts to these events. The system designer can use validation and verification to critically assess the system's intended function and if necessary, make any design corrections before the system's actual implementation. This paper's main focus is on modeling, validating, and verifying the structural design using colored Petri nets (CPN). Analysis of simulation data is used to verify the design's efficacy[16].

Examined[17] the installation of CBTC technology on two North American transit assets, namely New York City transit (NYCT) and the Southeastern Pennsylvania transportation authority (SEPTA), to assess the benefits obtained and implementation issues faced.

The analysis supports widespread industry knowledge that CBTC provides advantages not possible with earlier generations of signaling technology. The paper also highlights the necessity of being realistic about the challenges of updating the signaling and train control systems on an existing high-capacity mass transit system. To do this, the study suggests placing more focus on the systems engineering process throughout a CBTC upgrade project. They understood that CBTC might be applied in several ways across a variety of rail transit modalities. Because CBTC costs and associated advantages might vary greatly based on the precise nature and characteristics of the application, it is doubtful that the business case for one transit agency would be equally valid for another. Because of this, the approach taken in this study was to first identify the several components that could support an agency's business case for CBTC before determining those specific factors that were applicable at NYCT and SEPTA [17].

This study provides a deeper understanding of CBTC technology as well as a tool to assist in project planning, business case formulation, and management for transportation authorities considering launching a CBTC upgrade program. [17] provided the findings of an exhaustive investigation into the effectiveness of the project's implementation. In addition to a project narrative, two forms of analysis are provided: a quantitative cost-benefit analysis (CBA) and a qualitative analysis. The CBA considers aspects such as passenger wait and travel times, capital expenses, and operational and maintenance costs that may be described without relying too heavily on generic assumptions.

2.4.1Some Literature Review on CBTC System

The advantages and disadvantages of CBTC installations on various railway lines across the world were examined in a study by Xi'an Jiaotong-Liverpool University in China. According to the study, while CBTC has increased safety, capacity, timeliness, and maintenance benefits, it also has expenses associated with installing and maintaining hardware and software[11].

A second study conducted by the University of Birmingham in the United Kingdom assessed the financial viability of implementing CBTC on the West Midlands railway line. According to the analysis, there would be a net present value of £554 million if CBTC were implemented and the advantages outweighed the costs[18].

The international association of science and technology for development (IASTED) conducted research that evaluated the cost-benefit ratio of CBTC for the Tehran metro system in Iran. According to the calculation, the CBTC system would generate a net financial benefit of $4.04 million over its 20-year lifespan[5].

The differences, advantages, and difficulties of enhancing performance while retaining safety are demonstrated by the evolution of the rail signaling system from straightforward track circuit signaling to intricate CBTC systems. It explains how these systems have developed over the past three decades, going from roadside signals to cab signals to profile-based systems to communications-based train control systems, as a way of successfully overcoming the inherent weaknesses of the traditional track circuit-based system. Because of CBTC, which also provides safer train separation and enhanced train control flexibility, trains can run with noticeably less headway [18].

4.4.2 Evolution of Train Signalling/Train Control

CBTC systems improve train operations and administration by providing two-way train/wayside communications as well as more precise train location determination independent of track circuits. The operational and performance benefits of more advanced technical systems are underlined, as are the hurdles associated with their implementation. Furthermore, industry trends are explored, and the importance of standardization for communication-based signaling system operations is emphasized.

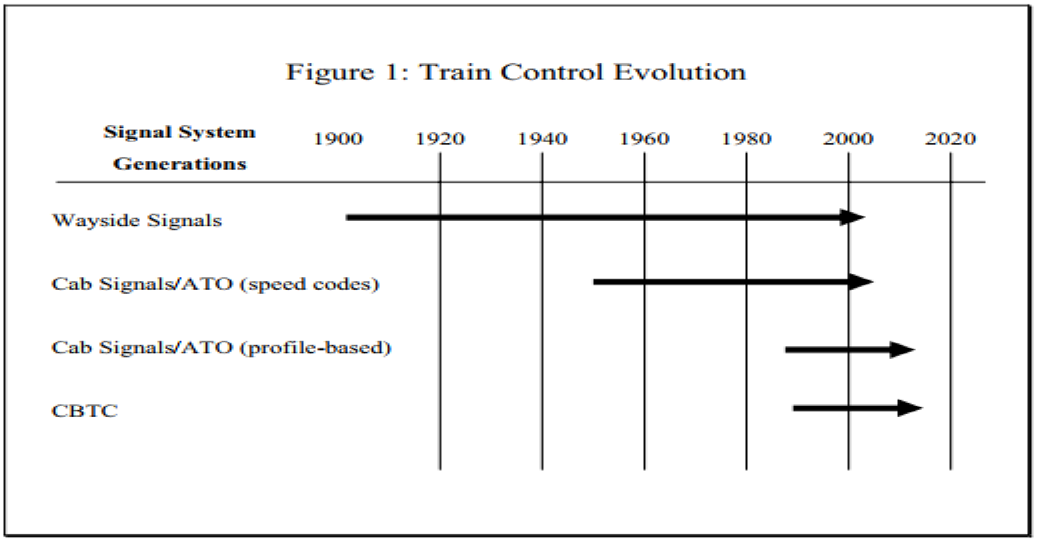


Figure 2.6: Train control evolution [11]

The traveler must receive high-quality services from modern train services during the entire voyage. These include increased safety, better performances, and fewer delays. In-train amenities like infotainment and accessibility to dependable communication systems are also necessary. In recent years, the railway sector has used a variety of communication systems kinds and generations. Early on in the development of the railway services signaling systems were employed[11]. The railway sector currently employs the second-generation communication system, also known as the global system for mobile communications (GSM), as well as the third-generation (3G) and fourth-generation (4G). In this essay, we provide a comprehensive review of the development, characteristics, and applications of railway communication systems. The technological challenges of in-train communications systems and potential solutions are also discussed, along with how data can be transported within and between coach cars using cutting-edge and hybrid communication technologies.

2.4.3 Applications of CBTC Signalling Systems in the World

CBTC technology has primarily been used in current subway systems. CBTC signaling systems are used on about 156 subway lines, as indicated in Figure 2.6. Furthermore, as indicated in Figure 2.7, half of these systems are employed in Asia. China, Japan, and India all have extensive metro systems, with the majority of them employing CBTC technology[8]. The United States and many European countries are also major users of CBTC signaling systems in their subway lines. To highlight some of the key metro lines used by the CBTC, here are some examples: Shanghai, Beijing, Guangzhou, Tokyo, Delhi, Singapore, Kuala Lumpur, Hong Kong, and so on.

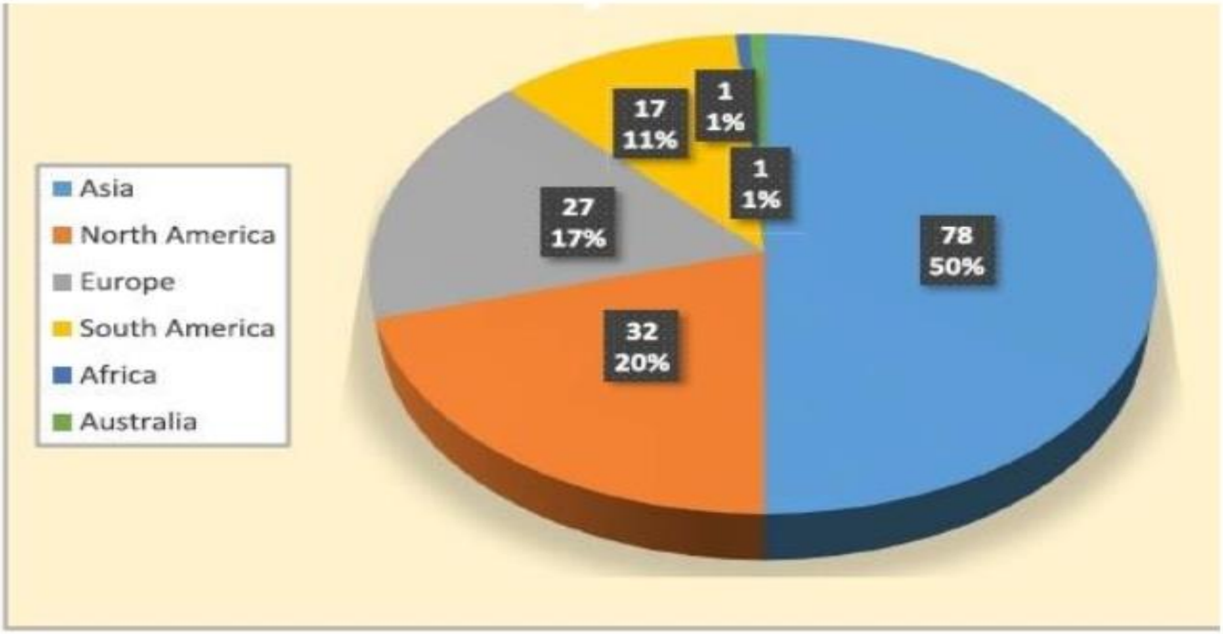


Figure 2.7: CBTC projects worldwide [8]

CBTC technology is utilized on several of Europe's major metro lines, including those in Madrid, London, Paris, Barcelona, Istanbul, Munich, and Amsterdam. The subway lines in New York, San Francisco, Las Vegas, Mexico City, Buenos Aires, and Sao Paulo all used CBTC signaling systems[8].

2.4.4 Technology Choice for CBTC System

There are several technology choices and categories involved in the operation of a Communication-Based Train Control (CBTC) system. These include:

1. Communication System: The communication system is essential for the operation of a CBTC system. It can be categorized into two types:

(A) Wayside Communication: This includes the use of wired or wireless communication systems to transmit train information between the wayside infrastructure and the trains.

(B) Train Communication: This involves the communication between various subsystems within the train, such as the on-board computers, sensors, and actuators.

2. Train Localization and Positioning: CBTC systems require accurate train localization and positioning for safe and precise train control. Some of the technology choices in this category include:

(A) Train-borne Sensors: This involves the use of sensors like accelerometers, gyroscopes, odometer systems, and GPS receivers to determine the train's position and speed.

(B) Trackside Beacons: These are physical markers placed along the track to provide additional reference points for train localization.

3. Train Control: CBTC systems rely on advanced train control algorithms to manage train movements and maintain safe distances between trains. Some technology choices in this category include:

(A) Automatic Train Protection (ATP): ATP systems monitor train movements and intervene if the train exceeds certain safety limits.

(B) Train Supervision: This refers to the central control system that monitors and manages train movements based on the information received from the wayside and train communication systems.

4. Human-Machine Interface (HMI): The HMI provides the interface for operators and maintainers to interact with the CBTC system. Some technology choices in this category include:

(A) Graphical User Interface (GUI): This includes user-friendly graphical displays and controls for operators to monitor train movements and intervene if necessary.

(B) Diagnostic Tools: These tools provide maintenance personnel with real-time information about the system's health and performance, allowing them to identify and resolve issues quickly.

5. Data Management and Analytics: CBTC systems generate a vast amount of data, which can be analyzed to optimize train operations and maintenance activities. Some technology choices in this category include:

(A) Data Storage and Processing: This involves the infrastructure and software required to process and store large volumes of data generated by the CBTC system.

(B) Predictive Analytics: By analysing historical and real-time data, predictive analytics can help identify patterns and trends, enabling proactive maintenance and operational improvements.

2.4.5 CBTC System Operation

CBTC exchanges train control information between the train and the wayside using high-capacity radio transmission. This would allow for train control functions, automatic train operation and supervision, as well as automatic train protection components. Simply put, the train's state, including speed, direction, and location, is communicated continuously to the wayside via a radio link[19]. As part of this system, the traffic control Center at the wayside gets information from the trains on the track and determines two factors: maximum speed and distance that the train is authorized to travel. The traffic control Center also handles a variety of other tasks, such as train scheduling and arrival time to destination [19].To ensure a constant connection, the CBTC system includes numerous Wi-Fi APs. These APs are arranged along the track in such a way that their coverage zones overlap. Each AP is then cable-connected to the traffic control Center and communicates with the train via a radio link. However, the installation cost of the cables that connect the APs to the roadside is very high and is regarded as one of the system's problems, reaching around 30000 EUR/km. The second problem is the handover procedure; the train should always be linked to an AP and should discover a new compatible AP as it goes. According to IEEE 802.11, the stages of the handover process are scanning, authentication, and re-association[19].

Scanning and authentication both contribute significantly to the process's delay. In general, active scanning is adapted in CBTC systems for latency reduction in such a way that the notification of searching for APs is made proactively by a node rather than waiting for APs announcement. To ensure a smooth transition, two or more radios are installed at each end of the train; while one of these remains linked to the previous AP, the other changes to another AP [20].

Transponders ("balises"), tachometers, Doppler radar, speedometers, odometers, and geolocation systems such as the global positioning system (GPS) are used in CBTC to assess train speed and location. Based on the data collected by such devices, the wayside traffic controller calculates the train's maximum speed and distance and sends it to the on-board equipment. The on-board equipment of the automated train control continuously adjusts the train speed and safety distance based on information received from the wayside ATC[21].When a train passes over transponders positioned between rails, the transponders transmit location information to the train via an antenna mounted beneath the track. Any mistakes in the location that may develop as the train goes will be corrected as soon as it passes the next transponder. Figure 2.8 depicts a high-level overview of the CBTC system.

CBTC systems' real-time information interchange explains why these systems might replace traditional systems. Using this technology minimizes the headway distance between trains, increasing line capacity and reducing the quantity of track-side equipment required by the previous system, such as color light signals and track circuits. The primary issue with using GPS is determining an accurate location when two trains are going very near to each other on the railway. Furthermore, CBTC providers do not rely on satellite signals inside tunnels. Furthermore, the GPS is regulated by an external authority, which makes CBTC suppliers cautious about relying on such a system, therefore its use in CBTC is supplemental.

As previously stated, typical railway train lines are divided into pieces. The major aim of these sections is to ensure that the separation gap between two adjoining trains is sufficient to stop the train in the event of a failure. These parts are known as blocks, and they are protected by a signal. Track circuits are placed to determine how the train moves within the blocks. The length of any section is determined by a variety of criteria, such as the maximum speed of the trains, the trains' braking capabilities, the bustle of the line, and the maximum allowable speed on the same line, among others.

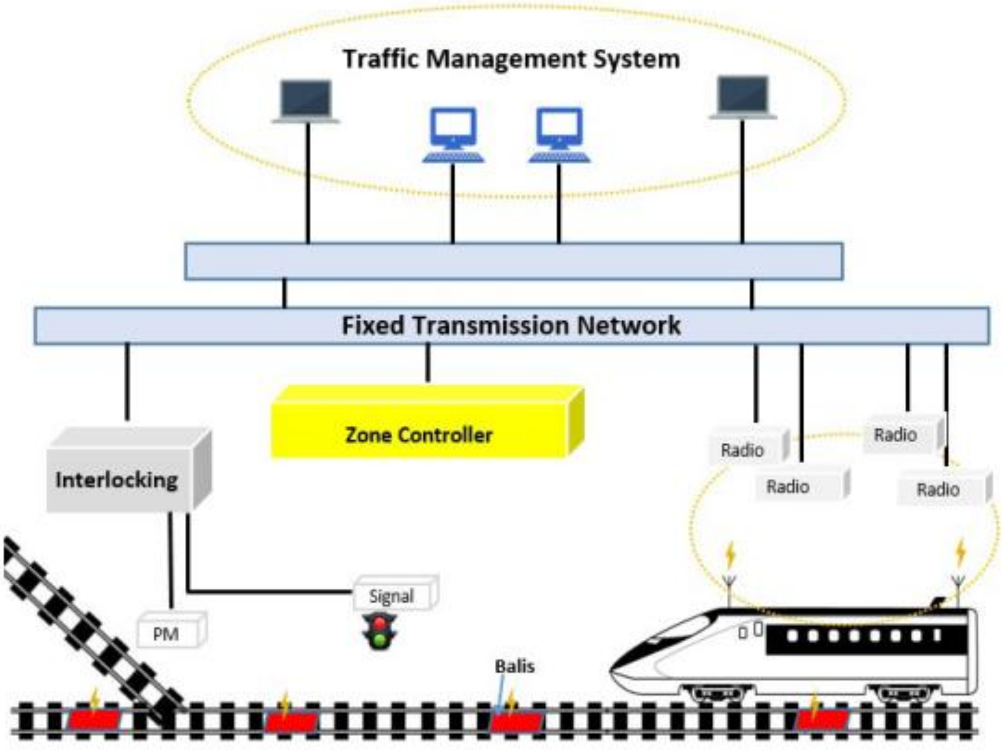


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Figure 2.8: Communications-based train control system overview [22]

If a train is found inside a block, no further trains are allowed to enter, and the entire block is considered occupied. These blocks are known as fixed blocks because their boundaries remain constant regardless of the train's speed or braking capacity[23]. Fixed block signaling, to put it simply, provides an artificial gap between trains.

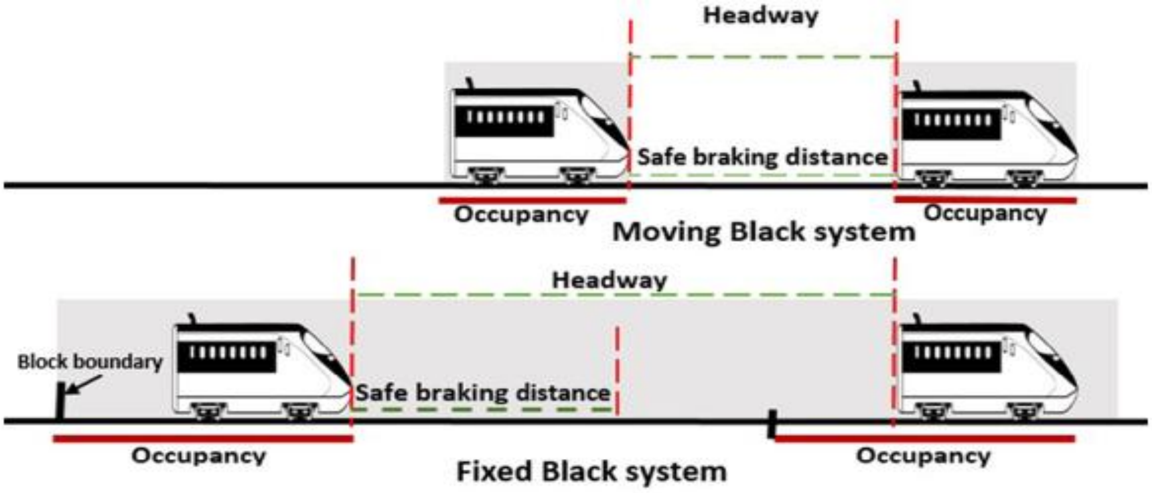


Figure 2.9: The difference between fixed and moving blocks [22]

Even though this technology has served the signaling community well for more than a century, urban growth necessitated the installation of a new, more dependable system to replace it. CBTC, on the other hand, employs moving block operation due to the utilization of real-time communication between the train and the wayside. Because the train's location is constantly rectified and updated, the occupancy blocks move with the train with no established limits, allowing trains to go closer to each other[24].The most significant advantage of this paradigm is that the safe braking distance is no longer constant but variable depending on the speed of the train; while the train is moving slowly; the headway is short and grows as the train speed increases.

As seen in Figure 2.9, which depicts stationary and moving blocks, the headway, or the gap between two trains following each other, is significantly large in conventional signaling systems compared to CBTC systems. This means that information such as location and train speed may not be received by the following trains on time. In such cases, the emergency brakes should be deployed, and the manual drive mode should be used.

2.4.6 CBTC System on GSM-R

GSM-R is an international wireless communication technology that has been provided specifically to European rail companies to replace the traditional railway communication system and to ensure that trains can safely travel to other nations without any communication concerns. The GSM-R mobile technology is a radio network that provides radio coverage for commuters as well as train workers. It is used to make phone conversations, send data, and control traffic. The communication between drivers and signalers is secure in this system since the train network is thoroughly covered, including deep cuts and tunnels. GSM-R and GSM systems are essentially identical; however, GSM-R has railway-specific functionality based on European norms and specifications.

Each driving cab has been fitted with a cab radio that the train's crew can utilize for communication. To configure the GSM-R system, dedicated base stations are erected alongside the train track. The distance between any two surrounding BSs varies by nation, depending on the local environment, for example, 3 to 5 km in China and 7 to 15 km in Europe[25].The cell range or area covered by each BS is around 8 km, and the frequency band used by the GSM-R system is approximately 800/900 MHz Extended GSM-R, on the other hand, refers to the use of extra frequency bands in GSM-R on a nationwide scale. These frequency bands are 873 to 876 MHz for up-link and 918 to 921 MHz for down-link, respectively[26].

The BSs are linked in groups and are managed by a base station controller (BSC). This BSC is also responsible for connecting the BSs to the mobile switching center (MSC). One of the mobile switching subsystems (SSS) is the MSC. The MSC is the network core that is in charge of connecting system users and controlling user mobility. Furthermore, its gateway is responsible for linking the GSM-R network to other public networks. The dynamic database and visitor location register (VLR) are the SSS's second functions[27]. When a mobile station moves to a new control area, the home location register (HLR) transmits the necessary data to the new VLR, such as location registration; the VLR maintains user information triggered by the HLR. The journey details should be entered into the train's cab radio by the driver for the GSM-R system to track the train's position and give services to that train[27].

The GSM-R system provides its users with a variety of services. Some of the services provided by the system include point-to-point and group conversations. The former is similar to a typical telephone connection in that it is between two users only, while the latter is a group call in which utilizing the press to talk is essential to participate in the call conversation[28]. Every user in the GSM-R area targeted by the group call will be linked to the conversation and will be disconnected when they leave the targeted cell or region. Another feature provided by the GSM-R is operational text messages. GSM-R users (drivers, signalers, and controllers) can send various operational text messages to improve communication, such as contact signaler, wait, standing at signal, and acknowledge. Figure 2.8 depicts the GSM-R system architecture[28].

The signal transmission in the GSM-R system is hampered by shadowing and the multipath effect. The proliferation of both GSM-R and public networks has caused electromagnetic interference between them. The arcing between the contact wire and pantograph during the current collection operation is the second source of conducted and radiated Electromagnetic interference[29].This is a typical event in electrified railway systems, and it occurs more frequently at higher speeds and loads. This interference may cause considerable communication disruption as well as network loss along the rail tracks. To reduce the influence of EM interference on the performance of GSM-R systems, a variety of methods have been offered in the literature, including increasing the coverage level, signal processing at the receiver, and improving the reception component of the trains.

The GSM-R's capacity is limited by its dedicated frequency bandwidth and circuit-switched design. Only frequency channels are available in the GSM-R systems' allocated 4 MHz bandwidth, which causes some technical challenges while delivering services to all trains in congested locations at the same time[30]. In certain cases, such as high traffic volumes, circuit-switched cannot guarantee reliable voice and data transmission at the same time, necessitating the use of an alternative technique. In such instances, packet-switched services based on general packet radio service (GPRS) and enhanced GPRS (EGPRS) can be utilized to expand the capacity of GSM-R systems by better utilizing the frequency spectrum. Another problem of the GSM-R technology is its capability. The limited transmission rate and system delay make real-time applications and emergency communication difficult to support. The GSM-R Gaussian minimum-shift keying (GMSK) modulation technique is substantially less flexible in terms of assigning resources to customers than the LTE-R orthogonal frequency-division multiple access (OFDMA) modulation scheme [30].

Even if GSM-R continuity is guaranteed for the next few years, due to the aforementioned restrictions, a switch to another system that can overcome these limits is required. At the moment, LTE-R based on LTE standards may be a better contender to replace the GSM-R system. Because it is a completely packet-switched network, the deployment of LTE-R systems can improve the capacity and capabilities of HSR communication systems[27].Furthermore, LTE-R's enhanced multiplexing and modulation can boost spectral efficiency.

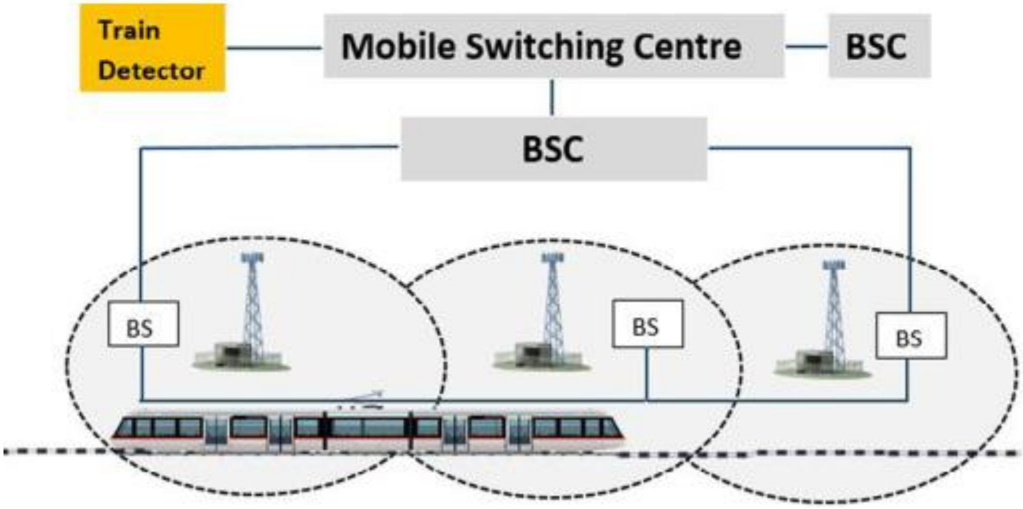


Figure 2.10: GSM-R system architecture [22]

Furthermore, LTE is a well-established and off-the-shelf system, and the coexistence of earlier HRS communication and LTE-R is expected to endure for some time, which significantly supports the transition from GSM-R to LTE-R[25].

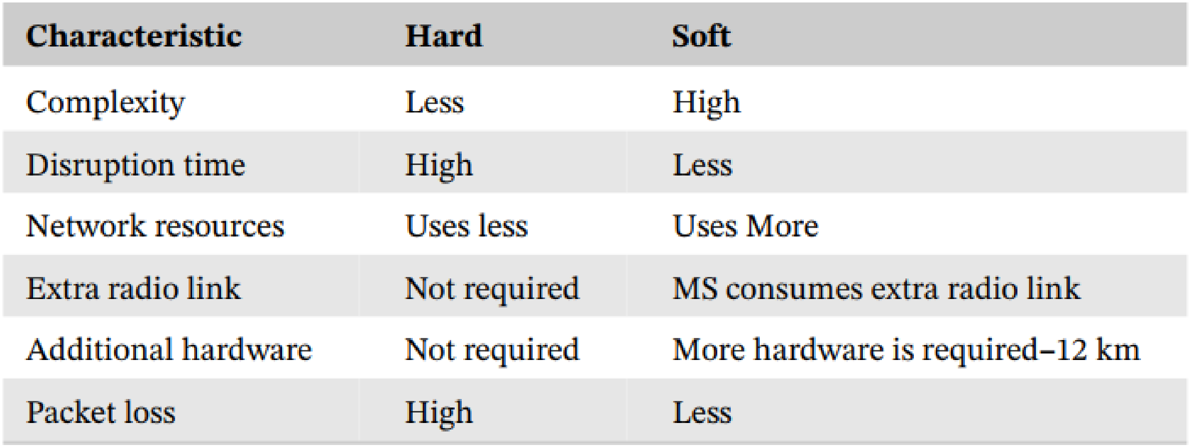
2.4.7 CBTC System on LTE-R

Because of the essential stability and availability of the railway communication system, public networks have evolved from systems with limited capabilities, such as GSM, to systems that can give better performance in terms of data rates, such as LTE. The primary goal of these technologies was to improve wireless network speed and capacity. At the beginning of the previous decade, new digital signal processing and modulation techniques were used to achieve this goal[30].Another goal was to simplify the system architecture by switching to an IP-based network, which has lower transmission latency than earlier wireless systems. LTE-R, which is based on LTE standards, is now seen as the greatest contender for replacing the current railway communication system. In this context, the International Union of Railways (UIC) made preliminary suggestions on the viability of utilizing standard LTE as a substitute for the current train communication system. However, the first LTE-R network is expected to be operational in some nations by the beginning of the next decade. Figure 4 depicts the evolution of wireless communication networks from GSM to 4G[27].In comparison to the GSM-R system, the LTE-R system provides a higher data rate of up to 50 and 10 Mbps for the down-link and up-link, respectively. The handover process in a GSM-R system is a hard change, which means that the MS's connection with the current BS is completely severed before it is transferred to the destination BS. Break-before-make is another name for this handover procedure. Although this process appears to network users to be flawless, a brief gap in the connection can be detected, especially during high-speed movement of the train, which generates frequent handovers during one conversation. Unlike the GSM-R system, which employs hard handover, the LTE-R system uses gentle handover between BSs. The MS is always connected to at least one channel in this configuration. This is known as make-before-break because the MS maintains the connection to the previous BS until it connects to the target BS[31]. When the MS is in the overlapping area coverage of neighboring BSs in the downlink direction of the soft handover scenario, the signals received from these BSs are mixed at the receiver. In the uplink direction, however, the signals from the BSs are compared frame by frame, and the best one is chosen. Although the make-before-break procedure is more difficult than the hard handover method, it can significantly improve QoS by lowering the likelihood of call drop and removing interference[30].

However, this is seen as one of the system's key issues. The system is designed to support high-speed trains traveling at speeds of up to 500 km/h. Because of the rapid speed of trains and the tiny area covered by each BS, the number of handovers between cells in the LTE-R network is growing. To begin the handover process in an LTE-R system, the user equipment transmits the signal strength to the serving cell, which determines whether or not the MS needs to be connected to the target cell[28]. If a handover is required, the current cell sends a handover request message to the destination cell, and the target cell sends an acknowledgment message if the handover request is accepted.

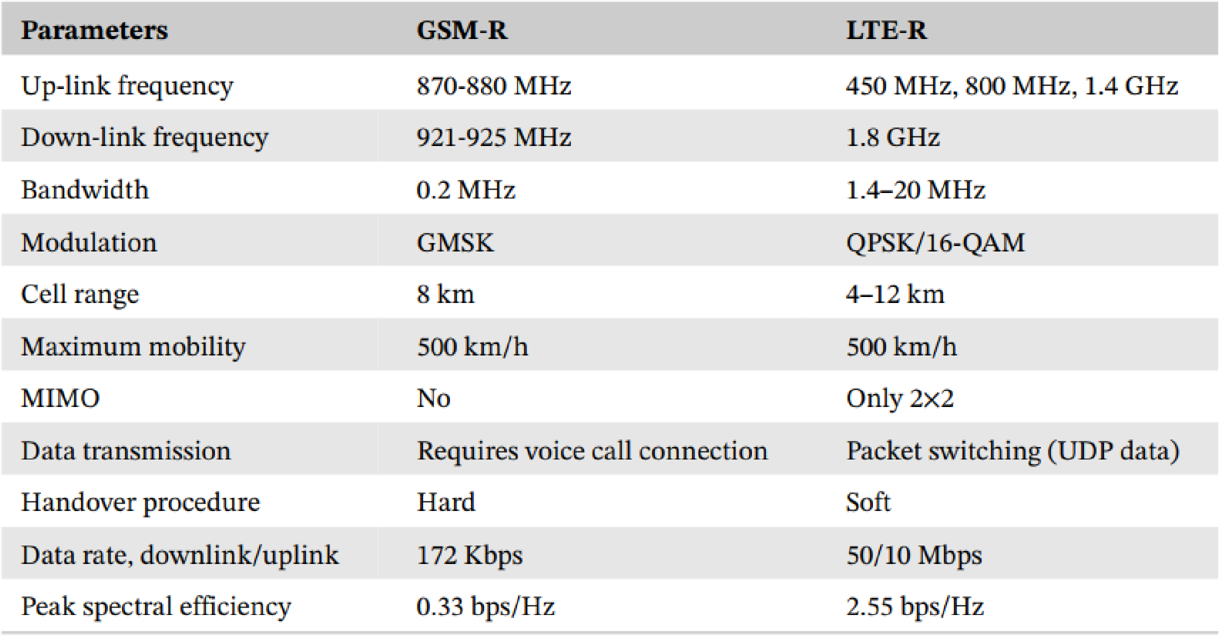
The proper utilization of the frequency and spectrum of LTE-R is critical to provide a stable and efficient communication system for HRS. Currently, 1 GHz bands such as 1.8, 2.1, 2.3, and 2.6 GHz are where the majority of LTE systems operate[27].Furthermore, it is well known that propagation loss and fading are much worse at higher frequency bands. As a result, lower frequency bands ranging from 450 to 470 MHz have been frequently studied for HRS.

Table 2.3: Characteristics of hard and soft handover processes



Characteristic	Hard	Soft
Complexity	Less	High
Disruption time	High	Less
Network resources	Uses less	Uses More
Extra radio link	Not required	MS consumes extra radio link
Additional hardware	Not required	More hardware is required–12 km
Packet loss	High	Less

Table 2.4: GSM-R and LTE-R parameters



Parameters	GSM-R	LTE-R
Up-link frequency	870-880 MHz	450 MHz, 800 MHz, 1.4 GHz
Down-link frequency	921-925 MHz	1.8 GHz
Bandwidth	0.2 MHz	1.4–20 MHz
Modulation	GMSK	QPSK/16-QAM
Cell range	8 km	4–12 km
Maximum mobility	500 km/h	500 km/h
MIMO	No	Only 2×2
Data transmission	Requires voice call connection	Packet switching (UDP data)
Handover procedure	Hard	Soft
Data rate, downlink/uplink	172 Kbps	50/10 Mbps
Peak spectral efficiency	0.33 bps/Hz	2.55 bps/Hz

There are some variations between public LTE and LTE-R networks, such as network layout, architecture, network configuration, and QoS. In the configuration of LTE-R networks, dependability takes precedence over capacity[27].Although capacity is less important than reliability in LTE-R, the LTE-R cell can service trains at one of the key rail stations at the same time, and the capacity provided by the cell is sufficient to serve additional trains at the same time. The LTE-R network is designed to function at high speeds of up to 500 km/h, even in complicated railway situations[32]. A rising number of research projects have been conducted to demonstrate that LTE-R can meet railway standards[33]. These studies' simulation findings and technical analysis have demonstrated that the LTE-R system is the chosen contender for the future of the railway communication system.

LTE-R can provide a variety of services that can considerably boost railway capacity and passenger capacity. To increase tracking accuracy, on-board technology detects the train's location; this information is then transferred via wireless connection with a latency time of less than 50 ms, which is termed real-time transmission[27].The system also provides real-time train, weather, and railway infrastructure video monitoring with a transmission latency of less than 300 milliseconds. The LTE-R system enables railway emergency communications in the event of natural disasters or incidents that may disrupt railway users. In such instances, instant voice, video, and data links can be established between the accident site and the control center. Other services that the LTE-R system can give to train passengers include seat reservation, electronic ticketing, and interaction of passenger information [2].

There are numerous challenges related to the use of LTE-R. One of these challenges is the coexistence of the LTE public safety network and the LTE-R network. Essentially, public safety networks such as police, fire fighters, and ambulances, as well as LTE-R networks, use the same frequency bands, 718 to 728 MHz and 773 to 783 MHz for up-link and down-link, respectively. As a result, one of the primary issues is determining how to reduce radio interference across both networks, as both are concerned with dependability and safety[2]. Train mobility causes Doppler shift, which is a shift in the received frequency and, in some situations, a phase shift of the signal, which can hamper the reception of angle-modulated signals. However, tracking and compensation are possible for the Doppler shift as trains move with a well-known speed and the position and real-time are recorded.

Propagation loss in HSR locations such as cuts, tunnels, bridges, and train stations can have a significant impact on LTE-R system performance. Although certain measurements were taken to define the channel for such situations, it is critical to construct a channel model that can fully reflect the transmission channel in HSR scenarios[34]. Other problems to consider when developing an LTE-R system include significant Doppler dispersion, which can cause signal-to-interference-plus-noise ratio degradation and OFDM corruption. Furthermore, delay spread can result in a loss of orthogonally between OFDM subcarriers and a certain type of guard interval. Furthermore, in train communication systems, linear coverage with directional antennas is used. Although this type of coverage uses less power and delivers greater performance, the impact of shadow fading causes outages at some rail stations[35]. Due to these constraints, as well as the need for high-capacity communications for the future generation of railway passengers, developing an alternative technology to the current railway communication systems has become required. However, the challenges of providing essential services, as well as focusing on QoS, dependability, and capacity, should be the primary concerns of the prospective technologies for future railway communication.

2.4.8 CBTC System on Fifth Generation (5G)

The next development in mobile communication technology is called fifth generation (5G). The following list outlines the anticipated requirements that must be met in order to experience 5G, while additional requirements may arise in order to meet user demands.

- High data rate: To accommodate the high data traffic the data rate should be as high as 10 Gbit/s.
- Capacity: Massive devices connectivity will emerge in 5G due to the Internet of things. The capacity and the number of device connectivity should be high.
- Efficiency: 5G's overall energy usage in terms of energy/bit must be significantly lower to make it a sustainable technology. To achieve longer battery life, 5G mobile terminals will demand decreased power usage.
- Mobility: In high-speed vehicular environments also there an increase in the demand for data rate. In high-mobility conditions with speeds of up to 500 km/h, 5G will need to provide faster data rates.
- Spectral efficiency: The reuse of frequency to meet the demands of 5G is also challenging. Hence the use of the range of frequency also plays important role in 5G.

2.4.9 Network Architecture for 5G-R

In many ways, the requirements of the public mobile communication network and the network architecture for railways are distinct. First, a specialized communication transmission network connecting the dispatching center at all levels should form the foundation of the railway network architecture. This guarantees that all components communicate with one another via various information channels, including video monitoring data for smart rail infrastructure, train operation control data, and voice conversations between the train driver and dispatching center. Furthermore, the rail communication network aims to create a dependable and integrated emergency command system that would use current scene information as a basis for decision-making in emergency situations (such as traffic accidents or natural disasters). Furthermore, dependable operations, specialized machinery, prompt transmission, and other elements all contribute to the particular performance needs of train operation and control.

2.4.10 Ethio-Djibouti Line Communication Architecture

The rugged area between Ethiopia's central levels and the border with Djibouti is home to the Addis Ababa-Djibouti railway line. The line begins in Sebeta, southwest of Addis Ababa, and runs westward. Labu, Indode, Gelan, Dukem, Bishoftu, Mojo, Adama, Welenchiti, Metehara, Awash, Asebot, Mieso, Mulu, Afdem, Bike, Gota, Dire Dawa to Dewele, and finally reaches Djibouti are all along its eastward path. After then, it goes by Holhol and ALI-SABIEH until ending at Nagad [36]. Figure 2.11 below shows the actual route of the Addis Djibouti line.

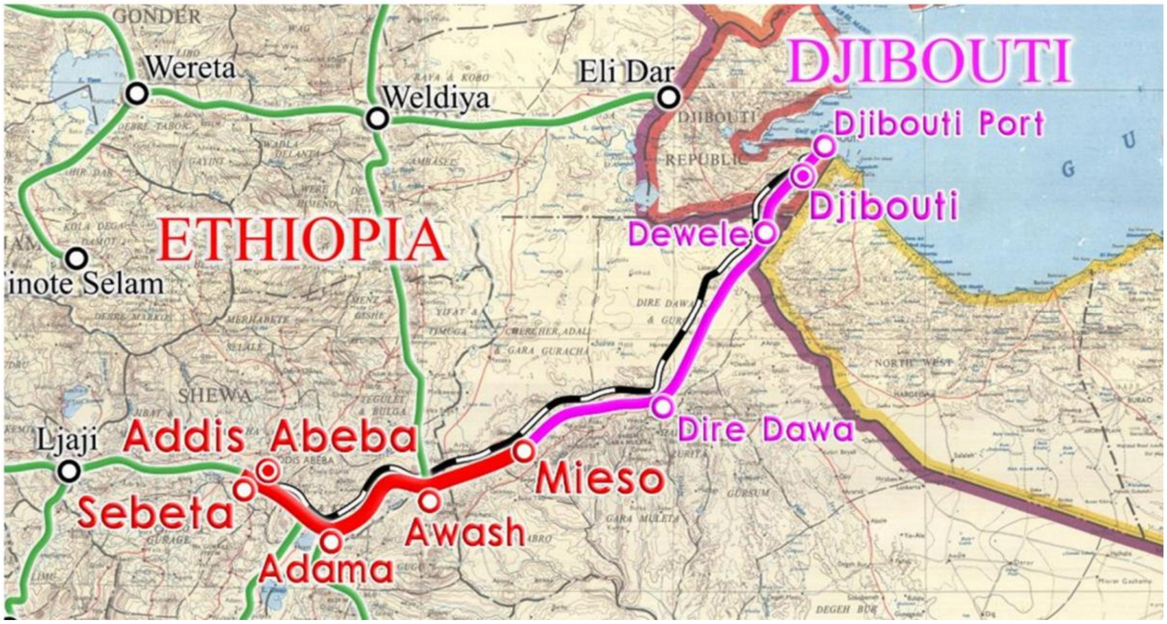


Figure 2.11: Addis Ababa-Djibouti Line [36]

The railway line is electrified and intended for both freight and passenger trains. The design speed of freight trains is equal to or less than 80 km/h, while the design speed of passenger trains is equal to or less than 120 km/h [36]. The entire international railway line from NAGAD to SEBETTA is 743.245 kilometers long. The included stretch of the double-track railway is 113.836 km long, has seven stations, and an average distance of 16.26 km between two stations [36].

The section from ADAMA (excluded) -MIESO (included) is single track railway, with a length of 213.418km, 12 stations, an average distance between two stations 17.78km. The section from

MIESO (excluded) - DEWELE (included) is single track railway, with a length of 334.014km, 21 stations, an average distance between two stations 15.91km. The section from DEWELE (excluded) -NAGAD (included) in single track railway, with a length of 81.977km, 5 stations and an average distance between two stations 16.4km [36]. In the initial stage (2020), 20 stations are constructed; conditions are reserved for construction of 5 stations in short term (2025) and 20 in long term (2035) [36].

2.4.10 Communication System Architecture

The communication architecture of the Addis Ababa-Djibouti Line is shown below

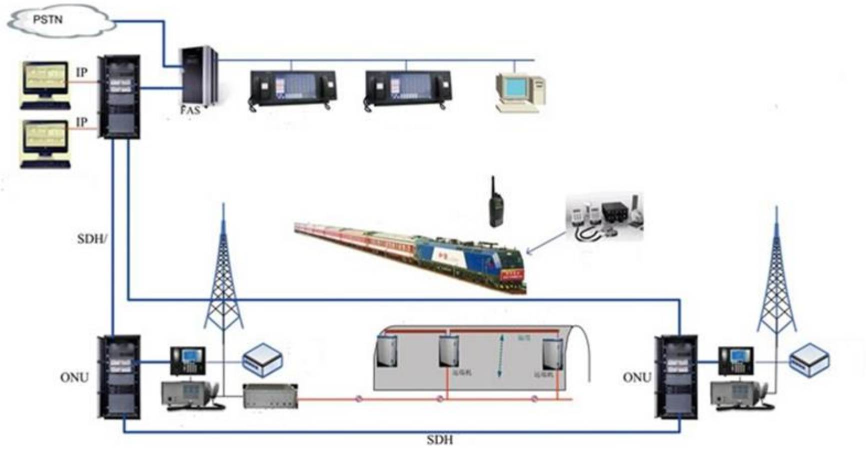


Figure 2.12: Addis-Djibouti Communication Architecture [37]

The communication network consists of [37]:

- Communication carrying network: including multi-service transmission system, access system and communication lines.
- Communication service network: including dispatching communication, private communication, in-station communication system and official telephone system
- Communication supporting network: clock synchronization system.

2.4.11 Addis-Djibouti Signalling System

The Sebeta-Nagad Railway's signalling system makes use of semi-automatic blocks. Computer interlocking inside station with 97-type 25Hz phase-sensitive track circuits used in a station, axel counters used between stations, and various equipment are employed in the station and approach section to assure train safety operation. [37].

2.4.12 Material required for CBTC implementation

The implementation of a Communication-Based Train Control (CBTC) system requires various materials and components. Here is a list of some essential materials and components:

1. Wayside Equipment:
   - Wayside signaling equipment (including signals, switches, and crossings)
   - Track circuits or axle counters for train detection
   - Wayside radio or wireless communication equipment
   - Power supply and distribution equipment for wayside components
2. On-board Equipment:
   - On-board signaling equipment for train control and communication
   - Train control computers and processors
   - On-board radio or wireless communication equipment
   - Positioning sensors (such as accelerometers, gyroscopes, odometer systems, or GPS receivers)
   - Train-to-ground communication antennas or transceivers
3. Control Center and Back-office Equipment:
   - Centralized control Center with computer systems and servers
   - Operator workstations with graphical user interfaces (GUI)
   - Network infrastructure for data communication
   - Backup power supply systems (e.g., uninterruptible power supply or generators)
   - Data storage and processing systems for analytics
   - Cables and Wiring:
   - Power cables for supplying electricity to wayside and on-board equipment
   - Data communication cables (e.g., Ethernet or fiber optics) for connecting various components
   - Wiring and harnesses for connecting onboard components
4. Ancillary Equipment:
   - Mounting brackets, enclosures, or cabinets for housing wayside and on-board equipment
   - Cooling systems for maintaining optimum temperature inside equipment enclosures
   - Lightning protection and surge suppression devices

- Safety equipment (e.g., barriers or fences) for protecting wayside equipment from external damage

5. Documentation and Manuals:

- System manuals and documentation for installation, operation, and maintenance
- Training materials for operators, maintainers, and technicians
- Configuration and software documentation for system customization and updates

2.4.13 Complexity of the CBTC System

In principle, solving the technical challenges of the CBTC system does not imply achieving feasibility; there is a large gap between dependability and safety in engineering. The research & development, engineering, and industrialization of rail transit CBTC signaling technology is a typically complicated system [12]. As an intelligent complex safety control system, CBTC systems must operate safely and reliably in a variety of weather conditions throughout their entire life cycle, as well as achieve collaborative control (among humans, trains, and railroads) with complex multivariate parameter characteristics.

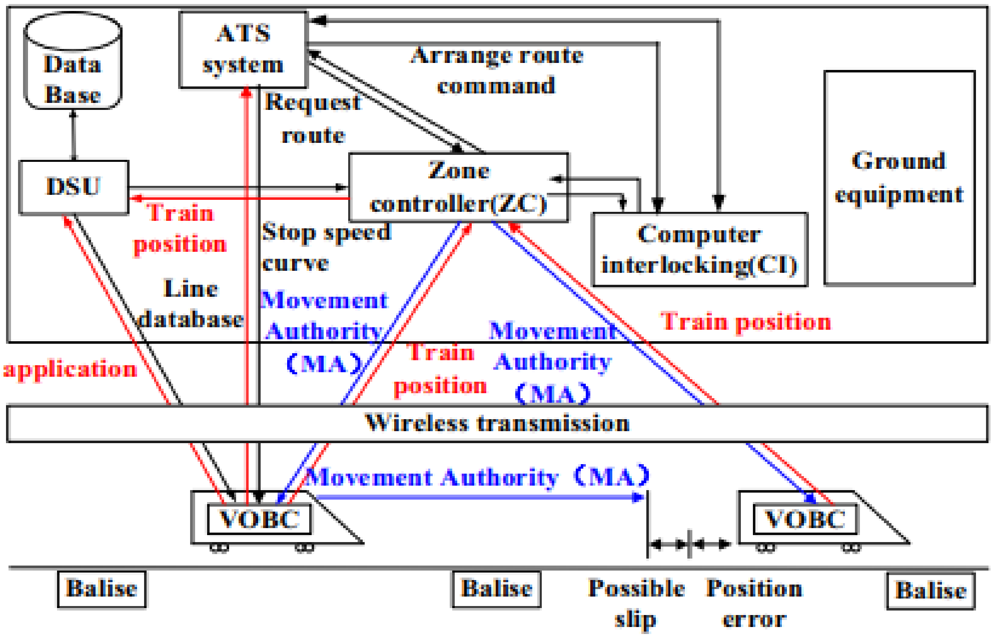


Figure 2.13: CBTC system structure [22]

Nowadays, most CBTCs use wireless local networks (WLAN) technology to transmit data. However, due to the train's high operating speed in urban rail transportation, WLAN technology is unable to fully meet the information transmission needs while the train is moving at a high pace. Due to its quick transmission speed, long-term evolution (LTE) technology is better able to cope with the real-time requirements of information transfer on trains and the ground [36].

In today's urban rail travel, LTE technology has turned into a focus of communication technology development. The use of LTE technology in urban rail transit has been the subject of numerous research, although little is known about the dependability of LTE-based train ground communication systems when using experimental data. The economic viability of a technical solution is frequently evaluated through the use of forecasting, network design, and investment analysis tools. New technologies or services are being developed over time by service providers. Implementing this new service and making necessary technical modifications will cost a lot of money[13].

TEA is regarded as a highly important instrument for evaluating the financial performance of industrial operations. Because of the overall competitiveness among firms across numerous industries, the TEA request has recently grown enormously. Furthermore, as a result of the industrial revolution, industrial processes are being turned into smart industries to protect the integrity of TEA[37].

TEA is a procedure and one of the most significant activities in the evaluation of the economic viability or feasibility of new products or services during the development phase. While this is not typically a characteristic of early research initiatives, it becomes increasingly important as one progresses down the innovation pathway toward successful commercialization TEA also provides insight into areas where more research and development could be focused to get the greatest economic improvement, maybe by substituting an expensive raw material or increasing the yield in a certain process step. This type of study expresses the service or product's expected selling price and manufacturing costs (input costs) at the market[18]. This type of data is used to forecast future cash flows and the likelihood of an investment's return. A project's net present value (NPV), which must be larger than zero, or internal rate of return, for example, must pass a specific test in discounted cash flow (DCF) models, which are indicators of a project's feasibility. Fully absorbed cost of production (FACP) is another name for single-year costing (SYC)[32].

However, one method of valuing intellectual property before licensing is also done using TEA. To determine which production processes and input components will generate the best-predicted revenues, various possibilities or alternatives can be related during TEA. Because the process is predicated on assumptions, it is crucial to continually assess the feasibility of changing these assumptions. Sensitivity analysis in this context enables a comparison of the size of the impact of modifying processes and economic parameters[16]. TEA is used to quickly assess the effects of various production strategies, choice of unit operations, assumptions regarding the production process, scale of production, scheduling, raw materials, consumables, etc. on OpeEx and CapEx. To direct process research and development efforts, it also identifies variables that affect CapEx and the cost of products sold. Finally, it is useful to determine the production scale required and the profitability of the selling price for a specific set of process assumptions[13].

Techno-economic analysis also referred to as TEA or techno-economic assessment, is a method for assessing how economically efficient industrial processes are. The technique used to demonstrate TEA involves several thorough evaluations, including process design, process modeling, equipment sizing, capital cost calculation, operating cost estimation, and cash flow analysis[38]. A high degree of demand for more complicated issues would necessitate paying close attention to numerous economic indicators (such as factory operation, design, transportation, market behavior, etc.). Depending on the level of views, TEA often employs a variety of modeling methodologies at achievable scopes. TEA is crucial for assessing the viability of industrializing or scaling up certain processes and technologies. Additionally, TEA employs predetermined assumptions and parameters for a variety of resolutions. Numerous decisions have been made conservatively over the past few decades based on an analysis of economic factors like net present value (NPV), payback period (PBP), internal rate of return (IRR), return on investment (ROI), discounted cash flow rate of return (DFROR), capital cost, general costs, profit or revenue, economic potential, overall economic feasibility, and process factors[37].

Technical economic analysis is necessary to make a variety of analyses, including those related to the design of technology projects, project capital costs, operation and maintenance costs, and operational cash flows. These studies are remarkably consistent, and each stage of the investigation requires a variety of skills and equipment[6].

TEA is a methodological approach for examining the technical and financial efficiency of a process a product or a product system. It has been widely used to evaluate systems across various industries and is an essential assessment tool for adopting cost criteria and the possible economic viability of innovations. However, additional upstream and downstream processes may also be included. It typically focuses on the production phase. Additionally, it can be applied to quantify the selling price of the finished product and improve process design[39].

2.5 CBTC Systems Integration

To communicate with the train and track equipment, a communications-based train control system uses communications to manage traffic and control infrastructure. With CBTC systems, a train's precise location is known with greater accuracy than with traditional signaling systems. As a result, it is easier and safer to manage railroad traffic. Increased headways can be achieved by metros (and other rail networks) while maintaining or even improving safety[3]. The IEEE 1474 standard states that automatic train control is constant. The Central Train Control (CBTC) system is an "ATC system utilizing continuous, high-capacity, bidirectional train to wayside data communications; high-resolution train location determination independent from track circuits; and train borne and wayside processors capable of implementing automatic train protection functions, as well as optional automatic train operation and automatic train supervision functions.". CBTC can be classified [5] according to their operational requirements.

The wayside equipment is dispersed throughout the route in current CBTC systems, and the trains regularly identify and communicate their status to it via radio. This status includes the precise location, speed, direction of travel, and stopping distance, among other things. Using this data, it is possible to determine the area that the train might conceivably occupy on the track. It also allows the wayside equipment to signal which sections of the track other trains on the same track are not permitted to use. These characteristics are supplied to the trains so that they can change their speed automatically and continually while maintaining the essential levels of comfort and safety (jerk). As a result, trains can adjust their safety distance in response to constant information regarding the distance to the train ahead [4].

For train control and signaling, the Ethio-Djibouti railway line network currently uses a traditional signaling system with line side signals and intermittent automatic train protection. The best technological solution or clarifications discovered is a balise system that complies with ERTMS Level 2 and is free of line signals. The wayside transmission unit called Balise makes use of magnetic transponder technology. Its main use is for signal transmission and reception across the air gap. A single device installed on the track can communicate with a train that is crossing the Balise. Level 2 calls for constant GSM-R connectivity between the train and trackside as well as oversight of train movement. In this instance, line side signals are optional, and trackside equipment outside the purview of ERTMS handles train identification and train integrity checks.

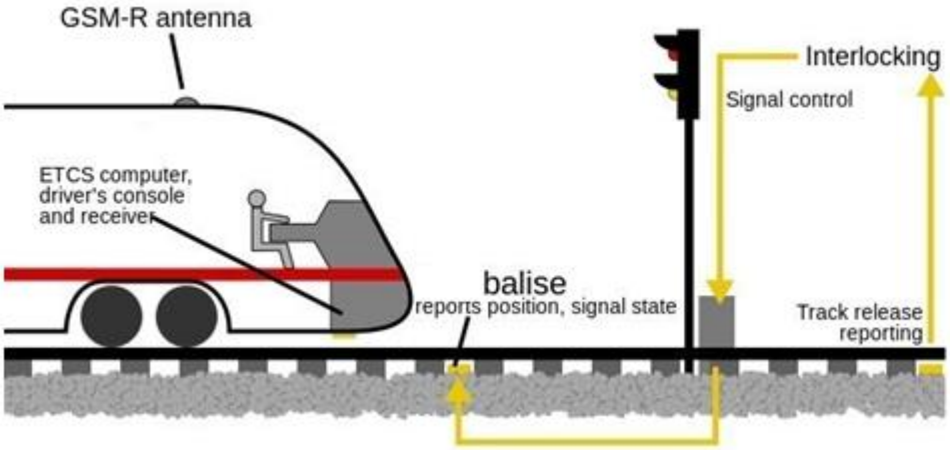


Figure 2.14: ERTMS Level 1

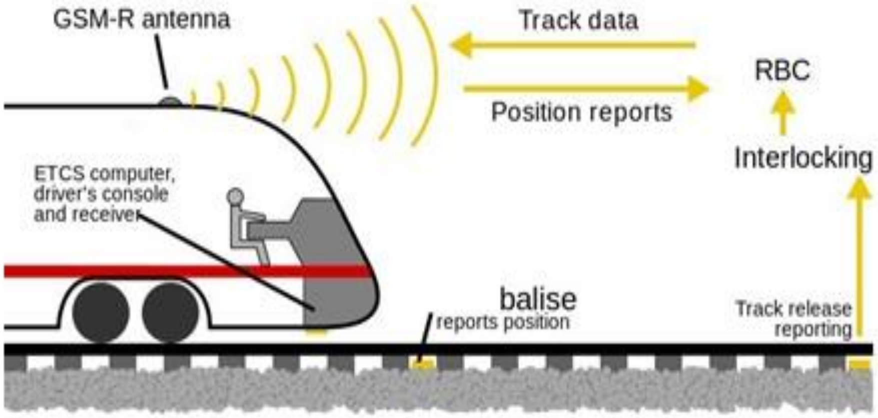


Figure 2.15: ERTMS Level 2

In level 1, the movement of the train is continuously monitored (the onboard computer continuously calculates the braking curve to the end of the movement authority and monitors the maximum allowable speed). Communication between the train and trackside at Level 2 is intermittent and typically made by Eurobalises. Level 2 demands continuous train movement control as well as continual GSM-R communication between the train and the trackside. Level 2 calls for ongoing GSM-R communication between the train and the trackside as well as continuous train movement control. Line side signals are not required in this scenario, and trackside equipment not controlled by ERTMS handles train identification and train integrity checks. The ground-based balise is an inert device that passively gathers energy from passing trains and then sends telegram signals to the train's BTM (balise transmission module) to tell it of its location[6].

2.5.1 System Architecture of CBTC System

The CBTC System is comprised of four major subsystems: ATS equipment, Wayside equipment, train-borne equipment, and data communication equipment. The block diagram of the CBTC System is described below.

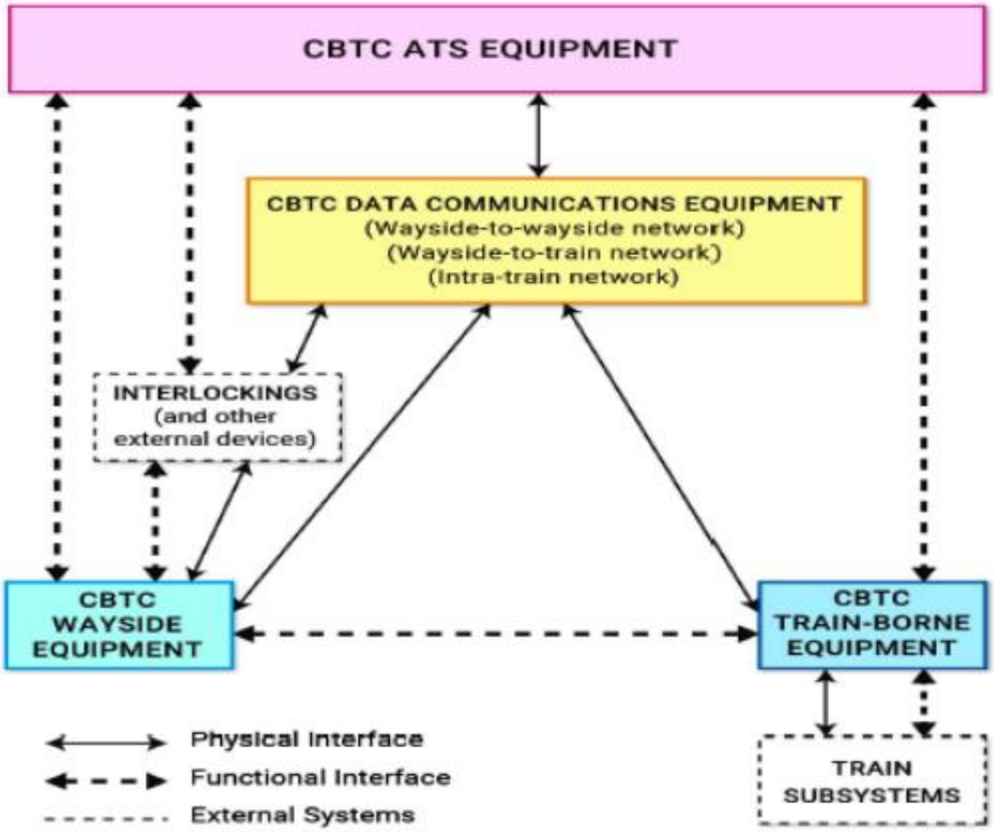


Figure 2.16: Block diagram of CBTC system design[7]

2.5.2 Moving Block Principle

Using the moving block principle, the CBTC system dynamically calculates the safe separation behind the leading train based on maximum operating speeds, braking curves, and train placements on the alignment. Due to the great resolution of position reporting, a following train may proceed as close as a safe braking distance to the latest verified position of the rear of a preceding train, depending on the current actual speed. The safety buffer, also known as a movable block, follows the train as it travels. The graph below depicts the braking curves of three distinct trains when service brakes are deployed, taking their velocities and the location of the preceding train into account.

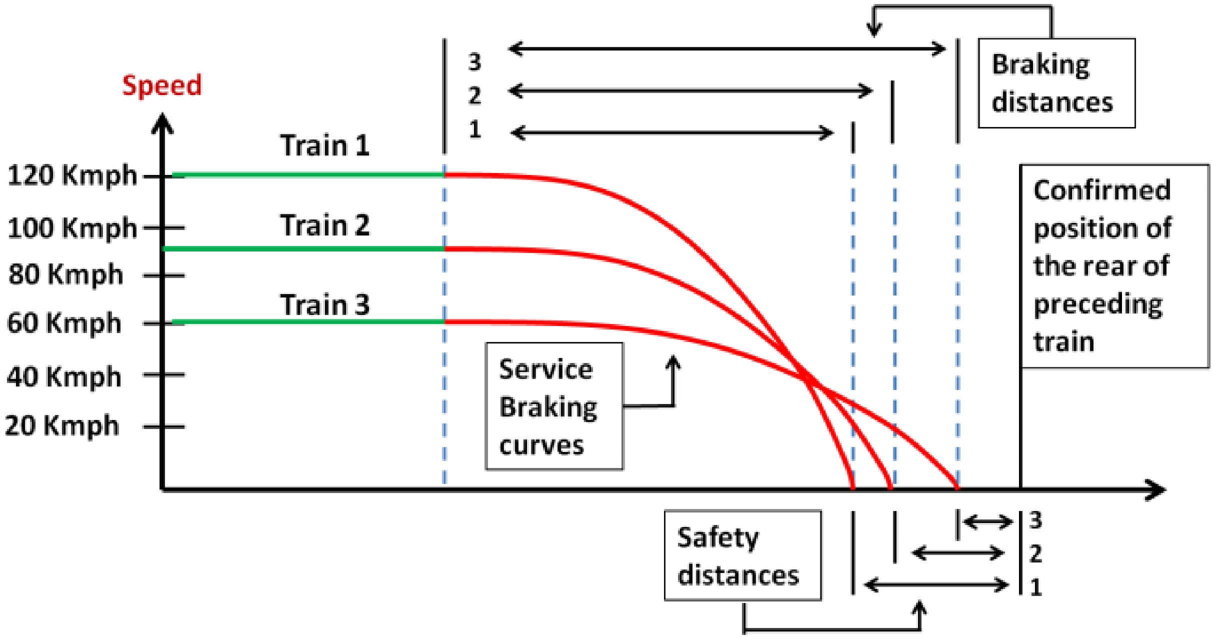


Figure 2.17: Service braking curves for trains with different speeds [22]

It is possible to reduce train separation, increase capacity, and assure safe braking distances in a moving block system by employing a data connection with an onboard controller (i.e., by removing the usage of wayside signal protection)[40]. The safe braking distance is the distance between the next train's ordered stopping point and the confirmed position of the previous train. This separation was established to provide safety in the face of many worst-case scenarios. Critical surveillance of safe train separation is carried out by alerting the onboard subsystem of the maximum authorized train speed and the present stopping position.

The communication is cycled and updated to provide the train with access to current information. As a result, the train can run safely within the limits set by the maximum ordered speed, the confirmed stopping location, the braking curve, and the track grade.

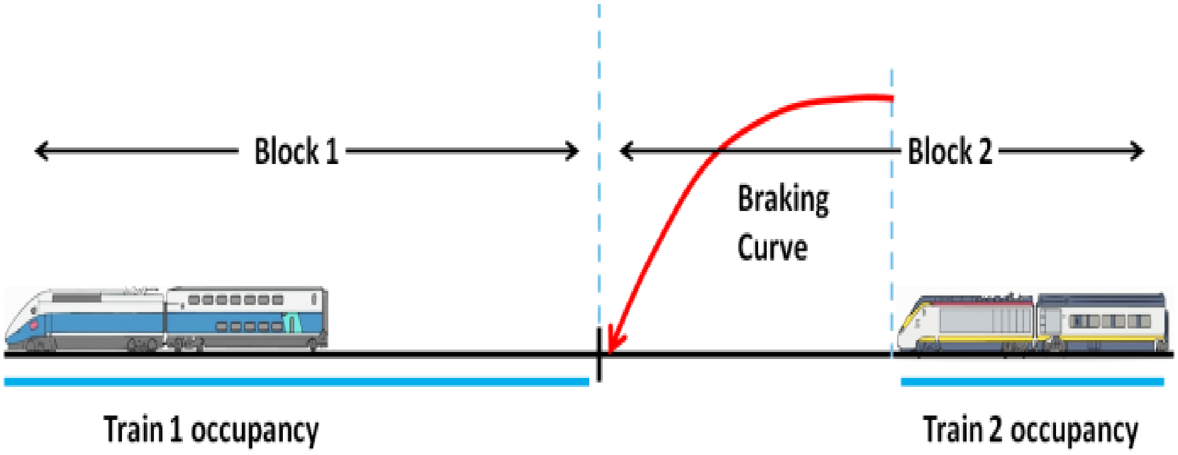


Figure 2.18: Fixed Block working

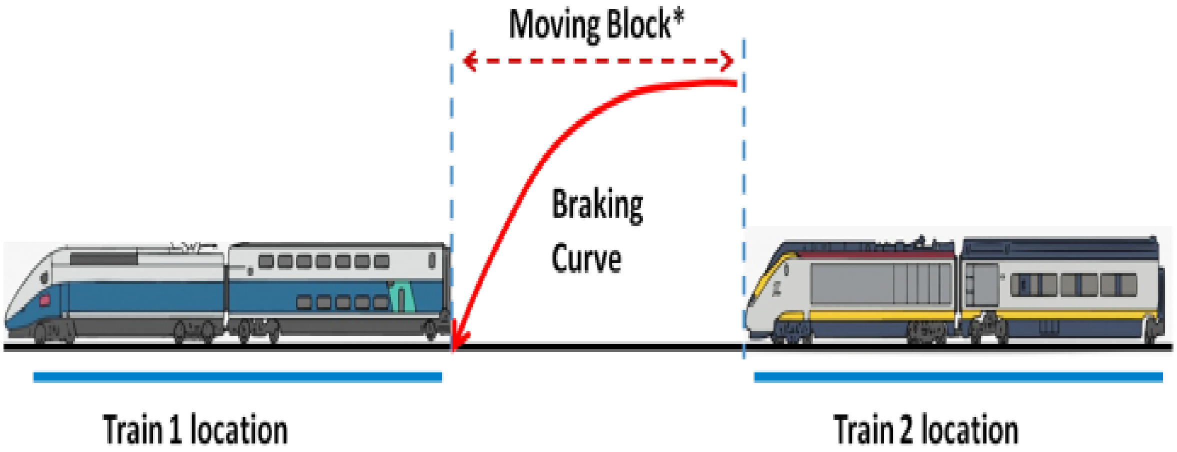


Figure 2.19: Moving block action [13]

The communication is cycled and updated to give the train access to current information. As a result, the train can operate safely within the limitations set by the maximum ordered speed, confirmed stopping point, braking curve, and track grade. This is due to the system's inability to pinpoint the precise location of the train within block 1. As a result, the next train 2 can only advance to block 2's final unoccupied border thanks to the fixed block system.

According to Figure 2.17, the trains in a moving block system continuously calculate the position of the train and its braking curve, which are subsequently radio-transmitted to the equipment at the wayside. So, up to the closest obstruction, wayside equipment can construct protected spaces, each of which is referred to as an MA (see the image at the back of Train 1).

2.6 Determination of train location in CBTC

The primary characteristic that sets a CBTC system apart from traditional signaling is its capacity to locate a train without relying on track circuits. Usually, balises or beacons placed along the track are used for this. The balises/beacons provide direction information for the train-borne device. The tachometers positioned on the axles give a flawless reading.

2.6.1 Train Operation under CBTC

The line is often divided into regions or areas on a section with CBTC, each of which has its radio transmission system and is managed by a zone controller (computer). Via a bidirectional radio link between the train and the zone, the main train detection technique controller offers constant vehicle position reporting.

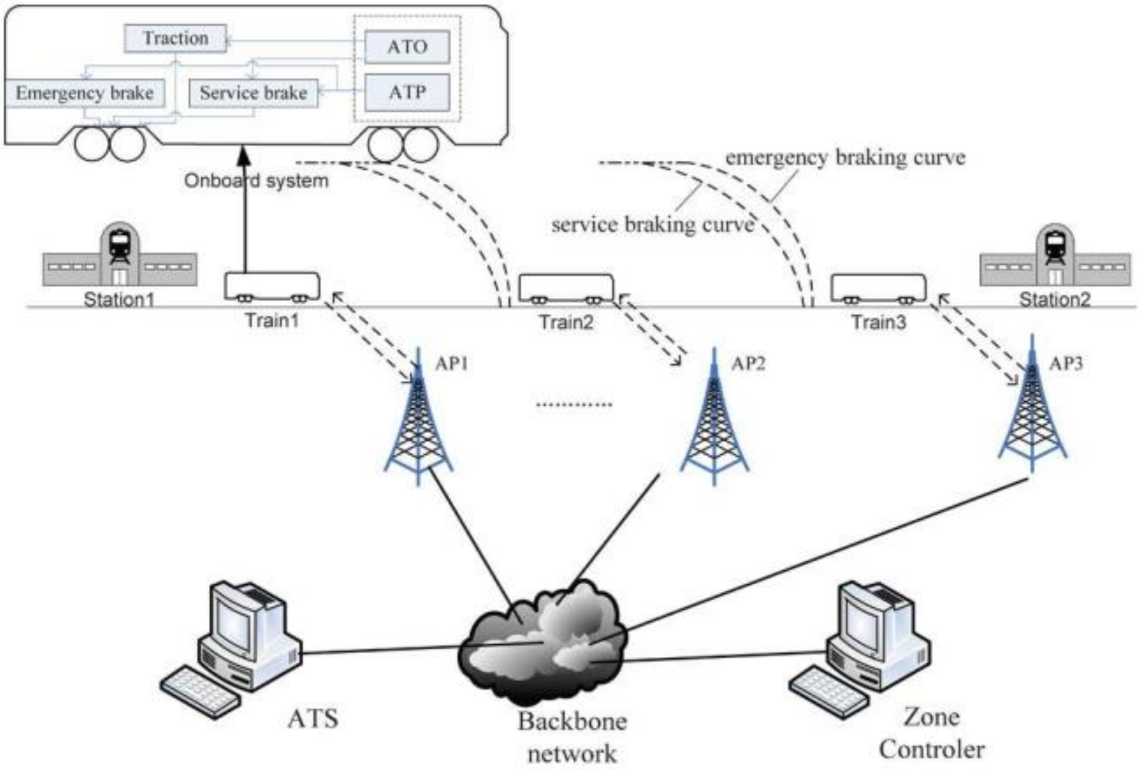


Figure 2.20: CBTC Systems [35]

The Onboard Controller (OBC) equipment determines its location using information from the transponder receiver and tacho-generator and transmits it to the trackside Zone Controller (ZC) via its Mobile Radio Unit (MRU). Each train sends information to the Way Side Radio Unit (WRU), which is positioned next to the track, to connect with the Zone Controller (ZC) via the

Backbone Network. The ZC unit develops train control information using the data it has acquired, which is then delivered along the same path to the onboard ATC equipment of the following train. The trains then establish the "limit of movement authority" the utmost distance that trains can travel using the control information they got from the central system regarding the status of the route, the kind of route established, and the locations of the trains. The gradient profile, train door response data, rolling stock specifications, and other relevant data are used to determine the LMA. The trains then run using this knowledge.

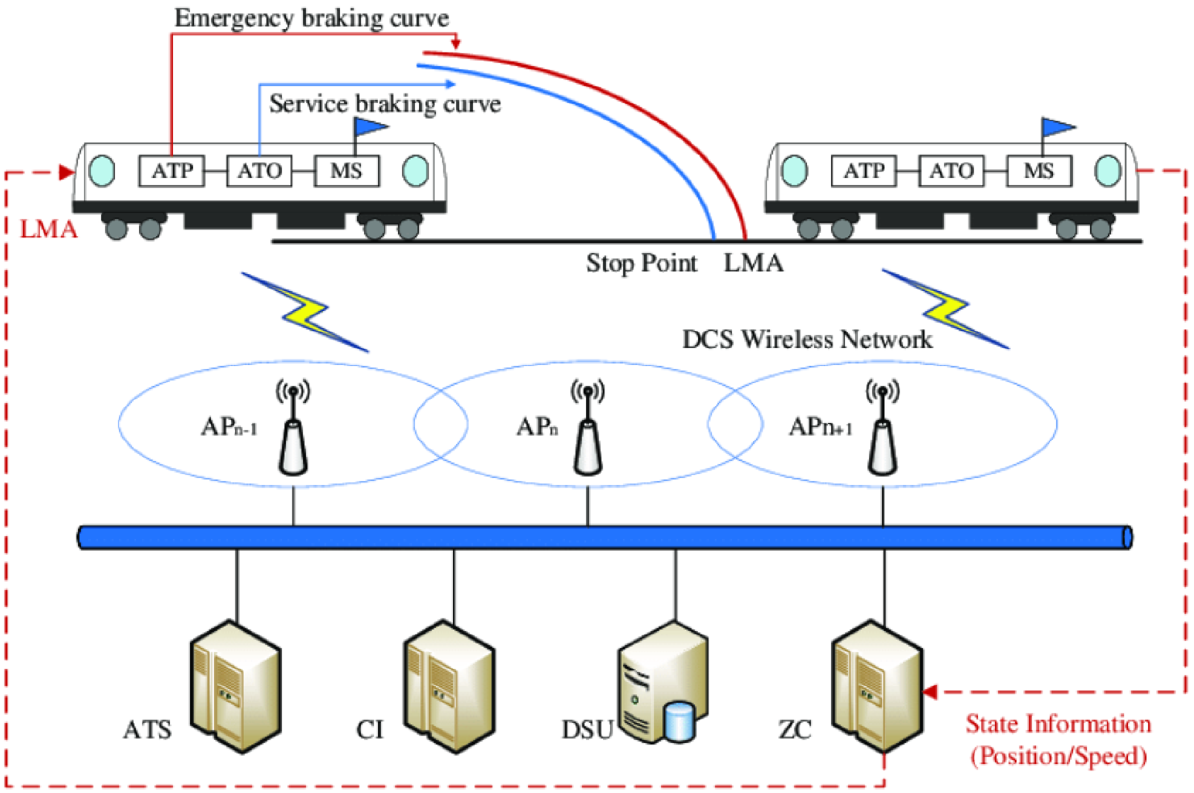


Figure 2.21: A Typical CBTC communication arrangement [40]

The train will communicate its location to the zone controller via WRUs and manage its speed following its authority to move. The onboard system constantly checks to make sure a train is traveling at a speed that is within the limits defined by signaling, including automated stops at particular signal features [40]. If this is not the case, ATP applies an emergency brake to bring the train to a halt. The automatic train supervision (ATS) responsibilities are performed by the operation control center (OCC), which also oversees the overall train operation. According to the operating timetable, OCC assigns lines to trains. Each line assignment specifies the terminal stations, stopping stations, and routes that a train will take.

2.6.2 Comparison of Current Railway and Proposed Railway Method

Table 2.5: Comparison of existing line and CBTC [35]

No.	Parameter	Current System	Proposed System
1	Average speed	45 to 70 Kmph	30 to 35 Kmph
2	Headway	5 to 7 Minutes	90 to 180 seconds
3	Inter Station Distance	6 to 10 Km	0.8 to 1,5 Km
4	Braking distance	800 m to 1.5 Km	About 250 m
5	Station yard Layouts	Generally complex	Simple yard Layout
6	Signal clearance	Typical 30 seconds to 3 minutes	Typical 3 to 5 Seconds
7	Stoppage time at Stations	2 to 5 minutes	20 to 30 seconds
8	Distance between two trains	In Absolute Block - 6 to 10 Km In Automatic Block - 1 to 1,5 Km	25 to 30 m

2.7 A CBTC Major Components

The following are the essential components of a CBTC system that contribute to the two-way communication network that connects the train and the roadside.

2.7.1 Onboard components:

These structures are made up of the following parts:

(A) Vehicle On-Board Controller

Among the onboard equipment is the Vehicle On-Board Controller/Computer (VOBC), also known as a Car-borne Controller or Onboard Control Unit (OBCU). This system is in charge of periodically transmitting train control information to the wayside. It either consists of the onboard ATP and ATO subsystems or functions in conjunction with them.

(B) Onboard ATP and ATO

The onboard ATC functionality includes the ATP and ATO subsystems. ATO runs the actual train, while ATP manages operations that pertain to safety

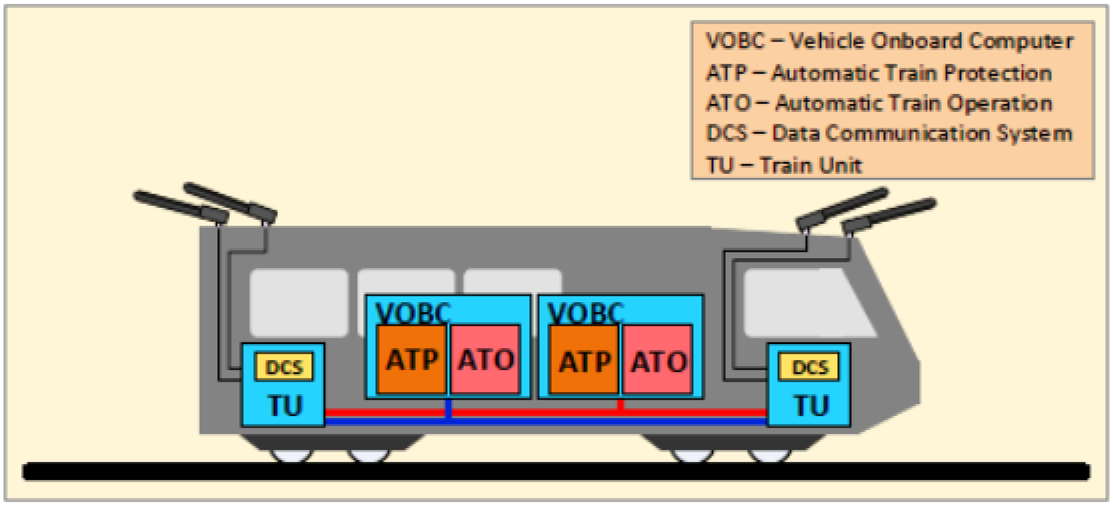


Figure 2.22: Onboard components of CBTC [40]

(C) Radio Communication System (RCS)

Another critical onboard component is RCS, commonly known as the Data Communication System (DCS). RCS, which is often a software and hardware combination that includes radios and antennas, handles radio communication between the train and the wayside. RCS can be integrated into VOBC or used alone. The computer system that runs RCS is commonly referred to as a Train Unit (TU) if it is independent.

2.7.2 Wayside components

The Wayside equipment (mentioned above) and FRONTAM, which will interface with the ATS and Zone Controller (ZC) & transponder tags, will be part of the Core CBTC subsystem. A carborne controller (CC) and a train operator display (TOD) will also be part of the onboard equipment. A data communication system (DCS) is used by this equipment to communicate with one another. The Wayside DCS, which is divided between fixed installations (wayside DCS) and mobile installations on board (carborne DCS), will communicate with CBTC wayside equipment such as the FRONTAM, ZC, and Interlocking. It will facilitate any potential connections with additional wayside equipment, such as an axle counter and a PSD that will play inactive roles within the CBTC system. The Carborne DCS will serve as an interface for the CC, which is onboard equipment for CBTC.

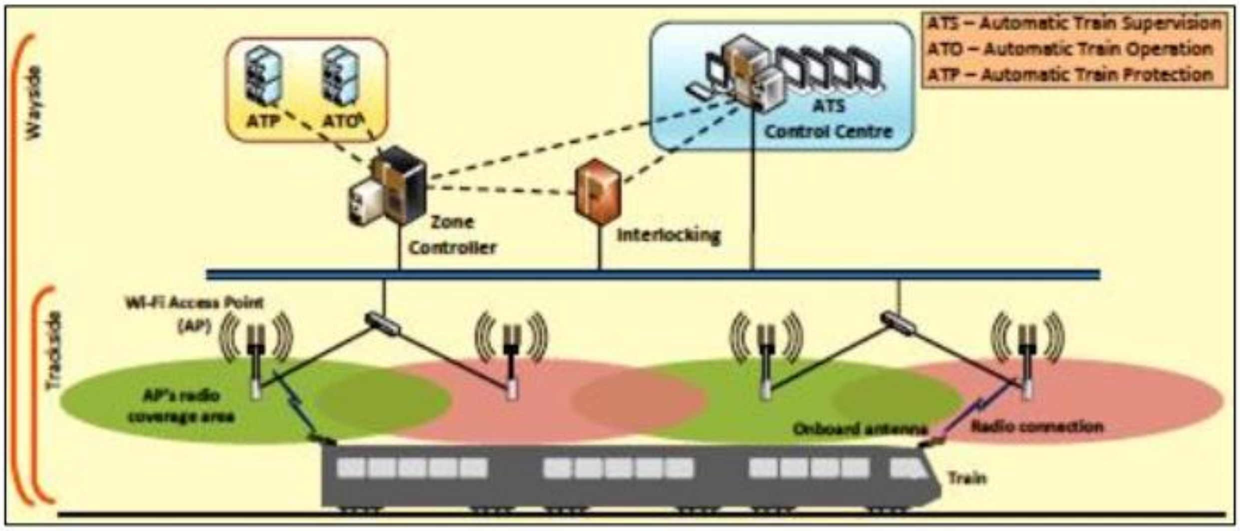


Figure 2.23: Wayside components of CBTC [41]

2.7.3 Zone Controller

Despite a single failure, the ZC will be resilient. In the event of a board failure, the ZC will implement an automatic reboot at the board level. The Zone Controller creates a train position map (the location of every train on the line) using data from the Computer Interlocking (CBI), CCs, and trackside inputs. It then sends each train a Movement Authority Limit (MAL). The configuration of the line and the number of trains under their supervision determine the total number of ZCs.

2.7.4 Carborne Controller

Through its ATO/TMS interface, the CC will monitor and control the train's movement and, if necessary for safety, will initiate an emergency braking intervention. Bi-CC configurations will be used on the KMRCL project trains. Each CC will be in charge of one cab and will be stationed in the cabin at each end of the train. Each CC has unique ancillary equipment.

Data will be transmitted between wayside equipment and carborne equipment (such as ATP and ATO) using the Mobile Radio (MR), a carborne radio device.

Figure 2.24: Train operator display [23]

2.8 Data Communications System

The data communications system (DCS), a broadband communication system, provides bi-directional, secure, and dependable transmission of important data from the onboard CBTC as well as noncritical data from BBRS to OCC. For CBTC and BBRS, a high availability level is necessary, so DCS will run on two parallel networks to achieve this. There will be two networks (Alpha and Beta) operating at the network level, but they won't be redundant; they'll . Work in tandem. 2.4 GHz and 5.8 GHz unlicensed frequency bands are in use.

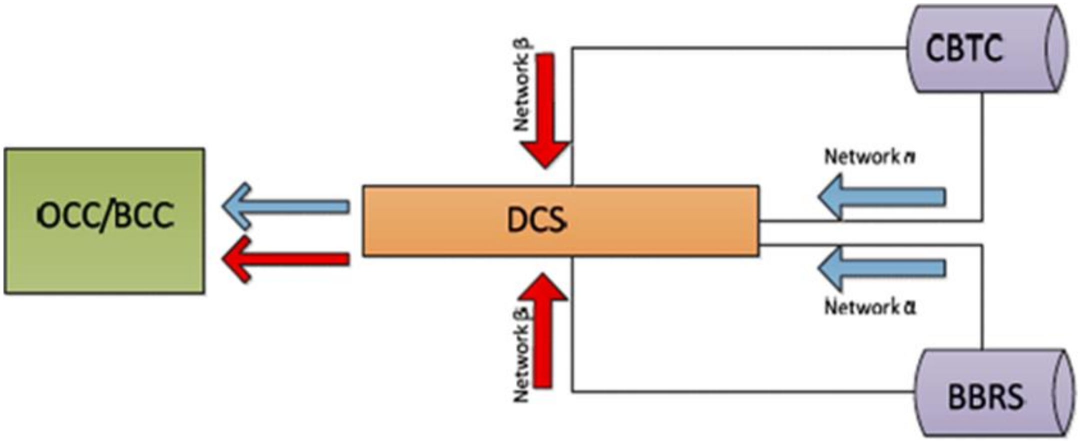


Figure 2.25: DCS as a medium for CBTC & BBRS [27]

2.8.1 Information Display System

The primary visual communication method with passengers at station concourses and platforms shall be the Information Display System (PIDS) for operating, normal, and emergency message displays to passengers, including evacuation guidance. Each Station, the OCC, and the BCC must have IDS control equipment installed in their equipment rooms. HP makes the servers, Industrial Grade makes the TFTD monitors, and Nusyn makes the software [18].

2.8.2 Functioning of CBTC

The CBTC system uses transponder tags mounted next to the track to control a train's location. The CC and CBI supply train operating information, while the Zonal Controller (ZC) supervises a train location map. As a result, based on the position reports of all moving trains and the present condition of the trackside controller, the ZC will generate a Movement Authority (MA) and send it to each train. The CC on each train manages the train's operation based on the received MA. All stations have IP-based CCTV cameras installed to monitor passenger boarding and deboarding at platform levels. Through the DCS, the OCC and Backbone Routers (BBRS) will exchange both vital and non-vital data. Over the TETRA network, the OCC communicates with the loco pilot, maintenance staff, Station Master, traffic supervisor, and others.

The Passenger Information Display System (PIDS), which has control equipment in the Equipment Rooms of each Station as well as the Operation Control Centre (OCC) and Backup Control Centre (BCC), provides visual communications to passengers. Each station includes a public address system that is used to communicate with passengers verbally.

2.8.3 IEEE 1474.1 Functional Requirements for CBTC

CBTC shall provide ATP, ATO & ATS functions

- ATO and ATS are overridden by the ATP-failsafe function.
- ATO -Operates functions that would otherwise be performed by the train operator.
- ATS -Provides system status information so that automatic control can be monitored and overridden.
- Bidirectional data connection in tunnels, tubes, cuts, elevated structures, and gates to support ATP, ATO, and ATS.
- Speed to meet set performance targets.

- The data link has a protocol framework that allows for the safe, fast, and secure delivery of train control messages.

2.9 General Advantage of the CBTC System

Communication-based train control (CBTC) is a modern train signaling system that utilizes wireless communication and computer technology to manage the movement of trains. Compared to traditional signaling systems, CBTC offers numerous advantages that can result in improved safety, efficiency, capacity, and customer experience. Some of the advantages of CBTC are:

1. **Real-time train control**: CBTC allows train operators to control trains in real-time, which means that they can immediately respond to changing conditions, such as unexpected delays, track obstructions, or passenger emergencies. This enables faster and more reliable train operations.

2. Increased capacity: CBTC can increase the capacity of a rail system by allowing trains to safely operate closer together, reducing the minimum safe distance between trains. This means that more trains can operate on the same tracks, which can reduce overcrowding and minimize congestion.

3. Improved safety: CBTC provides precise information about the location and speed of trains, which makes it easier to prevent collisions, derailments, and other accidents. CBTC also includes features such as automatic train protection, which can immediately slow down or stop a train if it approaches an unsafe condition.

4. Faster train operations: CBTC eliminates the need for physical signals along the tracks, which means that train operators do not have to rely on fixed locations to determine their location and speed. This can result in faster and more efficient train operations.

5. Lower maintenance costs: CBTC reduces maintenance costs by eliminating the need for Signals and other track-side equipment. This can also reduce maintenance-related disruptions and delays.

6. Better customer experience: CBTC can improve the customer experience by reducing delays, minimizing crowded conditions, and providing more accurate real-time information about train schedules and arrivals.

CHAPTER THREE

Techno-economic Evaluation Techniques

3.1 Overview of Techno-economic Analysis

When customers have access to several competing technologies, a new technology that is being introduced to the market must have a sizable technological and financial advantage. Technical and economic assessment is a crucial step in proving the viability of an investment. TEA is one of the key phases that provide guidance for choosing the best service or technology and for investments. It is a tool for making decisions that allow one to weigh various technological options according to technical, economic, environmental, social, and legal standards.

In this study, we suggested looking into TEA's potential adoption of a new CBTC technology on the railway lines connecting Ethiopia and Djibouti. For the adoption of the novel CBTC technology, we took into account cost, benefit, risk, and sensitivity to the analysis of TEA in this study. The following is a suggested methodology for carrying out a TEA, which is based on the scenario of adopting CBTC technology on the Ethio-Djibouti railway line.

A TEA must use high-quality data sets that are complete and current to produce results that are meaningful and usable. Thus, meaningful, acceptable, and actionable TEA results were obtained by taking into account the technical, economic, environmental, regulatory, market, and other criteria or aspects for designated technology, as illustrated in Figure 3.1. The technology is then evaluated using the relevant TEA model once the criteria have been specified.

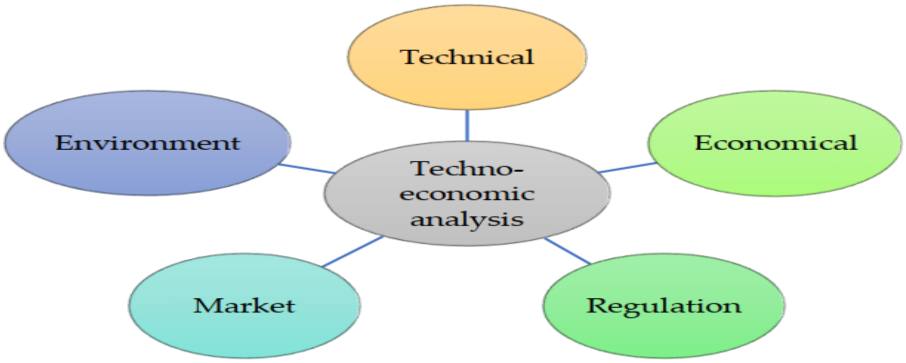


Figure 3.1: Techno-economic analysis[42]

In particular, TEA is used to:

- Compare various technical options and identify the best one.
- Examine the viability of various evolution theories.
- Discover technology and services that are effective in terms of social, environmental, and regular aspects.
- Find strategies that can withstand various demand patterns.
- Before entering existing or new markets, determine whether an investment is cost-effective.
- Examine possible outcomes when implementing new technology or using available resources.

3.2 The Proposed Framework

A TEA framework offers a methodical way to evaluate the advantages and disadvantages of implementing a new technology. TEA is critically used by businesses, policymakers, and researchers to evaluate investment decisions and inform decision-making related to the technology[32].

A technique for assessing a technology's economic performance is called techno-economic analysis, or TEA. A TEA evaluates a technology's overall worth, enabling analysts to impartially compare benefits and costs[39]. A new technology needs to be cost-competitive to be successfully commercialize

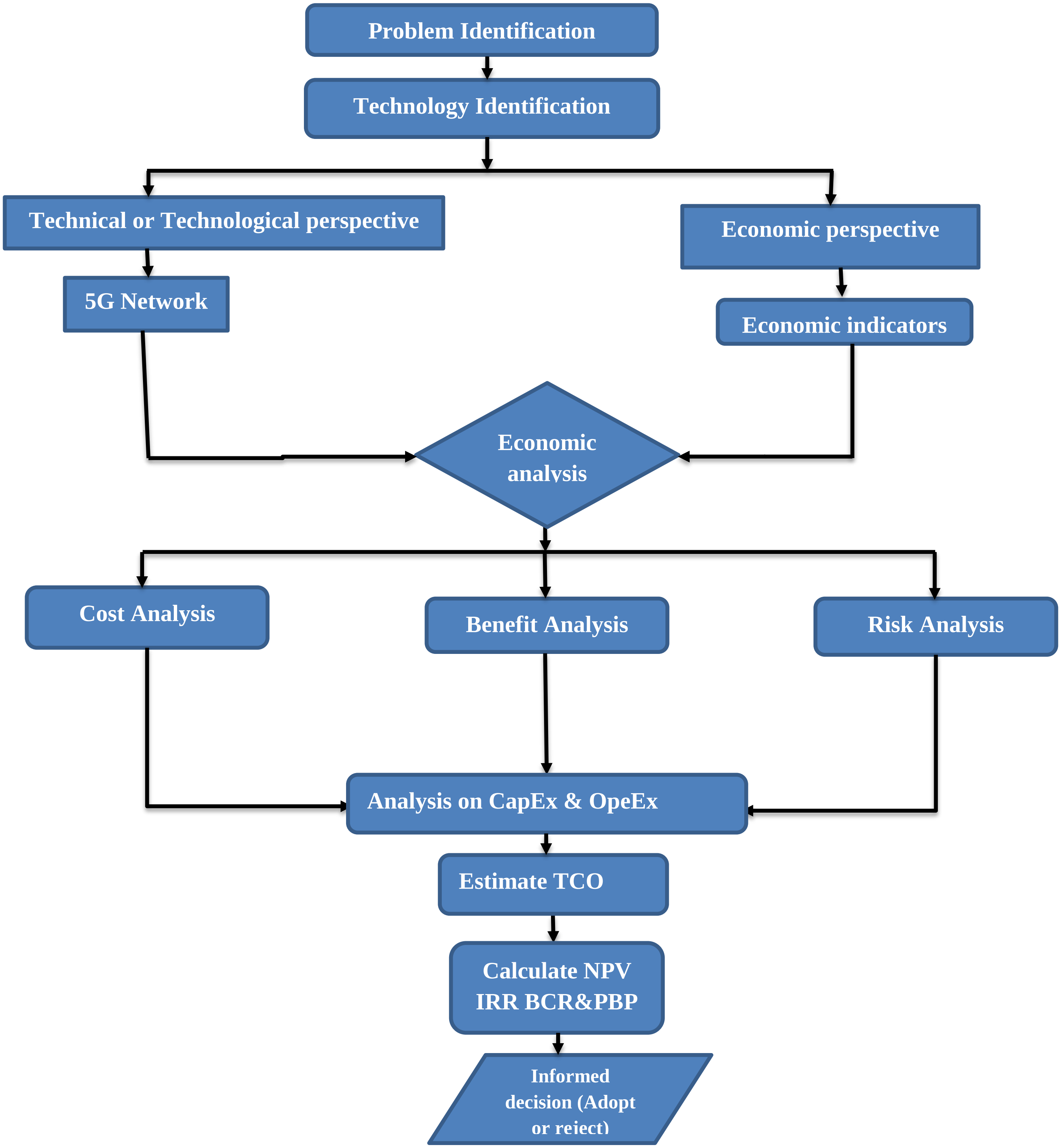


Figure 3.2: Our proposed model to analyze TEA on EDRL

In the proposed model, firstly, we identified the problem and opportunity that the CBTC technology aims to solve and provide an overview of the current signaling system's limitations (tracked circuit-based system already discussed in the previous chapters). Second, we also analyzed the CBTC technology's technical specifications, performance requirements, and compatibility with existing infrastructure. In the third step, we analyzed the cost, benefit, and risk analysis of CBTC technology, and also aggregated the total defined cost. In the fourth step, calculate the NPV. Finally, according to the analysis, we make an informed decision to adopt or reject CBTC technology adoption. While making the decision, we considered the feasibility, economic benefits, and technical challenges of the proposed technology.

Problem identification

In this step, the Ethio Djibouti railway lines outdated and unreliable signaling system is recognized as the issue. This system's fixed block system with an axel counter causes problems, leading to inefficient communications and careless use of the line's capacity. Considering its strategic significance, the Ethiopia-Djibouti railway line generally encounters a number of operational and technical difficulties[43]. The main areas of concern have been determined to be capacity restrictions, maintenance and operational issues, security and safety concerns, coordination and logistical issues, and environmental implications. In order to maximize the railway line's potential, enhance economic linkages, and encourage sustainable regional development, these issues must be resolved.

Technology identification

In this step, we examined the deployment of the CBTC technology as a viable solution. This cutting-edge signaling system uses radio communication to control train movements and speed. It has been demonstrated that CBTC technology improves train performance, frequency, and safety. The Fifth Generation (5G R) communication system combined with Communications-Based Train Control technology will allow the Ethio-Djibouti railway line to handle train operations in real-time, increasing efficiency and safety. For train control and passenger information systems, 5G R offers a dependable and secure communication network. The railway line gains precise train monitoring, efficient traffic control, automated train protection, real-time passenger information, and remote maintenance and diagnostics with CBTC and 5G R. All things considered, this technology improves the capacity, safety, and efficiency of the railway line.

3.3 5G R network planning phases

3.3.1Radio network planning phases

The central objective of radio network planning is to deliver a cost-effective solution for the radio network in terms of coverage, capacity, and quality. To dimension a viable 5G network for Ethio-Djibouti Railway line, the fundamental radio network planning used in this research is divided into preparation phase, nominal planning phase, detailed planning phase as shown in the figure below.

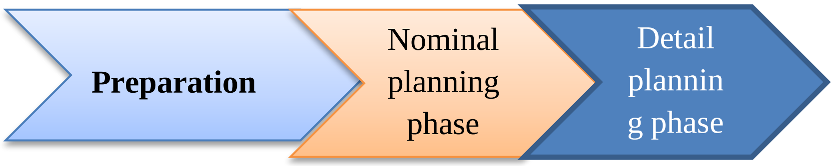


Figure 3.3: Radio network planning phase

3.3.2. Preparation Phase

This phase starts with formulating the requirements of coverage and capacity. Coverage requirement contain outlining the coverage areas, the service probability, and related signal strength such as Reference Signal Received Power (RSRP). On the other hand, the capacity requirements comprise traffic forecast (total number of subscribers supported by the network) and the traffic profile in the selected area [43]. The convenience of frequency bands, data collection, the selection of terrain morphology (Dense Urban (DU), Urban (U), Sub Urban (SU), or Rural (RU)), and propagation model selection are also done at this phase.

3.3.3. Data Collection

Geological Description of the Route Nature for Ethio-Djibouti Railway line

The length of the whole international railway line from SEBETTA～NAGAD is 743.245km. The section from SEBETTA～ADAMA (included) is double track railway, with a length of 113.836km, 7 stations, and an average distance between two stations 16.26km. The section from ADAMA （excluded）～MIESO included） is single track railway, with a length of 213.418km, 12 stations, and an average distance between two stations 17.78km.The total length from Sebeta to Meiso is 327.246 Km[43].

Geological Description

The area that the line goes through belongs to the landform of the Ethiopian plateau platform, Low Mountain and shallow hill. The ground is wide, the topographical relief is not great, and part of the zone has low Mountain and river valley landform. The elevation of road surface is about 850~2300m, the relative elevation difference is scores of meters, and the traffic condition is relatively poor [43]. Due to perennial scouring and undercutting of seasonal flood, the surface-incised dry gullies can be seen, which has a width of 2~5m, depth of 3~12m and length of hundreds of kilometers. Both sides of the trench wall are almost vertical sidewalls, and the bottom of the trench is mainly sandy soil.

3.3.4. General Requirement

Essential communications has highly strict standards that are now only met by dedicated systems and ordinary GSM-R technology. However, in the future, 5G technology will be a viable replacement for GSM-R for the majority of essential services. In actuality, 5G will provide highly dependable and available railway services to meet the majority of current and future demand [44].

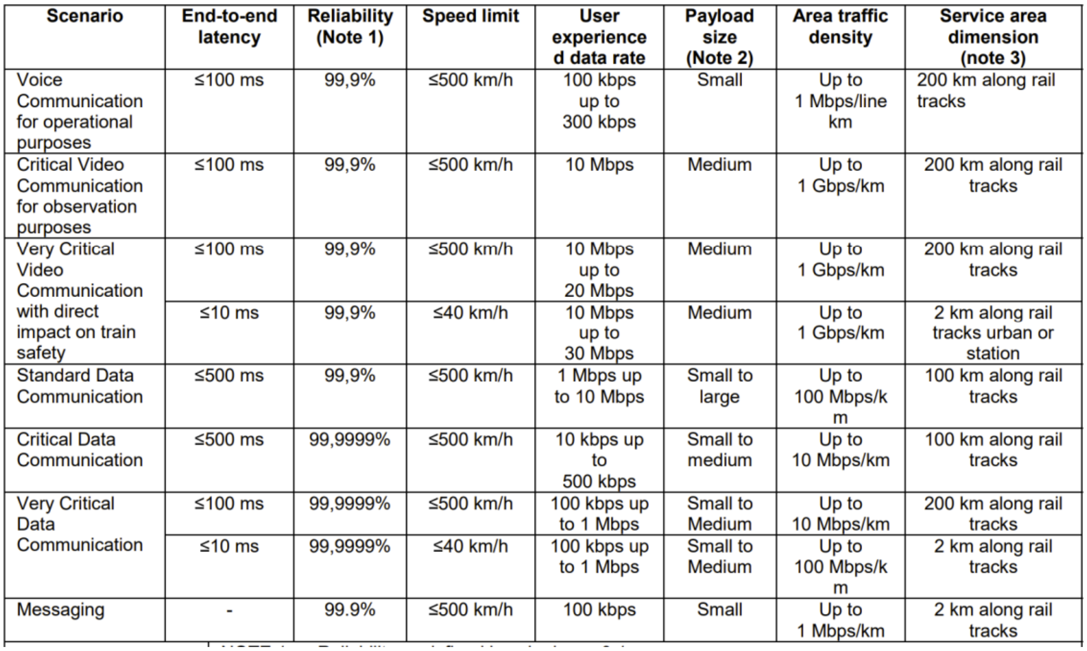
Scenarios and KPIs for main line

To support these various voice, video and data categories, the following rail communication scenarios under the aspect of train speed shall be considered:

- Voice Communication for operational purposes impacting train safety
- Critical Video Communication for observation purposes with indirect impact on train operation, e.g., passenger surveillance.
- Very Critical Video Communication with direct impact on train safety- related critical train control and operation, e.g., used in driverless (e.g., Grade of Automation - goa3/goa4) operation for automated detection of objects (no human in the loop) or video-based remote control (human in the loop);
- Standard Data Communication used for the exchange of train diagnostic information or communication relevant information.
- Critical Data Communication for present rail traffic management systems.

- Very Critical Data Communication for enhanced intelligent rail traffic management systems e.g., full automated train control systems (driverless – remote control); requires high reliable transmission and preservation of the response pattern.
- Messaging for the reliable exchange of short information e.g. Train departure procedure;

Table 3.1: Performance requirements for rail scenarios – main line [45]



Scenario	End-to-end latency	Reliability (Note 1)	Speed limit	User experienced data rate	Payload size (Note 2)	Area traffic density	Service area dimension (note 3)
Voice Communication for operational purposes	≤100 ms	99,9%	≤500 km/h	100 kbps up to 300 kbps	Small	Up to 1 Mbps/line km	200 km along rail tracks
Critical Video Communication for observation purposes	≤100 ms	99,9%	≤500 km/h	10 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks
Very Critical Video Communication with direct impact on train safety	≤100 ms	99,9%	≤500 km/h	10 Mbps up to 20 Mbps	Medium	Up to 1 Gbps/km	200 km along rail tracks
	≤10 ms	99,9%	≤40 km/h	10 Mbps up to 30 Mbps	Medium	Up to 1 Gbps/km	2 km along rail tracks urban or station
Standard Data Communication	≤500 ms	99,9%	≤500 km/h	1 Mbps up to 10 Mbps	Small to large	Up to 100 Mbps/km	100 km along rail tracks
Critical Data Communication	≤500 ms	99,9999%	≤500 km/h	10 kbps up to 500 kbps	Small to medium	Up to 10 Mbps/km	100 km along rail tracks
Very Critical Data Communication	≤100 ms	99,9999%	≤500 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 10 Mbps/km	200 km along rail tracks
	≤10 ms	99,9999%	≤40 km/h	100 kbps up to 1 Mbps	Small to Medium	Up to 100 Mbps/km	2 km along rail tracks
Messaging	-	99.9%	≤500 km/h	100 kbps	Small	Up to 1 Mbps/km	2 km along rail tracks

3.4. 5G System Components Selected for This paper

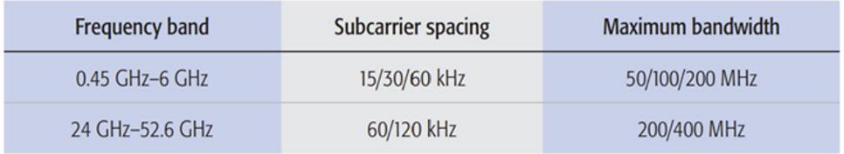
3.4. 1 Carrier Frequency band

Feasible subcarrier spacing for NR would depend on frequency range. Based on the initial study, for below 6 GHz, the feasible sub-carrier spacing is were identified, while above 6 ghz, the study was able to go no further than identifying potential candidates:

- For below 6ghz: 15khz, 30 KHz and 60khz are feasible
- For above 6 ghz: 60 kHz, 120 kHz and 240 kHz are potential candidates of feasible subcarrier spacing.

It should be noted which of the above-mentioned subcarrier spacing are supported depends on NR bands where UE and gNB operate.

Table 3.2: Subcarrier spacing for different frequency ranges [46].



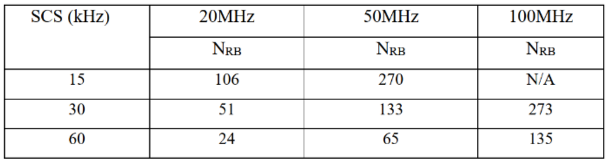
Frequency band	Subcarrier spacing	Maximum bandwidth
0.45 GHz–6 GHz	15/30/60 kHz	50/100/200 MHz
24 GHz–52.6 GHz	60/120 kHz	200/400 MHz

Since we used 28ghz selected subcarrier spacing is 60khz because the mobile transmission at high-speed subcarrier spacing should be considered due to Doppler effect, and very low latency. To achieve very low latency at high frequency the transmission from Bs to Ms should establish through micro cells using SCS of 60Hz.

3.4. 2 Resource Block:

In 5G, each NR Resource Block (RB) has 12 frequency-domain sub-carriers, identical to LTE. The resource block bandwidth in LTE is set at 180 khz, however, it is not in NR and is dependent on sub-carrier spacing. The NR is expected to operate in the millimeter-wave spectrum with a channel bandwidth of 100 mhz for lower bands up to 6 ghz and 400 mhz for higher bands. The table below shows maximum transmission bandwidth configuration based on 3GPP standards.

Table 3.3 Maximum transmission bandwidth configuration N_{RB}



SCS (kHz)	20MHz	50MHz	100MHz
	N_{RB}	N_{RB}	N_{RB}
15	106	270	N/A
30	51	133	273
60	24	65	135

3.4. 3 Duplex Schemes

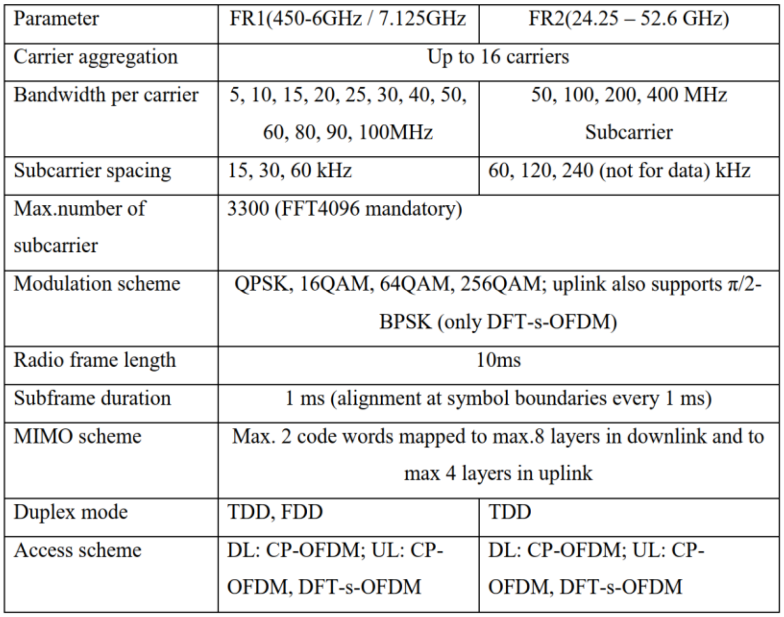
The duplex scheme to use is typically given by the spectrum allocation at hand. For lower frequency bands, allocations are often paired, implying frequency-division duplex (FDD). At higher frequency bands, unpaired spectrum allocations are increasingly common, calling for time-division duplex (TDD).

3.4. 4 Modulation scheme

5G support QPSK, 16QAM, 64QAM since high frequency is selected for this research TDD is the appropriate duplex schemes. Because beam forming massive MIMO best performed in TDD.Due to adjacent frequency resource being used at the same time in FDD, there is inter -

numerology interference. While in TDD it does not exist since each transmitted time interval segment have its own single numerology.

Table 3.4 Summary of key parameters for 5G New Radio [47]



Parameter	FR1(450-6GHz / 7.125GHz	FR2(24.25 – 52.6 GHz)
Carrier aggregation	Up to 16 carriers	
Bandwidth per carrier	5, 10, 15, 20, 25, 30, 40, 50, 60, 80, 90, 100MHz	50, 100, 200, 400 MHz Subcarrier
Subcarrier spacing	15, 30, 60 kHz	60, 120, 240 (not for data) kHz
Max.number of subcarrier	3300 (FFT4096 mandatory)	
Modulation scheme	QPSK, 16QAM, 64QAM, 256QAM; uplink also supports π/2-BPSK (only DFT-s-OFDM)	
Radio frame length	10ms	
Subframe duration	1 ms (alignment at symbol boundaries every 1 ms)	
MIMO scheme	Max. 2 code words mapped to max.8 layers in downlink and to max 4 layers in uplink	
Duplex mode	TDD, FDD	TDD
Access scheme	DL: CP-OFDM; UL: CP-OFDM, DFT-s-OFDM	DL: CP-OFDM; UL: CP-OFDM, DFT-s-OFDM

3.4. 5 Propagation model selection

The selected propagation model is dominant path loss model. The contributions of all rays are superposed to obtain the received power. In most cases only 2 or 3 rays are contributing more than 95% of the energy, i.e., by focusing on these dominant rays the accuracy (of the logarithmically superposed contributions) would be sufficient.

A second disadvantage of ray-optical models is their high dependency on small inaccuracies in the databases. As angular criteria are evaluated during the ray-optical prediction, the orientation of walls is extremely important. Unfortunately, databases with this very high accuracy are not available for most applications.

In addition to the two disadvantages mentioned above, another problem of ray-optical models arises: Either the computation time is very long or, if a preprocessing is done, the computation time for the preprocessing is high.

3.4.6 Dimensioning Process

After completed the preparation phase, dimensioning phase is done by using the selected parameters from the first phase as an input. The purpose of dimensioning is to estimate the required number of radio base stations needed to support a specified traffic load in an area. This number has a fundamental role in cost planning, giving an idea of the economic impacts in the countries under study. The aim of this whole exercise is to provide a model to design the cellular network such that it meets the quality requirements set forth by service providers, operators or even the end-users.

3.5 Coverage planning

3.5.1. Radio link Budget

Radio Link Budget (RLB) is of central importance to coverage planning, inputs including transmitter power, transmitter and receiver antenna systems, number and type of antennas, propagation models and their respective parameters, and conventional system gains and losses. Additionally, channel types (Pedestrian, Vehicular) and geographical information, such as area information (urban, suburban, rural) and size of each area type to be covered, are needed to start the coverage dimensioning exercise. Coverage depends on the area covered by the signal, which also depends on radio propagation characteristics in the given area, and varies from region to region, hence, it should be studied carefully. Furthermore, the required outdoor and indoor coverage probabilities play a vital role in the determination of cell size. Even a minor change in coverage probability can greatly affect the result.

Regarding dimensioning outputs, the cell radius is the main output of the exercise. Two values of cell radius are obtained, one from coverage evaluation and another from capacity evaluation. The cell radius based on capacity evaluation is taken as the final output if the network capacity is exceeded, otherwise the cell radius based on coverage estimation is taken as the final output.

Radio link budget contains all the gains and losses in the route of signal from transmitter to the receiver. Coverage planning is defined by the radio link budget calculation for both channels, DL and UL, with no specific concern on the capacity or quality of service from the link budget evaluation, the maximum allowed path loss (MAPL) can be computed based on the required SNR. With the appropriate propagation model, it is formerly possible to compute the cell radius and area, then, the total number of cells is calculated and computed for the required geographical target area. In the link budget, the essential parameters are related to power (transmission), gains (transmission, reception) and other elements, such as cable or user losses.

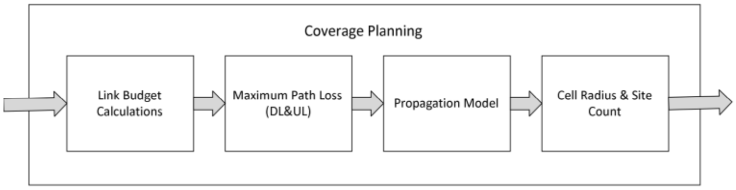


Figure 3. 1: coverage planning

Based on link budget calculations, the maximum allowed propagation loss is obtained for UL and DL. The maximum path loss is converted into distance by using appropriate propagation models. This distance or the radius of the cell is used to compute the number of sites required to cover the target geographical area. It is also important to notice that each model has its own limitation, input requirements and operation environment.

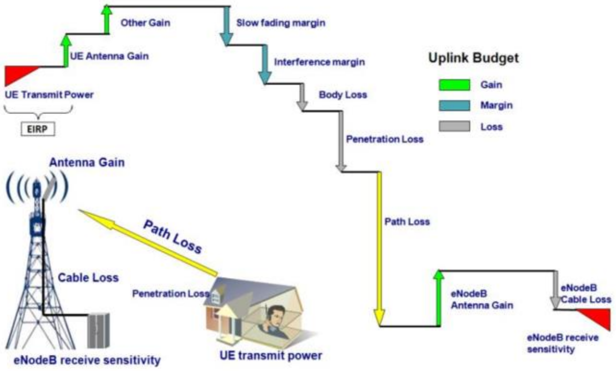


Figure 3. 2:link budget parameter [47]

3.5.2 Radio Link Budget Parameters

Effective Isotropic Radiated Power (EIRP): Stands for effective isotropic radiated power. The term is used to define how much transmitted power is radiated in the preferred direction. It considers the losses in transmission cables and connectors and includes the gain of the transmitter antenna as [48]:

$$\text{EIRP} = PTx + GTx - \sum Total\ Tx \text{ losses} \ldots\ldots\ldots \ (3.1)$$

Where.

- Ptx: is the transmitter power (dbm)
- Gtx : is the transmitter antenna gain (dbi)

Gnb output Power: In the link budget, output powers is 43dbm.

UE Maximum Total Transmitter Power: denotes to the UE transmit power which be contingent on the power class of the UE. Presently merely one power class is demarcated in 3GPP TS 36.101: class 3 with highest transmitter power of 23dbm.

Gnb Antenna Gain: The antenna gain is proportional to the antenna size, and beam width of the antenna patterns (horizontal and vertical). A large antenna with narrow beam width provides a high gain while a short antenna with wider beam width provides less gain. The selection of antenna gains and beam width depends on the clutter type and coverage requirement. The low gain antenna (15–17dbi) can be used in dense urban and urban clutters while a high gain antenna (18–20dbi) can be used in rural areas and highways to extend the RF coverage.

UE Antenna Gain: Depend on the stipulations of 3GPP, UE(s) are expected to have an essential antenna merely with a gain of 0 dbi for apiece of antenna ports.

Signal to interference noise ratio (SINR): SINR values are attained from the system level simulation outcome, and it be contingent on the receiver design. Accordingly, SINR is a vendor specific parameter.

Noise Figure: It is a main factor used to measure the receiver recital. The noise figure can be

Contingent on the bandwidth and the gnb competence. A distinctive value for the noise

Figure is among 6 to 8 db.

Thermal Noise: The thermal noise is a signal loss due to heat and can be formulated.

N=KBT……………………………. (3.2)

Where:

- K, the Boltzmann constant (1.38 x 10−23J/K);
- T, specifies absolute temperature at a value of 290K.

- B, channel bandwidth which is 20mhz.

Receiver Sensitivity ($\boldsymbol{PRx}$, [$\boldsymbol{dB}$]): It is the minimum level of signal that gNodeB or UE can receive.

Receiver Sensitivity = $Noise\ figure + SINR + Thermal\ Noise$

Prx, min[dB.] = -174 + 10. Log10(BRB[Hz]) + FN [dB.] + ρ[dB.]………………………(3.3)

Where:

- BRB: Bandwidth per RB, which depends on the SCS.
- FN: Noise figure of gNB receiver.
- P[dB.]: SINR requirement for the UL or DL traffic channel.

Minimum signal reception strength: It used to Calculate the receiver side losses and margin such as body loss, cable loss and marginal gain to receiver sensitivity and calculated as:

Minimum Signal Reception Strength (MSRS) = RS +IM +LR +RAG………………… (3.4)

Where:

- RS is receiver sensitivity.
- IM is interference Marginal.
- LR is receiver body loss + Cable loss.
- RAG is receiver antenna gain.

Maximum allowable path loss (MAPL): It permits the maximum cell range to be valued with suitable propagation models which offer number of base station sites requisite to concealment the target environment. The maximum allowable path loss expressed as:

MAPL = EIRP – MSRS – Penetration loss – Slow Fading Margin ……………………… (3.5)

Body loss: Shows the loss produced due to signal delaying and immersion when a terminal antenna is near to the body.

Transmitter Power: It includes the base station affecting downlink budget and terminal sides which affect the uplink budget.

Penetration loss: is declining of signals from an interior terminal to a base station because of obstacle by a building and vice versa.

Feeder loss: Loss produced by different devices that are situated on the path of the antenna to the receiver.

Table 3.5: Use cases for this study

Propagation scenario	Frequency Band	Propagation model
Rural	28ghz	Dominant path model

Table 3.6: The principle of 5G new radio Downlink radio link budget [43]

P_{tx}	A=43db
G_{tx}	B=20db
Tx cable or coper loss	C=5db
EIRP	D=A+B-C=58db
Temperature	E=290K
Bandwidth	F=100mhz
Thermal noise	G=KTB=-174dbm
Rx noise figure	H=8db
SINR	I=-10
Receiver sensitivity	$J=I+H-G+10*Log_{10}{}^{(60khz)}$ =-158.218dbm
Interference Margin	K=7db
Rx body loss	M=5db
Rx antenna gain (RAG)	N=2.5db
Minimum received power level of UE	O=J+K-L+M+N=-145.7dbm
Penetration loss	P=7db
Standard deviation of slow fading	Q=6db

Shadow fading margin	R=5.5db
MAPL	S=D-O-P-Q=190.7db

- Since the minimum received signal level greater than receiver sensitivity, channel status is passed.

Table 3.7: The principle of 5G new radio Uplink radio link budget [43]

Transmitted power	26=a
Antenna gain	0=b
Cable and connector loss	0=c
EIRP	A+b+c=26
Temperature	290
Bandwidth	100
Thermal noise	-174
Noise figure	2
SINR	-8
Receiver sensitivity	-148.218dbm
Interference margin	3
Antenna gain	11
Cable loss	2
Mast head amplifier	3
Minimum received power	-130.218dbm
Indoor penetration loss	13
Standard deviation of slow fading	5
Shadow fading margin	5
MAPL	145.218dbm

Coverage Based Site Counts

Using the selected propagation model and the UL and DL MAPL, it is possible to compute the cell radius directed by both the UL and DL path. As it existed said earlier in Chapter 3 the effective radius will be the lowest of the radiuses found in the UL and DL path. Let us contemplate the gNodeB and UE antenna height to be 30m and 1.5m respectively. The cell radius in the Downlink path, d_{DL} can be calculated by using Dominant path model (DPM) formula in Equation (4.6) and MAPL from Downlink radio link budget as follows:

$$PL = 20*\log10(4\pi\lambda) + 10*p*\log10(d) + \sum n\ i\ f(\varphi, i) ni + \Omega + gt \ldots\ldots\ldots\ldots\ldots\ldots\ldots (3.6)$$

Where.

- PL: path loss
- D: is the Distance between the transmitter and the receiver,
- p is the Path loss exponent and is equal to 2.0 in rural areas
- λ: is the Wavelength, $\lambda = c/f$,

Where,

C: speed of light=$3*10^8$m/s
F: frequency in MHz

- F (φ, i): is diffraction loss, (changing the direction of propagation)
- I: is number of changes in direction
- φ: is the angle between previous direction and new direction
- Ω: is empirical determined wave guiding for reflections and scattering. In typical

Scenarios the wave guiding effects can be turned off, this reduces the prediction time.

- Gt: is transmitter antenna gain.

Summary of result from link budget calculation performed at appendix 1 is shown below.

Table 3.8: Summary of parameter and result from link budget calculation [43]

Parameter	Downlink	Uplink
Frequency in MHz	28ghz	28ghz
gNodeB Antenna Height (m)	30	30
UE Antenna Height (m)	1.5	1.5
MAPL (dB.)	190.7	145.18
Cell radius(km)	4.563km	4.12km
Effective cell radius (Reff) km		4.12km

Antenna selections

Sector antennas, meanwhile, are classified as "directional" microwave antennas. A directional antenna or beam antenna is an antenna which radiates or receives greater power in specific directions allowing for increased performance and reduced interference from unwanted sources. Directional antennas provide increased performance over dipole antennas or omnidirectional antennas in general – when a greater concentration of radiation in a certain direction is desired. Since the area to be covered in our work is the Sebeta-Meiso railway line, which is almost a straight line, directional antennas suit well our goal and is selected.

So for 2 sector site configuration, site area is calculated as:

SA ($[km^2]$) = $\sqrt{3}.\ [4.12]^2$[km] =29.4km^2

Finally, the site count based on Coverage for Downlink is calculated as:

T_{CA}=730.23Km^2, where T_{CA} is target coverage area from Sebeta to Meiso railway line, the exact coverage area of Sebeta -Meiso route is not found from the data, but this area is measured from google earth.

$T_{NS} = T_{CA}/SA=730.23/29.4=24.8$, where T_{NS} is total number of sites

The effective radius, $Reffective$= min (d_{DL}, d_{UL}) which is 4.12km. Here, the reason behind selecting minimum cell radius is that, as we move away from cell or node, there is probability of outage and as distance increases, the loss is also increases. Therefore, a total of 25 Coverage based gNodeB are required to deliver the radio coverage for 730.23 Km^2 area of Sebeta-Meiso route.

3.6 Capacity planning

Capacity planning is based on the coverage maps and traffic estimates obtained from the coverage planning. The metric that is used in determining the capacity planning is the data density expressed as Mbps per km^2. Given a certain demographics region, determining the required data density is a multi-step process involving classifying users of the systems on different categories. User categories depend on the load they place on the system in terms of usage. Various demands that are placed by the users on the system include browsing the web, e-mailing, VoIP, download or upload of video content (real time services), train controlling and signaling which altogether pose different requirements on the system.

Data density is used for matching the base station capacity to the selected railway line communication service requirements. Projected railway line services requirements determine the base station capacity requirements.

3.6.1 Capacity Requirements

Throughput at cell-edge in downlink (DL) and uplink (UL)

Throughput at cell-edge design target in the downlink and uplink are assumed to be 1024.

Kbps & 512kbps respectively.

Capacity estimation

Professional users:

This type of users is assumed to be using the services in stationary and mobile environments. The type of services that are perceived to be mostly used are file download, streaming media, video conferencing, and email. In railway context professional users can be the one whose work is mainly concerned on train operation and safety issues. Some of those are Dispatchers, drivers, supervisors ……etc.

High end users:

These are type of users who use the services mostly for their personal use. They use the services on regular basis, and the dominant applications that they use the most are web browsing, gaming, music downloads, and so on. Passengers on trains can be categorized in this group.

Casual users:

These are type of users who need access to use broadband services (web browsing, data-oriented services) but are only connected few hours in a day. Passengers waiting trains in stations are assumed as casual users..

Data volume per month

Data volume per month is an accounting solution by which a user can buy a certain amount of data service. In the capacity estimation, the data service is expressed by a certain amount of data volume per month per subscriber. The capacity planning can be ongoing by estimating the daily traffic of the busy hour traffic as a percentage. In case of 5G new radio users for railway service in this study are users mentioned above i.e., professional, high end, and casual users.

The busy hour assigned to the professional user at the busiest hour of the day will allow him/her to download a document with high speed. The user will also be able to demand most of the services (apart from movie streaming, bulky data download, video surveillance and speed and position of trains) at a needed quality of service. It’s also considering that these figures come into play only during the peak/busy hours of a day (i.e when the number of travelers is maximum, and the number of trains is more than two at a station)

The daily traffic in this thesis design is assumed 14.6% of the busy hour traffic. Generally, the main advantage of traffic model is to describe the average subscriber activities during the most loaded day period (Busy Hour) and the capacity of site should be based on busy hour as the traffic is not equally distributed for 24 hours.

Assumptions made in this thesis capacity density estimation are outlined in the following table.

Table 3.9: Railway service user category [43]

Type of user	Traffic usage in GB/month/user	Usage ratio of the Services (%)	Traffic ratio of busy Hour to whole day (%)
Professional user	25	20	14.6
High end user	35	45	
Casual user	30	35	

First step: Average total throughput per subscriber@Busy hour(BH) per each user calculated at appendix 1 is shown below.

Professional user Average throughput (DL + UL): = 268.518

High end user Average throughput (DL + UL): = 375.925

Casual user Average throughput (DL + UL): = 322.22

- Then, the average total throughput per subscriber in busy hour is given by:

Total Av. Throughput per Subscriber@BH = = 320.851 Kbps

- Second step: Calculate 5G new radio aggregate throughput or data rate

5G New radio throughput or data rate (in Mbps) =

$10^{-6} . \sum^{J}{}_{j}=1(^{(j)}{}_{Layers}. {}^{(j)}.{}^{(j)}.R_{max} .N^{BW,\mu}{}_{\mathrm{PRB}}/\mathrm{T}^{\mu}{}_{s}.12(1-OH^{(j)}))$

Where:

- J: number of aggregated component carriers in a band or band combination
- R_{max}: 948/1024
- For the j-th CC (component carrier), $V_{layers(j)}$ is the maximum number of layers
- Qm(j): Maximum modulation order, Qm is 2 for QPSK, 4 for 16-QAM, 6 for 32-QAM,

8 for 256-QAM

- F(j): Scaling factor, can take any value from 1/0.8/0.75/0.4;
- M: 5G New radio numerology can take any value from 0 to 5;
- T_s^{μ}: Average OFDM symbol duration in a subframe for μ value,
- $N_{PRB}^{BW(j),\mu}$: Maximum RB Allocation in bandwidth, BW (j) with numerology (μ), BW (j) is UE supported maximum Bandwidth in given band or in band combinations.

Table 3.10: Parameters used in this thesis to calculate the throughputs for 5G New radio [43]

Parameters	Value
Frequency	28ghz
Bandwidth	100MHZ
Number of layer (v)	2
Number of carriers(J)	1
Bit per symbol from modulation scheme (QAM)	8
Scaling factor signal per band(f)	0.75
Maximum code rate (Rmax)	948/1024
Maximum number of resource block	137
Sub-carrier per resource block	12
Subcarrier spacing	60khz
Numerology	2
Average OFDM symbol duration (Ts)	$T_s^{\mu=}10^{-3}/(14*2^2)=1.7857*10^{-5}$
Overhead (OH)	0.18 DL/0.1 UL for FR2

Downlink Data rate (in Mbps)

Thus, Aggregate capacity throughput per site or data rate (DL) = 838.67 Mbps

Uplink Data rate (in Mbps)

Thus, Aggregate capacity throughput per site or data rate (UL) = 920.49 Mbps

The maximum subscriber’s number per site is now calculated as:

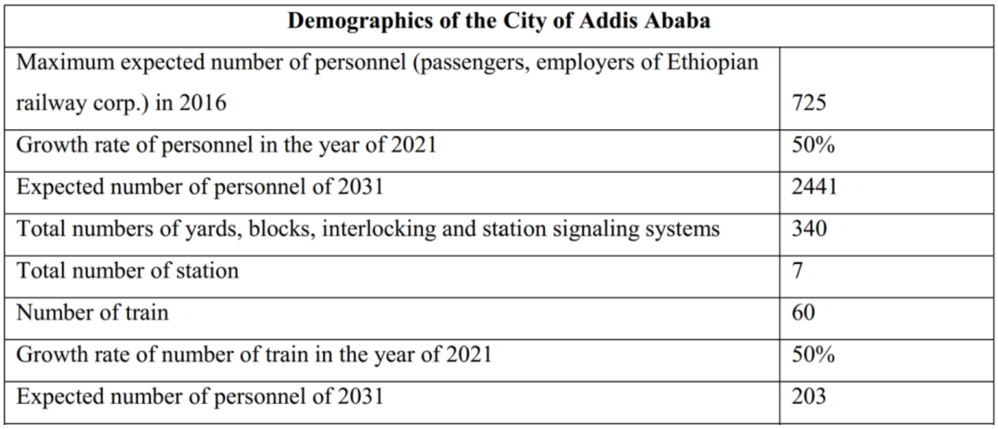
Max. No of Subs per Site ($_{DL}$)=

(Aggregate capacity throughput per site or data rate (DL))/(Total Av. Throughput per Subscriber@BH)=2613.89

Max. No of Subs per Site ($_{UL}$)= (Aggregate capacity throughput per site or data rate (DL))/(Total Av. Throughput per Subscriber@BH)=2868.9

To perform capacity based on site count and a total number of gNodeBs required to meet the capacity request, the number of subscribers of the required area should be known.

Table 3.11: Demographic data of Addis Ababa [43]



Demographics of the City of Addis Ababa	
Maximum expected number of personnel (passengers, employers of Ethiopian railway corp.) in 2016	725
Growth rate of personnel in the year of 2021	50%
Expected number of personnel of 2031	2441
Total numbers of yards, blocks, interlocking and station signaling systems	340
Total number of station	7
Number of train	60
Growth rate of number of train in the year of 2021	50%
Expected number of personnel of 2031	203

The data shown above is taken from Ethiopian Railway Corporation (ERC) document which entitled as “feasibility study” document for 2016, until we can get recent demographic data for Sebeta-Meiso route, we estimate total number of subscribers of the new 5G network based on the above table.

- The total 5G new radio subscriber, such us passengers, employers of Ethiopian railway corporation, and peoples live around expected to be 2441 in 2031.
- So, total subscriber number of the required area assumed as 2441.

Therefor capacity based site count for downlink

Capacity based Sites count (DL) =Total Subscriber number of the required area/Max.no of Subs per Site (DL)

2441/2613.89=0.93

Capacity based Sites count (UL) =

Total Subscriber number of the required area/Max.no of Subs per Site (UL)

2441/2868.9=0.8a

From the above capacity-based sites count (DL and UL) perspective we must select the maximum number of sites. But the number of gNodeBs get from capacity planning is too small to compare with coverage planning, so only coverage-based planning is considered in this thesis.

In the nominal planning phase, it is exposed that a total of 25 gNodeBs are required to meet the coverage condition and on the other hand a total of 0.93 gNodeBs are essential to meet the capacity necessity [43]. Since the target network should satisfy both the requirements of coverage & capacity, the total number of gNodeBs that will be used to analyze the target network further in the detail planning stage becomes 25gnodebs. That is Sites Count or number of gNodeBs is the maximum of the Coverage based sites count and Capacity based sites count.

Number of base stations = Max (capacity, coverage) = 25gnodebs

3.7 Coverage Requirements

3.7.1 Cell-edge Coverage Probability

All radio coverage is depending on probability concept. Since radio coverage cannot be certain 100%; radio coverage at a certain location, some distance away from a transmitter can be identified as 50%, 90% or more. The cell edge coverage probabilities be contingent on the fading margin; it is the safety factor recycled to define the level of probability of effective radio communication. Accordingly, in this thesis, it is supposed to have a cell-edge coverage probability of 84%, and hence a fading margin of 7db is used during radio link budget calculation.

3.7.2 Area Coverage Probability

Area coverage probability tells how much extant of the target area will be covered by the intentional network. In this study, the coverage probability is expected to cover 96% of the target area based on the table 3.12.

There are many reasons why signal performance can vary significantly, which is why it is important to accurately diagnose signal issues so that the correct solution can be implemented.

3.7.3 RSRP-Reference Signal Received Power

The power, expressed in decibel-mill watts, of the reference signal received from the cell tower. The reference signal is not the same signal that carries your data, but is a special, extra signal, which is exclusively used for estimating the power of the data-carrying signals coming from the cell tower, which the modem and tower use to negotiate data rates. An antenna can help you recover some RSRP, resulting in faster speeds. As always, proper installation of the antenna and related equipment is of critical importance and can turn a poor service into an excellent one [49].

3.7.4 RSRQ - Reference Signal Received Quality

The quality, expressed in decibel-mill watts, of the reference signal received from the cell tower. This is a ratio between the power of the reference signal and the rest of the signal in that current LTE and above band [49]. A higher quality reference signal indicates to the UE and tower to use more sophisticated data encoding schemes, packing more data into each resource unit, because the risk of data corruption is reduced.

3.7.5 SNR - Signal to Noise Ratio

This is the ratio of interfering noise to the actual signal you are using. The higher the ratio, the louder and clearer your signal can be "heard" over all the background noise, leading to better performance. While it is possible for our modems to transmit some data in a negative signal to noise ratio you will certainly not find it to be the best experience, which is why recommend keeping it above 0 dB., which represents the signal and noise levels being equal to one another [49]. As always, proper installation of the antenna and related equipment is of critical importance and can turn a poor service into an excellent one.

3.7.6. Received Signal Power for railway communication.

The railway mobile communication network must provide sufficient coverage in terms of the received signal power over the entire railway area in order to have proper transmission. EIRENE recommend a minimum acceptable power of the received downlink signal to be -92 dbm for ETCS levels 2/3 for speeds above 280 km/h [50]. This minimum value has been taken for the work here.

Table 3.12: Summary of Coverage requirements and Standard Signal Strength indicators [49]

Signal strength indicators	Quality	Value (dbm)	Description
RSRP	Excellent	≥-80	Signal strength enabling max. Data capacity
	Good	-80 to-90	Good signal and speeds with no dropouts expected
	Midcell	-90 to -100	Fair/usable signal with possibility of dropouts and slowdowns
	Cell edge	≤ −100	No usable signal-expect frequent disconnections and sluggish performance
RSPQ	Excellent	≥ −10	
	Good	-10 to -15	
	Midcell	-15 to -20	
	Cell edge	< −20	
SINR	Excellent	≥ 20	
	Good	13 to 20	
	Midcell	0 to 13	
	Cell edge	≤ 0	

Economic analysis

To ascertain the financial viability and profitability of a project, choice, or investment, economic analysis weighs the costs and rewards involved. It includes cost analysis, which assesses all project expenses, including upfront capital costs and continuing operating expenses. Potential risks and uncertainties that could affect the project's outcome are evaluated through risk analysis.

Benefit analysis measures the project's anticipated benefits and advantages, both monetary and non-monetary. For decision-makers to analyze costs, risks, and benefits in order to assess economic feasibility and make wise decisions, cost and benefit assessments are essential.

Cost analysis

In this step, we looked at the costs associated with implementing the suggested technology, which should take into account the price of the CBTC system's installation, maintenance, and operation. In addition, we also consider these costs may vary according to the scope of the project, the equipment, the manufacturer, and the manpower requirements. Therefore, we have used the estimated cost in each analyzed cost.

Capital expenses and operating expenses are the two main divisions of manufacturing costs.

Capital expenditure

CapEx**:** Evaluate the costs of purchasing, deploying, and installing the CBTC technology. CapEx refers to the funds that a company invests in acquiring or upgrading its fixed assets, which are expected to provide benefits for the long term. This typically includes investments in buildings, machinery, equipment, vehicles, and other assets that are vital to the company's operations.

The calculation of capital or investment cost in a TEA of implementing the CBTC technology on the Ethio-Djibouti railway line involves different items and factors. The capital cost is a crucial element to consider as it constitutes a significant portion of the total project.

We followed the following steps to calculate the equipment cost:

1. We define the estimated costs of procurement equipment such as transponders, signaling equipment, communication equipment, and onboard units among hardware and software components. We also define supportive infrastructure of the CBTC System such as communication systems, power supplies, and outdoor enclosures.
2. Outline the estimated cost below Table 3.13

Table 3.13: Estimated cost of the material for CapEx

No	**Capital cost**	**Description**	**Cost estimation**[51][52]
1	Wayside signalling equipment	Track circuit, signals, point machine, interlocking, axel counter wayside horns (alarm)[39]	Exist+$29,000,000.00 Total wayside Equipment
2	Onboard train equipment	ATC, CAB signal, GPS, ER, TCN Video monitoring system	Exist+$18,000,000.00
3	Operation Control Center (OCC) equipment	Room Operators Necessary material	Exist+$11,000,000.00
4	Radio communication equipment	Train radio systems Wayside radio systems LTE Connectivity	Exist+$5,000,000.00
5	Power system equipment	Power cable Control cable Transformer	Exist+$9,000,000.00
6	Network infrastructure equipment	Security equipment(CCTV) Fiber optics cables Sensors	Exist+$16,000,000.00
7	Signaling equipment	Simulated signals various hues of light Positional light indicators	Exist+$10,000,000.00
Contingency 2 %			$19,600,000.00
Total capital cost			$117,000,000.00

3. Calculate the Total Equipment Cost: Aggregate and calculate the total cost of all equipment and infrastructure components involved in implementing the CBTC system.
4. Finally, we have used the total equipment cost for further steps

Operational expenditure (OpeEx): We analyze the cost typically including day-to-day expenses required for running a business associated with the CBTC technology. OpeEx refers to the regular, ongoing expenses that a company incurs to operate its business. These expenses are typically incurred on a day-to-day basis and include wages, rent, utilities, maintenance, and other costs related to the company's ongoing operations.

We define the estimated costs of operational Costs listed below in table 3.2. We also define the supportive infrastructure of the CBTC System such as Spare parts and consumables, Training and support, and Employee salaries and benefits

Table 3.14: Estimated cost of the material for OpeEx

No	**Operational Cost**	**Description**	**Cost estimation**[51]
1	Maintenance equipment	diagnostic equipment and test devices[42]	Exist+$8,500,000.00
2	Staff training	employee and technician training programs	Exist+$16,500,000.00
3	Technical Support Services	IT support and customer support software maintenance and technical assistance	Exist+$3,000,000.00
4	Upgrades and Software Maintenance	Regular software updates, upgrades, and necessary system improvements	Exist+$6,500,000.00
5	Energy Consumption	power for operating equipment	Exist+$2,500,000.00
6	Employee salaries	payment that an employee receives for their work	Exist+$19,000,000.00
7	Replacement and Spare Parts	Equipment spare parts for the CBTC system	Exist+$6,500,000.00
Contingency 2 %			$12,400,000.00
Total operation cost			$74,400,000.00

TEM method overview

Engineering, business, and research and development (R&D) are all connected via techno-economic modeling (TEM). Businesses can gain a better understanding of the variables affecting the profitability of their technology development initiatives by connecting process characteristics to financial measures.

The entire lifetime of technology development utilizes TEM. The method can be used by innovators to evaluate the potential and viability of new ideas from an economic standpoint. It can be used by scientists to pinpoint the process variables that have the biggest impact on profitability at the bench scale. Engineers can utilize TEM to compare the financial effects of various process conditions and configurations while building a process [46]. TEM uses information from each of these developmental stages to give a basis for objective decision-making.

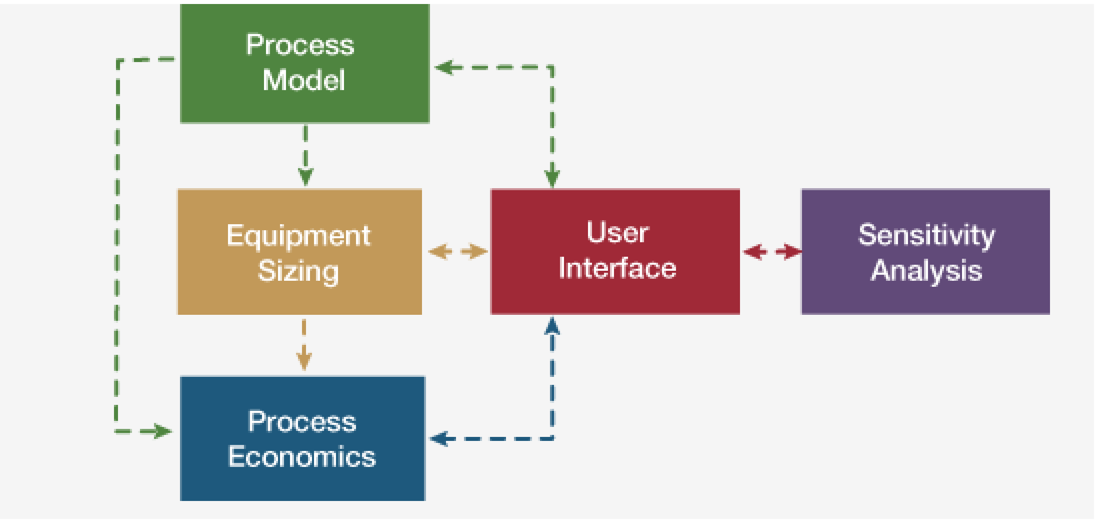


Figure 3.4: Simple spreadsheet techno-economic model structure and data flow

We must first create a process model and establish the factors determining equipment size before estimating capital and operating expenses and creating the techno-economic model's user interface. Information from the stream table is used in equipment size calculations to establish the parameters required for forecasting capital and operating costs. The user interface simplifies model operation and sensitivity analysis by collecting significant input and output on a single sheet. The process model generates a stream table, which serves as the foundation of the techno-economic model.

Benefit Analysis

Total TEA is a thorough process that assesses a project's economic, social, environmental, and other effects to determine its viability. The following advantages can be examined with TEA while establishing a CBTC (Communication-based train control) system on a railway line:

- Increased Capacity: CBTC technology enables trains to operate closer together with shorter headways while maintaining safety. This results in increased capacity of the railway system, allowing more passengers to be transported in less time.
- Increased dependability: Real-time train tracking and monitoring made possible by CBTC systems allows for better management of train movements and a decreased risk of delays and disruptions. The railway system becomes more reliable as a result.
- Enhanced Safety: CBTC systems have multiple safety features such as automatic train protection, speed checks, and emergency braking, which help prevent accidents and ensure passenger safety.
- Operational efficiency: The precise control of train movements in CBTC systems results in efficient use of energy and reduction in operating costs, including maintenance.
- Environmental benefits: With reduced delays, congestion, and idle times, CBTC systems decrease emissions and improve air quality.
- Economic returns: The increased capacity, improved reliability, and cost savings from efficient operation result in increased revenue and profitability.

3.3 Economic Performance Indicators

Regarding the project, the following economic performance indicators can be identified:

Total Cost of Ownership (TCO)

In this study, we will concentrate on the TCO, which is a financial assessment of a system's or products' direct and indirect costs over an established time frame and is made up of CapEx and OpeEx [31].

$$TCO = CapEx + OpeEx \qquad (3.7)$$

Where: TCO= Total Cost of Ownership
CapEx=Capital expenditure
OpeEx=operational expenditure

Net present value (NPV) for the economy

For the project to be desirable economically, it needs to be greater than zero. But the standard NPV calculation formula is:

$$NPV = \sum_{t=0}^{n} \frac{CFt}{(1+r)^t} \qquad (3.8)$$

Where:

CFt = Cash flow in a specific period

r = Discount rate

t = Specific period

You must first predict the cash flows that a specific project is likely to produce before you can compute NPV. These cash flows could happen across several years and could be either positive or negative. We must use a discount rate to account for the time value of money after forecasting the cash flows. Finally, we calculate the NPV by adding the present values of all expected future cash flows and subtracting the initial investment[47].

Benefit-Cost ratio (BCR)

It should be greater than one. It is calculated by dividing the present value of Costs for the present value of Benefits. In mathematical terms:

$$BRC = \frac{\text{Present value of benefits}}{Present\ value\ of\ costs} \geq 1 \qquad (3.9)$$

Where:

Present value of benefits = Total discounted value of all benefits over the project's lifetime

Present value of costs = Total discounted value of all costs incurred over the project's lifetime

Internal rate of return (IRR)

The internal rate of return on an investment or project is the annualized effective compounded return rate" or "rate of return" that causes the net present value (NPV as NET*1/ (1+IRR) year) of all cash flows, positive and negative, from a particular investment to equal zero [48]. The IRR, in more specific terms, is the discount rate at which the investment's net present value of expenses (negative cash flows) equals its net present value of benefits (positive cash flows)[49].

Mathematical

$$0 = \text{NPV} = \sum_{t=0}^{n} \frac{CFt}{(1+r)^t} \qquad (3.10)$$

Payback Period (PBP)

The payback period is the length of time needed to recoup an investment's costs or reach a break-even point for an investor. Longer payback periods are less enticing, but shorter payback periods are far more appealing [9]. Divide the investment amount by the annual cash flow to calculate the payback period.

You can use the following formula to determine the payback period:

$$\mathrm{PBP} = \frac{Initial\ investment}{Cash\ flow\ per\ year} \tag{3.11}$$

CHAPTER FOUR

RESULT AND DISCUSSION

4.1 Introduction

According to the techno-economic analysis of its deployment, investing in the Communication Based Train Control System (CBTC) provides significant benefits in terms of net present value (NPV), total cost of ownership (TCO), payback period (PBP), internal rate of return (IRR), and discounted cash flow (DCF). The study takes into account the deployment of CBTC's related capital expenditures (CapEx) and operational expenditures (OpeEx).

The NPV analysis suggests that a significant return on investment (ROI) is possible when deploying CBTC. The TCO analysis shows that the total costs of deploying and operating CBTC over its lifetime are lower than other train control systems. The PBP calculation indicates that the initial investment cost can be recouped within a few years.

The IRR analysis demonstrates that the rate of return produced by using CBTC exceeds the investor's hurdle rate. The investment has been determined to be financially sound by the DCF analysis, which considers the time value of money. Overall, the findings imply that CBTC represents a financially rewarding investment for transit organizations seeking to upgrade their train control systems.

4.2 Costs Benefit Analysis

When an intervention's costs and benefits are both described in monetary terms, cost-benefit analysis can be used to compare them. Health outcomes are considered in cost-benefit analyses (CBA).

4.2.1 Capital Expenditure

Depending on the project's scope and particular requirements, a communication-based train control (CBTC) system's material requirements can change. However, some common materials that are needed for a CBTC system deployment are:

- Transponders: These devices are required to provide precise location information for the trains and are installed both on the trackside and onboard the trains.
- Signaling equipment: This includes the hardware and software required to control and manage the trains' movements, including interlocking systems and train control centers.

- Communication equipment: This includes the communication network that connects the signaling devices, trackside equipment, and onboard systems of the trains to provide real-time information.
- Control equipment**:** This includes the hardware and software for managing and controlling the train movements and providing the interface between the control center and the onboard systems.
- Power supply equipment: This includes the power supply systems required for all the CBTC components, including the signaling and communication equipment and the train's onboard systems.
- Testing and commissioning equipment: This equipment is required to test and commission the CBTC system before it can be fully operational.

The cost of these materials can vary depending on the project size, scope, and other factors, and should be estimated by the engineering firm or consultant responsible for the CBTC system design and implementation.

4.2.2 Operational Expenditure

Materials are generally required for upkeep, maintenance, and enhancements to establish a communication-based train control (CBTC) system. Some of the common materials required for operational expenditure are:

- Spare parts and consumables: CBTC systems require regular maintenance and repairs, so spare parts and consumables such as batteries, cables, sensors, and connectors may be needed to keep the system running properly.
- Software licenses: The CBTC system software requires periodic updates and upgrades, which may require additional software licenses.
- Training and support: Ongoing training and support are required to keep the system running smoothly, including training for new staff and technical support for any issues that arise.
- Power and communication costs: CBTC systems require power and communication infrastructure, and the ongoing costs of these services need to be considered.
- Testing and commissioning costs**:** When the CBTC system is upgraded or modified, testing and commissioning are required to ensure that the system works as intended. The costs associated with these activities need to be included in operational expenditure.

The cost of various materials may vary depending on the size, complexity, and maintenance plan of the CBTC system. The maintenance team responsible for the upkeep of the CBTC system should estimate these costs based on the specific needs of the system and the expected maintenance schedule.

4.3 Economic analysis by Economic indicators

A TEA of the deployment of the CBTC system on the Ethiopia-Djibouti railway line has been conducted, and the results have led us to the conclusion that the initial capital investment of $10 billion is both feasible and profitable over the long term. The benefit-cost ratio (BCR), net present value (NPV), internal rate of return (IRR), and total cost of ownership (TCO) of the analysis are all favorable.

These indicators show that the CBTC system's advantages outweigh its disadvantages, and the project is anticipated to produce positive cash flows over time, making it financially viable. Therefore, investing $ 191 million for both CapEx and OpeEx on CBTC system deployment in the Ethiopia-Djibouti railway line is a good decision from a techno-economic perspective.

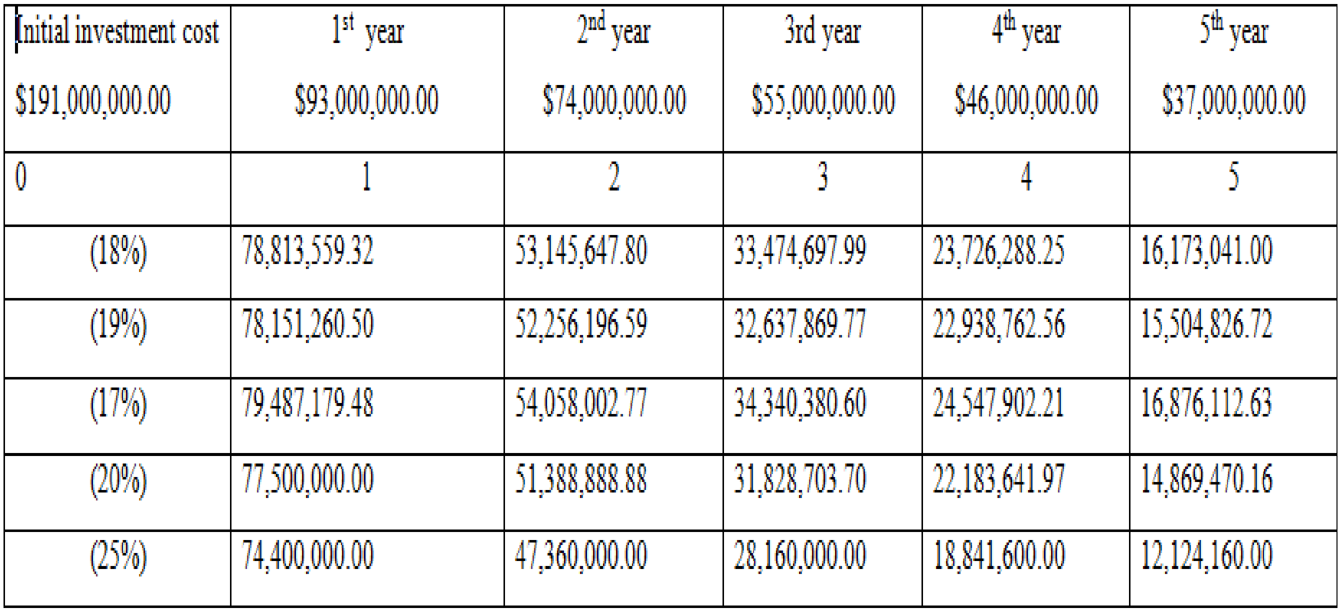
4.3.1 Net Present Value

The Net Present Value (NPV) method of financial analysis determines the present value of future cash inflows and outflows at a given interest rate. NPV can be used to assess whether an investment or project will result in a net profit or loss by comparing the present value of anticipated cash inflows and outflows.

- Initial investment (CFt): The initial investment cost
- Expected cash inflows: The anticipated cash inflows
- Discount rate (r): The rate at which future cash flows are discounted to their present value. It takes into account both the risk involved in the investment and the time value of money.
- The number of periods (n) over which cash inflows and outflows take place

If the NPV is positive, it is expected that the investment will provide a net gain after accounting for all cash inflows and outflows. If the NPV is negative, however, it is expected that the investment will result in a net loss. If the NPV is 0, the investment is expected to break even.

Table 4.1: Result of economic indicator for net present value



Initial investment cost $191,000,000.00	1st year $93,000,000.00	2nd year $74,000,000.00	3rd year $55,000,000.00	4th year $46,000,000.00	5th year $37,000,000.00
0	1	2	3	4	5
(18%)	78,813,559.32	53,145,647.80	33,474,697.99	23,726,288.25	16,173,041.00
(19%)	78,151,260.50	52,256,196.59	32,637,869.77	22,938,762.56	15,504,826.72
(17%)	79,487,179.48	54,058,002.77	34,340,380.60	24,547,902.21	16,876,112.63
(20%)	77,500,000.00	51,388,888.88	31,828,703.70	22,183,641.97	14,869,470.16
(25%)	74,400,000.00	47,360,000.00	28,160,000.00	18,841,600.00	12,124,160.00

PV (18%) within 5 years =$205,333,234.36

PV (19%) within 5 years= $201,488,916.14

PV (17%) within 5 years= $209,309,577.69

PV (20%) within 5 years= $197,770,704.71

PV (25%) within 5 years= $180,885,760.00

-$191,000.000+$205,333,234.36=$14,333,234.36

In this scenario, the calculation shows the present value (PV) of potential cash flows within 5 years based on different interest rates. The values range from $180,885,760.00 (at a 25% interest rate) to $209,309,577.69 (at a 17% interest rate). The project's net present value (NPV) is calculated by subtracting the initial investment of $191,000,000 from the PV of potential cash flows. If the NPV is greater than zero (in this case, it is $14,333,234.36), the project should be accepted. If the NPV is less than or equal to zero, then the project should be rejected.

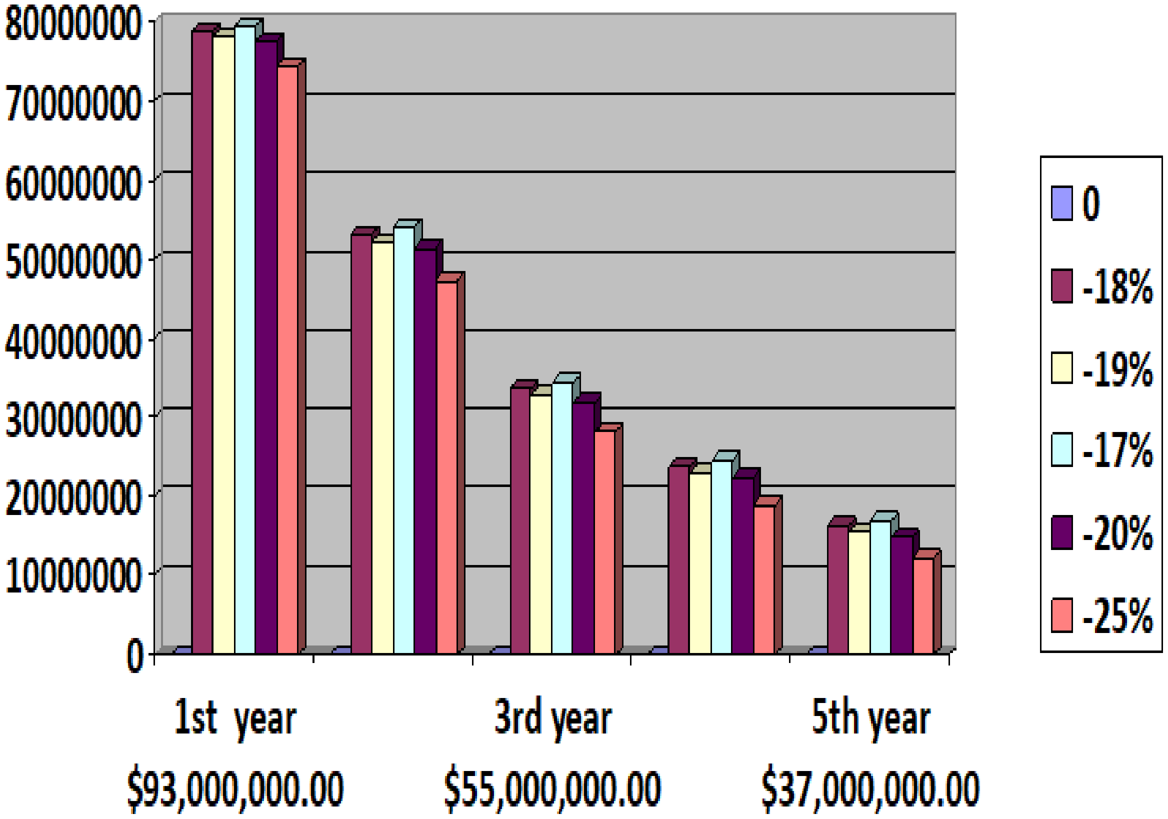


Figure 4.1: graphically result of economic indicator

4.3.2 Benefit-Cost ratio

The benefit-cost ratio (BCR), a financial statistic, is used to evaluate investment projects and proposals. It involves dividing the financial gains from a project or proposal by its financial expenses. The BCR is used to determine whether a proposal's or project's benefits outweigh its drawbacks.

A project or plan is considered to be profitable if the benefits outweigh the expenses and the BCR is larger than 1. However, if the BCR is less than 1, it may indicate that the project or proposal is not a viable investment because its costs are higher than its expected benefits.

The BCR is commonly used by businesses, governments, and organizations when evaluating potential investments including infrastructure projects, research and development initiatives, and new products or services. It is a useful tool for decision-making when comparing multiple investment options and assessing their financial viability.

$$\mathrm{BCR} = \frac{\$205{,}333{,}234.36}{\$191{,}000{,}000} \geq 1$$

4.3.3 Internal rate of return

To determine if a project or investment will be profitable, a financial indicator known as the IRR is used. It is the rate at which the net present value of each cash flow from a project or investment reaches **zero**. The IRR is the expected amount of return that the investor will experience throughout an investment. The higher the IRR, which is calculated as a percentage, the more successful the investment is deemed to be. The IRR is a metric that investors can use to compare the profitability of various investments and decide whether or not a proposed investment is worthwhile.

4.3.4 Payback Period

Calculating the amount of time it will take for a project or investment to recover its initial investment expenses is done using a financial indicator called the PBP. It is often used in capital budgeting to assess the viability and profitability of various investment proposals.

The Payback Period is calculated by dividing the initial investment cost by the projected yearly cash flow. The result is the number of years the investment will need to generate enough cash flow to recover its initial investment cost.

The payback period of a project refers to the time it takes to recover the initial investment. In the case of our investigation, the Payback Period (PBP) analysis reveals that the difference between the project's total cost ($193,000,000) and the cash inflows ($167,000,000) is $26,000,000.To determine the number of years required to recover the initial investment, the PBP analysis is divided by the annual cash inflows ($26,000,000/$55,000,000). This calculation gives a value of 0.4, indicating that less than a year is needed to recover the initial investment.

Furthermore, considering the exact month required to recover the initial investment, the decimal value of 0.4 is added to the initial two years. This results in a total of 2.4 years, implying that the project will cover the initial investment within two years and four months. Therefore, based on the PBP analysis, it is estimated that it will take approximately two years and four months to recover the initial investment for the project.

CHAPTER FIVE

CONCLUSION AND FUTURE WORKS

5.1 CONCLUSIONS

The CBTC application for railway technical systems as the control/signaling solutions has been specifically designed for the case of the Ethio-Djibouti railway network by taking into consideration technology selection, deployment, and cost aspects that change between the project and the baseline scenarios. This analysis suggests that CBTC is a superior technological solution for the railway network in Ethiopia and Djibouti because it transmits precise and fast train control information via radio transmission. Rail companies that specialize in mass transit, like Ethio Djibouti Railway, prefer CBTC. This technology is simple to use, and Ethio Djibouti Railway's cost-benefit analysis ensured the project's viability. This study concluded that CBTC can be used by the Ethiopia-Djibouti Railway easily, affordably, and effectively.

In general, several factors, such as the price of the original investment, ongoing operating costs, predicted increases in capacity and safety, and possible revenue, would affect the results of a techno-economic analysis of putting in place a CBTC system. The analysis typically entails estimating the cash flows throughout the project's anticipated lifetime and computing metrics like NPV, IRR, and PBP. If the NPV is positive, the IRR surpasses the hurdle rate, and the PBP is below a predetermined threshold, the project is often considered to be financially viable. In contrast, if the NPV is negative, the IRR is lower than the hurdle rate, and the PBP is too long, the project might not be financially feasible. Ultimately, whether to accept or reject the project would depend on the organization's risk tolerance, strategic objectives, and general financial status.

5.2 Recommendation

The specific recommendations for the TEA to deploy CBTC on the Ethiopian Djibouti Railway line would need to be done following a detailed analysis, but here are some future recommendations that can be considered:

- Conduct a comprehensive cost-benefit analysis of the CBTC system to ensure that it is delivering the anticipated benefits as measured against the cost of implementation.

- Continuously monitor the performance of the CBTC system, including its reliability, availability, maintainability, and safety, to identify areas for improvement and to maintain a high level of operational readiness.
- Optimize CBTC system capacity by implementing predictive maintenance plans to minimize downtime and improve overall equipment effectiveness.
- Consider the deployment of additional CBTC systems at other railway lines to promote interoperability and standardization across the system.
- Collaborate with relevant stakeholders, such as transportation providers and regulators, to develop common standards and optimize the use of CBTC technology to enhance performance, safety, and operational efficiency.
- Measure and assess the social and environmental impact of the CBTC system deployment on the community it serves, and make sure it aligns with the ethical and sustainability objectives of the society.

These recommendations are meant to encourage the optimization of the CBTC system on the Ethiopian Djibouti Railway line, providing a framework for its continuous improvement and increasing the system's efficiency, safety, and economic benefits.

5.3 Future Studies

Future research could be done to better comprehend the CBTC system's economic effects on the Ethiopian Djibouti railway. Studies on cost-benefit analysis, system performance, operating costs, the effects of climate change, potential cost savings from new technology, system maintenance and replacement, and demographic changes would all help to improve the system's performance in real-world applications. These studies would enable the selection of the CBTC system configuration that would increase railroad line users' productivity, security, and economic performance.

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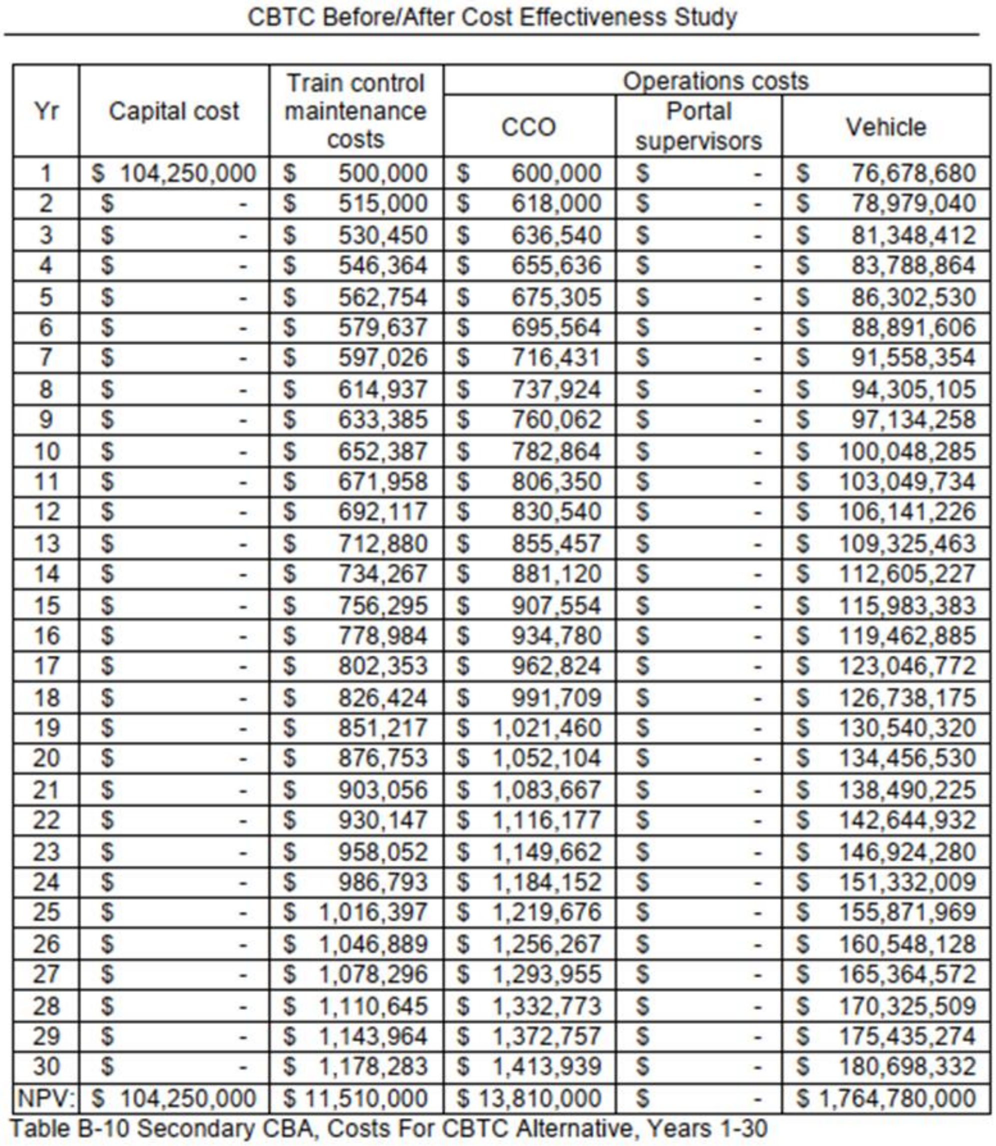
APPENDIX

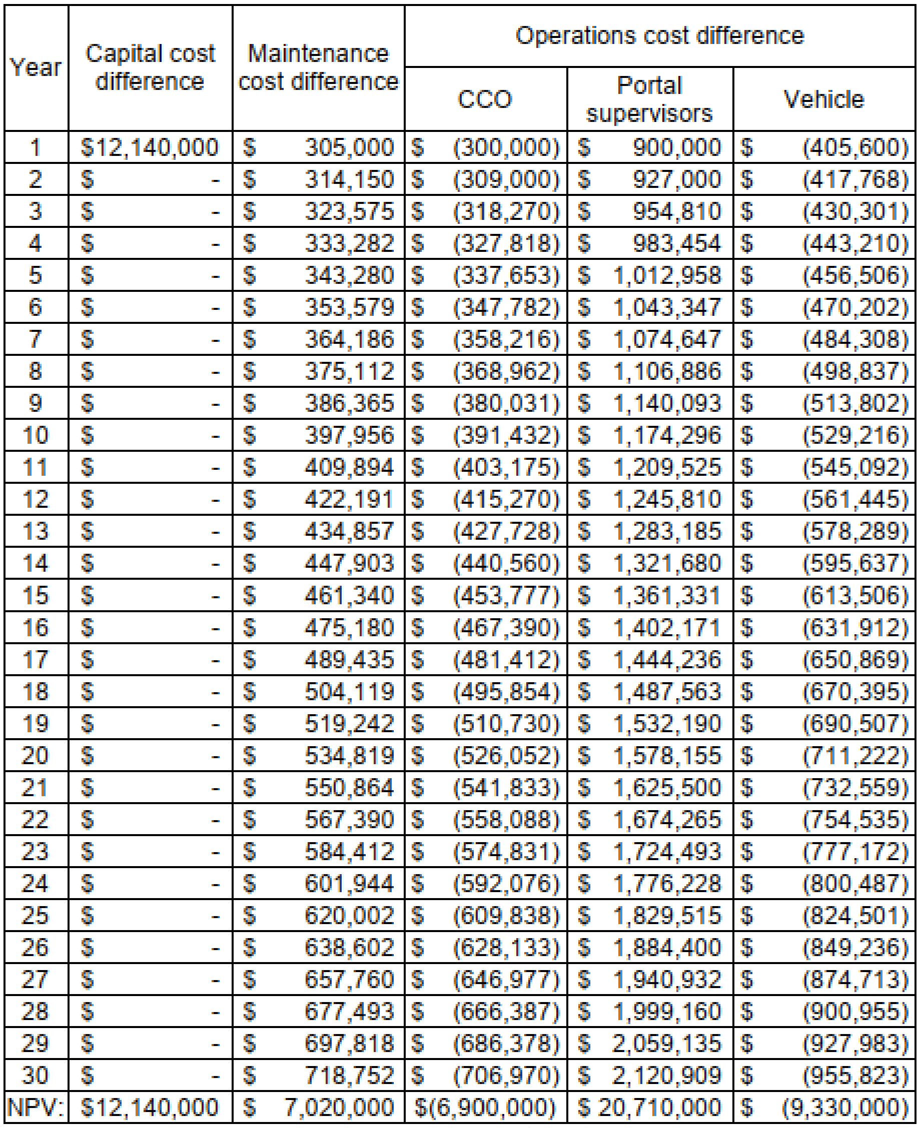
Table B-10 Secondary CBA, Costs for CBTC Alternative, Years 1-30



CBTC Before/After Cost Effectiveness Study

Yr	Capital cost	Train control maintenance costs	Operations costs		
			CCO	Portal supervisors	Vehicle
1	$ 104,250,000	$ 500,000	$ 600,000	$ -	$ 76,678,680
2	$ -	$ 515,000	$ 618,000	$ -	$ 78,979,040
3	$ -	$ 530,450	$ 636,540	$ -	$ 81,348,412
4	$ -	$ 546,364	$ 655,636	$ -	$ 83,788,864
5	$ -	$ 562,754	$ 675,305	$ -	$ 86,302,530
6	$ -	$ 579,637	$ 695,564	$ -	$ 88,891,606
7	$ -	$ 597,026	$ 716,431	$ -	$ 91,558,354
8	$ -	$ 614,937	$ 737,924	$ -	$ 94,305,105
9	$ -	$ 633,385	$ 760,062	$ -	$ 97,134,258
10	$ -	$ 652,387	$ 782,864	$ -	$ 100,048,285
11	$ -	$ 671,958	$ 806,350	$ -	$ 103,049,734
12	$ -	$ 692,117	$ 830,540	$ -	$ 106,141,226
13	$ -	$ 712,880	$ 855,457	$ -	$ 109,325,463
14	$ -	$ 734,267	$ 881,120	$ -	$ 112,605,227
15	$ -	$ 756,295	$ 907,554	$ -	$ 115,983,383
16	$ -	$ 778,984	$ 934,780	$ -	$ 119,462,885
17	$ -	$ 802,353	$ 962,824	$ -	$ 123,046,772
18	$ -	$ 826,424	$ 991,709	$ -	$ 126,738,175
19	$ -	$ 851,217	$ 1,021,460	$ -	$ 130,540,320
20	$ -	$ 876,753	$ 1,052,104	$ -	$ 134,456,530
21	$ -	$ 903,056	$ 1,083,667	$ -	$ 138,490,225
22	$ -	$ 930,147	$ 1,116,177	$ -	$ 142,644,932
23	$ -	$ 958,052	$ 1,149,662	$ -	$ 146,924,280
24	$ -	$ 986,793	$ 1,184,152	$ -	$ 151,332,009
25	$ -	$ 1,016,397	$ 1,219,676	$ -	$ 155,871,969
26	$ -	$ 1,046,889	$ 1,256,267	$ -	$ 160,548,128
27	$ -	$ 1,078,296	$ 1,293,955	$ -	$ 165,364,572
28	$ -	$ 1,110,645	$ 1,332,773	$ -	$ 170,325,509
29	$ -	$ 1,143,964	$ 1,372,757	$ -	$ 175,435,274
30	$ -	$ 1,178,283	$ 1,413,939	$ -	$ 180,698,332
NPV:	$ 104,250,000	$ 11,510,000	$ 13,810,000	$ -	$ 1,764,780,000

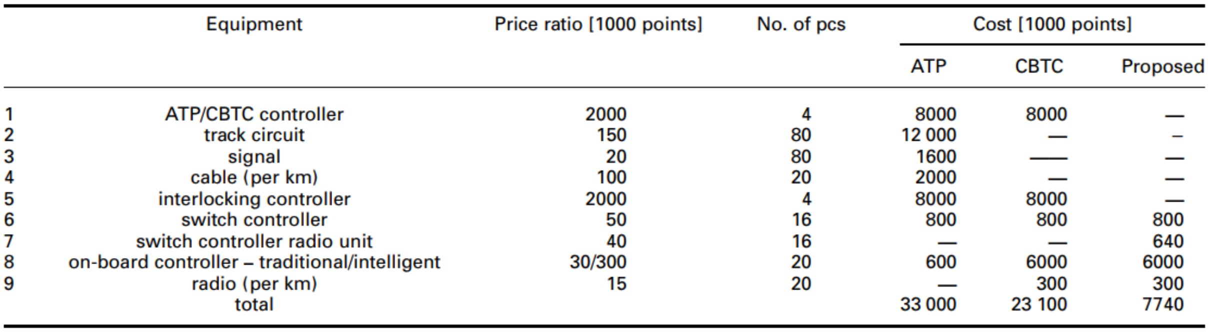
Table B-10 Secondary CBA, Costs For CBTC Alternative, Years 1-30



Year	Capital cost difference	Maintenance cost difference	Operations cost difference		
			CCO	Portal supervisors	Vehicle
1	$12,140,000	$ 305,000	$ (300,000)	$ 900,000	$ (405,600)
2	$ -	$ 314,150	$ (309,000)	$ 927,000	$ (417,768)
3	$ -	$ 323,575	$ (318,270)	$ 954,810	$ (430,301)
4	$ -	$ 333,282	$ (327,818)	$ 983,454	$ (443,210)
5	$ -	$ 343,280	$ (337,653)	$ 1,012,958	$ (456,506)
6	$ -	$ 353,579	$ (347,782)	$ 1,043,347	$ (470,202)
7	$ -	$ 364,186	$ (358,216)	$ 1,074,647	$ (484,308)
8	$ -	$ 375,112	$ (368,962)	$ 1,106,886	$ (498,837)
9	$ -	$ 386,365	$ (380,031)	$ 1,140,093	$ (513,802)
10	$ -	$ 397,956	$ (391,432)	$ 1,174,296	$ (529,216)
11	$ -	$ 409,894	$ (403,175)	$ 1,209,525	$ (545,092)
12	$ -	$ 422,191	$ (415,270)	$ 1,245,810	$ (561,445)
13	$ -	$ 434,857	$ (427,728)	$ 1,283,185	$ (578,289)
14	$ -	$ 447,903	$ (440,560)	$ 1,321,680	$ (595,637)
15	$ -	$ 461,340	$ (453,777)	$ 1,361,331	$ (613,506)
16	$ -	$ 475,180	$ (467,390)	$ 1,402,171	$ (631,912)
17	$ -	$ 489,435	$ (481,412)	$ 1,444,236	$ (650,869)
18	$ -	$ 504,119	$ (495,854)	$ 1,487,563	$ (670,395)
19	$ -	$ 519,242	$ (510,730)	$ 1,532,190	$ (690,507)
20	$ -	$ 534,819	$ (526,052)	$ 1,578,155	$ (711,222)
21	$ -	$ 550,864	$ (541,833)	$ 1,625,500	$ (732,559)
22	$ -	$ 567,390	$ (558,088)	$ 1,674,265	$ (754,535)
23	$ -	$ 584,412	$ (574,831)	$ 1,724,493	$ (777,172)
24	$ -	$ 601,944	$ (592,076)	$ 1,776,228	$ (800,487)
25	$ -	$ 620,002	$ (609,838)	$ 1,829,515	$ (824,501)
26	$ -	$ 638,602	$ (628,133)	$ 1,884,400	$ (849,236)
27	$ -	$ 657,760	$ (646,977)	$ 1,940,932	$ (874,713)
28	$ -	$ 677,493	$ (666,387)	$ 1,999,160	$ (900,955)
29	$ -	$ 697,818	$ (686,378)	$ 2,059,135	$ (927,983)
30	$ -	$ 718,752	$ (706,970)	$ 2,120,909	$ (955,823)
NPV:	$12,140,000	$ 7,020,000	$(6,900,000)	$ 20,710,000	$ (9,330,000)

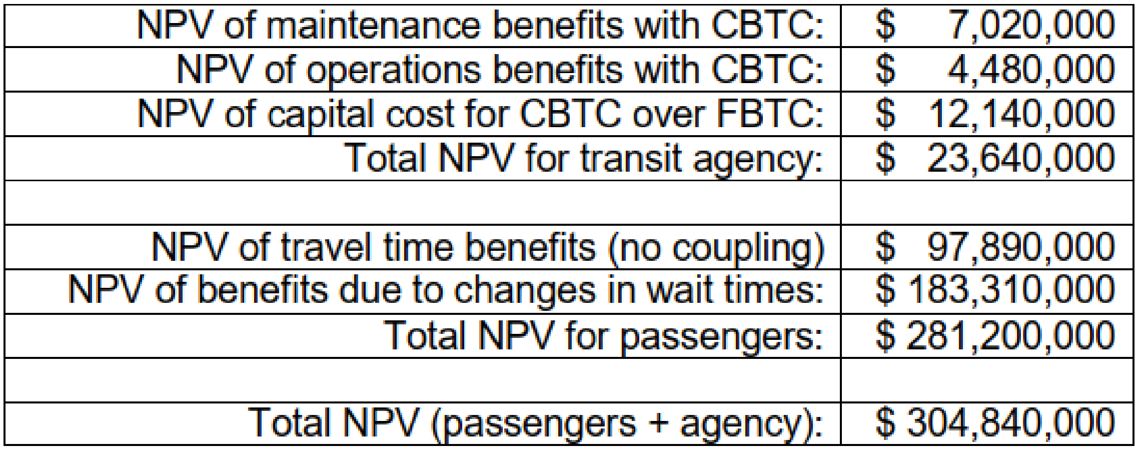
Table B-11 Secondary CBA, Differences In Costs Between FBTC And CBTC Alternatives, Years 1-30

Table 2 Comparison of the required equipment and cost



	Equipment	Price ratio [1000 points]	No. of pcs	Cost [1000 points]		
				ATP	CBTC	Proposed
1	ATP/CBTC controller	2000	4	8000	8000	—
2	track circuit	150	80	12 000	—	–
3	signal	20	80	1600	——	—
4	cable (per km)	100	20	2000	—	—
5	interlocking controller	2000	4	8000	8000	—
6	switch controller	50	16	800	800	800
7	switch controller radio unit	40	16	—	—	640
8	on-board controller – traditional/intelligent	30/300	20	600	6000	6000
9	radio (per km)	15	20	—	300	300
	total			33 000	23 100	7740

Table 4-2 for summary).



NPV of maintenance benefits with CBTC:	$ 7,020,000
NPV of operations benefits with CBTC:	$ 4,480,000
NPV of capital cost for CBTC over FBTC:	$ 12,140,000
Total NPV for transit agency:	$ 23,640,000
NPV of travel time benefits (no coupling)	$ 97,890,000
NPV of benefits due to changes in wait times:	$ 183,310,000
Total NPV for passengers:	$ 281,200,000
Total NPV (passengers + agency):	$ 304,840,000

Table 4-2 Summary of NPV of Secondary CBA