



A STUDY ON RAILWAY SIGNALLING COMPONENTS

THESIS
SUBMITTED BY
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“Statement of Originality”

I, *Susmita Sau*, registered on 14th December, 2016 do hereby declare that this thesis entitled “*A Study on Railway Signalling Components*” contains literature survey and original research work done by the undersigned candidate as part of Doctoral studies.

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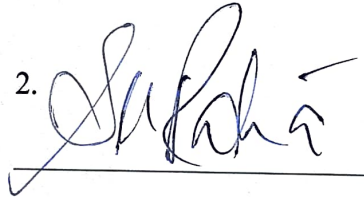
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Dedicated to

The Soul of My Father....

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Abstract

The growing demand for faster transportation and increasing traffic are putting significant pressure on global railway and highway systems. Railways, a key element of the transportation network, efficiently and sustainably move passengers and goods using locomotives and rails. Compared to road transportation, railways are more environmentally friendly and cost-effective, reducing carbon emissions and fuel consumption. They play a crucial role in connecting cities, regions, and countries, promoting economic growth while alleviating road congestion and minimizing environmental impacts. Railway signaling systems, much like traffic lights for roads, are vital for managing train movements and ensuring safe and efficient operations. These systems provide train operators with instructions on when to stop, proceed, and control speed, thus preventing accidents and maintaining organized train traffic. With fast-moving and heavy trains, signaling systems are crucial to avoiding collisions, aided by track circuits and interlocking systems that help detect train positions and ensure safe distances between trains.

In complex rail networks, these systems control the flow of trains, manage track changes using switches, and handle emergencies like derailments by halting trains and rerouting traffic. High-speed trains, in particular, rely on advanced signaling due to their longer braking distances. These systems integrate mechanical, electrical, and electronic components, making safety dependent on their combined performance along with that of human operators. In India, the government-run Indian Railways operates with diverse signaling systems, often influenced by environmental factors. Research focuses on the Kolkata Metro, India's first metro system, operational since 1984. Covering a 27.22 km network and serving over 650,000 passengers daily, the metro is a critical part of Kolkata's public transportation. Metro Railways, known for being cost-effective and eco-friendly, helps reduce road congestion through its rapid transit systems. Among its subsystems, the axle counter plays a critical role in detecting train occupancy on tracks, and its failure can disrupt operations. This paper analyzes the failure patterns of axle counters and estimates their availability. Over 15 months, the overall equipment effectiveness (OEE) was approximately 75%, with a

10% variation. The study further examines the reliability, availability, and maintainability of axle counters in metro railway systems. Here, Failure analysis of railway signaling components one of the important issues in recent times, image processing has become an essential tool for quality control across various industries, especially for identifying deformities by comparing distorted images to reference images. This technique can be applied to assess the failure of metal-to-carbon relays, a crucial component in Indian railway signaling systems. These relays, made with silver-impregnated graphite (SIG) and silver contacts, function by making or breaking connections based on signaling logic. However, oxide and sulphide layers can form on the SIG contacts, increasing resistance and reducing reliability, which compromises rail safety and speed. This study utilizes image processing to analyze the failure of SIG contacts and assess their impact on relay performance. In recent times, image processing has become an essential tool for quality control across various industries, especially for identifying deformities by comparing distorted images to reference images. This technique can be applied to assess the failure of metal-to-carbon relays, a crucial component in Indian railway signaling systems. These relays, made with silver-impregnated graphite (SIG) and silver contacts, function by making or breaking connections based on signaling logic. However, oxide and sulphide layers can form on the SIG contacts, increasing resistance and reducing reliability, which compromises rail safety and speed. This study utilizes image processing to analyze the failure of SIG contacts and assess their impact on relay performance.

1. Introduction

Introduction

The growing demand for faster transportation and increased traffic requirements present an escalating challenge for highway and railway systems worldwide [Tee, K.F.et al. 2019][Ekpiwhre,E.O et al. 2018] which is a crucial component of the global transportation network. It involves the movement of passengers and goods on track using locomotives and rails. Railway transportation is known for its environmental friendliness and efficiency compared with road transportation. Furthermore, railway transportation is a cost-effective option for both individuals and businesses as it reduces carbon emissions and fuel consumption, leading to significant savings in the long run. They play a vital role in connecting cities, regions, and countries, contributing to economic development, and reducing road congestion and environmental impacts, according to the International [International Union of Railway Statics 2021].

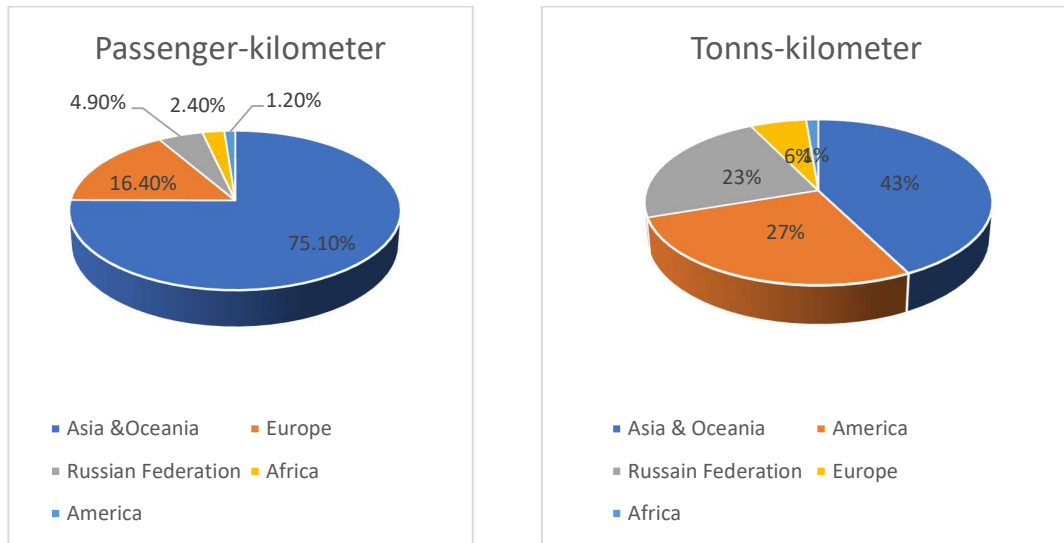


Fig 1.1: UIC Railway Statics of 2022(UIC ,2022)

The A total of 75.10% of passengers and 43% of freight travelled through the railway transportation system in Asia and Oceania. Europe, followed by 16.40% of passengers

and 6% of freight, travelled through the railway transportation system. Russian Federation was followed by 4.90% of passengers and 22.90% of freight travelled through Railway Transportation. America is followed by 1.2% of passengers and 27.4% of freight travelled through Railway Transportation. Africa is followed by 2.4 % of passengers and 1.3% travelled through Railway Transportation across the world.

1.1 Railway Signaling System

The Road Transportation systems are guided by traffic signals. on the other hand, railways rely on railway signals to control train movements. A railway signaling system is a critical infrastructure that ensures safe and efficient train operations, Road Transportation systems are guided by traffic signals. However, railways rely on railway signals to control their movements [Soilán, M et. al. 2019]. This system helps to maintain efficient and eco-friendly rail transport operations. The primary needs and purposes of a railway signalling system are as follows.

Safety: The paramount need for a signaling system is to ensure the safety of both passengers and railway staff [Torralba, A et.al 2020]. Trains are heavy, fast-moving vehicles that can cause catastrophic accidents if they collide or operate on the same track without proper coordination.

Collision Avoidance: To avoid collisions, signaling systems use various components such as signals, track circuits, and interlocking systems. Signals are placed at strategic points along the track and communicate with train operators. They indicate whether it is safe to proceed, slow, or stop. Track circuits detect the presence of trains[Jin Z.,Dong et. al (2022)] on a specific section of the track and maintain a safe distance between the trains.

Traffic Management: Railway networks are typically complex with multiple tracks, junctions, and crossings [Patil, Y.H et.al.2024]. Signaling systems play a vital role in managing train traffic flow. They ensure that trains are routed efficiently, prioritize them based on schedules, and avoid congestion.

Switch Control: Switches, known as turnouts [Kljaić, Z. et.al. 2023], are critical components of a signaling system. They control the direction of a train at the junctions. Allowing trains to switch from one track to another.

Emergency Situations: Signaling systems are equipped to handle emergency situations such as derailments, sudden stops, or other unexpected events. Signals can quickly halt train movement and reroute traffic to avoid hazards.

High-speed Control: High-speed trains require a greater breaking distance to stop at full speed, emphasizing the importance of effective signaling systems. These systems primarily control train movements between stations by ensuring that the track ahead is clear of the other trains traveling in the same direction. Although high-speed trains carry a load, to avoid collisions, a greater breaking distance is required to stop the train from full speed. A signalling system is required to control the movement of trains from one station to another after ensuring that the track on which this train will move to reach the next station is free from the movement of another train in the same direction.

Therefore, the signalling system is at the heart of a railway transportation system. It is very complex, and it has a large number of subsystems and components to perform its purpose at different levels of operation. Its successful operation and functioning also depend on other railway systems and operating personnel. The man-machine interrelationship is an important issue and is very complex to design and develop. In this context, the failure analysis and risk assessment of signalling systems depend on the joint performance of several subsystems such as mechanical, electrical, and electronic systems, operators, and drivers involved in the process of signalling.

1.1.1 History of Signaling System

The evolution of railway signaling systems is a narrative of advancement and innovation that has transpired alongside the progression of rail transportation. During the early days of rail travel, signaling was elementary, primarily depending on

manual techniques. The communication between trains and stations was enabled by flagmen and lanterns, which facilitated basic interaction.

A major breakthrough in the 1830s was the introduction of semaphore signals, mechanical devices that used movable arms to convey specific instructions such as signaling a train to stop, proceed, or exercise caution. The implementation of semaphore signaling represented a significant advancement, providing a more precise means of communication for railway operations [T. R. Singh et.al. 2023]. As rail networks expanded, the need for more sophisticated signaling systems became evident. This led to the introduction of block signaling systems, which divided the railway track into distinct sections or blocks [Nina D et.al. 2024]. The fundamental principle was to allow only one train to occupy a given block at any given time. This innovative approach significantly enhanced safety measures and mitigated the risk of collisions. Further progress was achieved with the development of interlocking systems [Anne Elisabeth, et.al. 2023][Amendola, A. *et al.* (2020)]. These systems were designed to coordinate signals and switches, ensuring that conflicting routes could not be established simultaneously. The mechanical interlockings became integral to railway safety, preventing potentially hazardous situations. In the early 20th century, a transition from mechanical to electric signaling systems occurred.

The shift from traditional semaphore signals to electric signals utilizing color lights revolutionized railway signaling mechanisms. This change resulted in a more adaptable and visible system for operators. During the mid-20th century, the introduction of Centralized Traffic Control (CTC) systems marked a new era in railway signaling. These systems allowed operators to manage and regulate multiple sections of track from centralized control centers, significantly enhancing operational efficiency.

As technology progressed, computer-based interlocking and signaling systems were integrated into railway signaling in the late 20th century. These systems leveraged computer technology to automate control processes, optimizing train movement and improving safety measures [A. Ferrari et.al. 2022]. In the 21st century, Positive Train

Control (PTC) systems emerged as a groundbreaking innovation. By incorporating GPS and advanced communication technologies, PTC systems actively monitor and control train movements, aiming to prevent collisions and unsafe conditions by automatically halting trains when necessary. The future of railway signaling systems appears poised for continued innovation, with ongoing developments in artificial intelligence, machine learning, and cutting-edge communication technologies. These advancements aim to further refine the efficiency, safety, and intelligence of modern railway signaling systems, ensuring the continued evolution of rail transportation.

1.2 Indian Railway

Indian Railways (IR) is the fourth largest railway network in the world. Total track length is 68,103 route kilometers. It carried daily 8.086 billion passengers, and Transporting 1418.1 million tons of freight per day. [Indian Railways 2022-2023]

The Indian railway system stands out due to its distinctive characteristics in terms of design, production, and operational structure. Railway signalling systems are crucial for the safe and efficient operation of trains.

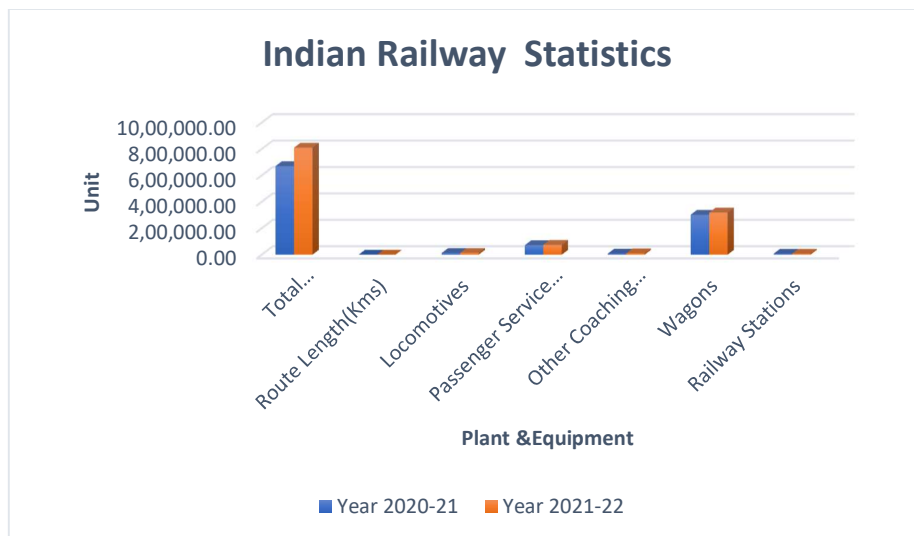


Fig 1.2. Indian Railway statistics for the year 2020 to 2022

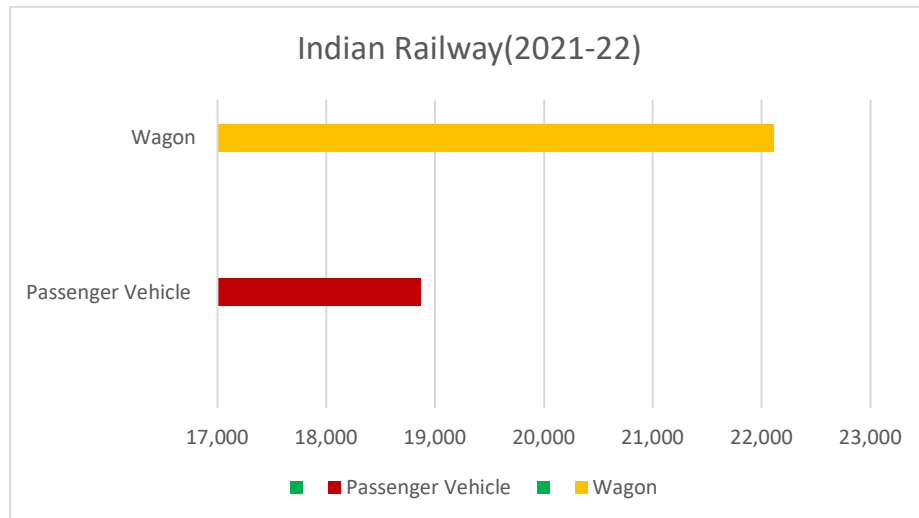


Fig 1.3. Indian Railway statistics wagon, passenger vehicle in million (2020- 2022)

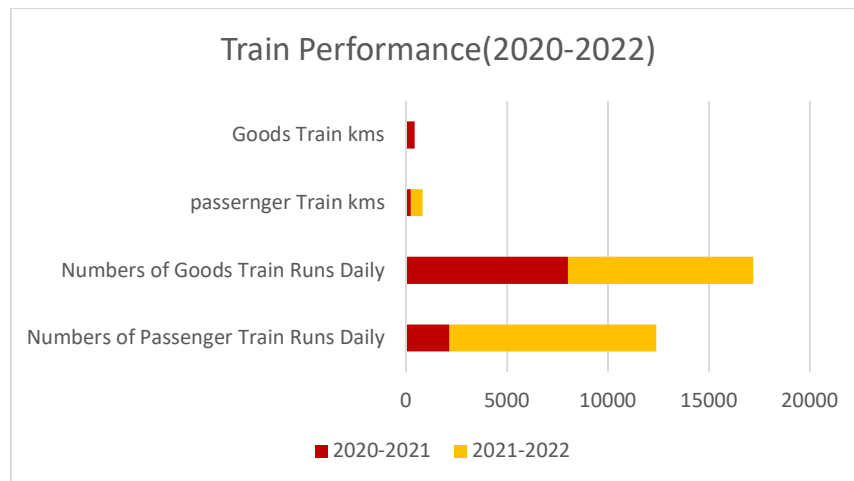


Fig 1.4. Indian Railway statistics for Goods and Passenger Trains (2020- 2022)

1.2.1 History of Indian Railways

The history of Indian Railways is a journey that began in the 19th century during British Colonial rule. The inaugural passenger train journey occurred on April 1853 between Bombay and Thane, covering a distance of 34 Kilometers. This marked the inception of railway operations in India and laid the foundation for a vast network that would transform transportation across the subcontinent. Under British influence, the railway network expanded rapidly, serving strategic and economic interests. By the early 20th century, major railway lines connected key cities, facilitating the movement of raw materials, goods, and passengers [Hurd, J., Kerr, I. J. (2012)]. The

railways played a pivotal role in integrating regions and fostering economic development.

The post-independence period saw significant changes in Indian Railways. The network was nationalized in 1951 bringing all railway systems under a single umbrella [India's Railway History. (2006)]. A series of five-year plans aimed at modernization and expansion were initiated to enhance efficiency and meet growing demands. New railway zones were established to streamline operations and electrification projects were introduced to improve sustainability.

In the late 20th century, iconic trains like Rajdhani and Shatabdi Express were introduced, revolutionizing long-distance travel with improved speed and amenities. The 21st century witnessed a focus on high-speed rail projects, signalling, and commitment to modernization and technological advancement.

Indian Railways continues to be a lifeline for the century, playing a vital role in the movement of goods and passengers. The network's resilience and adaptability reflect its enduring significance in India's socio-economic landscape. As the nation progresses ongoing efforts in infrastructure development and technology integration ensure that the Indian Railways remains a key player in the country's growth story.

A long history, evolving to meet several key needs:

- Railway signalling systems have been in use for over a century, initially based on manual signalling.
- The introduction of electric and electronic signalling systems revolutionized railway safety and efficiency.
- Modern systems incorporate advanced technologies like computer control interlocking and communications networks.

India is experiencing rapid urbanization, significantly impacting its environment and urban infrastructure. The increasing urban population, driven by aspirations for a better quality of life, is straining the environment and placing considerable stress on city systems, especially transportation.

Rapid Transit Systems (RTS) are essential components of urban transport infrastructure. Though not universally defined, RTS often include metros, subways, and elevated or surface systems. They are characterized by high capacity, frequent service, and a dedicated right-of-way, differentiating them from light rail systems that may share roads or tracks [Zhu, C. Chen et.al. 2024]. Originating with the London Underground in 1863, RTS technology has spread globally, with significant development in Asia and the advent of driverless systems. Currently, over 160 cities feature RTS, with ongoing expansions.

In India, rapid urbanization is marked by substantial population growth, both natural and due to migration from rural areas. This surge in population has dramatically increased transport demand, often exceeding the capacities of existing road infrastructure [Awad, F. A., et.al. 2023] Private vehicle use, which has been rising due to higher incomes and industrial activities, exacerbates traffic congestion, air pollution, and noise. These issues highlight the urgent need for effective mass rapid transit solutions.

The introduction of Mass Rapid Transit Systems (MRTS) is crucial for addressing these challenges MRTS are capital-intensive and require long-term planning and development [Lambat, Nitin et.al. 2022]. In developed countries, MRTS planning begins when city populations exceed 1 million, with implementation as populations approach 2 to 3 million. As cities grow beyond 4 million, expansions are actively pursued [Dong Lin et.al. 2022].

The current urban growth trends in India reveal severe issues such as a 10% annual increase in motor vehicle population, significant vehicular emissions contributing to global pollution, and intense traffic congestion. These problems underline the need for robust public transport systems to mitigate the adverse effects of rapid urbanization and improve overall urban mobility and environmental sustainability.

1.3 Research Issues

The Indian Railway (IR) is a Governmental Organization. Indian Railway (IR) is the only service provider of railway traffic in India. It has several unique features and problems related to its design, operations, and organization.

In the technical category, the following features are worth mentioning.

- The speed of the train varies between 20 and 140 km/h.
- Various types of signaling components are present
- The performance of a signalling system is affected by various environmental factors and electromagnetic interference.

The Present research work has been done over the Kolkata Metro Railway (MR). Growing cities, growing populations, and growing traffic have invariably called for a shift from private modes of transport to public transport. A glance at the world's developing nations indicates that well-planned Mass Rapid Transit Systems (MRTS) exist successfully. In India's first metro, the Kolkata Metro started working almost 25 years ago. In 1984 24th October, the first stretch, a length of approximately 3.4 km between Esplanade and Bhowanipur, was completed. The network currently consists of one operational line of 27.22 km from Noapara to the Kavi Subhash[Kolkata Metro Rail corporation]. There are 300 metro services that carry more than 650, 000 passengers daily. A large mass was carried by Kolkata Metro every day. Performance analysis is essential in this context. Signalling systems play a vital role in the fail-safe operation of trains. Signalling system consists of the following signalling subsystems and components: interlocking system (Panel, Route Relay, and Electronic), Audio Frequency Track Circuit (AFTC), Multi-section Digital Axle Counter (MSDAC), Relay, Automatic or Semi-automatic Signal unit, Panel, Power supply. Hence, component failure and reliability-based component analysis are important. Kolkata metro has both elevated and underground rail, therefore proper maintenance and degradation analysis are essential.

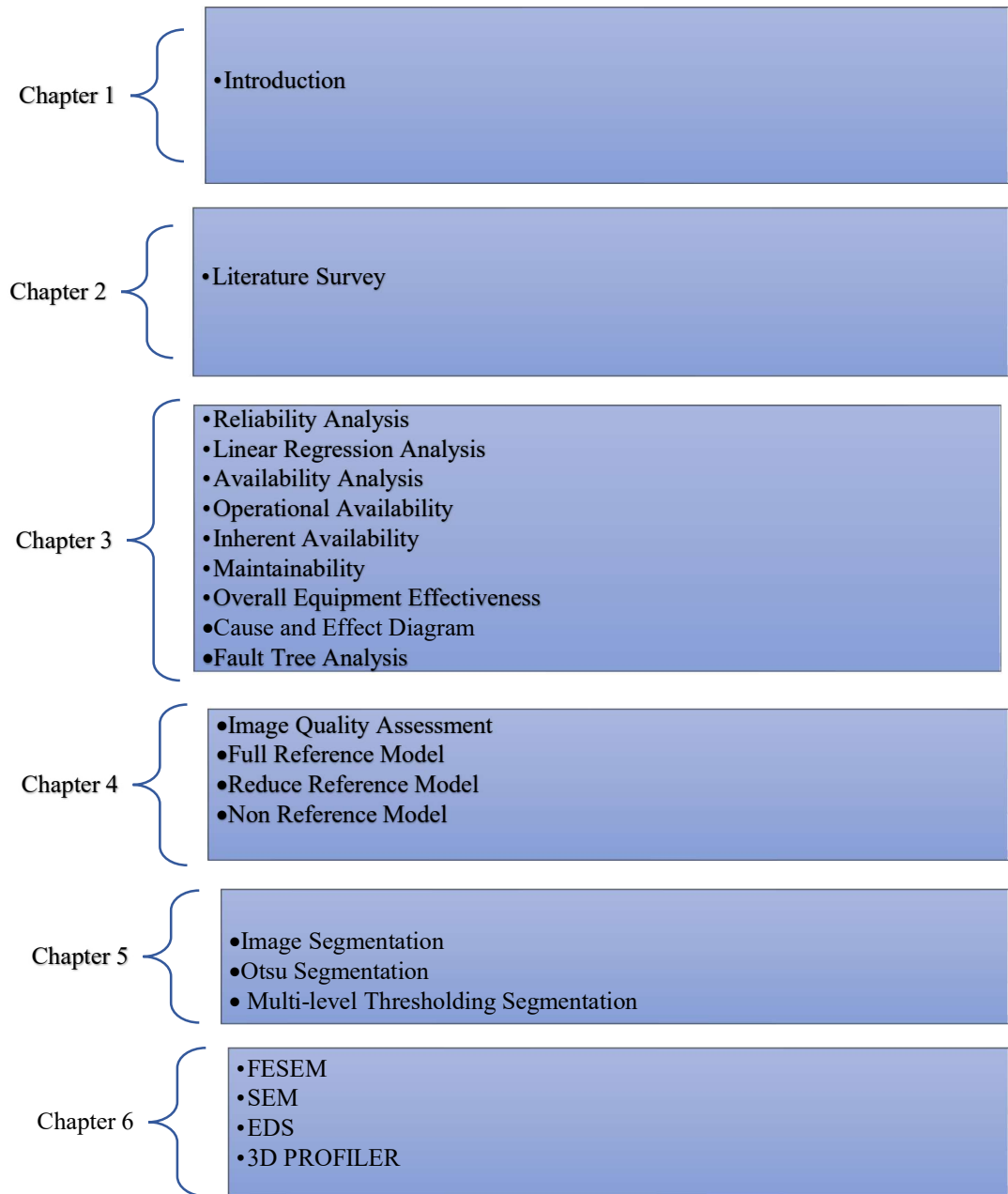
1.4 Research Objectives

This research work focuses on performance study of Metro railway signalling components and subsystems based on failure and reliability analyses. As per the signalling system Axle counter and Relay are the vital components. Therefore, research work focuses on these two components.

The following objectives are:

- To identify the causes and effects of signaling failures.
- To analyse the performance of Axle counter on the basis of reliability, availability, maintainability and OEE.
- To model the surface pattern, as obtained by SEM, with the help of Image processing.
- To analyse failed Relay surface topography using FESEM, SEM, EDS, XRD
- To Analyse the surface roughness of failed Rela
- To Analyse Contact surface using 3D Profilometry and identify the degradation pattern of relay failure with respect to time.

1.5 Methodology



1.6 Thesis Framework

The PhD research is structured into six chapters, starting with a foundational introduction and progressing to a detailed and intricate analysis. Each chapter unfolds distinct aspects, contributing to a comprehensive exploration of the subject matter.

The outline of the thesis can be described as follows:

Chapter 1 Begins by summarizing the historical context and projected future of the worldwide railway transportation system, including specific insights into the situation in India. For a better understanding requirement signaling system has been explained briefly. The signaling in the Indian Railway is a critical component ensuring the safe and efficient operation of the big railway network. To enhance operational safety and efficiency, Indian Railways continues to invest in modernizing and upgrading signaling infrastructure. Rapid Transit has been introduced and requirements have also been explained in this chapter. Kolkata Metro was the first metro in India. Briefly explained statistics of Kolkata Metro.

Chapter 2 Starts with the various signalling components. Railway signaling systems are composed of complex components, including critical subsystems like signal units, track circuits, and point machines, which ensure system reliability and safety. Signalling systems are divided into indoor components, such as interlocking systems and relays managed from control rooms, and outdoor components, like track circuits and axle counters, located in the yard. Interlocking systems, essential for safe train movements, have evolved from mechanical to computer-based systems, ensuring trains follow designated routes without conflicts. Axle counter and Relay are two crucial components that have been taken. The reliability of electromagnetic relays in railway signaling systems is compromised due to factors like production, environmental stress, and usage, which is concerning given the high safety requirements. Metal-to-carbon Q-series relays, commonly used in railway signaling, suffer from poor reliability, particularly due to significant increases in contact resistance, leading to failures. These failures account for about 7% of total signaling equipment failures in Indian Railways, highlighting the need for a thorough reliability and performance analysis.

Chapter 3 is focused on eco-friendly rapid transit system. Rapid transit systems in India rely on advanced signalling systems for safety and efficiency. These signalling systems are crucial for ensuring smooth operations. The axle counter is an integral part of signalling system, its failure hampers the train movement. To run the train smoothly reliability, availability, maintainability analysis have been done. Overall

Equipment Effectiveness Analysis and Linear Regression Analysis has done using data collected from representative station of Kolkata Metro Railway. Therefore, to identify the actual reasons of Axle Counter failure, focus has been done on the causes and effects of the signalling failure. Thus, the analysis of its failure and availability is a vital issue. The cause-effect (CE) diagram and Fault Tree analysis have been used here to identify possible causes of its failures.

Chapter 4 is starts with another crucial signaling component -Relay. Metal to carbon relay is widely used in signaling system in Indian railway to operate various signaling components viz. Track circuits /points / signals etc. Due to substantial stress, environmental impacts guide to the irregularities on the signalling relay of the silver impregnated graphite surface. A thin layer of Oxide, Sulphides is formed on the surface of the SIG contact, which causes high resistance on the relay. Failure of these relays cause interruption in train movement and delays the time schedule. Reliability of these relay is poor. The surface texture of metal to carbon relay contact is an important feature, for quality assessment of deformed surface. To do quality assessment, Image samples of defected relay contacts are collected in this work. Image-based grading has been applied on these images to analyse the deformation of the relays. Here Image quality has been estimated as an elementary vital factor. An Objective based machine assessment has been applied. Quality Index model of any distortion based on loss of correlation, mean distortion, and variance distortion. Mean Square Error(MSE), Peak signal to Noise Ratio (PSNR), Structural Similarity Index (SSIM) has been calculated over reference image and distorted images.

Chapter 5 is start with collection of defective relays and the analysis of SIG contact images through image processing techniques. The methodology includes image acquisition, pre-processing, image segmentation, and defect detection. Image segmentation serves to separate foreground elements from the background. In this within the image, with the foreground representing these defective areas and the background encompassing the non-defective regions. Here Otsu and Multilevel segmentation have been applied.

Chapter 6 is start with surface failure analysis of signalling relay, QN1 series relay. The operating contact resistance of the QN1 series relay is less than two hundred milliohms. After thousands of operations, contact resistance becomes greater than two hundred mili-ohms, and safety issues arise for train movement. Mechanical damage occurred after certain use. A metal-to-carbon contact relay has A graphite contact is a movable contact, and a silver contact is a fixed contact. Graphite contact is a softer material than silver contact; for that reason, mechanical damage occurs on the surface of the contact surface. Hence, Surface roughness has been analyzed using 3D profilometry. A detailed surface topography inspection based on SEM analysis of failed relays of the SIG contact and silver contacts are the research objectives of the proposed work. Therefore, the graphite contact surface is examined for preceding and succeeding failures to find the reasons for relay contact failure. FESEM and SEM analyses have been done on the graphite contact surfaces. EDS was also performed on the silver contact and graphite contact pre-failure and post-failure to find the chemical distribution of elements on the surface.

2.Literature Survey

Introduction

The railway transportation system is very environment friendly and efficient than any other road transportation. In road transportation, road is fully guided by signal. Railway signals are essential for directing train movements, informing operators when to stop, and proceed, and the speed limits they must adhere to as they pass a signal [Milewicz J 2023 et al..]. As well as in railways, there is a need to provide control on the movement of trains in the form of Railway signals which indicates the operator to stop or move and also the speed at which they can pass a signal.

Though high-speed trains carry load, to avoid collisions more breaking distance is required to stop the train from full speed. Signalling system is required mainly to control the movements of trains from one station to another after ensuring that the track on which this train will move to reach the next station is free from the movement of another train in the same direction. Signalling system is the heart of a railway transportation system. It is a very complex one and it has a huge number of subsystems and components to perform its purpose in different levels of operation. Its successful operation and functioning are also dependent on other railway systems and operating personnel. The man-machine interrelationship is an important issue and very complex to design and develop. Another prior issue, the growth of transportation infrastructure must account for ecological effects, including land use, pollution, water resources, and biodiversity [R. Stabak et al. 2023]. Another study also examined the adverse ecological impacts of railway systems [Roy,Stabak et al. 2022]. Here, the adverse effects of railway transport were examined by studying changes in NDVI and FVC. A spatial regression model and a prediction model using cellular automata and Markov chains were employed to assess these externalities. The study found that railway station development in Tripura, India, significantly harms the environment. [Roy,Stabak et al. 2022]. Another paper addresses ecological concerns in railway transport, highlighting the crucial role of safety measures in preventing environmental damage resulting from failures in railway signaling system components [V.N. Plakhotnik. 2005]. The electromagnetic environment greatly

influences the reliability of railway signaling systems, as interferences can affect their performance. Therefore, thorough assessments are necessary to ensure component functionality under various railway conditions studied in another research [Ryan et al. 2021]. In this context, the failure analysis and risk assessment of signalling systems depends on the joint performance of several subsystems, such as mechanical, electrical, and electronic systems, the operators and the drivers involved in the process of signalling.

2.1 Railway Signalling Components:

Railway signaling systems consist of complex components that together oversee and secure railway operations. Critical subsystems, such as signal units, track units, and point machines, play a vital role in maintaining system reliability and safety [De Bruin et al. 2017][Cornaro A et al. 2023]. To improve reliability, maintenance and inspection modeling techniques have been utilized for fault detection and optimization, ensuring long-term system sustainability. Each component is assigned a unique identifier, enabling secure updates through a central computer with cryptographic protection Michael LeMay et al. 2021]. Moreover, advanced features like rail signal lamps with light emitter sub-arrays have been included, managed by a monitoring system that provides real-time status updates to the operations management system [A. S. Pashina et al. 2020].

In modern complex and complicated electrical, power, and signalling systems, millions of equipment, subsystems, and components are connected to feed high voltage, low to high voltage, and vice-versa. In this section different signalling components has been discussed. Signalling system components play a vital role in successive train movement from end-to-end station. Modern signalling system in nature is a complex system. Signalling components mainly two types:

- Indoor Components.
- Outdoor components.

Indoor Components: components are under a room. Mainly station masters control room, relay room and interlocking room etc. components are Interlocking system, Panel, Relay, Power supply etc.

Outdoor Components: Components are in yard area. Mainly Track Circuit, Axle counter, Level crossing, Point machine, Signal Unit, Line Relay, Track Relay, Cable etc.

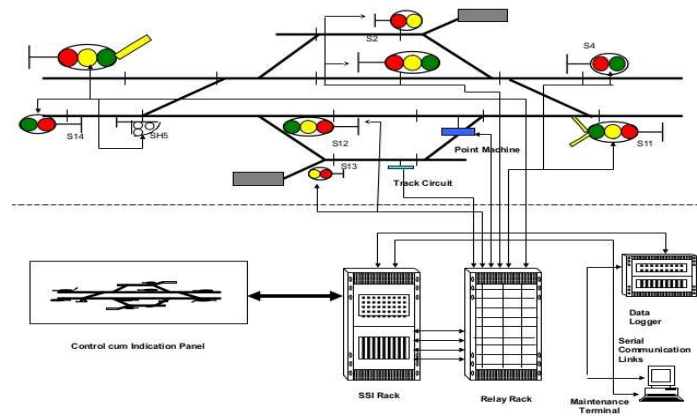


Fig 2.1: Railway Signalling Components

2.1.1 Indoor Components of signalling system-

- **Interlocking system**

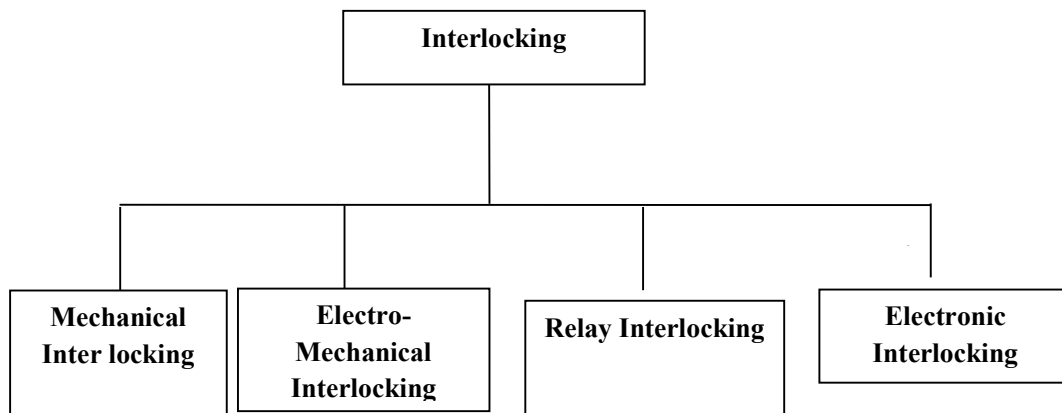
An interlocking system in railway signaling is an advanced framework designed to manage train movements safely and efficiently by preventing conflicts and accidents. It coordinates various functions, such as signals, points, sidings, and level crossings, through a panel or lever frame to ensure that operations occur in a predetermined, safe sequence.

Recent advancements in interlocking technology, as proposed by L. Shanmukha in *Advances in Interlocking Technology(2022)*, published in the *International Journal of Railway Systems*; emphasize enhanced safety and efficiency in managing train movements. These advanced interlocking devices improve monitoring and control, reducing human error risks by ensuring that signals cannot be cleared without adhering to the proper interlocking logic. The systems feature a control panel that replicates the yard layout, displays signal

statuses, and integrates both external logic-proving relays and internal processor logic to enforce safety rules.

Historically, railway interlocking systems have evolved through three main stages: mechanical interlocking, relay interlocking, and computer-based interlocking. Each stage has brought improvements in safety and operational efficiency. The current systems utilize control panels that visually represent the yard layout and include mechanisms for maintaining interlocking rules, thereby ensuring that all devices operate in harmony for safe train movements.

Overall, interlocking systems are crucial for preventing accidents and ensuring smooth railway operations, with ongoing developments aiming to enhance their reliability and safety.



- **Mechanical**

Interlocking Systems in Railway Signalling

Traditional Interlocking: Traditional interlocking involves mechanical levers connected to signals and points via wires. These wires run from a control box located beside the track, traversing across and parallel to it. The system operates by manipulating these wires to control signals and points, ensuring that movements are executed safely and in coordination.

Electro-Mechanical Interlocking: In electro-mechanical interlocking systems, levers are more compact and do not directly control field devices. Instead, they operate switches and signals through electrical or electro-pneumatic mechanisms. Levers are only movable if the locking mechanism confirms that the field devices have shifted to the requested positions. This system ensures that levers can only be adjusted when all conditions for safe operation are met.

Relay Interlocking: Relay interlocking systems use complex electrical circuitry made up of relays to manage signal and point positions. This system involves relay logic to monitor and control each device's status. As signal or point positions change, circuits are opened or closed to prevent conflicting movements. Relay interlocking systems are categorized into two types:

- **Non-Route Setting Type (Panel Interlocking, PI):** This type manages signals through a fixed panel configuration, without setting specific routes.
- **Route Setting Type (Route Relay Interlocking, RRI):** This system allows for the configuration of specific routes, providing more flexibility in managing train movements.

Electronic Interlocking: Electronic interlocking systems utilize microprocessors to read inputs from the yard and control panels, process them according to predefined rules, and generate outputs accordingly. These systems are an advanced alternative to traditional relay-based interlocking, complying with specific standards such as the RDSO specification No. RDSO/SPN/192/2005 on Indian Railways. Electronic interlocking systems offer enhanced reliability and efficiency in managing railway operations.

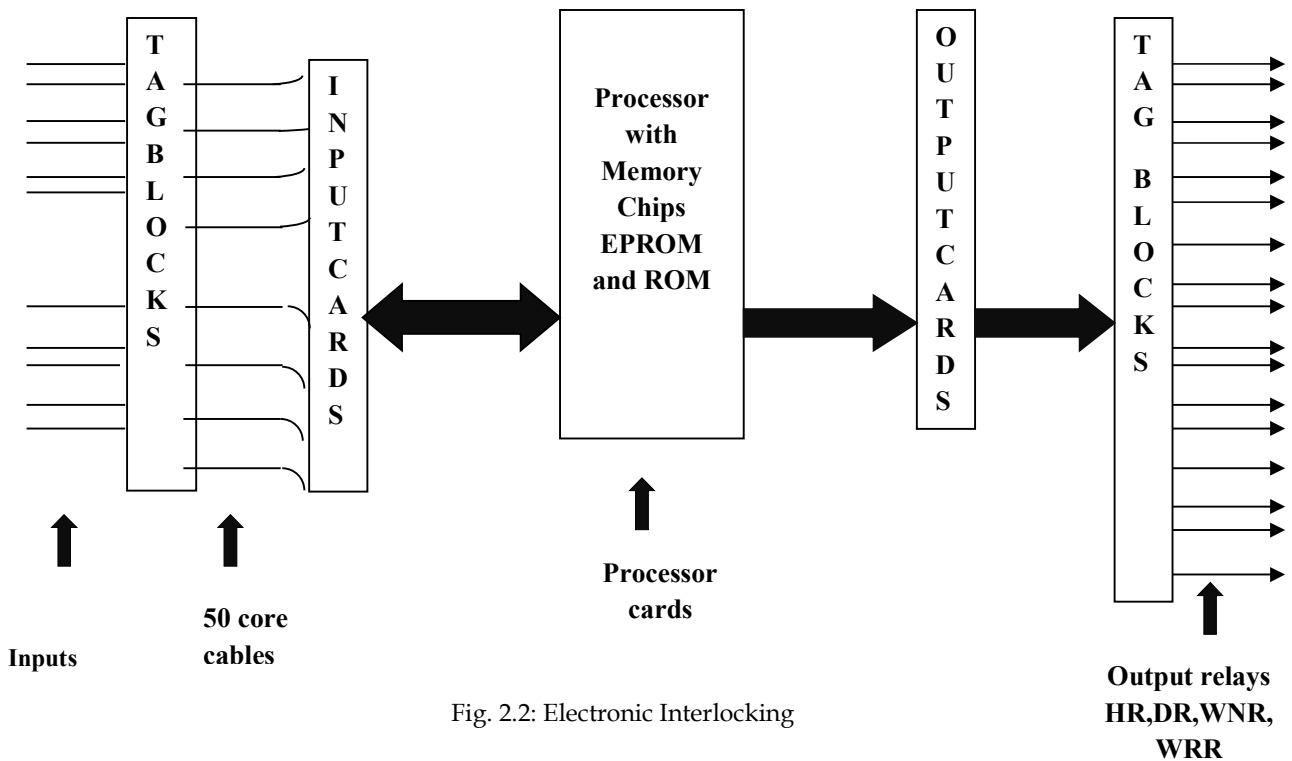


Fig. 2.2: Electronic Interlocking

- **Panel-**The Station master can control the signals / points etc by means of individual buttons and switches, and is provided with information on the state of the system by means of illuminated displays within the panel.
- **Control Panel-** In station master control room there is a signal box with a control panel, the levers are replaced by buttons or switches, usually appropriately positioned directly onto the track diagram. These buttons or switches are interfaced with an electrical or electronic interlocking.
- **VDU based Display system-**These are a logical extension of panels, but utilise VDU technology to provide the same and sometimes enhanced information. The station master control interface is via a keyboard and mouse. This is the predominant form of control and display system for new signalling systems.

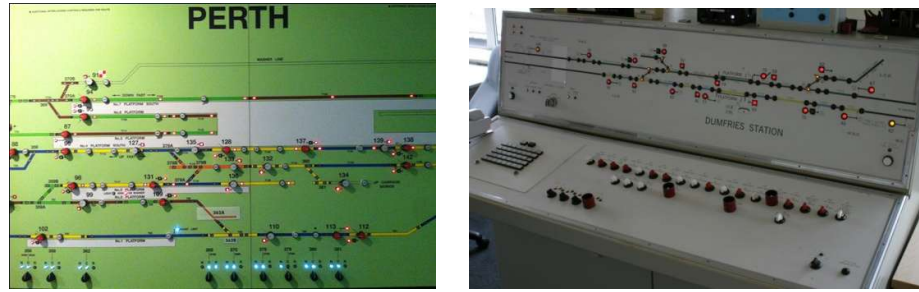


Fig 2.3: Panel and control panel

- **Relay-** A relay is an electromagnetic device which is used to convey information from one circuit to another circuit through a set of contact i.e. front or back contact. Constructional and electrically, relays may be divided in to DC and AC relays because the means by which the electrical energy in the coil is converted in to mechanical Energy in order to move the contacts are fundamentally different.

In DC type, the contacts are carried on an armature forming part of a magnetic circuit in which a field is set up by the current in the coils.



Fig 2.4: Electromagnetic Relay

In AC types, the contacts are attached by a link mechanism to a metal sector, disc or cylinder in which currents are induced by the alternating magnetic field produced by the current in the coils.

CLASSIFICATION OF SIGNALLING RELAYS:

According to the method of their mounting or fixture, they are classified as:

- a. **Shelf type:** Relays which are loosely kept on shelves.
- b. **Plug in type:** Relays which are plugged in to a pre wired plug boards.

According to their connection and usage, they are classified as:

Classification of Relays

Relays can be categorized based on their mounting methods, connection types, importance in train safety, contact reliability, and power source. Here's a detailed classification:

By Mounting Method:

Shelf Type: These relays are placed loosely on shelves, allowing for easy access and adjustment.

Plug-In Type: These relays are inserted into pre-wired plug boards, facilitating quick installation and replacement.

By Connection and Usage:

Track Relays: These relays are directly connected to the track to detect the presence of vehicles.

Line Relays: These include all relays other than track relays, typically connected to selection circuits for various functions.

By Importance for Train Safety:

Vital Relays: These relays are crucial for traffic control, including signals, point controls, and track detection systems.

Non-Vital Relays: These relays manage control aids and accessories, such as warning buzzers and indicators, which are not critical to train safety.

By Contact Reliability:

Proved Type: These relays have contacts that must be proven to be normalized after each operation. They feature metal-tipped springs that may fuse due to high sparking currents, making proving necessary to ensure safe traffic control.

Non-Proved Type: These relays do not require proof of normalization after each operation, as they have at least one non-fusible contact, such as a carbon contact.

By Power Source:

DC Relays: These relays operate on direct current (DC) power. They include:

DC Neutral Relays: These relays maintain the same set of contacts regardless of whether the supply polarity is normal or reversed.

Polar Relays: These relays close different sets of contacts depending on the polarity of the supply and may or may not have a contact that closes when de-energized.

AC Relays: These relays operate on alternating current (AC), including induction motor track relays, time element relays, and flashing indication controls.

Electronic Relays: These are DC relays integrated with electronic components to enhance functionality and control.

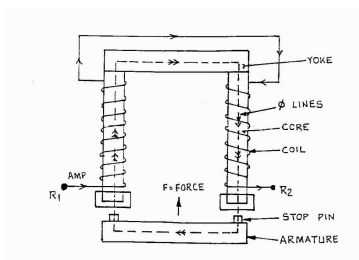


Fig 2.5 NEUTRAL RELAY

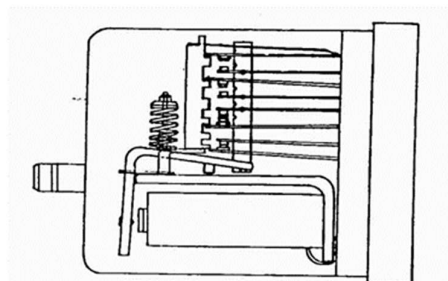


Fig 2.6.QN1 Plug in Type Relay

Electromagnetic relays are extensively used in control circuitry, which governs steady operation of the whole electrical system. As discussed in the above according to the method of mounting relays are two types: shelf and Plug-in relay. The shelf type is

old. Now a day's Plug-in type Metal to carbon contact and Metal to Metal contact relay widely in use. An electromagnetic relay has two parts-magnetic circuit and mechanical circuit.

The reliability of electromagnetic relay is poor due to production, environmental stress, storage, transportation and use process. Electromagnetic relay perform a vital role in railway signalling system. Railway signalling system requires a high level of safety.

To enhance safety more reliable component is necessary. Metal to carbon Q-series, non-proved type relays are used in railway signalling systems. Q-series relays operate various electrical and mechanical systems viz. point, track, signal and axle counter etc. These relays have Silver and Silver Impregnated Graphite (SIG) contacts, which can operate signalling equipment, makes and breaks according to signalling logic.

The reliability of this type of relay is very poor [H. Khagra 2013] and its major reason is abnormally high increments in Contact Resistance, due to which the relay fails. Indian Railways reveals that the failures of metal to carbon relays amount to approx. 7% of the total signaling equipment failures. This failure rate is quite substantial and totally unacceptable. In this context reliability and performance analysis of metal- to carbon relay is required.

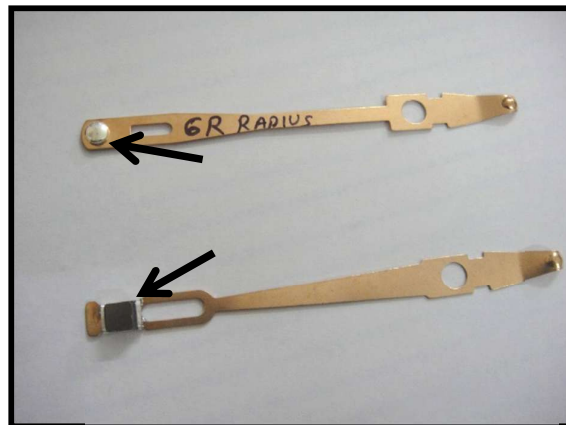


Fig 2.7 Metal to carbon Relay Contacts

- **Power Supply-**

The single phase 50 Hz power for the electric traction is obtained from 220/132/110/66 kVA Extra High Voltage 3-phase grid system through step

down single phase transformers. For this purpose duplicate feeders comprising of only 2 phases are run from the nearest grid substation of the Supply Authority to the traction substation.

2.1.2 Outdoor Components of signalling system-

- **Track Circuit-** A portion of rail electrically isolated from adjoining rails, make a continuous path. Using track circuit it can be identify the occupancy or vacancy of the track portion for the rail. Track relay can identify the status of the rail.

Track circuits are of two types - a) Open Track Circuit. b) Closed Track Circuit

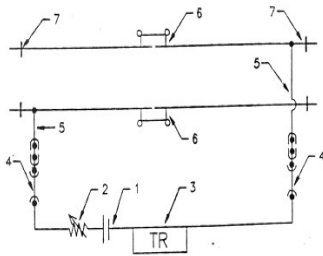


Fig.2.8 Open Track Circuit

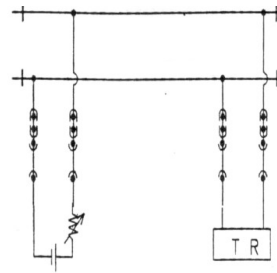


Fig 2.9 Close Track circuit

The components of the track circuit are:-

- (1) Battery, (2) Adjustable Resistance, (3) Track Relay, (4) Track Lead Cables, (5) G.I.wires connecting cables to the rails, (6) Continuity rail bonds, (7) Insulated rail joints.

The closed track circuit is continuously live and open track circuit is made live when occupied by rails.

Axle Counter- Axle counter is a signalling subsystem used for safety and automatic signalling control. An axle counter is a device on a railway that detects the passing of a train between two points on a track. The mounted outdoor part consists of pairs of sensors (Transmitter and Receiver), and when the train enters a particular section of the rail, is considered an occupied section. The section becomes free when the number of axle entered in to the section is equal to number of axle left section. A counting head (or detection point) is installed at each end of the section, and as each train axle passes

the counting head at the start of the section, a counter increment. As the train passes a similar counting head at the end of the section, the counter compares count at the end of the section with that recorded at the beginning. If the two counts are the same, the section is presumed to be clear for a second train.

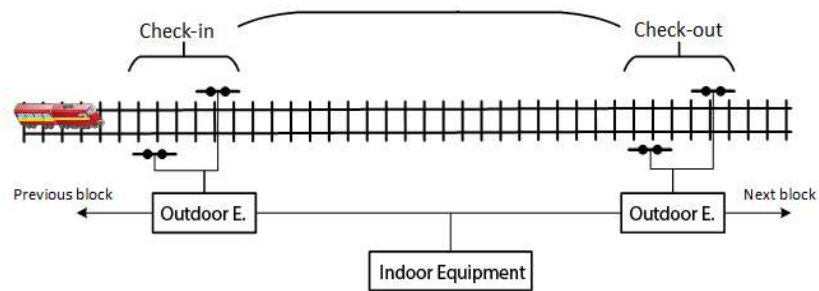


Fig. 2.10. Axle counter on Rail

Magnetic field is created within the sensor, LC oscillator can detect the change in magnetic field when flange of rail wheel has passed, modified the magnetic field.

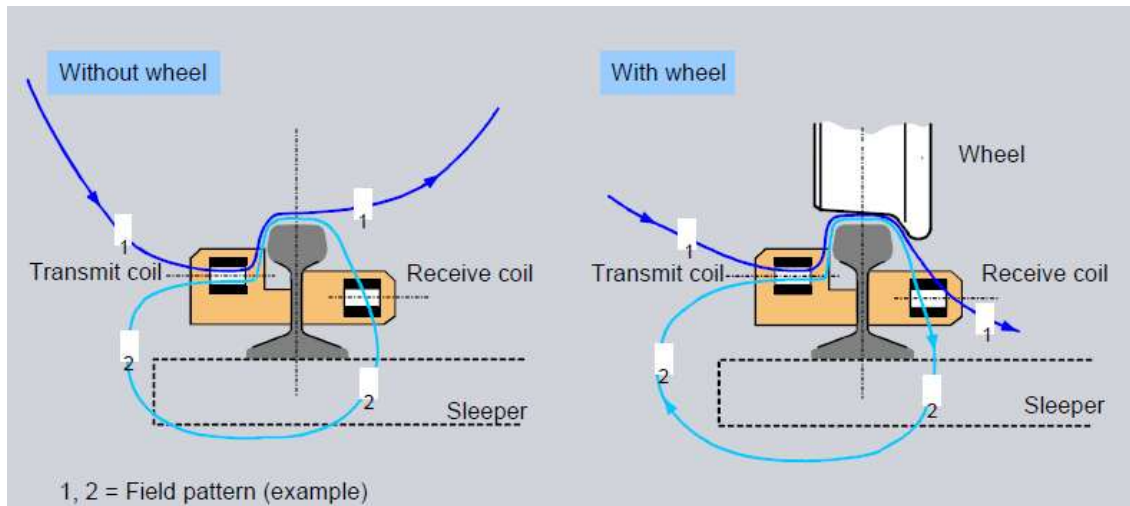


Fig. 2.11 Working of Axle counter

There is an Evaluator which is centrally located, with the detection points located at the required sites in the field. The detection points are either connected to the evaluator via dedicated copper cable or via a telecommunications transmission system. This allows the detection points to be located significant distances from the

evaluator. This is useful when using centralised interlocking equipment but less so when signalling equipment is distributed at the line side in equipment cabinets.

Components of the system

- a. Outdoor equipment (detection points in the track area)
- b. Information transmission equipment (cables)
- c. Indoor equipment (evaluation, indication & resetting)

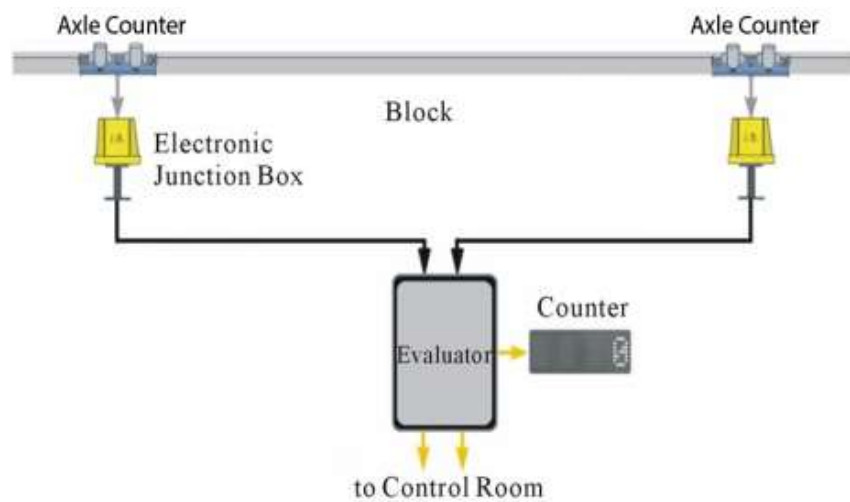


Fig. 2.12. Axle counter components

Advantage

- a. Axle Counter Systems do not necessitate the use of wooden sleepers in areas where concrete sleepers are unavailable. They are typically used with short track circuits to manage counts affected by the movement of insulated trolleys.
- b. Axle Counter Systems are capable of monitoring extensive track sections, covering distances up to 15 kilometers.
- c. Unlike track circuits, which are vulnerable to issues caused by track flooding or poor maintenance, axle counters remain unaffected by these conditions, ensuring reliable performance regardless of track conditions.

d. Axle Counters eliminate the need for insulating rail joints, allowing for continuous rail welding. This feature reduces maintenance costs, minimizes wear and tear on tracks and vehicles, and enhances travel comfort.

The effectiveness and safety of axle counter systems are not influenced by various track parameters or environmental factors, such as track length, ballast condition, drainage, stray voltages, track feed voltage, and lead cables, which can impact the performance of track circuits.

- **Point and Point Machine** - An electro-mechanical device, which can perform the function of unlocking and operating the point switches in the desired position and lock them and detect their correct setting with the aid of an electric motor, similar to that performed by an operator through a lever in a mechanical lever frame. It consists of crossings, cross-over, stock-rails, rods, cranks, levers, electric motor and locking arrangements.



Fig.2.13 Point Machine



Fig.2.14 Parts of Point Machine

- **Level crossing Gate**-when road traffic crosses rail traffic over a bridge or under a bridge at same level, these signalling arrangements know as level crossing.



Fig.2.15 Railway level crossing gate

- **Cable-** PVC insulated, sheathed copper cables are used in the signalling system. Cables should be robust enough to withstand the physical conditions to which they are subjected during laying and the environmental conditions they must endure during their working life. According to use of cables mainly three types of cable in Railway-Indoor cables, Outdoor cables, Power cables.

Indoor cables- all the PVC insulated conductors are bunched and kept in a thin PVC insulation tube.

Outdoor Cables-copper conductors are having equal diameter with PVC insulation. All the PVC insulated conductors are bunched and kept in insulation tube.

Power Cables- cables are conducting power supply upto 440 volts.PVC insulated, sheathed and armoured with aluminium conductors, capable of withstanding specified electrical load.

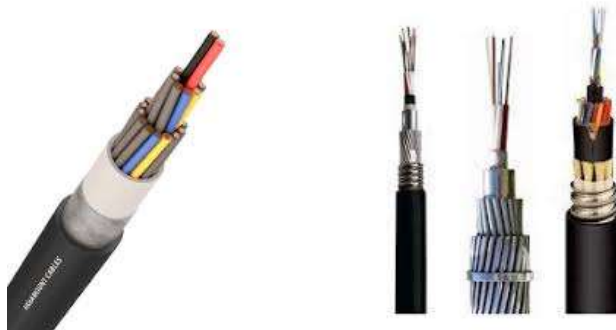


Fig.2.16 Cables in Railway

- **Signal Unit-** signal post is connected to the transformers. There are two types signal post-, Colour-lamp signal, Semaphore signal

Semaphore signal- It is the oldest forms of signal display. Signal displayed by a physically movement of a board, which is fully visible to the driver.

Colour-lamp Signal- Color-lamp signals are now widely employed around the world. The advent of electric light bulbs allowed for the creation of color light signals that are sufficiently bright to be seen even in daylight. Modern color-lamp signals use high-transmission glass to ensure visibility from distances up to 3,500 feet (1,100 meters) under bright sunlight. These signals typically utilize low-voltage lamps (12V) to achieve high current density, which generates increased light output and efficiency through elevated temperatures. To enhance reliability, multi-aspect color signals often incorporate double filament lamps. In the event of a filament failure, an auxiliary filament ensures that the signal remains operational and visible..

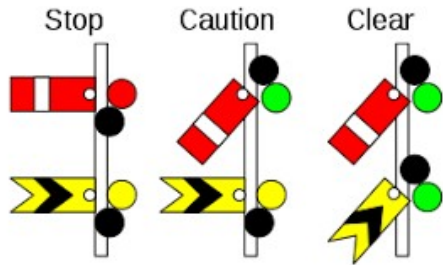


Fig.2.17 Semaphore Signal

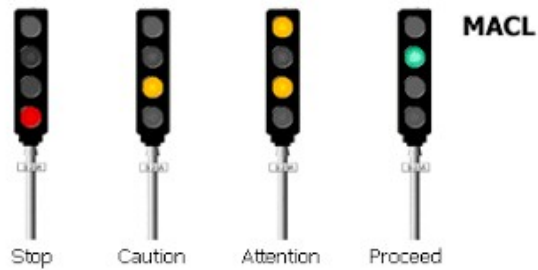


Fig.2.18 Colour-lamp Signal

Chapter 3(Literature Survey)

In Indian metro railways, it is observed that signaling systems consist of different types of components and systems, such as Audio Frequency Track Circuit (AFTC), Multi Section Digital Axle Counter (MSDAC), Panel, Point-to-Point Machine, Relay, Interlocking, Cable, etc., depending upon their uses and period of use. Hence, it requires various maintenance activities to fix the failures caused by the severe axle load of the rolling stocks. However, maintenance actions associated with repairing these component failures and detailed analysis associated with RAMS are necessary for the smooth functioning of trains. Reliability, availability, maintainability, and safety (RAMS) analysis fulfills the reliability of existing infrastructure and the safety demands of customers. Reliability can predict possible failure modes in terms of their

probability of occurrence and effects on the functionality of the system. The reliability analysis of a typical railway signaling system refers to the study of the failure modes of its subsystems and components. In this context, failure mode and effect analysis were applied to the Indian Railway Signaling System to analyze the risk of these subsystems during the operational condition of the railway signaling system [Panja S.C. et al. 2008]. Therefore, the railway industry uses different methods and tools to improve the performance of different subsystems in order to ensure safety and reliability. Hence, reliability analysis of field failure data of wheel sets over different time intervals is needed to determine the reliability function, which can be used for preventive maintenance. In this context, reliability analysis of the track circuit of the Indian Railway Signaling System has been done [Panja S. C., Ray P.K. 2007]. They made the reliability modeling of the track circuit, a vital part of the signaling system of Indian Railways (IR). Also, reliability analysis of points and point machines of Indian Railway has been done [Panja S.C. et al. 2007]. The man-machine interrelationship is an important factor in preventing the occurrence of accidents. One of the most important functions of interlocking is to provide protection for rolling stock against the multiple occupancies of individual sections of a track [Faulkner and Storey 2001]. Therefore, to enhance safety, an anti-collision system has been proposed that can identify train positions and detect collisions on railway tracks and points using advanced sensing technology and RF communication [Gautam S et al. 2010]. Thus, another measurement system was proposed that could measure the harmonic current and evaluate the impact of the harmonic current on the track circuit system when the train is running. To detect rail breakage [Espinosa F. et al. 2018], a measurement methodology was designed and an experimental validation of an electronic system for monitoring the electrical discontinuity in rails of double-track railway lines was conducted. In addition, long-short-term memory (LSTM) recurrent neural networks [Bruin T., Verbert K. et al. 2016] are used to diagnose faults caused by the spatial and temporal dependence of multiple track circuits in a geographic area. In the advancement of technology, the Fuzzy Track Monitoring System (FTMS) has been proposed [Chellaswamy C. et al. 2013] for estimating the irregularities present in the railway track at running time. In another research work, Z. Vintz describes

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In the above-mentioned literature survey, so many works have been done on reliability, availability, and maintainability analysis of different types of electromechanical systems, but not such a significant amount of work has been done on axle counters. Though axle counters play an important part in the smooth running of trains, reliability and availability analysis are required to avoid accidents and enhance the system's performance. The axle counter is a vital component of the railway signaling system. The axle counter is a track monitoring device that checks

the occupancy of the train on a particular part of the track. The present study proposes a reliability, availability, and maintainability analysis of the axle counter of Kolkata Metro Railways.

Chapter 4

Metal to carbon relay is widely used in signaling system in Indian railway to operate various signaling components viz. Track circuits /points / signals etc. These relays have mainly two types of contact namely, silver Impregnated Graphite (SIG) and silver contact, which keeps close and open continuously as per signaling logic. Due to substantial stress, environmental impacts guide to the irregularities on the signalling relay of the silver impregnated graphite surface. The surface texture of metal to carbon relay contact is an important feature, for quality assessment of deformed surface. A thin layer of Oxide, Sulphides is formed on the surface of the SIG contact, which causes high resistance on the relay.

the reliability of these relays is very poor. Image samples of defected relay contacts are collected in this work. Image-based grading has been applied on these images to analyse the deformation of the relays. Image quality estimation is most predominant features for various type of image processing application. Camera captured images are affected by various contortion factors, such as noise, blur, blockiness etc., which destructed the quality of the image. Image Quality Assessment (IQA) is an influential index for evaluating the image processing and video processing algorithm execution. Therefore, image quality assessment is an elementary vital factor. However subjective assessment is antiquated due to various subjective inspection factors. Objective based machine assessment of an image is a challenging task in vision technology. Therefore, to assign quality score of an image elementary reliable objective assessment method can be applied. According to the availability of the reference image, Objective IQA method can be classified into three categories: full-reference (FR), , reduced-reference (RR), and no-reference (NR). FR method deal with distorted signal with reference image signal and RR method needs only distorted signal with reduced portion of reference signal and NR method needs only distorted signal. Human Vision System

(HVS) is challenging with psychological activities in image processing. HVS draw out structural information from visual scene (Wang and Bovik 2004). HVS describe the sharpness of the image. However, the quality of the image evaluated through pixel-by-pixel difference method where pixel by pixel of the defective image is compared with reference image. MSE and peak Signal to noise ratio algorithms are the trendy examples of the pixel-by-pixel difference method. Most popular method is PSNR in FR method due its simplicity and effectiveness. However, PSNR is also found irrational under certain conditions, such as deformed images with identical PSNR can show different subjective quality. In this context [Wang et al. 2004] introduced new approach SSIM which obtain structural information from the visual system. Therefore, structural variation can detect image quality deterioration. In this context [Wang Zhou et al.2004] proposed a model based on error sensitivity, named SSIM index model. SSIM index estimates the quality of the defected image by comparing the correlations in luminance, contrast and structure locally between distorted image and reference image and equalling these quantities over the entire image. The structural similarity has applied to JPEG compressed image to find structural distortion. This approaches significantly different from traditional SSIM indexing algorithm. No reference model appropriate for this approach. Therefore, In FR method numerous algorithms [Mohammadi P et.al 2015] have been used in their work Structural similarity index(SSIM), Multi-scale similarity index measure(MS-SSIM), Visual information fidelity(VIF), Most apparent distortion(MAD), Feature similarity measure(FSIM), Feature similarity measure for colour images(FSIMC), Dynamic range independent measure (DRIM) and Tone mapped images quality Index (TMQI). This work is essential for multimedia application. Without concentrating one particular feature of reference image and distorted image.

[Ruikar D. et al. 2014] has done a comparative study of objective image quality algorithms and quality index with different types of data sets. MSE, PSNR, SSIM has been applied on these data sets, which takes less time to figure out the quality information with respect to other algorithms. [Hore Alain et al.2010] has analysed objective type full reference image quality metrics. PSNR and SSIM algorithms have

been applied on various degraded images. They have found a correlation between them, sensitivity changes according to the intensity of degradation.

Another type is Correlation measurement with the reference image and defective image [Z.Wang et al. 2002]. Defects have been identified by this method. Image quality assessment is mainly of two types- subjective quality assessment and objective quality image assessment. Objective quality assessment is commonly used in image processing applications. In this proposed work we applied image processing to exhibit quality and degradation measure of the signaling system

[Ma Xiaoyue et al. 2017] proposed a metric based analysis of distortion process. In the proposed model of Full reference image quality assessment, the degradation process is linearly mapped from an original pixel to corresponding distorted pixel. To analyze the mapping weights they have utilized linear regression analysis. In another work [Angelis A. et al. 2007] has applied image quality assessment through statistical approach to estimate the unpredictability of the IQA objective method. He has done a case study on noise affected images [Iyer M. et al. 2014]. has researched on real time defect detection methodologies and proposed a system to monitor deformation on the cast extrusion manufacturing. Defects originate from various stages of manufacturing industries [Du.Tsai et al. 2006]. Failure study and proper classification of failure degree using failure image is another challenging job in this proposed work.

Chapter 5

Electromechanical relay failures can be attributed to external factors like power disruptions, fuse issues, and internal factors like manufacturing defects and poor component quality. Other causes such as high contact resistance, coil damage, foreign matter, and more have been identified through modern maintenance practices to address potential failures. Any flaws in the relay manufacturing process can result in immediate malfunctions upon installation.

One key reason for the poor reliability of metal-to-carbon relays is the high contact resistance in silver impregnated graphite (sig) contacts. The presence of oxide and sulphide layers on sig contacts accentuates this issue, highlighting the importance of surface topography inspections for failed relays. Image processing techniques are

crucial in detecting defects in relays, especially through feature extraction and identifying unique characteristics in images. Feature extraction and identification of local features that can be distinguished from other object of interest of the image is one of the main objectives of defect detection through image processing technique [H.Mohammad-2014]

feature extraction through image segmentation is also consider as one the basic approaches of digital image processing [x.e.pantazi-2019],in case of image segmentation technique, image is subdivided into different subset, which provides attributes of different subset [G.T Shrivakshan-2012]. By this process, defect in images may be detected. Thus, the defect detection as mentioned can be treated as beneficial method in real life situation [W. X. Kang-2009]. Micro research may also be adopted through image segmentation [Nida M. Zaitoun-2015] which subdivides an image into background region and object according to its intensity value, texture, and colour. Image segmentation methods are categorized on the basis of similarity and discontinuity of image properties. On the basis of similarity, region based segmentation, can further categorized as edge based, and thresholding-based segmentation. Region based segmentation cover more pixels information than edge based. Thresholding methods play a significant role in this process by distinguishing between foreground and background elements in images, ultimately enhancing defect detection capabilities. The use of advanced thresholding techniques like otsu thresholding has proven to be an optimal solution for separating objects of interest from the image background.

In railway applications, signalling relays endure harsh environmental conditions that can damage their surfaces. To assess the degree of failure in defective relay surfaces, Otsu thresholding and advanced multi-level thresholding methods are employed. These techniques aid in recognizing and addressing surface defects, ensuring the reliability of railway signalling systems.

This segmentation produce more accurate result for noisy image than edge based segmentation [n.sharma-2012]. Threshold based image segmentation overcome the limitation of the previous segmentation method. Therefore, thresholding method is one of the effective methods. Moreover, it is treated as simple as it execute in terms of

local, global and adaptive image segmentation techniques. Thresholding method is discriminating the foreground and background of an image by selecting an adequate threshold value. All these steps finally can be represented by histogram, which is developed on the basis of intensity of images. Histogram thresholding one of the primitive thresholding method, but there are some limitations. in the ideal case when histogram is bimodal, but practically image is more complex when intensity of the histogram shows multi-modal, it is difficult to identify the adequate threshold. to overcome otsu thresholding technique [N. Otsu-1979, Wang Hongzhi-2007] may be adopted, which can select optimal threshold value automatically, for separating the object of interest from the background of gray-level image.

Signalling relay is a crucial component of the railway signalling system. Within this system, various electro-mechanical relays have been utilized as switches [Andrew J Wileman-2015]. Both surface railway and metro railway systems have employed relays with metal to carbon contacts and metal to metal contacts. The metal to carbon contact relays are operated based on predetermined signalling logic to control different signalling elements such as track circuits, points, and signals. Reliability of silver (metal) to silver Impregnated Graphite (SIG) contact relay is poor [H. Kagra-2013]. The prime rationale of indigent reliability is high contact resistance developed on the SIG contact. As a result, recognizing the degree of failure of SIG contacts is imperative in establishing a failure model [Xuerong Y et al.-2012].

Otsu thresholding is an automated technique for selecting optimal thresholds to differentiate between the background and foreground of a grey-level image Yoges-2017]. The Otsu-revised method determines the threshold value by maximizing the weighted sum in order to effectively separate the grey level classes. It is particularly effective for images with bimodal and multimodal histogram distributions. It provides satisfactory outcome for bimodal and multimodal histogram distribution [Zouhir Wakaf-2018]. Another [Agus Arifin et al.-2006] proposed work a taxonomic relationship of gray level histogram of an image, depending upon the continuity property of the image which classifies inter-class variance cluster and intra-class variance cluster. They said classification is required to get the optimum threshold of

images. The threshold value of images may be extended to multi-thresholding which has proposed by [Du-Ming et al.-1992] have developed histogram based hill-clustering approach for multi-level thresholding. Computation time effectively reduce. In another work [Satapathy Suresh 2016] proposed multi-level thresholding Otsu on standard test images. This algorithm was compared with other standard algorithm with respect to root mean square error, peak signal-to-noise ratio, CPU iteration time, and structural similarity index. In this paper we have applied two types of thresholding method in the SIG contact of defective images-Otsu thresholding and multilevel Otsu thresholding. Signalling relay has adversely used in railway, due to environmental stress conditions surface of the relay may got damaged. To identify the degree of failure of defected relay surface, otsu thresholding and advanced multi-level thresholding techniques have been used here.

We use railway signaling relays for high-safety purposes. Electromagnetic relays operate in different conditions, each with distinct variables such as temperature, storage, dust, transport, humidity, and vibration. Over time, this can cause ion deposition on the contact surface, resulting in aging. Fluctuating temperatures affect relay parameters and may cause increased contact resistance. In addition to that, humidity is one of the factors of surface oxidization that leads to contact corrosion, another contaminant present on the surface causes sulphation, carbide formation, and contact resistance significantly become high and the relay got failed [3]. Electromagnetic relays are a vital component of railway signalling systems. These relays in railway signaling are grouped by various types such as mounting on plug board, AC-DC supply, contact types (metal or carbon), line and track relays. Material failure and deviation from intended logic can occur due to factors such as atmosphere, overuse, and improper contact. Railway transportation organizations may face significant economic loss due to the failure of metal-to-carbon relays. In this context, it is of utmost need to study and analyze the operating behavior and failure pattern of the relay to maximize its reliability [4].

The reasons, related to this electromechanical relay failure, can be categorized as follows [5]:

- Different external reasons such as discontinuous power supply, defective wearing or blowing-off of fuses, and
- Various internal reasons such as manufacturing defects, poor component quality and malfunctioning of relay components.

The above-mentioned causes are not the only ones: high contact resistance, coil breakage, coil burning, foreign matter interference, sulphation of springs/connectors, breakage of an armature, relay cover, and slipping of retaining clips are also causes. As a way to identify potential risks of unexpected relay failures in modern maintenance technologies and practices, performance is analysed in modern maintenance technologies and practices. Any deficiencies in the relay manufacturing process result in instant failure when installed in the circuit. All these kinds of failures suggest the need for a reliability analysis of the product outcome [8]. Additionally, the high contact resistance of silver-impregnated graphite (SIG) contacts seems one of the reasons for poor reliability of metal-to-carbon relays [3]. A thin film layer of oxide and sulphide may also be found on the silver-impregnated graphite (SIG) contact. An important research area of interest is the detailed analysis of surface topography of failed relays of the SIG contact, based on SEM analysis. In another application, the relay within military weapon systems is subject to thorough scrutiny and evaluation examination [9]. It is believed that decomposition of these systems causes a gradual accumulation of polluting agents on contact surfaces, eventually resulting in relay failures. Eventually, relays fail due to failures associated with contact adhesion because the coated contact material erodes, increasing its resistance. Additionally, contact adhesion affects the lifespan of electromechanical relays [11-12]. In another research work, in order to evaluate relay reliability, testing involves applying various loads using capacitors, subjecting them to varying current levels across numerous cycles to assess relay reliability [13-15]. Therefore, to better understand the structural changes in movable and fixed contacts, a degradation model was used to simulate the relay in this research [16-17]. The experiment was conducted with 1000 and 6000 cycles. Demonstrated the involvement of polymer decomposition plays a role in arc erosion. As a result of this arc reaction, oxide contaminations were formed, with phosphorous being detected on the contact surface.

Furthermore, contact surface erosion was observed during stress and the formation molten arc. To combat corrosion and prolong contact lifespan, a thin coating with solid or semi-solid lubricants of carbon allotropes can be applied. Additionally, the use of Composite and layered materials can help mitigate damage to the contact interface [20-22]. The examination involved graphene-coated contacts with various coating depths, comparing their effects to those of different thin-layer coatings using finite element analysis. To prevent relay failures, careful selection of contact materials is crucial, aiming for elements that enhance lifespan and withstand adverse atmospheric conditions.

Therefore, evaluating contact surfaces is essential. FESEM is a valuable tool for inspecting cell and material surfaces, particularly for detecting mechanical deformation on relay contact surfaces [23-24]. EDS identifies chemical contaminants distribution on contact interfaces, with energy distribution revealing the mass concentration of surface atoms [25-26]. In another context surface roughness parameters analysis using a profilometer effective approach. Various techniques encompass visual evaluation, SEM, profilometer, laser, specular reflectance, and AFM [27-28]. A comparative approach has been taken between SEM and profilometer. The objective was to assess the efficacy and practical applicability of indirect method for characterizing surface topography. SEM images visually describe subjective information about surface topology but profilometry showed better result for hight dispersion. Profilometry proves a valuable and efficient tool from other analyses [29]

3. RAMS Analysis for Multi-section Digital Axle Counter (MSDAC)

Introduction

In railways, infrastructure safety is an important issue. Safety is given more attention in developed countries nowadays. Railway infrastructure is designed to work in fail-safe conditions with a minimum number of failure occurrences. Fatal railway accidents cause life losses, material damage, and environmental damage as well. Every individual country puts in a lot of effort to avoid accidents by taking safety measures and enforcing strict laws and regulations that must be followed by railway personnel, maintenance staff, operators, etc.

In Indian metro railways, it is observed that signaling systems consist of different types of components and systems, such as Audio Frequency Track Circuit (AFTC), Multi Section Digital Axle Counter (MSDAC), Panel, Point-to-Point Machine, Relay, Interlocking, Cable, etc., depending upon their uses and period of use. Hence, it requires various maintenance activities to fix the failures caused by the severe axle load of the rolling stocks. However, maintenance actions associated with repairing these component failures and detailed analysis associated with RAMS are necessary for the smooth functioning of trains. Reliability, availability, maintainability, and safety (RAMS) analysis fulfills the reliability of existing infrastructure and the safety demands of customers. Reliability can predict possible failure modes in terms of their probability of occurrence and effects on the functionality of the system. The reliability analysis of a typical railway signaling system refers to the study of the failure modes of its subsystems and components. In this context, failure mode and effect analysis were applied to the Indian Railway Signaling System to analyze the risk of these subsystems during the operational condition of the railway signaling system [Panja S.C. et al. 2008]. Therefore, the railway industry uses different methods and tools to improve the performance of different subsystems in order to ensure safety and reliability. Hence, reliability analysis of field failure data of wheel sets over different time intervals is needed to determine the reliability function, which can be used for

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3.1 Railway Axle Counter

The axle counter is a signaling subsystem used for safety and automatic signaling control. It consists of two parts: an indoor unit and an outdoor unit. In the outdoor unit, a sensor is connected, which is mounted on the rail. Through this sensor, the axle counter can detect the direction and speed of the train, whether it is leaving or entering

any particular section. The mounted outdoor part consists of pairs of sensors (transmitter and receiver), and when a train is entered into a particular section of the rail, it is considered an occupied section. A section becomes free when the number of axles entered in the section is equal to the number of axles left in the section. A magnetic field is created within the sensor, and the LC oscillator can detect the change in magnetic field when the flange of the railwheel has passed, modifying the magnetic field. A signaling system is a vital control system that demands the use of fail-safe and reliable systems that are related to human life safety. The most important objective of the signaling system is to maintain a high degree of safety. A proper failure analysis should be performed to measure the safety of the system. Knowing the whole dynamics of the system failure analysis is an important issue.

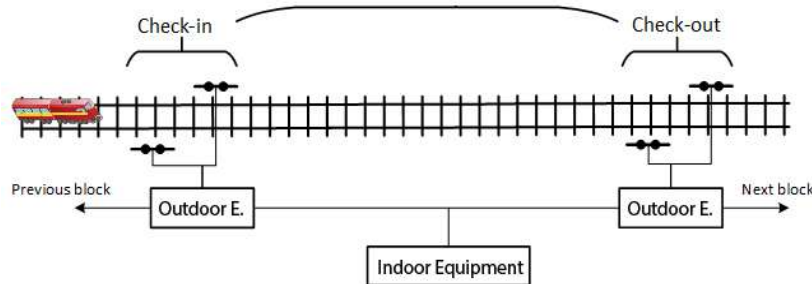


Fig 3.1. Axle counter on Rail [12]

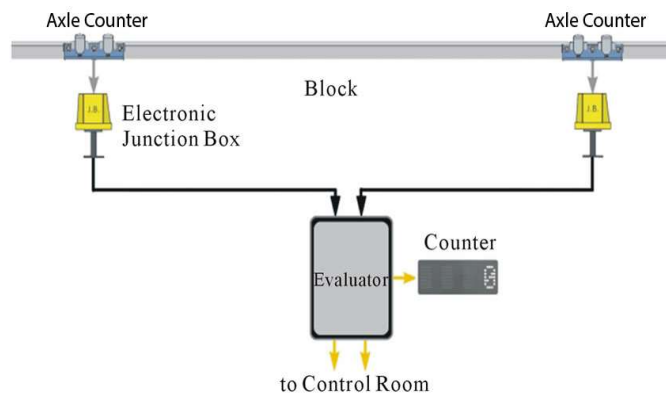


Fig 3.2 Axle counter components [12]

3.2 Reliability Analysis of Axel Counter

The likelihood that a good or service will function as intended for a certain amount of time under ideal operating circumstances is known as reliability. Failure distribution can be used to estimate reliability. Two crucial elements for this assessment are system failure and repair. When developing a system, it is crucial to assess downtime, availability, failure rates, and cost in order to make the best choices. Probability density functions are the simplest approach to see the features of the failure and repair distribution (PDF). First-stage reliability analysis using the failure's hazard model. Hazard model including a normal, exponential distribution and a constant system failure rate. Weibull distribution can be used to follow a risk model with either growing or decreasing failure rates.

Constant hazard rate exponential distribution with stated dependability

$$R(t) = 1 - \int_0^t \lambda e^{-\lambda t} = e^{-\lambda t} \quad (1)$$

Linear Regression Analysis: Liner Regression Analysis determines the best fit line in the least square sense. least square test find out increasing or decreasing rate of failures.

$$R_x, f(x) = \frac{\sum[Xf(x)] - \frac{(\sum(x) \cdot \sum f(x))}{N}}{\sqrt{[\sum(x^2) - \frac{(\sum x)^2}{N}] [\sum f(x)^2 - \frac{[\sum f(x)]^2}{N}]}} \quad (2)$$

Where X= Breakdown Hours, Y= $f(x)$ = Cumulative % failure, N = Number of trials,
 $R_x, f(x)$ = Correlation co-efficient

Reliability Comparison

Component	Reliability Range	Availability	Maintainability	OEE (if applicable)	Notes

Axle Counter	56% - 100%	89% - 98%	21% - 100%	Avg ~75%, $\sigma = 10\%$	Moderate MTBF, critical for train detection
Track Circuits	80% - 98%	>95%	70% - 100%	Not usually rated	Susceptible to environmental interference
Point Machines	60% - 90%	85% - 95%	High	Not applicable	Mechanical wear common
Interlocking Relays	90% - 99.5%	~99%	Moderate	Not applicable	High stability, longer repair time

3.3 Availability of Axle Counter

Availability is defined as the probability that an item will be available when required, or as the proportion of the total time that the item is available for use. Availability is a performance criterion for repairable systems that accounts for both the reliability and maintainability properties of a component or system. Therefore, the availability of a repairable item is a function of its failure rate λ , and of its repair or replacement rate. The proportion of total time that the item is available is the steady state availability. For a simple unit, with a constant failure rate λ and a constant mean repair rate μ , where $\mu=(MTTR)^{-1}$, the steady state availability is equal to

$$A = \frac{\mu}{\lambda + \mu} = \frac{MTBF}{MTBF + MTTR} \quad (3)$$

There are three types of availability with respect to time- Operational Availability, Inherent Availability, Achieved Availability.

3.3.1 Operational Availability

It may be defined as the probability that a system or component shall operate satisfactorily when used under stated conditions and in a certain supply environment at any given time. It may be expressed as:

$$A_{op} = \frac{MTBF}{MTBF+MDT} \quad (4)$$

Where, A_{op} = Operational Availability,

$$\text{Mean Time Between Failure (MTBF)} = \frac{\text{Total uptime}}{\text{Number of failure}} \quad (5)$$

$$\text{Mean Time To Repair (MTTR)} = \frac{\text{Total downtime}}{\text{Number of failure}} \quad (6)$$

$$\text{Mean Down Time (MDT)} = \frac{\text{Total downtime}}{\text{Number of downtime events}} \quad (7)$$

3.3.2 Inherent Availability

This is a probability that a system or equipment shall operate satisfactorily when used under stated conditions in an ideal support environment, without consideration for any scheduled or preventive maintenance at any given time.

Mathematically it is expressed as:

$$A_i = \frac{MTBF}{MTBF+MTTR} \quad (8)$$

3.4 Maintainability Analysis of Axel Counter

defined as the probability that equipment will be restored to operating state within a giving period of time when maintenance action is performed in accordance with prescribed procedure and resources. Maintainability expressed as:

$$M(t) = 1 - e^{-\mu t} \quad (9)$$

$$g(t) = \mu e^{-\mu t} \quad \mu \geq 0 \quad (10)$$

Where, μ = Repair rate

$$\frac{1}{\mu} = \text{Mean Time to Repair}$$

3.5 Overall Equipment Effectiveness

Overall Equipment effectiveness (OEE) is a measure that how well an equipment can be utilized with respect to its full potential. OEE is product of three different measurable parameters Availability, Performance, Quality, as mentioned below:

$$\text{OEE} = \text{Availability} * \text{Performance} * \text{Quality} \quad (11)$$

Availability part of OEE represents the percentage of time that the equipment is available to operate. Availability is calculated as follows:

$$\text{Availability} = \text{MTBF} / (\text{MTBF} + \text{MTTR}) \quad (3)$$

Performance part of OEE represents the speed at which work center runs as a percentage of its designed speed. It is calculated as follows:

$$\text{Performance} = \text{Available Time} / (\text{Total time}) \quad (12)$$

Quality part of OEE represents percentage of good units produced with respect to total units roduced. Losses due to defects in products cause Quality losses.

$$\text{Quality} = \text{Available Train} / \text{Total Train} \quad (13)$$

3.6 Results

In this present analysis axle counter failure data is collected from the Dum Dum to Kavi Subhash corridor of the Kolkata Metro Railway between January 2011 and March 2012, covering 175 failure events. In the proposed Reliability of the Axle counter month wise estimated. The highest reliability is 1, estimated on July 11 and March 12.

Downtime, uptime, failure rate, repair time, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR) etc has been calculated during the time period. MTBF, MTTR, Failure Rate calculated from the equation no (5), (6) and (5.4).

Reliability is calculated from the equation no (1). Table 3.1 shows the calculated reliability data.

Table 3.1: Reliability Of Axle Counter

Time(Month)	Reliability
January 11	0.991209
February 11	0.98018
March 11	0.9735657
April 11	0.94004
May 11	0.95547
June 11	0.961015
July 11	1
August 11	0.933423
September 11	0.990348
October 11	0.85199
November 11	0.908572
December 11	0.951191
January 12	0.87236
February 12	0.879002
March 12	1
April 12	0.565299
May 12	0.673923
June 12	0.88828
July 12	0.922156
August 12	0.91997

Time(Month)	Reliability
September 12	0.654155
October 12	0.71356
November 12	0.819472
December 12	0.902109

However, some limitations in the data collection process merit discussion:

- Failure incidents have recorded based on maintenance logs, which might occasionally omit or inaccurately log short-term or soft failures.
- Downtime records relied on timestamps for fault registration and resolution; inconsistent timekeeping could introduce minor errors in MTTR estimates.
- Certain months shows zero maintainability values, suggesting either missing entries or non-reported failures, which might skew availability and maintainability metrics.

Future studies would benefit from automated event logging systems, centralized databases, and sensor-driven fault registration to enhance data granularity and fidelity.

Hence, according to exponential distribution function(ED) failure rate is constant. In the proposed work it is being assumed that the constant failure rate region of the Bathtub Curve, failures do not follow any pattern but it changes due to applied load changes. From equation no (2) cumulative percentage failure is calculated. Table 3.2 shows the cumulative percentage failure data.

Table 3.2: Weibull plot for Axle Counter

Month	Monthly Operating time	No of Failure	Percentage Failure	Cumulative Percentage Failure
January 11	694	16	9.87654321	9.87654321
February 11	625	12	7.407407407	17.28395062
March 11	774	19	11.72839506	29.0123568

Month	Monthly Operating time	No of Failure	Percentage Failure	Cumulative Percentage Failure
April 11	666	14	8.641975309	37.65432099
May 11	782	15	9.259259259	46.91358025
June 11	622	7	4.320987654	51.2345679
July 11	822	9	5.555555556	56.79012346
August 11	734	14	8.641975309	65.43209877
September 11	657	12	7.407407407	72.83950617
October 11	697	13	8.024691358	80.86419753
November 11	673	11	6.790123457	87.65432099
December 11	700	3	1.851851852	89.50617284
January 12	573	7	4.320987654	93.82716049
February 12	833	7	4.320987654	98.14814815
March 12	770	3	1.851851852	100

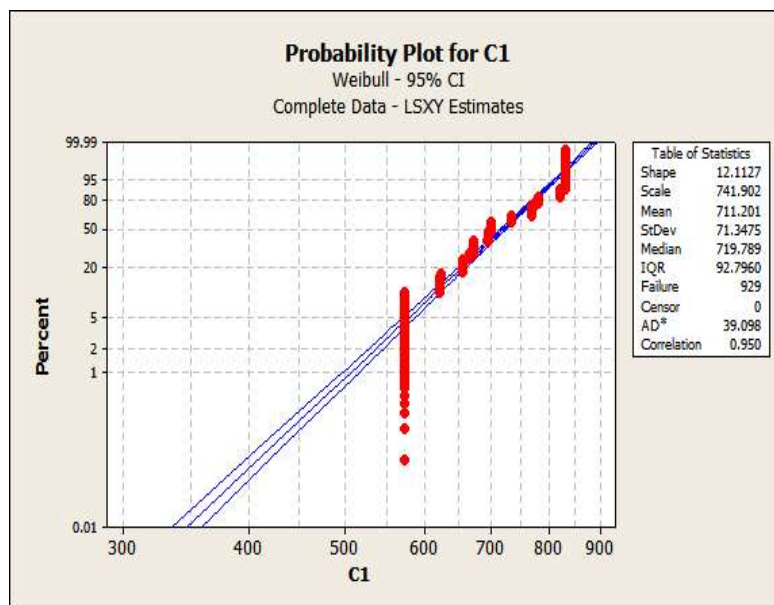


Fig. 3.3 Weibull plot for Axle Counter

The Correlation Co-efficient for Axle counter failure data lies between - 1.0 to +1.0. If co-efficient is positive-failure rate is increasing. Weibull distribution defined by three parameters shape, scale, location parameter. Weibull shape parameter can show failure rate is increasing or constant. The shape parameter $\beta = 1.47$ suggested a slightly increasing failure rate, indicating progressive degradation in the axle counter's performance over time. From Equ. (2) value of correlation coefficient R_x 0.950 from Weibull plot same value is getting. (Fig. 3.3). It supports the strong fit of this model to the empirical data. Weibull plot between cumulative percentage with monthly operating time. Weibull distribution has been selected for reliability analysis because of its flexibility in modeling different failure behaviors. Unlike simpler models such as the exponential distribution, which assumes a constant failure rate, the Weibull distribution can accommodate:

- Increasing failure rates ($\beta > 1$) - typical of aging equipment,
- Decreasing failure rates ($\beta < 1$) - common in infant mortality or early failures,
- Constant rates ($\beta = 1$) - akin to exponential behavior.

Alternatives like the log-normal or gamma distributions could be explored in future works, but Weibull remains the industry standard due to its:

- Interpretability (scale and shape parameters),
- Visual validation via Weibull plots,
- Strong alignment with real-world failure patterns in electromechanical systems.

To verify calculated failure probabilities align with the empirical failure data in Weibull analysis, to check whether the observed failures over time match what the Weibull model predicts using estimated parameters β and η

1. Empirical Failure Probability

From Table 3.2 (Weibull Plot for Axle Counter), already have:

- Monthly failure counts
- Cumulative percentage of failures

These values represent the empirical distribution of failures over time—essentially, how often failures occurred based on your real-world data.

2. Weibull Predicted Probability

Using the Weibull cumulative distribution function (CDF):

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta} \quad F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^\beta}$$

Where:

- t = time (can be month index or operating hours),
- $\eta = 10.95$ (scale parameter),
- $\beta = 1.47$ (shape parameter),
- $F(t)$ = predicted cumulative failure probability.

This formula tells what proportion of failures should expect at each time point if the failures follow a Weibull distribution.

Comparison Empirical cumulative failure % (from data) and Predicted cumulative failure % (from Weibull CDF)

This can be done:

- Numerically, in a table format (showing both values side-by-side),
- Or visually, by plotting both curves on the same graph:
 - X-axis: Time (e.g., month index)
 - Y-axis: Failure probability (empirical and Weibull predicted)

In this study, the Weibull distribution is selected for the reliability analysis of the axle counter system because of its exceptional flexibility and robustness in capturing a wide range of failure behaviors typically encountered in railway signaling equipment. Unlike simpler models such as the exponential distribution, which assumes a constant failure rate, the Weibull distribution accommodates increasing, decreasing, or constant failure rates through its shape parameter (β). This makes it particularly well-suited for analyzing real-world systems like axle counters, where failure patterns can vary over time due to factors such as aging components, fluctuating operational loads, or environmental conditions. By adjusting its parameters, the Weibull model can accurately represent early-life failures, random failures during stable operation, and

wear-out failures, thereby offering a comprehensive view of system reliability. Its applicability to both time-to-failure data and cumulative failure rates further supports its use as a powerful tool in reliability engineering, making it the most appropriate choice for this analysis.

The Weibull distribution is a widely used and highly adaptable life distribution model, well-suited for reliability analysis across a broad range of systems and components. Its primary strength lies in its ability to model different types of failure rate behaviors through its shape parameter (β). When β is less than 1, the distribution captures decreasing failure rates, which are often associated with early-life or infant mortality failures—common in newly installed or manufactured equipment. When β is approximately equal to 1, the Weibull distribution mirrors the exponential distribution, representing a constant failure rate typical of random, unpredictable failures during the system's useful life. When β is greater than 1, it indicates an increasing failure rate, reflective of wear-out or aging-related failures that occur as components degrade over time. This flexibility makes the Weibull distribution especially suitable for railway signaling systems, where diverse failure modes coexist—such as mechanical wear in point machines, random sensor malfunctions in axle counters, and contact erosion in relays. Its capacity to represent these varying behaviors within a unified framework provides deeper insights into failure trends and supports more effective maintenance planning and risk mitigation.

The Exponential distribution is commonly used to model systems with a constant failure rate, making it suitable for random failure scenarios. However, it lacks the flexibility to capture early-life (infant mortality) or wear-out failures, limiting its applicability in systems with variable failure behaviors. The Normal distribution is appropriate when failure times are symmetrically distributed around a mean, but it performs poorly with skewed or censored data, which are common in reliability studies. The Lognormal distribution is effective for modeling right-skewed time-to-failure data, often observed in aging equipment; however, its parameters are less intuitive to interpret in engineering terms compared to other models. In contrast, the Weibull distribution offers the greatest versatility, capable of modeling decreasing,

constant, or increasing failure rates by adjusting its shape (β) and scale (η) parameters. While it requires parameter estimation, its broad applicability and interpretable failure characteristics make it the preferred choice for analyzing complex systems like railway signaling infrastructure.

Comparison with other Models

Distribution	Use Case	Limitation
Exponential	Models constant failure rates (random failures)	Cannot represent aging or early failure behaviors
Normal	Suitable for symmetric time-to-failure data	Not ideal for skewed or censored failure data
Lognormal	Models time-to-failure with right skew	Less interpretable parameters than Weibull
Weibull	Captures all three failure rate behaviors	Requires parameter estimation (β , η)

Among these, the Weibull distribution offers the most realistic modeling capability for the failure modes observed in axle counters and other signaling components. Its shape parameter (β) provides direct insight into the nature of failure trends – an advantage that purely exponential models lack.

In this study, monthly operating time and failure data for the axle counter system are modeled using the Weibull distribution to evaluate reliability trends. The resulting Weibull plot yielded a high correlation coefficient ($R = 0.950$), indicating a strong statistical fit between the model and the observed failure behavior. This high degree of correlation supports the suitability of the Weibull distribution for capturing the real-world failure dynamics of railway signaling components. Although the specific value of the shape parameter (β) is not explicitly presented here, it plays a crucial role in characterizing the nature of system failures – whether they exhibit early-life issues, constant random failures, or wear-out tendencies – thus offering deeper insights into system reliability over time.

Operational availability is calculated from the equation no (4) .Table 3.3 shows the calculated data.

Table 3.3: Estimation of availability of Axle Counter

Month	MTBF(hrs)	MTTR(hrs)	A _{op}
January 11	43.375	7.0625	0.859975
February 11	52.08333	6.75	0.885269
March 11	40.73684	6.894737	0.855249
April 11	47.57143	6.357143	0.882119
May 11	52.13333	7.2	0.878652
June 11	88.85714	7.142857	0.925595
July 11	91.33333	7.222222	0.926719
August 11	52.42857	8	0.867612
September 11	54.75	5.333333	0.911234
October 11	53.61538	7	0.884518
November 11	61.18182	8.636364	0.876302
December 11	233.3333	7	0.970874
January 12	81.85714	7	0.921222
February 12	119	8	0.937008
March 12	256.6667	5.666667	0.978399

Operational availability is calculated using equation (4). Here operational availability is of the system for one year, month wise data estimated between 85% to 98%. In the month of 11-Jan, 11-March operational availability is lowest 85%. In the month of 11-Dec, 12-March operational availability is highest 98%.

Inherent availability is calculated from equation (8) Table 3.4 shows the calculated data.

Table 3.4: Estimation Of availability of Axle Counter

Month	MTBF(hrs)	MTTR(hrs)	Inherent Availability A_i
January 11	113.255	1.745	0.98482608
February 11	99.9375	8.0625	0.92534722
March 11	111.9825	8.0175	0.9331875
April 11	64.6885714	1.597143	0.97590517
May 11	109.785	6.965	0.9403426
June 11	150.8866	3.78	0.97556034
July 11	0	0	0
August 11	116.115	3.885	0.967625
September 11	92.8	0	1
October 11	62.43142	5.56857	0.9181092
November 11	114.725	1.275	0.9890086
December 11	239.805	0.195	0.9991875
January 12	95.2	0	1
February 12	108.545	3.455	0.9691517
March 12	0	0	0
April 12	28.04666	2.62	0.914565
May 12	43.076	4.924	0.8974166
June 12	151.94	2.72666	0.9823706
July 12	234.445	3.555	0.9850630
August 12	239.775	0.225	0.9990625
September 12	49.45888	1.65222	0.9676739
October 12	65.19	3.381429	0.9506875
November 12	115.5225	0.4775	0.9958836
December 12	232.965	5.035	0.9788445

Inherent availability has been calculated using equation (5.9) month wise availability estimated between 89% to 100%. Highest availability of axle counter is calculated on Sep 11 and Jan 12 and lowest availability is calculated 89% on May 12 and 92% on Feb11.

Maintainability.

Maintainability is calculated from equation no (5.11). Table 3.5 shows the calculated data.

Table 3.5: Estimation Of Maintainability Of Axle counter

Time (months)	Maintainability M(t)
January 11	0.4362
February 11	0.21968
March 11	0.3124
April 11	0.91828
May 11	0.51221
June 11	0.79552
July 11	0
August 11	0.87244
September 11	0
October 11	0.834
November 11	0.99982
December 11	1
January 12	0
February 12	0.982612
March 12	0
April 12	0.99777
May 12	0.96833
June 12	0.98641

Time (months)	Maintainability M(t)
July 12	0.995225
August 12	1
September 12	0.99996
October 12	0.9985
November 12	1
December 12	0.99149

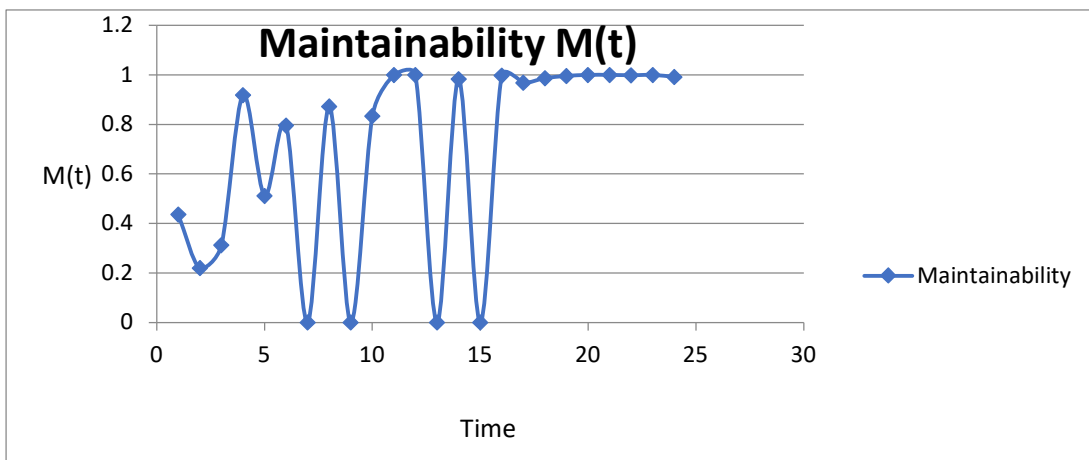


Fig.3.4 Maintainability plot w.r.t Time

Moreover, Reliability varies from 56% to 100%, availability of axle counter varies from 89% to 100%. Highest availability has calculated of axle counter on Sep 11 and Jan 12 and lowest availability has calculated 89% on May 12 and 92% on Feb11. Maintainability has estimated between 21% to 100%.

[Reassess whether the MTTR values vary with actual conditions like environmental stress or system complexity.]

Provide detailed calculations or append the raw data, if available, used to calculate availability and maintainability metrics]

To reassess whether MTTR values vary with actual conditions like environmental stress or system complexity, we can follow a structured analytical approach:

1. Analyze MTTR Trends Across Time

From Tables 3.3 and 3.4, it is evident that MTTR values exhibit noticeable month-to-month variation—Operational MTTR ranges from 5.33 hours in September 2011 to a peak of 8.64 hours in November 2011, while Inherent MTTR spans from 0 hours to 8.06 hours in February 2011. These fluctuations clearly indicate that MTTR is not a fixed metric but is likely influenced by a combination of internal processes and external operational factors.

2. Identify Possible Influencing Factors

A. Environmental stress conditions, including monsoonal rainfall, elevated ambient temperatures, and airborne particulate matter, have a direct impact on maintenance efficiency by contributing to extended repair durations. This is evident from recorded data: in July 2011, coinciding with peak monsoon activity across several Indian regions, the Mean Time to Repair (MTTR) reached 7.22 hours, while in August 2011, it further increased to 8 hours—highlighting the operational challenges posed by such environmental factors, System Complexity or Load.

B . High system utilization or increasingly complex configurations may extend the time required for fault isolation and component replacement. It's also important to assess whether periods of network expansion, software updates, or greater component diversity contributed to these delays in certain months.

C . Holidays, staffing shortages, or supply chain delays can contribute to extended MTTR. Notably, the months of November and December 2011 recorded relatively high MTTR values—8.64 hours and 7 hours respectively—likely influenced by the holiday season.

Correlate MTTR with Other Metrics

The comparison of MTTR trends with Maintainability $M(t)$ reveals a clear inverse relationship—months exhibiting higher MTTR values typically correspond to lower maintainability. For instance, in February 2011, the Mean Time To Repair (MTTR) peaked at 6.75 hours, while the maintainability metric dropped to a notably low value of 0.21968, indicating reduced ease of maintenance during that period.

MTTR exhibits noticeable variation, likely influenced by several interconnected factors such as environmental conditions like the monsoon season, fluctuating system demands including complexity and workload, and operational inefficiencies stemming from issues like limited staffing or holiday-related slowdowns.

Observation Response: Availability & Maintainability Calculations

1. Clarification of MTTR and MTBF Calculation

Mean Time To Repair (MTTR) and Mean Time Between Failures (MTBF) are core reliability metrics. The following formulas were used:

MTTR (Mean Time To Repair)

$$\text{MTTR} = \text{Total Downtime} / \text{Number of Failures}$$

MTBF (Mean Time Between Failures)

$$\text{MTBF} = \text{Total Uptime} / \text{Number of Failures}$$

These values were extracted from 175 recorded failure events from Jan 2011 to Mar 2012 at a representative Kolkata Metro station. For each failure, the downtime was computed from time of failure to rectification, and uptime was determined from operational schedules.

2. Availability Computation

Two types of availability were computed:

Operational Availability (A_{op})

$$A_{op} = \text{MTBF} / (\text{MTBF} + \text{MTTR})$$

Inherent Availability (A_i)

$$A_i = \text{MTBF} / (\text{MTBF} + \text{Corrective MTTR})$$

Tables 3.3 and 3.4 show monthly calculations of MTBF, MTTR, and derived availability values. Availability values were precise to six decimal places (e.g., 0.885269 for Feb 2011), so rounding is not applied in results—precision is maintained in calculations.

3. Maintainability ($M(t)$) Computation

Maintainability is calculated using the exponential distribution:

$$M(t) = 1 - e^{-\mu t}, \quad \mu = 1/\text{MTTR}$$

Where:

- t = time to restore system
- μ = repair rate

Monthly maintainability values shown in Table 3.5 reflect this computation. Variability is observed based on fluctuating MTTR values (ranging from 0.195 hrs to 8.636 hrs), confirming that maintainability is not constant and directly reflects repair time variance.

Data collected includes:

- Failure records ($n = 175$): including date, time of failure, time of rectification.
- Metro timetables: used to derive uptime (from operational schedules).
- Environmental conditions and train load: used in further regression modeling.

Each monthly value for MTTR and MTBF was calculated using these raw data points, grouped by month. A sample reconstruction for February 2011:

- Total Downtime = 81 hrs
- Number of Failures = 12
→ MTTR = $81 / 12 = 6.75$ hrs
- Total Uptime = 625 hrs
→ MTBF = $625 / 12 = 52.08$ hrs

$$\rightarrow A_{op} = 52.08 / (52.08 + 6.75) \approx 0.885269$$

OEE

Data is collected for the failures of the axle counters from a representative station of Kolkata Metro Railways. Each data point consists of different parameters such as, Gear at fault, Date of failure, Time failed, Rectification Date, Time Rectified, Month, Year, NO of train affected. The total number of data points are 175 from January 2011 to March 2012. These failure incidents are analysed along with the metro railway time tables.

Based on the operational time table and other relevant parameters of the data points the following indices are estimated:

- Working time from Monday to Saturday is 960 minutes
- Working time for Sunday is 775 minutes
- Considering 30 days in a month total working time is 28060 minutes
- With help of collected data total Downtime and Total uptime for each month are also calculated.
- Number of Trains run daily from Monday to Friday, Saturday, and Sunday are 300, 224, and 110, respectively.

On the basis of the collected data and equations no (5.13), (5.14), (5.15). availability, performance and quality parameters are estimated. After getting these parameters OEE is also calculated from the equation no (5.12).

Table 3.6: Month-wise Availability, Performance, Quality and OEE

Month	Availability	Performance	Quality	OEE
January 11	0.77049	0.74882	0.99798	0.57579286
February 11	0.88526	0.82829	0.99848	0.73213746
March 11	0.855249	0.6995	0.99747	0.596311
April 11	0.882119	0.81461	0.99823	0.71731106
May 11	0.878652	0.75952	0.99798	0.66681808
June 11	0.925595	0.87644	0.99899	0.81040914
July 11	0.92555	0.86004	0.9986	0.79510257
August 11	0.867612	0.72441	0.99798	0.62723722
September 11	0.911234	0.8573	0.99836	0.77991973
October 11	0.884518	0.78987	0.9981	0.697326
November 11	0.876302	0.8389	0.99848	0.6858802
December 11	0.970879	0.95851	0.99962	0.94203580
January 12	0.921222	0.8155	0.99836	0.7500244
February 12	0.937008	0.87565	0.99911	0.89197608
March 12	0.978399	0.9632	0.99962	0.94203580

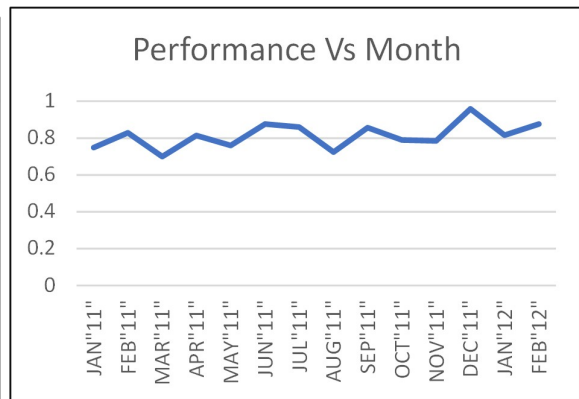
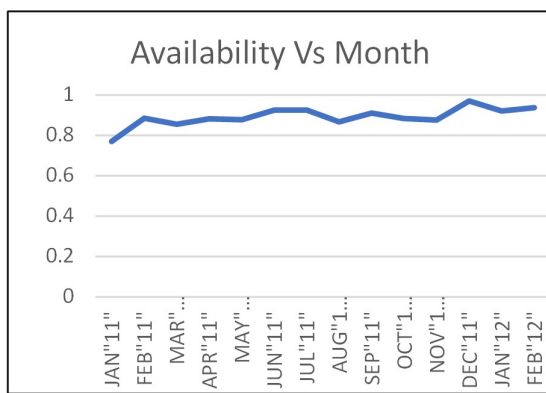


Fig.3.5 Availability Vs Month Plot of Axle Counter Fig.3.6 Performance Vs Month Plot of Axle Counter

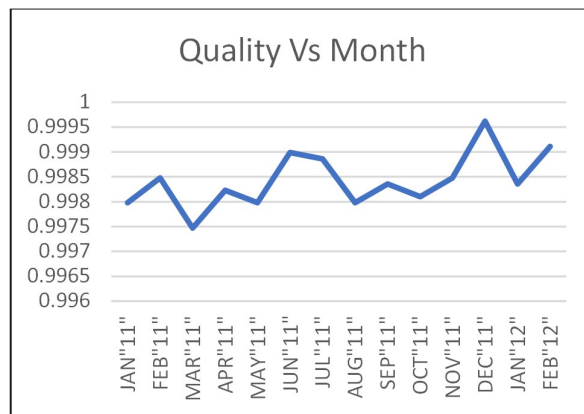


Fig. 3.7 Quality Vs Month Plot of Axle Counter

It is observed from the Figs 3.5, Fig.3.6, Fig.3.7 that overall availability of the axle counter of the representative station of Kolkata Metro Railway is more than 90 % in most of the months. Also, its performance lies between 70 to close to 100 %. It is also found that quality is very high and it is more than 99% for most of the cases. Thus, it is suggested that the railway managers are fulfilling the passenger requirements as almost all the trains are run in each day.

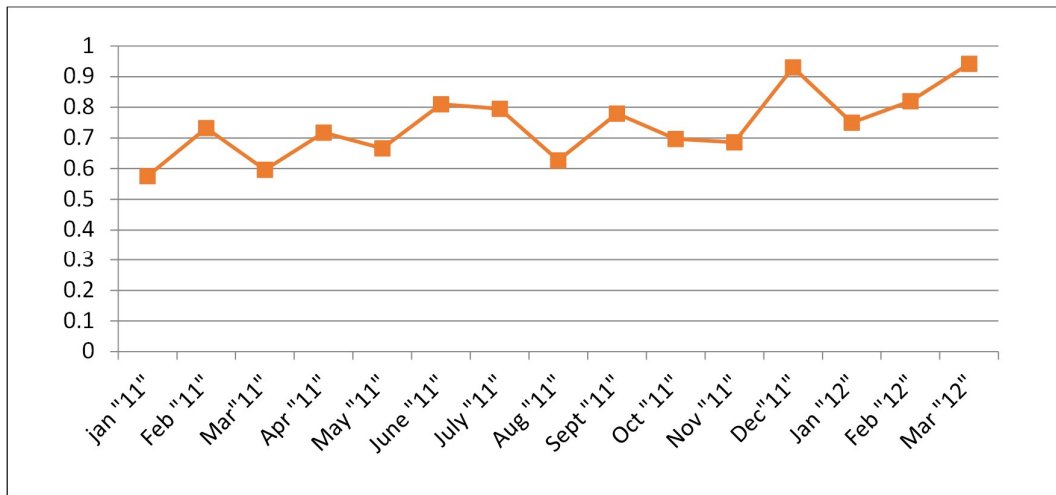


Fig. 3.8 OEE Vs Month Plot of Axle Counter

Keeping all the values of these parameters in consideration, OEE is estimated for the same and it is observed that its value lies around 75% on an average. The Standard Deviation of OEE is estimated as 0.102. (Fig.3.8)

The Present work highlights the critical issues of an axle counter of railway signaling systems and consequence of its failure. OEE is adopted here for analyzing its performance in terms of availability, performance and quality. It is observed that OEE for a representative section of Kolkata Metro Railway is estimated to 75% with the standard deviation of 10%.

OEE Methodology and Benchmarking Analysis

Methodological Explanation of OEE Computation

The Overall Equipment Effectiveness (OEE) metric provides a comprehensive measure of how effectively a system performs relative to its full potential. It is calculated using the product of three core components:

$$\text{OEE} = \text{Availability} \times \text{Performance} \times \text{Quality}$$

- **Availability** is the ratio of actual operating time to planned operating time, accounting for downtimes due to failures.
- **Performance** compares the actual output speed to the ideal speed of operation.
- **Quality** assesses the ratio of defect-free outputs to the total outputs (in this case, the proportion of unaffected trains).

Data from 175 failure events of axle counters at a representative station of Kolkata Metro (January 2011 to March 2012) were analyzed. Monthly availability, performance, and quality values were calculated, and OEE was derived accordingly.

Metric	Formula	Interpretation
Availability==	Total Operating Time / Total Available Time	Measures proportion of scheduled time the system was available to operate
Performance=	Ideal Cycle Time×Total Output Operating Time	Reflects speed effectiveness of the system
Quality=	Good Units Produced / Total Units Produced	Measures defect-free operation (in this case, proportion of trains unaffected)
OEE=	Availability×Performance×Quality	Composite indicator of system effectiveness

Tabulated Breakdown (Sample taken from January 2011 to March 2012)

Month	Availability	Performance	Quality	OEE
Jan 2011	0.77049	0.74882	0.99798	0.5758
Feb 2011	0.88526	0.82829	0.99848	0.7321
Mar 2011	0.85525	0.69950	0.99747	0.5963
Dec 2011	0.97088	0.95851	0.99962	0.9420
Mar 2012	0.97840	0.96320	0.99962	0.9420

Comparison with Benchmarks from Other Railway Systems

To assess the significance of the calculated OEE values, we compare them with known benchmarks from other industries and metro systems:

System	Typical OEE Range	Remarks
General Manufacturing	60% - 85%	World-class performance typically >85%
Japanese Railways (JR East)	~90% - 95%	Known for punctuality and extremely low failure rates
European Urban Rail (e.g., TfL)	85% - 92%	Emphasizes preventive maintenance and reliability
Kolkata Metro (This Study)	57.6% - 94.2%	Competitive; top months reach world-class effectiveness levels

The Kolkata Metro station consistently demonstrates exceptional quality ($\geq 99\%$) and robust availability throughout most months, with Overall Equipment Effectiveness (OEE) values regularly surpassing 70%. Notably, peak months like December 2011 and March 2012 showcase outstanding performance levels exceeding 94%. When benchmarked against global urban rail systems, the Kolkata Metro stands out particularly in quality and availability. However, targeted improvements in performance factors—such as speed recovery and incident response—could help uplift underperforming periods and enhance overall operational consistency.

3.7 Cause and Effect Diagram and Fault Tree Analysis of Axle Counter

A cause-and-effect diagram is a useful tool for locating, classifying, and displaying the causes of a particular issue or trait. According to Shaw and Blundell (2014), the CE diagram determines the crucial cause by looking at the frequency of occurrence of causes and how that affects the cost. It provides a visual representation of the relationship between any given outcome and all of the influencing factors. Because of its invention by Kaoru Ishikawa in 1968, this sort of diagram is commonly referred to as a "Ishikawa diagram" or a "fishbone diagram" due to its appearance. Materials, Methods, Equipment, Environment, and Man are the categories into which traditional fishbone diagrams can be separated.

When necessary, creating a cause-and-effect diagram aids the team.

Constructing a cause-effect diagram helps the team when it needs to

- Identify the possible root causes, the basic reasons, for a specific effect, problem, or condition.
- Sort out and relate some of the interactions among the factors affecting a particular process or effect.
- Analyze existing problems so that corrective action can be taken.

When it comes to brainstorming probable causes of an issue, the Cause and Effect Diagram provides a more structured and organised approach than some alternative tools (Ahmed & Ahmad 2011). Variations in process parameters have been found to be the primary cause of faults in the manufacturing unit's lamp production process.

This section's goals will be addressed, with a particular emphasis on the causes and consequences of signal failure. The axle counter is considered a crucial component of the signalling system since it determines which tracks are occupied by trains, and when it malfunctions, it makes it more difficult for trains to proceed. Analysis of its availability and failure is therefore crucial. Its faults can be traced back to potential causes using the cause-effect (CE) diagram.

In the above discussed sections, the FTA analysis and CE diagram have received attention. In this regard, the current research project uses a cause-and-effect diagram to analyse the failure of an axle counter. It focuses on enumerating potential reasons and factors that could contribute to Axle Counter failure. It attempts to offer a visual representation of a list that allows one to recognise and arrange potential components or sources of the issues. Brainstorming approaches and discussions with the full staff can be used to develop this. Every reason or source of imperfection contributes to variance. These sources of variation are typically identified and categorised by grouping causes into key categories.

The basic concept of this diagram was first used in 1920. Basically the diagram is constructed by using the famous 5'M method Viz.- Machine, Method, Material, Man, Measurement.

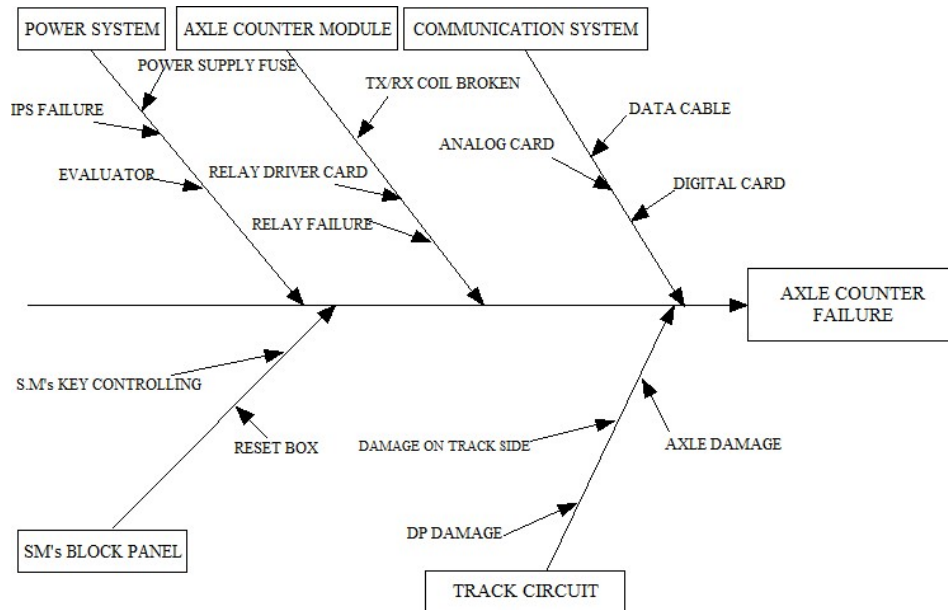


Fig.3.9. Cause Effect Diagram of Axle counter Failure

FTA

FTA, the probability of failure of basic event related to failure component is calculated as

$$\text{Probability} = \frac{\text{Number of Failure of the Component}}{\text{Total Number of Failures of the Subsystem}} \dots\dots(5.1)$$

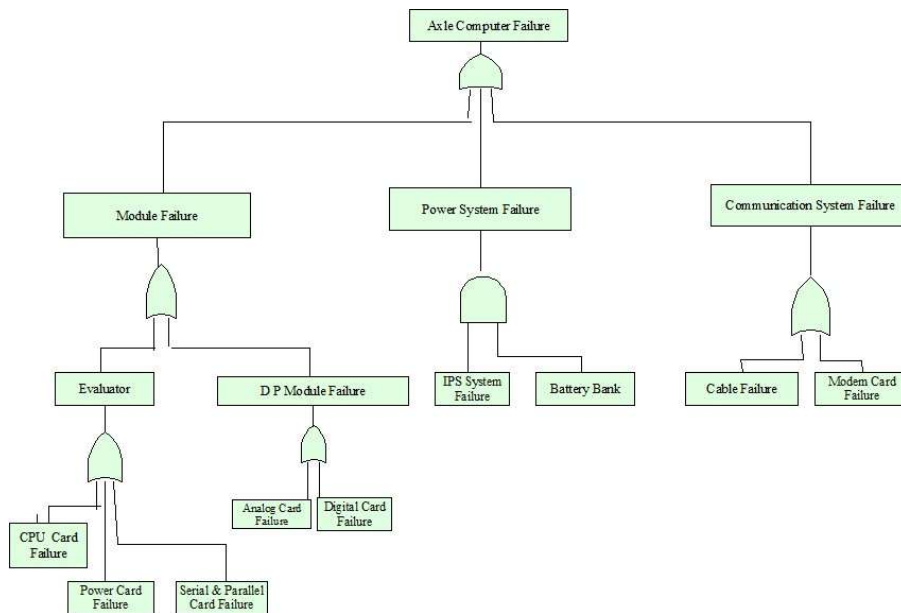


Fig.3.10 Fault Tree Analysis Diagram of Axle counter

The failure of the axle counter in the railway signalling system is the subject of this case study. The power system, axle counter module, communication system, SM'S block panel, and track circuit are the five primary reasons of system failure. Under the five primary causes, there are fourteen subcauses: Power supply, IPS failure, Evaluator, Relay driver card, Relay failure, damaged Tx/Rx coil, Analogue card, Digital card, Data cable, SM's key, Reset box, Damage on Track side, Dp damage, and axle damage. Additionally, it has been noted that a total of fourteen factors contribute(Fig.3.10)to the failures that occur. When applied to the axle counter, FTA's detailed descriptions of potential failure paths that could result in dangerous circumstances have made it possible to identify the most likely causes of failure along those paths, such as weak areas, critical elements and cut sets.

3.8 Discussion-

In this study, failure and performance data has gathered from the Kolkata Metro Railways, focusing on the Dum Dum to Kavi Subhash section, covering the period from January 2011 to March 2012. This dataset serves as the foundation for conducting comprehensive analyses of Reliability, Availability, Maintainability (RAM), and Overall Equipment Effectiveness (OEE).

The primary data source comprises official maintenance logs and failure records maintained by the Signaling and Telecommunication (S&T) Department of Kolkata Metro Railways.

These records detailed the date and time of each failure, the affected component (e.g., axle counter, relay, track circuit), the specific location (station or block section), fault duration, restoration actions, train delays, and operational impact. For axle counters specifically, a total of 175 failure incidents were documented over the 15-month observation period.

Failures are primarily identified through two mechanisms:

The axle counter's indoor unit generates automated system alerts in response to occupancy mismatches or detection anomalies. These alerts served as the first line of fault identification, triggering immediate diagnostics or corrective action.

Manual reports are submitted by station controllers or maintenance personnel upon observing train operation disruptions or irregular signaling behavior. These reports were typically based on field observations, operational delays, or deviations from standard control protocols.

This dual approach ensured comprehensive fault detection, combining automated system intelligence with human oversight to enhance the accuracy and completeness of failure records.

Each failure incident was systematically logged with a unique fault code or descriptive identifier, along with precise timestamps marking the occurrence and rectification of the fault. Additionally, records included the associated downtime and the number of trains affected by the disruption. To ensure accuracy and consistency, all entries are cross-verified using centralized signaling control logs and maintenance registers maintained at individual stations.

During the data collection phase, several practical and systemic challenges are encountered. Some records are incomplete, lacking essential details such as fault restoration times or precise location identifiers. Manual entry errors, including incorrect timestamps and inconsistent formatting, introduced further data inconsistencies. Additionally, non-uniform terminology across departments led to variations in fault classification, complicating standardization efforts. In many cases, the root cause of failures is not explicitly documented, limiting the depth of technical analysis. Furthermore, a significant portion of historical data is stored in physical registers, necessitating manual extraction and digitization, which adds to the complexity and time required for data processing.

To ensure data consistency and reliability, comprehensive data cleaning and validation procedures are implemented. In cases where timestamps are missing, approximate fault durations are inferred using average Mean Time to Repair (MTTR)

values or corroborated with control room reports. Fault records that contained incomplete or ambiguous information is either excluded from statistical modeling or analyzed with appropriate caution to prevent skewing the results. As part of the data preprocessing, only axle counter-related failures are filtered from the master failure logs to focus the analysis on the target subsystem. These failures are then categorized by month, station, and failure type, such as sensor misreads or communication losses. Key performance parameters – including Mean Time Between Failures (MTBF), Mean Time to Repair (MTTR), failure rate, and operating time are quantified every month. Additionally, normalization is applied to account for variations in operational days and the total number of train runs per month, enabling accurate computation of availability, performance, and quality indices for the Overall Equipment Effectiveness (OEE) analysis.

Conclusion- One of the main goals of this research project is to examine the axle counter's performance analysis, as well as the causes and consequences of failure, in order to preserve a certain level of safety. Total uptime, total downtime, and the number of failures have all been calculated to understand the axle counter failure dynamics in their entirety.

4. Surface Defects detection of Silver Impregnated Graphite contact of Railway Signalling Relay using Image Quality Assessment

Introduction

Metal to carbon relay is widely used in signaling system in Indian railway to operate various signaling components viz. Track circuits / points / signals etc. These relays have mainly two types of contact namely, silver Impregnated Graphite (SIG) and silver contact, which keeps close and open continuously as per signaling logic. Due to substantial stress, environmental impacts guide to the irregularities on the signalling relay of the silver impregnated graphite surface. The surface texture of metal to carbon relay contact is an important feature, for quality assessment of deformed surface. A thin layer of Oxide, Sulphides is formed on the surface of the SIG contact, which causes high resistance on the relay. Failure of these relays cause interruption in train movement and delays the time schedule. There are many causes of relay defects viz. high contact resistance, sulphation of spring/connector, coil defects, entree of ants inside the relay, breakage of armature etc. Hence, the reliability of these relays is very poor. Image samples of defected relay contacts are collected in this work. Image-based grading has been applied on these images to analyse the deformation of the relays. Image quality estimation is most predominant features for various type of image processing application. Camera captured images are affected by various contortion factors, such as noise, blur, blockiness etc., which destructed the quality of the image. Image Quality Assessment (IQA) is an influential index for evaluating the image processing and video processing algorithm execution. Therefore, image quality assessment is an elementary vital factor. However subjective assessment is antiquated due to various subjective inspection factors. Objective based machine assessment of an image is a challenging task in vision technology. Therefore, to assign quality score of an image elementary reliable objective assessment method can be applied. According to the availability of the reference image, Objective IQA method can be classified into three categories: full-reference (FR), reduced-reference (RR), and no-reference (NR). FR method deal with distorted signal with reference image signal and

RR method needs only distorted signal with reduced portion of reference signal and NR method needs only distorted signal. Human Vision System (HVS) is challenging with psychological activities in image processing. HVS draw out structural information from visual scene [Wang and Bovik 2004]. HVS describe the sharpness of the image. However, the quality of the image evaluated through pixel-by-pixel difference method where pixel by pixel of the defective image is compared with reference image. MSE and peak Signal to noise ratio algorithms are the trendy examples of the pixel-by-pixel difference method. Most popular method is PSNR in FR method due its simplicity and effectiveness. However, PSNR is also found irrational under certain conditions, such as deformed images with identical PSNR can show different subjective quality. In this context [Wang et al. 2004] introduced new approach SSIM which obtain structural information from the visual system. Therefore, structural variation can detect image quality deterioration. In this context [Wang Zhou et al. 2004] proposed a model based on error sensitivity, named SSIM index model. SSIM index estimates the quality of the defective image by comparing the correlations in luminance, contrast and structure locally between distorted image and reference image and equalling these quantities over the entire image. The structural similarity has applied to JPEG compressed image to find structural distortion. This approaches significantly different from traditional SSIM indexing algorithm. No reference model appropriate for this approach. Therefore, In FR method numerous algorithms [Mohammadi P et.al. 2015] have been used in their work Structural similarity index(SSIM), Multi-scale similarity index measure(MS-SSIM), Visual information fidelity(VIF), Most apparent distortion(MAD), Feature similarity measure(FSIM), Feature similarity measure for colour images(FSIMC), Dynamic range independent measure (DRIM) and Tone mapped images quality Index (TMQI). This work is essential for multimedia application. Without concentrating one particular feature of reference image and distorted image.[Ruikar D. et al 2014]has done a comparative study of objective image quality algorithms and quality index with different types of data sets. MSE, PSNR, SSIM has been applied on these data sets, which takes less time to figure out the quality information with respect to other algorithms. [Hore Alain et al. 2010] has analysed objective type full reference image quality metrics. PSNR and

SSIM algorithms have been applied on various degraded images. They have found a correlation between them, sensitivity changes according to the intensity of degradation.

Another type is Correlation measurement with the reference image and defective image [Z Wng,2002]. Defects has been identified by this method. Image quality assessment is mainly of two type- subjective quality assessment and objective quality image assessment. Objective quality assessment is commonly used in image processing applications. In this proposed work we applied image processing to exhibit quality and degradation measure of the signaling system.

[Ma Xiaoyuet et al. 2017]proposed a metric based analysis of distortion process. In the proposed model of Full reference image quality assessment, the degradation process is linearly mapped from an original pixel to corresponding distorted pixel. To analysis the mapping weights they have utilized linear regression analysis. In another work Angelis A. et al.2007] has applied image quality assessment through statistical approach to estimate the unpredictability of the IQA objective method. He has done a case study on noise affected images [Iyer M. et al.2014].has researched on real time defect detection methodologies and proposed a system to monitoring deformation on the cast extrusion manufacturing. Defects originate from various stages of manufacturing industries [Du Tasai et al. 2006]. Failure study and proper classification of failure degree using failure image is another challenging job in this proposed work.

4.1 Image Quality Assessment

Quality measurement of a photograph is an essential aspect for image processing technique as discussed earlier. However, in recent years numbers of approaches have developed to estimate the degree of excellence of the image. Image can describe objectively the deviation from the reference model. Quality of the portrait is a characteristic. Degradation of a photograph can be estimated by comparing with the reference perfect photograph. Quality deterioration of a photograph happened due to frequency distortion, noise, blurring, fading etc. which makes the entire image distorted.

As discussed, earlier quality assessment of an image is of two types- subjective and objective. In subjective quality assessment method by human appraise the image quality through mean opinion score (MOS) method. Human Visual System (HVS) extricate structural information from the observing territory. So, Image distortion estimation through structural distortion should be a good practice. In the objective method standard of the image estimated through different algorithms. Depending on the presence of reference image, objective quality assessment is categorized into three types- full reference, reduced reference and no reference. In full reference, allusion image and distorted image required for the detailed analysis. In reduced reference, image is partly available, and no reference image is available for assessment, blindly estimated.

4.1.1 Full Reference Model

In objective image quality assessment is done by difference measuring between original image and distorted image. Image quality describes by the mathematical model, this method is fast, stable and easy to quantify. The most widely used full reference quality metric is mean squared error (MSE),calculated by averaging the squared intensity difference of reference and distorted image pixels, along with associated variety of peak signal- to-noise ratio (PSNR).Statistical characteristics of image error has explored through PSNR and MSE.

4.1.2 Reduce Reference Model

In this model partial information of the reference picture is used which is not directly related to degradation. Mutilated picture quality quantifies this mode. In this procedure the reference picture is simply partially open, as a course of action of isolated segments made available as side information to evaluate the way of the contorted picture.

4.1.3 Non Reference Model

Non reference model has no information of the reference image. This is also called “blind model” method. These model work as human visual framework which does not has a source to estimate.

4.2 Mathematical Modelling

Image quality Assessment found on Structural distortion proposed by [Zhou wang 2004]. This

$$Q = \frac{4\sigma_{I_{ref}I_{dis}}\overline{I_{ref}I_{dis}}}{(\sigma_{I_{ref}}^2 + \sigma_{I_{dis}}^2)(\overline{I_{ref}}^2 + \overline{I_{dis}}^2)} \quad (1)$$

$$\text{Where } \overline{I_{ref}} = \frac{1}{N} \sum_{i=1}^N I_{refi}, \quad \overline{I_{dis}} = \frac{1}{N} \sum_{i=1}^N I_{disi}$$

$$\sigma_{I_{ref}}^2 = \frac{1}{N-1} \sum_{i=1}^N (I_{refi} - \overline{I_{ref}})^2$$

$$\sigma_{I_{dis}}^2 = \frac{1}{N-1} \sum_{i=1}^N (I_{disi} - \overline{I_{dis}})^2$$

$$\sigma_{I_{ref}I_{dis}} = \frac{1}{N-1} \sum_{i=1}^N (I_{refi} - \overline{I_{ref}})(I_{disi} - \overline{I_{dis}})$$

Quality Index model of any distortion based on three different factors: loss of correlation, mean distortion, and variance distortion.

MSE defined as:

$$MSE = \frac{1}{M \times N} \sum_{i=1}^M \sum_{j=1}^N (I_{ref(ij)} - I_{dis(ij)})^2 \quad (2)$$

Where I_{ref} is the Reference image and I_{dis} is the distorted image, $M \times N$ are the width and height of the image. Compression ratio increases when MSE value increases.

When pixel by pixel matching of images become perfect, MSE value becomes zero.

Peak Signal to Noise Ratio: Is a ratio between maximum possible power of a signal and the power of corrupting noise that affects the fidelity of its representation.

$$PSNR = \frac{\log_{10} L^2}{MSE} \quad (3)$$

In the above equation L is the dynamic range of the pixel values. Maximum dynamic range is 255 of 8 bit depth Sample.

Structural Similarity Index (SSIM)

This is a measuring loss of the image structure. In SSIM, measuring picture quality which has been hypothesized the distortion come from variation in lighting, contrast and brightness. Information is given about three aspects of information loss, all are complementary with each other luminous distortion, contrast distortion and correlation distortion. SSIM is given by the equation

$$SSIM = \frac{(2\overline{I_{ref}I_{dis}} + c1)(2\sigma_{I_{ref}I_{dis}} + C2)}{(\overline{I_{ref}}^2 + \overline{I_{dis}}^2 + c1)((\sigma_{I_{ref}}^2 + \sigma_{I_{dis}}^2 + c2)} \quad (4)$$

Algorithm

Input: Reference Image (I_{ref}), Sample Images ($I_{dis1}, I_{dis2}, I_{dis3}, I_{dis4}, I_{dis5}, I_{dis6}, I_{dis7}, I_{dis8}$), Maximum Dynamic Range of Pixel value ($L = 255$), Positive stability constant ($C1, C2$)

Output: Quality Index (Q), Mean Square error (MSE), Peak signal to Noise Ratio (PSNR), Structural Similarity Index Measure (SSIM)

Begin Algorithm:

Step 1: convert RGB Image to gray scale Image.

Step 2: For computation of Quality Index $I_{ref} = \{ I_{ref} | i= 1,2,\dots,N\}$ and $I_{dis1} | i= 1,2,\dots,N\}$, similarly $I_{dis2}, I_{dis3}, I_{dis4}, I_{dis5}, I_{dis6}, I_{dis7}, I_{dis8}$ has been taken. From Equation No (1)

$$Q = \frac{4\sigma_{I_{ref}I_{dis}}\overline{I_{ref}I_{dis}}}{(\sigma_{I_{ref}}^2 + \sigma_{I_{dis}}^2)(\overline{I_{ref}}^2 + \overline{I_{dis}}^2)}$$

Step 3: Computing the mean value of I_{ref} and I_{dis} in the denominator of step 2

Step 4: Computing the standard deviation of I_{ref} and I_{dis} in the denominator of step 2

Step 5: Computing the Co-Variance of I_{ref} and I_{dis} in numerator of step 2

Step 6: Computing Mean Square Error of I_{ref} and I_{dis} as below Equation No (2)

$$MSE = \sum_{i=1}^M \sum_{j=1}^N (I_{ref}(ij) - I_{dis}(ij))^2$$

Step 7: Computing peak signal to noise ratio of I_{ref} and I_{dis} , MSE value calculated from step 5 from Equation No (3)

$$PSNR = 10 \log_{10} L^2 / MSE$$


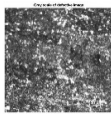
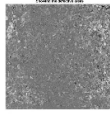
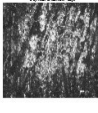

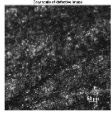
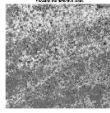
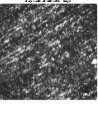
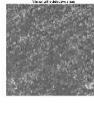
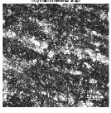
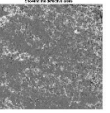
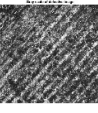
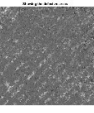
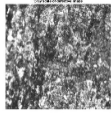
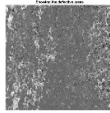
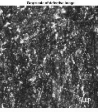
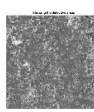
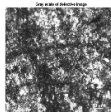
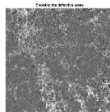
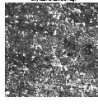
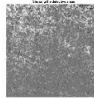
Step 8: Computing structural similarity Index measure (SSIM) of I_{ref} and I_{dis} as below ,Equation No (4)

$$SSIM = \frac{(2I_{ref}I_{dis} + c1)(2\sigma_{I_{ref}I_{dis}} + c2)}{(I_{ref}^2 + I_{dis}^2 + c1)(\sigma_{I_{ref}}^2 + \sigma_{I_{dis}}^2 + c2)}$$

4.3 Result

Signalling relay, QN1 series line relays has used with sixteen no of contacts. This is divided into four vertical columns (A.B.C.D). In this work column A has taken for the experiment. In this work, One QN1 relay is unused and other one is defected. Silver impregnated graphite(SIG) relay contacts have collected from these relays. Size of 7x5 mm. In this proposed work A, B and C columns have been used, twenty samples of used relays have been collected.

TABLE. 4.1 Image of samples

SAMPLE NUMBER	IMAGE OF THE SAMPLES	DISTORTED AREA OF EACH SAMPLE	SAMPLE NUMBER	IMAGE OF THE SAMPLES	DISTORTED AREA OF EACH SAMPLE
Original/ Reference Image		No distortion	Sample Image 6		
Sample Image 1			Sample Image 7		
Sample Image 2			Sample Image 8		
Sample Image 3			Sample Image 9		
Sample Image 4			Sample Image 10		
Sample Image 5					

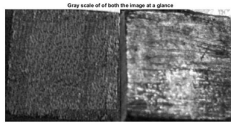


Fig 4.1.Gray scale Images of Reference and Distorted

TABLE. 4.2 Numbers of knocking per samples

Sample No	No of Knocking	Sample No	No of Knocking
1	2260	12	46880
2	3580	13	68655
3	15770	14	25899
4	22390	16	26782
5	18768	17	54689
6	32856	18	14866
7	15689	19	22832
8	22,780	20	46872
9	82545	21	45322
10	90622	22	68435
11	86344	23	72845

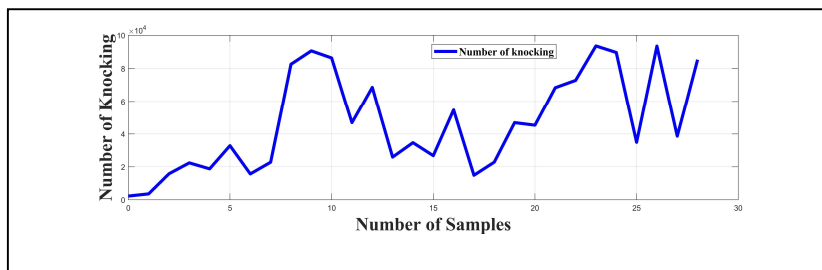


Fig 4.2 Different Knocking Samples

TABLE. 4.3 Quality Assessment of samples

Sample No	Qaulity Index	MSE	PSNR	SSIM
1	0.4194	23.5453	34.4118	0.1924
2	0.9932	36.8356	32.4681	0.1213
3	0.0725	33.3283	32.9027	0.0725
4	0.5390	49.0325	31.2260	0.1562
5	0.2051	11.1938	37.6410	0.1299
6	0.2179	9.6135	38.3020	0.0883
7	0.9555	99.3932	28.1572	0.2671
8	0.9154	38.3539	32.2927	0.1184
9	0.2706	7.4038	39.4362	0.1109
10	0.9763	26.3232	33.9274	0.1110
11	0.4537	15.5716	36.2075	0.0457
12	0.2239	7.2043	39.5549	0.1160
13	0.9456	60.4209	30.3189	0.1016
14	0.4082	15.0906	36.3437	0.1186
15	0.7997	28.2655	33.6182	0.0838
16	0.5701	20.7130	34.9684	0.0523
17	0.2400	3.0070	43.3495	0.3432
18	0.4686	6.0856	40.2878	0.4686
19	0.2051	11.1938	37.6410	0.1299
20	0.2179	9.6134	38.3021	0.0883

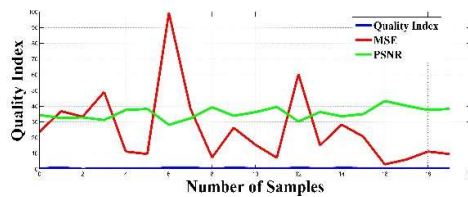


Fig. 4.3. Quality Index, MSE, PSNR vs distorted samples

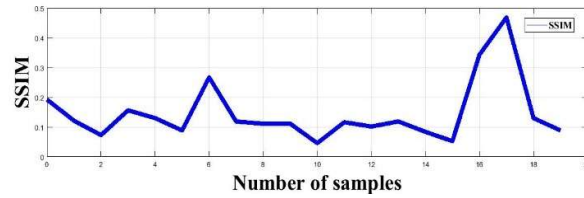


Fig 4.4.SSIM of distorted samples

Full reference image quality assessment viz. Peak signal to noise ratio(PSNR), Mean Square Error(MSE), Quality Assessment and Structural Similarity Index(SSIM) etc. have been applied on the sample images. Degradation level varies according to number of knocks per sample.

Here, MSE and PSNR values are very close and show the inverse trend. This just happens when the differences are small. It's still valid. (Sample 2 MSE 36.84 PSNR 32.47, Sample 3 MSE 33.33 PSNR 32.90, Sample 8 MSE 38.35 PSNR 32.29)

Although some samples show similar MSE and PSNR values (e.g., Samples 2, 3, 8), the expected inverse trend is preserved overall. Minor variations occur due to image-specific content differences, not computational error.

The values of PSNR and MSE listed in Table 4.3 were computed using the standard formula for PSNR with a peak signal value of 255, assuming 8-bit grayscale images. As expected, an inverse relationship between MSE and PSNR is observed: higher MSE corresponds to lower PSNR, and vice versa. For example, Sample 17 has the lowest MSE of 3.007 and the highest PSNR of 43.35 dB, indicating minimal distortion. Conversely, Sample 7 shows a high MSE of 99.39 and a low PSNR of 28.16 dB. While some samples (e.g., Samples 2 and 3) have similar MSE and PSNR values due to subtle distortions, the trend is generally consistent and validates the integrity of the image quality evaluation.

To ensure consistency between MSE and PSNR, the standard PSNR formula has been used:

$$PSNR=10 \cdot \log_{10} L (Max^2)/MSE)$$

Where:

- MAX = 255 (for 8-bit grayscale images)
- MSE is the Mean Squared Error between the distorted and original image

$$MSE = \frac{1}{M \times N} \sum_{i=1}^M \sum_{j=1}^N (I_{ref(ij)} - I_{dis(ij)})^2$$

This relationship is inverse: as MSE increases, PSNR decreases, and vice versa. For example:

- Sample 17 has an MSE of 3.007, corresponding to a high PSNR of 43.35 dB.
- Sample 7 has an MSE of 99.39, corresponding to a low PSNR of 28.16 dB.

Although some PSNR values appear close for slightly varying MSE values (e.g., Samples 2, 3, and 8), these variations are mathematically consistent due to the logarithmic scale of PSNR.

Therefore, the SSIM values listed in Table 4.3 were calculated using the same reference image as above. Each distorted sample was compared with the original (reference) image using the standard SSIM formula, which considers luminance, contrast, and structural information. This methodological detail has now been added for clarity. Here, distortions were induced primarily due to mechanical knocking and carbon-to-carbon contact degradation in the relay images. This has been clarified in the methodology section (Section 4.2) and explicitly mentioned alongside Table 4.3 to strengthen the interpretation of SSIM and Quality Index results.

Discussion

The signaling relays studied have a life span of 1,000,000 operations, with degradation levels varying based on the number of knockings per sample, where affected areas often exhibit corrosion due to oxygen exposure and rapid deformation from mechanical impacts. The distortions analyzed in this study are genuine, arising from real-world degradation of carbon-to-carbon relay contacts, caused primarily by mechanical knocking—resulting in physical shifts, surface damage, and blurring—carbon contact wear and arcing—leading to structural erosion, pits, and carbon

buildup—and minor environmental and imaging noise from capture conditions. These natural distortions provide a practical context for evaluating quality metrics such as PSNR, SSIM, and a custom Quality Index, ensuring the relevance of findings beyond synthetic noise models. Given that the data were collected from used relay contacts in the Kolkata Metro Railway system, variability in PSNR and MSE values across different samples is expected due to differences in operating environments, time frames, manufacturing processes, and contact histories. Visual image quality assessments help identify the formation and nature of these degradations, as shown in Fig. 4.2 through the number of knockings. This study employs an efficient defect detection approach to analyze the progressive failure patterns of carbon-to-carbon relay surfaces caused by repeated impacts, while also highlighting chemical and environmental influences on contact surfaces. PSNR values were calculated using the standard formula based on MSE, assuming 8-bit grayscale images ($MAX_I = 255$), and as reflected in Table 4.3, generally exhibit an inverse relationship with MSE, though some variations occur due to differences in image content or localized distortions that influence MSE without significantly altering perceptual quality. The Peak Signal-to-Noise Ratio (PSNR) and Mean Square Error (MSE) were used to quantify pixel-level differences, while the Structural Similarity Index (SSIM) measured structural variations. Although defective regions were accurately identified, they were not classified in this study; detailed defect classification remains a direction for future work.

5. Surface Defect Detection of Relay contact using Image Processing

Introduction

Railway signalling systems depend greatly on relays, which have a vital role to play. The classification of these relays can be determined by their mounting types, power sources, contacts, and applications. This includes shelf type, plug-in-type, ac-dc type, metal-to-metal, metal-carbon, line relay, track-relay, and more. Relay failures, particularly metal-to-carbon relays, can result in major financial losses for railway organizations due to factors like adverse weather conditions, material wear, overuse, and inadequate contact logic. Therefore, it is imperative to thoroughly study the behaviour and failure patterns of relays to enhance their efficiency.

Electromechanical relay failures can be attributed to external factors like power disruptions, fuse issues, and internal factors like manufacturing defects and poor component quality. Other causes such as high contact resistance, coil damage, foreign matter, and more have been identified through modern maintenance practices to address potential failures. Any flaws in the relay manufacturing process can result in immediate malfunctions upon installation.

One key reason for the poor reliability of metal-to-carbon relays is the high contact resistance in silver impregnated graphite (SIG) contacts. The presence of oxide and sulphide layers on sig contacts accentuates this issue, highlighting the importance of surface topography inspections for failed relays. Image processing techniques are crucial in detecting defects in relays, especially through feature extraction and identifying unique characteristics in images. But, there are several other causes like high contact resistance, coil breakage, coil burning, foreign matter interference, sulphation of springs/connectors, breakage of armature, relay cover and slipping of retaining clips [A. Wileman-2015, H. Kagra 2013] which are reported for analysing performance in modern maintenance technologies and practices, to find potential risk of unexpected failures in relay. Any deficiencies in the relay manufacturing process result in instant failure when installed in the circuit. All these kinds of failures suggest the need of reliability analysis of the product outcome [B. Leitner -2017] in

continuation to this, high contact resistance, developed in the silver impregnated graphite (sig) contact [H. Kagra- 2013] seems one of the reasons of poor reliability of metal to carbon relay. a thin film layer of oxide and sulphide may also be found on the silver impregnated graphite (SIG) contact. A detail of surface topography inspection based on image processing of failed relays of the sig contact gradually becomes an important research area of interest. Feature extraction and identification of local features that can be distinguished from other object of interest of the image is one of the main objectives of defect detection through image processing technique [H.Mohammad-2014]

feature extraction through image segmentation is also consider as one the basic approaches of digital image processing [x.e.pantazi-2019],in case of image segmentation technique, image is subdivided into different subset, which provides attributes of different subset [G.T Shrivakshan-2012]. By this process, defect in images may be detected. Thus, the defect detection as mentioned can be treated as beneficial method in real life situation [W. X. Kang-2009]. Micro research may also be adopted through image segmentation [Nida M. Zaitoun-2015] which subdivides an image into background region and object according to its intensity value, texture, and colour. Image segmentation methods are categorized on the basis of similarity and discontinuity of image properties. On the basis of similarity, region-based segmentation can further categorized as edge-based, and thresholding-based segmentation. Region based segmentation cover more pixels information than edge based. Thresholding methods play a significant role in this process by distinguishing between foreground and background elements in images, ultimately enhancing defect detection capabilities. The use of advanced thresholding techniques like otsu thresholding has proven to be an optimal solution for separating objects of interest from the image background.

In railway applications, signalling relays endure harsh environmental conditions that can damage their surfaces. To assess the degree of failure in defective relay surfaces, Otsu thresholding and advanced multi-level thresholding methods are employed. These techniques aid in recognizing and addressing surface defects, ensuring the reliability of railway signalling systems.

This segmentation produces more accurate results for a noisy image than edge based segmentation [n.sharma-2012]. Threshold-based image segmentation overcome the limitation of the previous segmentation method. Therefore, thresholding method is one of the effective methods. Moreover, it is treated as simple as it execute in terms of local, global and adaptive image segmentation techniques. Thresholding method is discriminating the foreground and background of an image by selecting an adequate threshold value. All these steps can finally be represented by histogram, which is developed on the basis of intensity of images. Histogram thresholding one of the primitive thresholding method, but there are some limitations. in the ideal case when histogram is bimodal, but practically image is more complex when intensity of the histogram shows multi-modal, it is difficult to identify the adequate threshold. to overcome otsu thresholding technique [N. Otsu-1979, Wang Hongzhi-2008] may be adopted, which can select optimal threshold value automatically, for separating the object of interest from the background of gray-level image.

Signalling relay has adversely used in railway, due to environmental stress conditions surface of the relay may got damaged. To identify the degree of failure of defected relay surface, otsu thresholding and advanced multi-level thresholding techniques have been used here.

5.1 Material &Method

Signalling relay is a crucial component of the railway signalling system. Within this system, various electro-mechanical relays have been utilized as switches [Andrew J Wileman-2014]. Both surface railway and metro railway systems have employed relays with metal-to-carbon contacts and metal-to-metal contacts. The metal-to-carbon contact relays are operated based on predetermined signalling logic to control different signalling elements such as track circuits, points, and signals. Reliability of silver (metal) to silver Impregnated Graphite (SIG) contact relay is poor [H. Kagra-2013]. The prime rationale of indigent reliability is high contact resistance developed on the SIG contact. As a result, recognizing the degree of failure of SIG contacts is imperative in establishing a failure model [Xuerong Y et al.-2012].Otsu thresholding is an automated technique for selecting optimal thresholds to differentiate between the background and foreground of a grey-level image [Yoges-2017]. The Otsu-revised

method determines the threshold value by maximizing the weighted sum in order to effectively separate the grey level classes. It is particularly effective for images with bimodal and multimodal histogram distributions. It provides satisfactory outcome for bimodal and multimodal histogram distribution [Zouhir Wakaf-2018] The proposed work a taxonomic relationship of gray level histogram of an image, depending upon the continuity property of the image which classifies inter-class variance cluster and intra-class variance cluster. They said classification is required to get the optimum threshold of images. The threshold value of images may be extended to multi-thresholding which has proposed by [Du-Ming et al.-1992] have developed histogram-based hill-clustering approach for multi-level thresholding. Computation time is effectively reduce. In another work [Satapathy Suresh 2016] proposed multi-level thresholding Otsu on standard test images. This algorithm was compared with other standard algorithms with respect to root mean square error, peak signal-to-noise ratio, CPU iteration time, and structural similarity index. In this paper, we have applied two types of thresholding method in the SIG contact of defective images-Otsu thresholding and multilevel Otsu thresholding. This proposed work involves the collection of defective relays and the analysis of SIG contact images through image processing techniques. The methodology includes image acquisition, pre-processing, image segmentation, and defect detection. High-quality images were obtained using the Axio imager microscope as depicted in Figure 5.1.

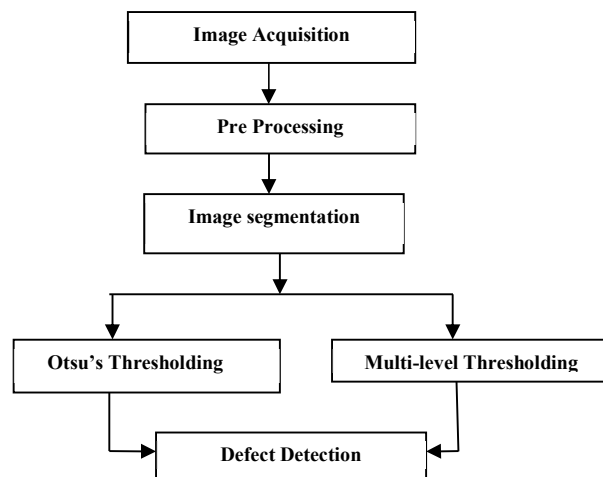


Fig.5.1: Process Flow Diagram of Proposed Method

5.2. Image Acquisition & Pre-Processing

Surface images of defective SIG contact has been captured using Axio Imager microscope under controlled lighting resolution and keeping a constant distance between the object and camera of microscope. Eventually to diminish the computational loads, images are resized to standard dimensions. Here, figure 5.2(a) has shown Plug-in-type signalling relay and figure 5.2(b) has shown the surface image

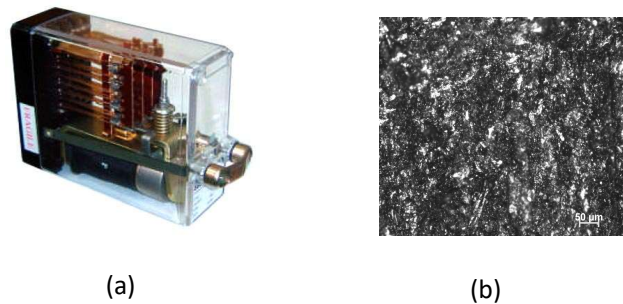


Fig. 5.2: (a) Plug-in-type Relay, and (b) Surface image of SIG Relay Contact before use

5.3 Image Segmentation

Upon completion of the initial pre-processing stage, the task of image segmentation was undertaken. Image segmentation serves to separate foreground elements from the background, with various methods available based on the specific context. In this particular study, the focus lies on identifying and segmenting the defective regions within the image, with the foreground representing these defective areas and the background encompassing the non-defective regions. It is imperative to carefully select the optimal grey level threshold intensity for segmentation purposes. Pixels above this designated threshold are classified as defective, while the remaining pixels are categorized as non-defective. This research employs two prominent segmentation techniques, namely Otsu's thresholding and Multi-level thresholding. Otsu's method, known for its simplicity and effectiveness, facilitates automatic region-based image segmentation by establishing a global threshold. Although this approach relies on grey level histograms, it only provides one-dimensional grey level information. Otsu's methodology involves determining the grey-level threshold for each pixel in both

classes and integrating spatial correlation information from the neighborhood. By minimizing the similarity pattern of background and foreground class variances while maximizing the dissimilarity between the two variances, Otsu's method achieves segmentation accuracy. Non-uniform images often exhibit multi-modal histogram distributions, necessitating the utilization of multi-level thresholding to partition the image into distinct regions of interest. In cases where images feature multiple thresholds due to their complexity or color variations, multi-level thresholding proves more effective than traditional bi-level thresholding methods. This approach strategically leverages various threshold values to effectively extract different regions of interest within the image.

5.4 Otsu Method

In this section, we have applied Otsu's method on the gray-scale image is characterized in M gray levels ($0, 1, \dots, M-1$) having pixel with gray-levels from the set of integer $\{0, 1, 2, \dots, 255\}$. In this approach, the image is partitioned by threshold at t into two classes, A_0 and A_1 . Class A_0 consist of gray region in the range of 0 to t and class A_1 consists of gray regions from $t+1$ to $M-1$. The gray level distribution probability ($\omega_1(t)$ and $\omega_2(t)$) for A_0 and A_1 , can be expressed as follows:

$$A_0 = \frac{p_0}{\omega_1(t)} \dots \frac{p_t}{\omega_2(t)}, \text{ and } A_1 = \frac{p_{t+1}}{\omega_1(t)} \dots \frac{p_{M-1}}{\omega_2(t)} \quad (5.1)$$

Where, $\omega_1(t) = \sum_{i=0}^t p_i$ and $\omega_2(t) = \sum_{i=t+1}^{M-1} p_i$. ω_1 and ω_2 are the probabilities of foreground and background. μ_1 and μ_2 are the mean gray level of foreground and background of class A_0 and A_1 .

$$\mu_1 = \sum_{i=0}^t \frac{ip_i}{\omega_1(t)}, \text{ and } \mu_2 = \sum_{i=t+1}^{M-1} \frac{ip_i}{\omega_2(t)} \quad (5.2)$$

Total mean intensity (μ_T) of the entire image can be characterized as:

$$\mu_T = \omega_1\mu_1 + \omega_2\mu_2 \quad \dots (5.3)$$

$$\omega_1 + \omega_2 = 1 \quad \dots (5.4)$$

The class variances are

$$\sigma_1^2 = \sum_i^l (i - \mu_1)^2 p_i / \omega_1 \quad \dots\dots(5.5)$$

$$\sigma_2^2 = \sum_i^l (i - \mu_2)^2 p_i / \omega_2 \quad \dots\dots(5.6)$$

The within-class variance is

$$\sigma_w^2 = \sum_{i=1}^l \omega_i \sigma_i^2 \quad \dots\dots(5.7)$$

The between-class variance $\sigma_B^2(x)$ of the two classes A_0 and A_1 is given by

$$\sigma_B^2(x) = \omega_1 (\mu_1 - \mu_T)^2 + \omega_2 (\mu_2 - \mu_T)^2 \quad \dots\dots(5.8)$$

The total variance of gray levels is

$$\sigma_T^2 = \sigma_w^2 + \sigma_B^2 \quad \dots\dots(5.9)$$

In the formula (5.9), μ_T is the mean value of the image and μ_1 and μ_2 are the mean value of the object and μ_2 the background region respectively. When variance $\sigma_B^2(x)$ between two classes is taken maximum value, X is the optimal threshold solution of the Otsu algorithm, which is maximizing the inter-class variance also, equivalent to minimizing the intra-class variance. The total variance is the sum of within-class variance and between-class variance.

$$X = \arg \max_{0 \leq t \leq M-1} \{\sigma_B^2(x)\} = \arg \max_{0 \leq t \leq M-1} \{\sigma_w^2(x)\} \quad (5.10)$$

Defective surface detected through Otsu method. Percentage defect has been calculated.

5.5 Multi-level Thresholding Method

In multi-level thresholding image is segmented several region of interest with various threshold values. In case of multilevel thresholding, assuming the image gray level

has $L-1$ thresholds and image pixels are divided into different intervals by threshold levels t_1, t_2, \dots, t_x ($0 \leq t_1 \leq t_2 \leq \dots \leq t_x \leq L-1$), that splitting the image into x classes. A_0 with gray levels in the range 0 to t , A_1 with enclosed levels from t_{1+1} to $t_2-1 \dots$ and C_x includes levels from t_x to $L-1$.

$$A_0 = \frac{P_0}{\omega_1(t)} \dots \frac{P_t}{\omega_2}, \text{ and } A_1 = \frac{P_{(t+1)}}{\omega_1(t)} \dots \frac{P_{(t_2-1)}}{\omega_2} \quad (5.11)$$

$$A_x = \frac{P_{(t_x-1)+1}}{\omega_1(t_n)} \dots \frac{P_{255}}{\omega_2(t_n)} \quad (5.12)$$

The optimal thresholds $t_1, t_2, \dots, t_{(x-1)}$ are chosen by maximizing the between class variance σ follows:

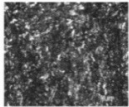

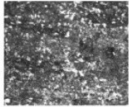



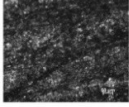
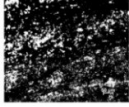
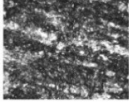
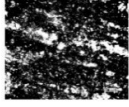


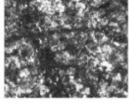
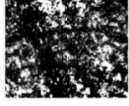
$$\sigma_B^2(x_1, x_2, \dots, x) = \sum_{i=0}^{x-1} \sum_{j=i+1}^x \omega_1 \omega_2 (\mu_1 - \mu_2)^2 \quad (5.13)$$

Therefore,

$$\begin{aligned} \{t_1, t_2, \dots, t_{L-1}\} &= \arg \left\{ \max \left\{ \sigma_B^2(t_1, t_2, \dots, t_{L-1}) \right\} \right\} \\ &= \arg \left\{ \min_{0 \leq t \leq M-1} \left\{ \sigma_B^2(t_1, t_2, \dots, t_{L-1}) \right\} \right\} \end{aligned} \quad (5.14)$$

In this work, Otsu thresholding and Multi-level thresholding has applied on failed SIG contact of metal to carbon relay. Surface of SIG contact is not uniform, has tried to find the degree of failure. Single level threshold with global segmentation is not accurate most of the time. The multilevel thresholding has applied to modify the segmentation technique. Five thresholds level has selected on the basis of defective region, these five level thresholds have given optimum result. Each level has given a percentage of defects based on the defected pixel count. Here, total percentage of defects has been calculated for each of the test images. In this algorithm every

threshold level have different contribution to the final defect percentage. Percentage defect has been calculated as per segmented defective region divide by total no of pixel and Average damage has calculated as

Sample Number	Original Picture of Samples	Otsu Segmented
1		
2		
3		
4		
5		
6		
7		

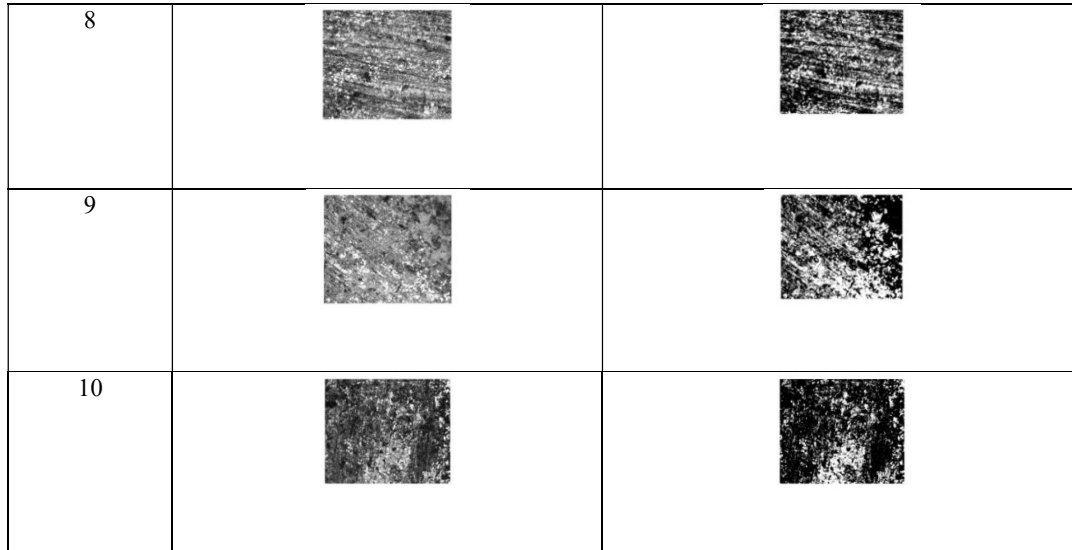


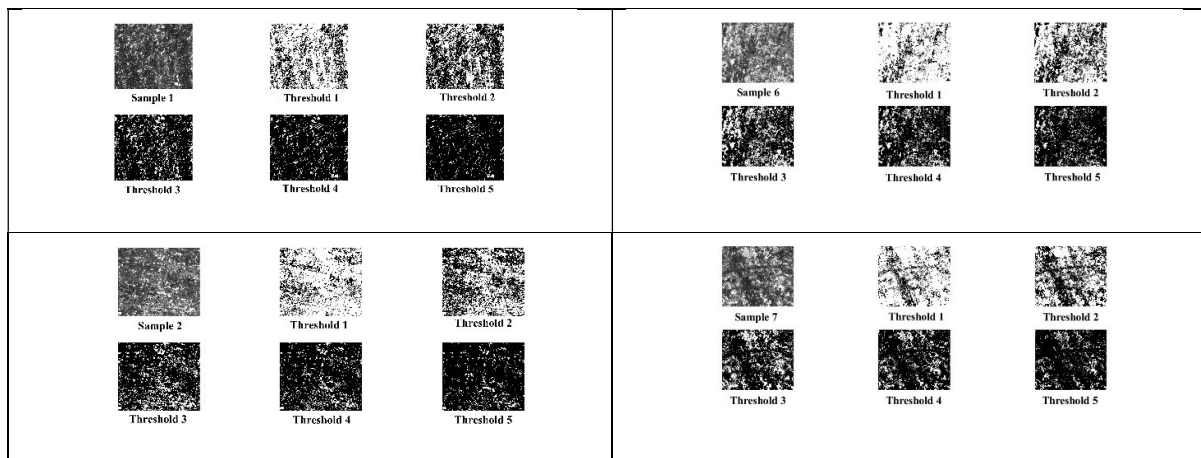
Fig 5.3: Sample1 to Sample10 Defective SIG microscopic image and segmented images by Otsu

$$X = (a_1 \times 6 + a_2 \times 2 + a_3 \times 1 + a_4 \times .5 + a_5 \times .5) \div 10 \quad (5.15)$$

Here, $a_1 = per_dam1, a_2 = per_dam2, a_3 = per_dam3, a_4 = per_dam4$ and

$a_5 = per_dam5$ are different threshold values. These threshold values have given different contribution to the average damage X.

In Fig5.3 ten defective relay contact surface picture samples have taken using Axio Imager Microscope and corresponding Otsu segmented samples which have shown defective region.



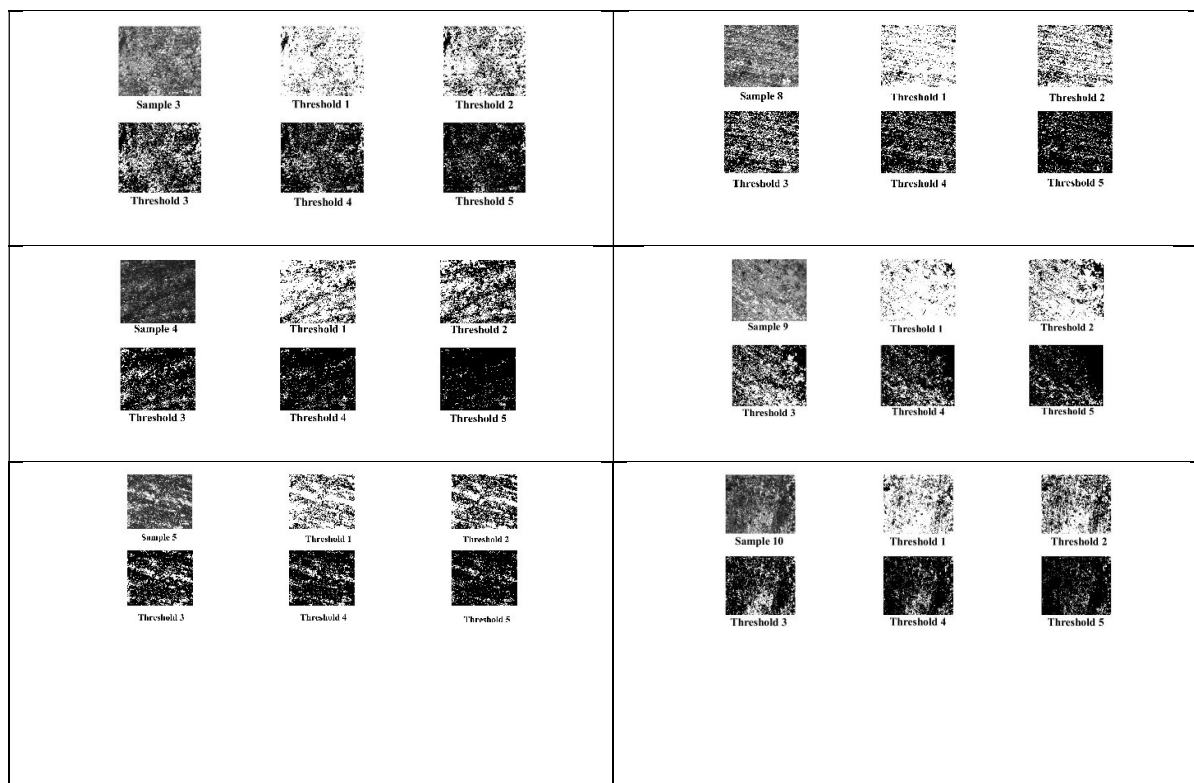


Fig 5.4: Sample1 to Sample10 image with multilevel segmentation effect: original image with five Thresholds

Table 5.1: Percentage damage with different Thresholding methods

Sample Images	Otsu's Thresholding	Multilevel Thresholding	Sample Images	Otsu's Thresholding	Multilevel Thresholding
Sample 1	16.9669	51.9662	Sample 16	9.8501	61.6002
Sample 2	22.0409	59.7783	Sample 17	9.1872	56.8513
Sample 3	36.8894	70.6986	Sample 18	14.7352	72.1319
Sample 4	18.3255	55.6661	Sample 19	15.9005	80.6732
Sample 5	23.9675	55.6273	Sample 20	11.3737	71.5228
Sample 6	32.7037	66.0383	Sample 21	16.9492	76.0727
Sample 7	27.2090	60.3522	Sample 22	17.9370	78.3635
Sample 8	39.0421	71.4680	Sample 23	11.4217	73.7459
Sample 9	41.0422	75.4169	Sample 24	12.8881	73.3874
Sample 10	23.6944	60.8614	Sample 25	13.4098	74.0591
Sample 11	27.9500	60.3221	Sample 26	10.8538	73.2529

Sample 12	29.6229	67.3134	Sample 27	18.6466	75.4857
Sample 13	41.6984	70.7544	Sample 28	16.6314	69.0030
Sample 14	7.6315	52.5440	Sample 29	20.0899	75.2536
Sample 15	6.0633	50.4045	Sample 30	13.2892	74.5707

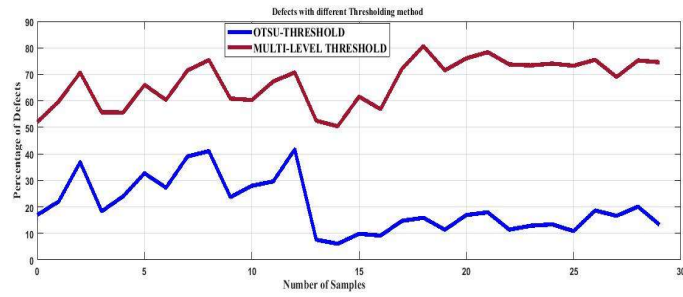


Fig 5.5: Defect with Otsu Thresholding and Multi-level Thresholding Method

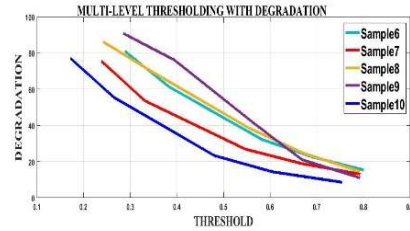
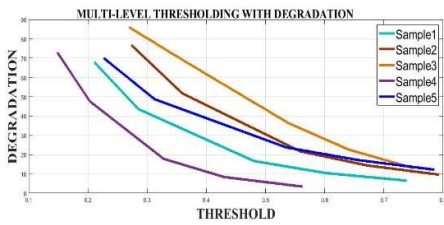


Fig 5.6: Degradation with Multilevel Thresholding from sample 1 to sample 5 Fig 5.7: Degradation with Multilevel Thresholding from sample 6 to sample 10

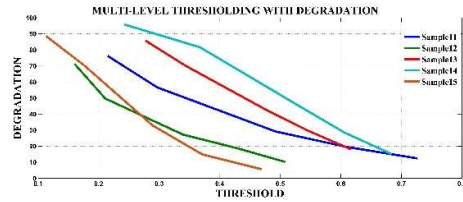
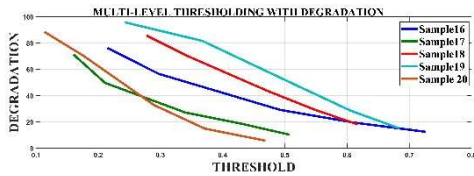


Fig 5.8: Degradation with Multilevel Thresholding from sample 11 to sample 15 Fig 5.9: Degradation with Multilevel Thresholding from sample 16 to sample 20

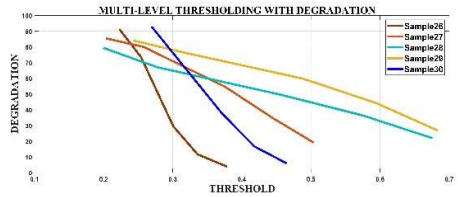
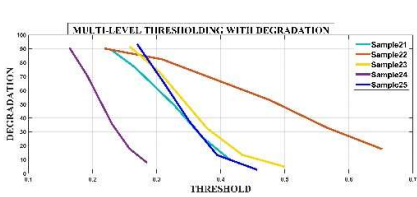


Fig 5.10 : Degradation with Multilevel Thresholding from sample 21 to sample 25 Fig 5.11: Degradation with Multilevel Thresholding from sample 26 to sample 30

Discussion

In this proposed work, defective signalling relay contacts image has been taken. Image segmentation has done through thresholding algorithm, is an effective technique to segregate objects from the back ground. Spatial content of an image has been analyzed through segmentation technique. Here, we have taken thirty defective samples. Otsu thresholding algorithm and multi level thresholding algorithm have applied on these samples and segmentation have been done by using equations (9) and (11) and equations (15),(16) and (17). Proposed approach newly adopted, for the purpose of failure degradation analysis in the railway signalling relay contact. In this proposed work firstly we have applied Otsu’s algorithm, here equation (3) for mean level of gray level of foreground and background class and equation (9) maximized the inter class variance but when the number of classes increases, normal Otsu’s method consumed more computation time. Therefore further modification has been done through Multi-level Otsu’s algorithm. Multi-level thresholding can solve the problem of proper threshold selection when the number of peak increases in the gray level images. Multi-level thresholding is sub divides the region of gray level image at different threshold value. In this present work multi-level thresholding has been applied to the defective images of SIG contact. Five dynamic optimal thresholds have been calculated at different region of defective image. Figure (5.3),(5.5)depicts the five defective clustering region. Percentage defect has calculated using equation (16) and (19). Table 1list the results of comparative study between percentage defects of Otsu and multi-level thresholding method. In this work, Fig 5.3.depicts gray image of ten defective samples and segmented through Otsu thresholding technique. Figure (5.7),(5.8),(5.6) shows the segmented images through multi-level thresholding. We

have compared the percentage of defects for Otsu's and Multi-level thresholding method. Fig 5.5 shows the comparative study between Otsu thresholding and Multi-level thresholding algorithm of the percentage defects of thirty samples. From Fig 5.6 it has been revealed that the multi-level thresholding has performed better in finding defecting region than Otsu's thresholding. Damage has been calculated according to the threshold region. Multi-level thresholding has shown better result than Otsu thresholding as can be seen in (Fig-5.7). Here we have calculated the degradation pattern of thirty samples with respect to every threshold value of multi-level thresholding method. In multi-level thresholding every threshold level have different contribution to the final defect percentage. Lower threshold levels have given better result than higher threshold levels, because lower threshold values contribute more in defects detection. Plots in Fig 5.8 to Fig 5.11 shows the degradation pattern at various threshold level for thirty samples. Degradation pattern has optimized between thresholds 0.3 to 0.4 of these thirty samples. For all thirty samples degradation level and percentage of degradation has been calculated. While the chapter underscores the importance of image processing for assessing relay degradation, it does not sufficiently explore the inherent limitations and challenges associated with deploying these techniques in operational railway environments. In practice, computational constraints such as the high processing power and storage required for handling large volumes of high-resolution images can hinder real-time monitoring and large-scale implementation. Similarly, hardware requirements—including advanced imaging systems, controlled illumination setups, and vibration-resistant equipment—are often difficult to maintain in field conditions where space, cost, and accessibility are limiting factors. Beyond these technical considerations, environmental challenges such as dust, humidity, fluctuating temperatures, and mechanical vibrations can significantly compromise image quality, introducing noise and inconsistencies that affect the reliability of the algorithms. A more balanced perspective would therefore acknowledge these barriers and suggest strategies to overcome them, ensuring that the transition from laboratory analysis to real-world railway applications is both practical and sustainable. To overcome the limitations of applying image processing

methods in real-world railway environments, several avenues for future work can be explored.

Conclusion

The process of defect identification on the SIG contact surface was carried out using Otsu thresholding and Multi-level thresholding in this paper. The defect percentage has been computed for both thresholding methods. The analysis of failure images indicates that Multi-level thresholding is more effective than Otsu thresholding in identifying defects. Lower level threshold values have demonstrated better results in the degradation pattern of multi-level thresholding.

6. Signaling Relay Contact Surface Failure Analysis using analytical nondestructive testing

Introduction

Electronic/electrical device malfunctions can occur due to relay failures [Zhou Zhijie 2017]. The dependability of the overall electrical system is greatly impacted by the reliability of the relay. Contact issues account for approximately 70% of relay failures [Yu GF et al. 2021]. We use railway signaling relays for high-safety purposes. Electromagnetic relays operate in different conditions, each with distinct variables such as temperature, storage, dust, transport, humidity, and vibration. Over time, this can cause ion deposition on the contact surface, resulting in aging. Fluctuating temperatures affect relay parameters and may cause increased contact resistance. In addition to that, humidity is one of the factors of surface oxidization that leads to contact corrosion, another contaminant present on the surface causes sulphation, carbide formation, and contact resistance significantly become high and the relay got failed [Kagra H. 2013]. Electromagnetic relays are a vital component of railway signalling systems. These relays in railway signaling are grouped by various types such as mounting on plug board, AC-DC supply, contact types (metal or carbon), line and track relays. Material failure and deviation from intended logic can occur due to factors such as atmosphere, overuse, and improper contact. Railway transportation organizations may face significant economic loss due to the failure of metal-to-carbon relays. In this context, it is of utmost need to study and analyze the operating behavior and failure pattern of the relay to maximize its reliability [SUN Yong-kui et al. 2018].

The reasons, related to this electromechanical relay failure, can be categorized as follows [Mocki J., Vlacic L. et al.2013]:

- Different external reasons such as discontinuous power supply, defective wearing or blowing-off of fuses, and
- Various internal reasons such as manufacturing defects, poor component quality and malfunctioning of relay components.

The above-mentioned causes are not the only ones: high contact resistance, coil breakage, coil burning, foreign matter interference, sulphation of springs/connectors,

breakage of an armature, relay cover, and slipping of retaining clips [Wileman A.J. et al.2014] [Kagra H., et al.2013] are also causes. As a way to identify potential risks of unexpected relay failures in modern maintenance technologies and practices, performance is analysed in modern maintenance technologies and practices. Any deficiencies in the relay manufacturing process result in instant failure when installed in the circuit. All these kinds of failures suggest the need for a reliability analysis of the product outcome [Leitner B. (2017)]. Additionally, the high contact resistance of silver-impregnated graphite (SIG) contacts seems one of the reasons for poor reliability of metal-to-carbon relays [Kagra H. (2013)]. A thin film layer of oxide and sulphide may also be found on the silver-impregnated graphite (SIG) contact. An important research area of interest is the detailed analysis of surface topography of failed relays of the SIG contact, based on SEM analysis. In another application, the relay within military weapon systems is subject to thorough scrutiny and evaluation examination [Wan B et al.2016]. It is believed that decomposition of these systems causes a gradual accumulation of polluting agents on contact surfaces, eventually resulting in relay failures[Wang C et al. 2012] Eventually, relays fail due to failures associated with contact adhesion because the coated contact material erodes, increasing its resistance. Additionally, contact adhesion affects the lifespan of electromechanical relays [Gao C et.al. 2014] [Wang ZB et al. 2016] In another research work, in order to evaluate relay reliability, testing involves applying various loads using capacitors, subjecting them to varying current levels across numerous cycles to assess relay reliability [Zhang C et. al.2019a] [Zhang X et. al. 2019b] [Zhang X et al. 2019c] Therefore, to better understand the structural changes in movable and fixed contacts, a degradation model was used to simulate the relay in this research [Gonzalez D et. al. 2016][Gonzalez D et al. 2018]. The experiment was conducted with 1000 and 6000 cycles. Demonstrated the involvement of polymer decomposition plays a role in arc erosion. As a result of this arc reaction, oxide contaminations were formed, with phosphorous being detected on the contact surface [Behrens V et.al. 2019][Nachiketa R et. al. 2015].Furthermore, contact surface erosion was observed during stress and the formation molten arc. To combat corrosion and prolong contact lifespan, a thin coating with solid or semi-solid lubricants of carbon allotropes can be

applied. Additionally, the use of Composite and layered materials can help mitigate damage to the contact interface [Nasir S et.al. 2018][Robert F 2020]. The examination involved graphene-coated contacts with various coating depths, comparing their effects to those of different thin-layer coatings using finite element analysis. To prevent relay failures, careful selection of contact materials is crucial, aiming for elements that enhance lifespan and withstand adverse atmospheric conditions.

Therefore, evaluating contact surfaces is essential. FESEM is a valuable tool for inspecting cell and material surfaces, particularly for detecting mechanical deformation on relay contact surfaces [Cao G et al..2019][Li W et al. 2021]EDS identifies chemical contaminants distribution on contact interfaces, with energy distribution revealing the mass concentration of surface atoms [Biyik S 2016]. In another context surface roughness parameters analysis using a profilometer effective approach. Various techniques encompass visual evaluation, SEM, profilometer, laser, specular reflectance, and AFM [Campbell SD 1989][Yuzugullu B.et al. 2009] A comparative approach has been taken between SEM and profilometer. The objective was to assess the efficacy and practical applicability of indirect method for characterizing surface topography. SEM images visually describe subjective information about surface topology but profilometry showed better result for hight dispersion. Profilometry proves a valuable and efficient tool from other analyses [Pavlovic Z et al.2012].

In this proposed work, a novel methodology has been applied to an electromechanical railway signaling relay with metal-to-carbon contact. As discussed, the resistance of the contact surface became high after thousands of switching operations. The operating contact resistance of the QN1 series relay is less than two hundred milliohms. After thousands of operations, contact resistance becomes greater than two hundred mili-ohms, and safety issues arise for train movement. Previous research focused on the contact resistance of the relay contact, which had increased but whose reliability was poor. However, surface failure analysis has not been done. Here, a detailed failure analysis has been done in this proposed work. Reduction reactions and oxidation occurred from the surface of the metal to the carbon surface. A similar kind of work has been done using normal electrical relays and aerospace relays, but

the proposed methodology has been applied to the QN1 series relay with sixteen numbers of different types of contacts. A metal-to-carbon contact relay has A graphite contact is a movable contact, and a silver contact is a fixed contact. Graphite contact is a softer material than silver contact; for that reason, mechanical damage occurs on the surface of the contact surface. The selection of FESEM, SEM, EDS, and 3D profilometry for the failure analysis of signaling relay contacts has deliberated, based on the unique advantages each technique offers in understanding the mechanical and chemical degradation mechanisms of metal-to-carbon interfaces. Surface roughness has been analyzed using 3D profilometry. This non-contact, high-resolution technique is particularly suitable for quantifying surface roughness and topography without damaging delicate contact surfaces. It enables precise measurement of parameters such as Ra, Rq, Rp, Rv, and Rt, which are essential to assess the extent of mechanical wear due to knocking cycles. Alternative techniques like stylus profilometry, while effective, may introduce surface artifacts or lack the 3D visualization required for detailed contact analysis. The roughness of the surface of the relay maximizes after certain mechanical damages. Moveable graphite contact roughness parameters have been analyzed under varying circumstances. As the contact resistance rose, the relay failed. A thin film layer of oxide and sulfur dioxide may also be found on the silver-impregnated graphite (SIG) contact previously mentioned. A detailed surface topography inspection based on SEM analysis of failed relays of the SIG contact and silver contacts are the research objectives of the proposed work. Therefore, the graphite contact surface is examined for preceding and succeeding failures to find the reasons for relay contact failure. FESEM and SEM analyses have been done on the graphite contact surfaces. EDS was also performed on the silver contact and graphite contact pre-failure and post-failure to find the chemical distribution of elements on the surface. From January 2016 to April 2016, South-Eastern Railway faced multiple relay failures, and their corresponding factors of relay failure data are shown in Table 6.1

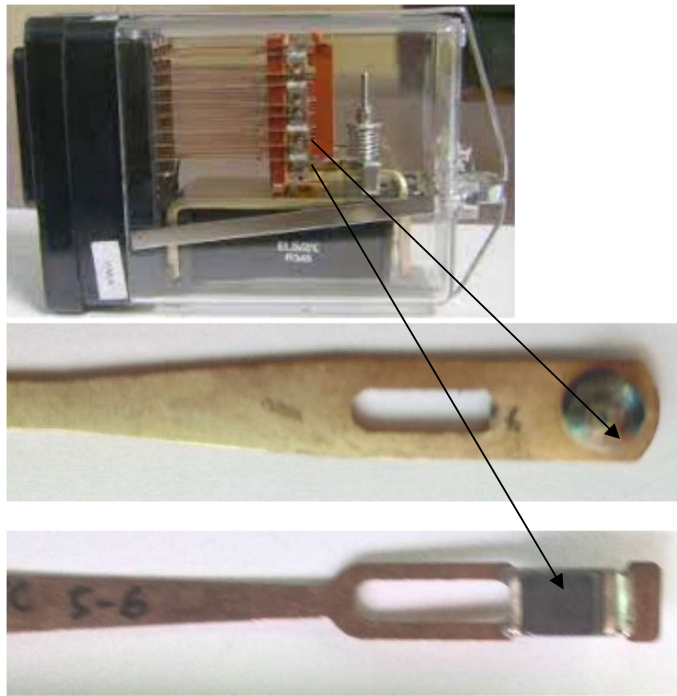


Fig 6.1. QN1 Series Signalling Relay and Relay contacts dismantled SIG Contact and Silver Contact

6.1 QN1 Series Relay

A signalling relay with metal to carbon contact relay is used here. Metal-to-carbon contact relays are used in various signalling circuits. These relays have silver and silver-impregnated graphite (carbon). The make-and-break sequences mimic various choices within signaling circuits. The signalling relay consists of contacts, coil, and spring. Here we have used a QN1 series plug-in type relay in this work. QN1 series signalling relay and its dismantled SIG contact and silver contact are shown in Figure 6.1. It has 8 front contacts and 8 back contacts. The Operating voltage is 24V relays. Pickup time is 150 ms and Discharge time 20ms. Operating current 60mA, Maximum pick-up voltage 19.2 V and DA volts 3.6V.

Factors like atmosphere, overuse, and improper contact can lead to material failure and deviation from intended logic. The failure of metal-to-carbon relays may cause significant economic loss for railway transportation organization. In this context, it is of utmost importance to study and analyse the operating behaviour and failure pattern of relay to maximize its efficiency. Before the failure, contact surface

was smooth and free from irregularities, but after the failure detailed analysis was done for both contacts.

Table 6.1 Factors for Relay failure

Cause of Relay failure	Percentage of failure
High contact Resistance	85%
Coil defect	5%
Holding clip broken	5%
others	5%

6.2 Surface Topography Analysis

In this research, a plug-in type signalling relay, with metal to-carbon contact relay has been used for surface anatomy analysis. Roughness parameters have been analysed using 3D profilometry. The graphite contact surface roughness parameter has been analysed before knocking condition and after ten thousand knocking conditions in 2D and 3D dimensions.

Therefore, Arithmetic Average Roughness (Ra), R.M.S Average Roughness (Rq), Max Profile Peak hight (Rp), Max. Profile Depth (Rv), Sum of the max. peak hight and max. profile depth (Rt) has been calculated using below formulas.

$$Ra = 1/l \int_0^l |y(x)| dx \quad (1)$$

$$Rq = \sqrt{\frac{1}{l} \int_0^l \{y(x)\}^2 dx} \quad (2)$$

$$Rp = \max(y_{pi}) \quad (3)$$

$$Rt = \max(y_{pi}) + \max(y_{vi}) \quad (4)$$

$$Rv = \max(y_{vi}) \quad (5)$$

Hence, to more detail anatomy has analysed through FESEM and SEM, provide high-resolution magnifications. Graphite contact has been examined preceding and succeeding failure in various magnified images. EDS has investigated fixed silver and graphite contact preceding and succeeding failure conditions. EDS was performed to find the chemical content of the elements present on the contact interface.

6.3 Results and Discussion

The performance of the contact interface was observed at different conditions of relay contact failure. Section 6.3.1 deliberates the performance of the SIG contact pre-failure

and the post-failure conditions. In the study of failures, movable SIG contact has been considered because SIG Contact material is softer than fixed silver contact. SIG and silver contacts of the relay preceding and ensuing failure states are examined separately and outcomes are explored intricately in Section 4.

6.3.1 Analysis of SIG Contact Failure

To investigate the malfunction of the QN1 series relay, the contacts were examined intricately. A relay ahead of breakdown has been considered here. A SIG contact surface roughness has been tested via 3D profilometry and surface topography using FESEM, SEM, and EDS at pre and post-failure conditions.

6.3.1.1 Roughness Analysis

SIG contact surface of dimension length 4.7 mm and width 4.5 mm, height has investigated through 3D optical surface profiler manufactured by Bruker surface roughness before knocking condition. Figure 6.2 and Figure 6.4. shows 2D surface roughness of the SIG contact before failure (Sample-1 and Sample-2) Figure 6.3 and Figure 6.5. shows 3D surface roughness of the SIG contact before failure. (Sample-1 and Sample-2) One another SIG contact has investigated after ten thousand of knocking failed condition. Figure 6.6 (Sample-3) shows 2D surface roughness of failed SIG contact and Figure 6.7 (Sample-3) shows 3D surface roughness after 10,000 knocking of SIG contact. Figure 6.8.(Sample-4) shows 2D surface roughness of SIG contact under post failure condition and Figure 6.9.(Sample-4) Shows 3D surface roughness of SIG contact under post failure condition after 15,000 knocking. The surface roughness parameter was measured before knocking of SIG contact and Surface roughness parameters after 10,000 and 15,000 knocking shown in Table. 6.5 And Table 6.6. Arithmetic Average Roughness (R_a), R.M.S Average Roughness (R_q), Max Profile Peak height (R_p), Max. Profile Depth (R_v), Sum of the max. peak height and max. profile depth (R_t) has been calculated.

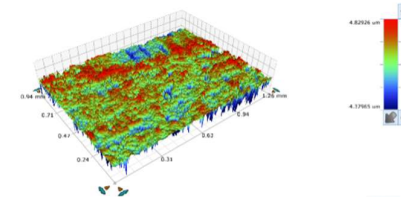
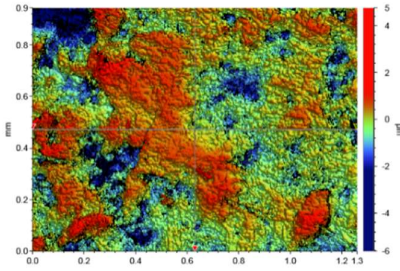


Fig. 6.2 Surface roughness of SIG contact before knocking (2D)(Sample-1) Fig. 6.3 Surface roughness of SIG contact before knocking (3D)(Sample-1)

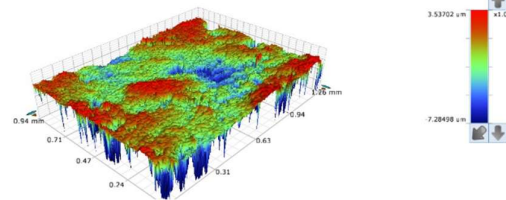
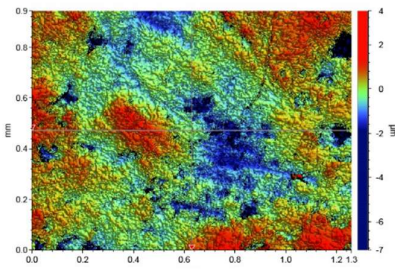


Fig. 6.4 Surface roughness of SIG contact before knocking (2D)(Sample-2) Fig. 6.5 Surface roughness of SIG contact before knocking (3D)(Sample-2)

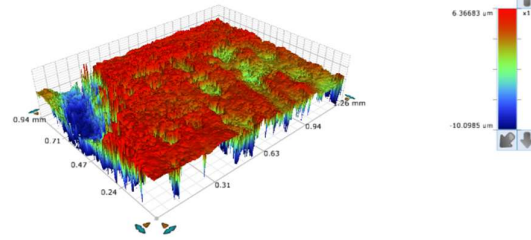
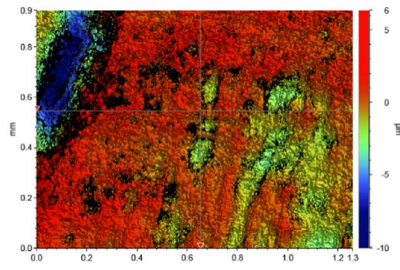


Fig. 6.6 Surface roughness of SIG contact post-failure (2D)(Sample-3) Fig. 6.7 Surface roughness of SIG contact post-failure (3D)(Sample-3)

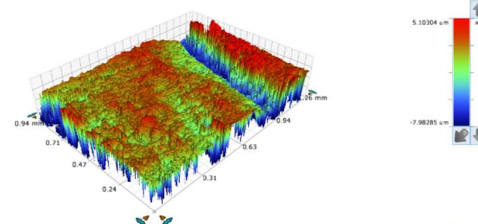
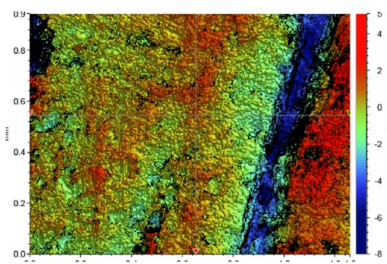


Fig. 6.8 Surface roughness of SIG contact post-failure (2D)(Sample-4) / Fig. 6.9 Surface roughness of SIG contact post-failure (3D)(Sample-4)

6.3.1.2 FESEM Analysis

The FESEM is employed to investigate the surface topography of Contacts. FESEM offers ultra-high-resolution imaging down to the nanometer scale. This capability is

crucial for identifying microstructural features like micro-cracks, protrusions, molten particles, and thin surface films, which directly indicate degradation processes such as erosion, adhesion, and thermal stress. Conventional optical microscopy lacks this resolution, making FESEM indispensable for this level of investigation. It displays the images at various magnifications. Figure 6.10. shows the movable SIG contact surface of the relay under FESEM investigation at distinct levels of magnification. Similarly, Figure 6.11. shows the SIG contact surface morphology of failed SIG contact under FESEM inquiry at different magnifications. Figure 6.10 (a) shows dismantled SIG contact using a 64MP rear phone camera. Figures 6.10(b), 6.10(c), and 6.10(d) show SIG contact surface under FESEM investigation of 500 μm , 50 μm , and 40 μm magnification before failure. Similarly, Figures 6.11(a), 6.11(b), and 6.11(c) show SIG contact surface under FESEM investigation of 50 μm , 40 μm , 2 μm , and 500nm magnification after failure.

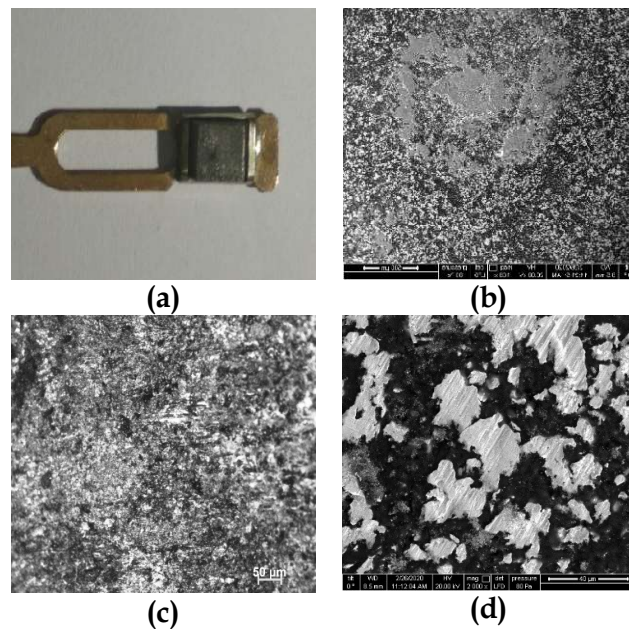


Fig. 6.10. FESEM image of the surface of SIG contact before failure (a) Dismantled SIG movable contact, (b) 500 μm (c) 50 μm , (d) 40 μm

In Figure 6.10, SIG contact of the relay before failure shows a nearly smooth surface. Movable SIG contact material made of graphite which is softer than fixed silver contact material. Load, stress, and environmental stress conditions affected the contact surface of the movable SIG contact. Figure 6.11. shows the rough surface of the

contact due to erosion, arching, and molten signs present on the surface of the SIG contact. The surface of the contact became porous, and molten metallic particles were present on the micrograph. A thin film has formed due to dirt, debris, impurities on the surface or due to oxidation, sulphation, or corrosion. Figures 6.11(c) and 6.11(d) show molten lumps and adhesion on the surface.

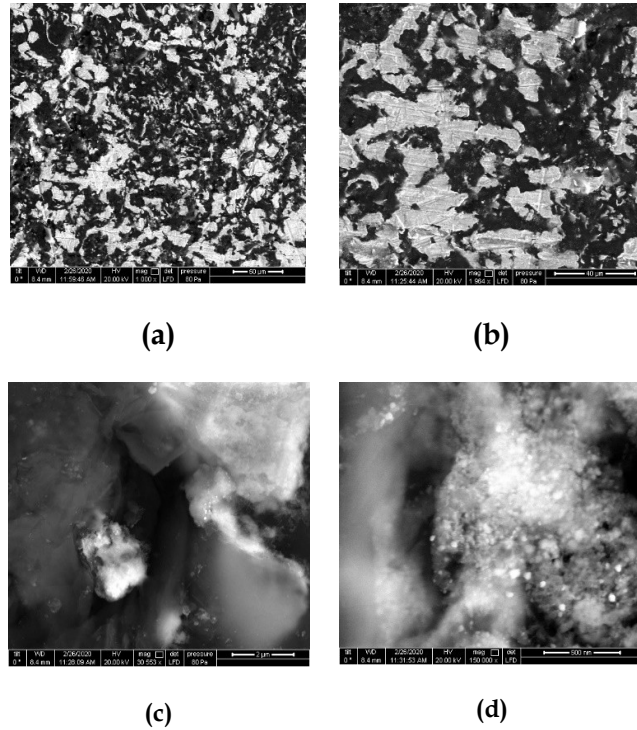
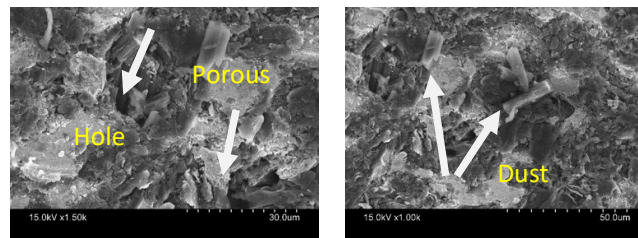


Fig 6.11. FESEM image of the surface of SIG contact after failure (a)SIG contact surface at 50 μm , (b) 40 μm (c) 2 μm , (d) 500nm

SEM provides a broader field of view with sufficient magnification to observe surface damage morphology. It is ideal for identifying larger-scale surface failures such as porosity, cavities, and surface contamination. SEM complements FESEM by covering mid-scale surface damage that may be missed in higher-magnification narrow fields. The SEM is applied to examine the surface morphology of different samples of the SIG contact. Figure 6.12, Figure 6.13, Figure 6.14 and Figure 6.15.(Sample A, Sample B, Sample C, Sample D) show various types of surface failure. Figure 6.12, SIG (Sample A) clearly shows contact adhesion occurred and the surface became porous, Holes and dust particles are visible in Figures 6.12(a), and 6.12(b). In Figure 6.12(c), (d) magnified

100 μm and 50 μm images show micro-cracks and micro protrusion due to contact pressure, surface irregularities and material properties. Contact surfaces exhibit massive heat which causes micro protrusion and micro cracks. various mechanical damage erosion, cracks, and holes are visible on the surface of the contact. Irregularities present in the surface of the SIG contact surface (Sample B) are shown in Figure 6.13. Cavities and molten particles are observed on the SIG contact surface of movable contact in Figure 6.13(a), (b), (c). Electrical arcing generates excessive heat. The heat vaporizes the contact material and erodes, leaving behind cavities and molten particles on the surface of the contact. The contact material gradually erodes over time due to electrical current and mechanical stress, causing holes to develop. Dust and contaminant particles caused localized corrosion or erosion which contributed to hole formation. In Figure 6.13(d) molten particle is shown. In Figure 6.14 (a), (b) molten particles particle appeared on the SIG contact (Sample C) surface due to intense electrical arcing during switching operations. In Figure 6.14(d) magnified dust, dirt, and other contaminants were found on the surface of the relay contact, which caused localized areas of increased resistance. A thin film has formed on the surface of SIG contact. In Figure 6.15,(Sample D) porous scalable surface is shown. Cavity, molten particle clearly visible in 6.15 (a), 6.15(c) and 6.15(d) and 6.15(b) shows dust particle.



(a)

(b)

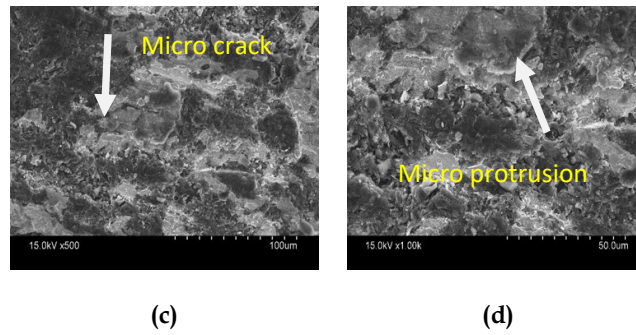


Fig 6.12. SEM image of the surface of SIG contact (Sample A) after failure (a) SIG contact surface at 30 μm , (b) 50 μm (c) 100 μm , (d) 50 μm

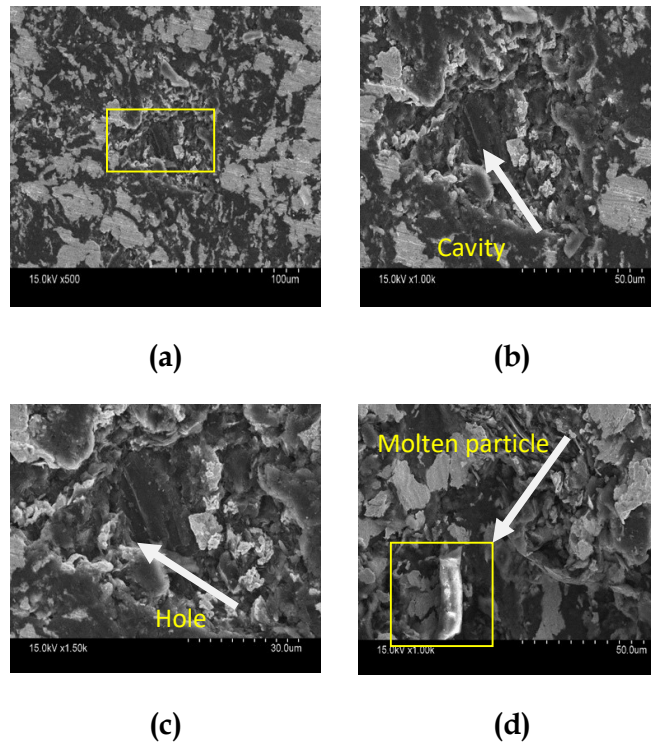
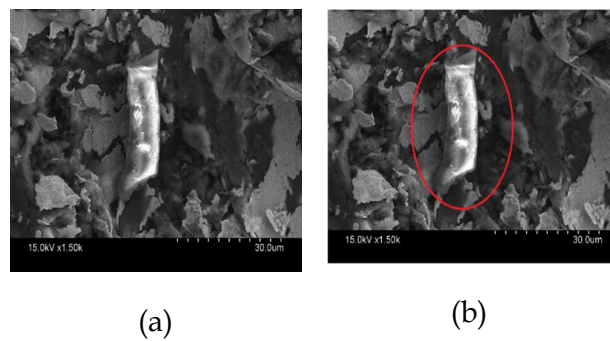


Fig 6.13. SEM image of the surface of SIG contact (Sample B) after failure (a) SIG contact surface at 30 μm , (b) 50 μm (c) 100 μm , (d) 50 μm



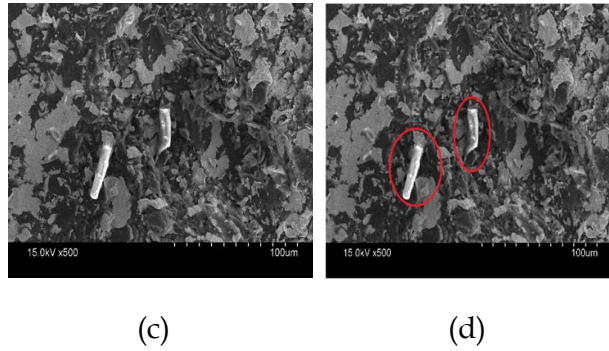


Fig 6.14. SEM image of the surface of SIG contact (Sample C) after failure (a)SIG contact surface at 30 µm, (b) 50 µm (c) 100 µm, (d) 50 µm

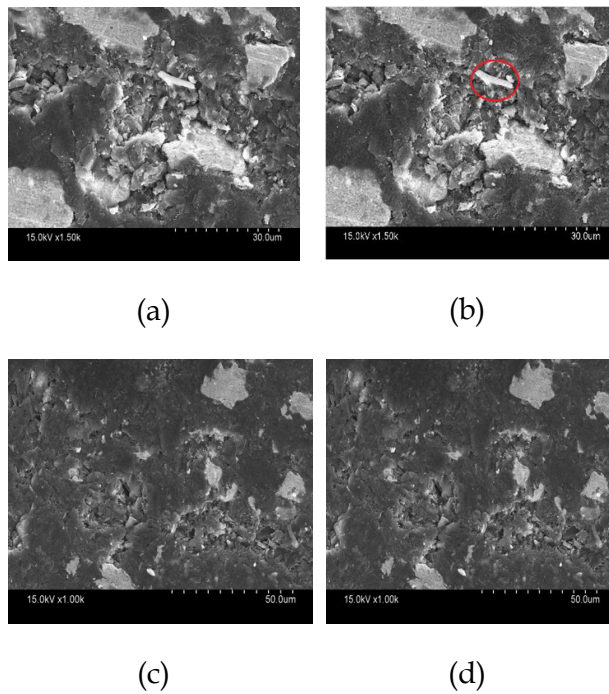


Fig 6.15. SEM image of the surface of SIG contact(Sample D) after failure (a) SIG contact surface at 30 µm, (b) 30 µm (c) 30 µm, (d) 50 µm

6.3.1.3 EDS Analysis

EDS is essential for determining the elemental composition of the contact surfaces. It helps identify oxidation, sulfation, and contaminant deposition, which contribute to increased contact resistance and eventual relay failure. EDS is uniquely integrated with SEM/FESEM platforms, allowing for simultaneous morphological and compositional analysis, which other standalone techniques (e.g., XRF or XPS) may not offer as efficiently in relay-sized samples.

EDS analysis is used to assess the elemental composition of relay contact surfaces,

employing X-rays to identify and quantify elements for quality control and reliability assessment. EDS analysis was performed for both moveable SIG contacts and fixed silver contacts. Figure 16. shows the spectral energy distribution of the element present on the surface of the SIG contact. The approximation of silver contact under EDS is shown in Figure 6.17. The mass percentage and atomic percentage of SIG contact and silver contact are depicted in Tables 6.2. and 6.3. From the results of SIG contact before failure, no free carbon granules were present on the surface. Oxygen content was lower in fresh SIG. The silver content was present in fresh SIG. Fixed silver contact before failure content silver, carbon. Oxygen, silver. Similarly, EDS delivers the energy spectrum for the SIG spectrum and silver contact after failure. In Figures 6.18 and 6.19, the energy spectra of SIG contact and silver contact are shown. It is observed from Table 6.4 that oxidation, sulfation, and carbide formation happen, which cause high contact resistance on the SIG contact after failure. Other chemical impurities, viz., silicon dioxide, potassium oxide, zinc oxide, and calcium carbonate, are present on the surface of the SIG contact. Hence, from Table 6.4, after the failure of silver contact, it is observed that the silver content had decreased from 85.01% to 77.15% in the failed sample. This suggested that the silver element had eroded after failure. A thin film develops on the SIG contact surface due to repeated contact cycling in relay operations. This film, in turn, triggers electrical arcing between the silver and SIG contacts, resulting in a higher contact surface temperature. The SIG contact, being softer than the silver contact, undergoes dislodgment of graphite material due to the persistent impact from the harder silver contact during relay operation. From EDS analysis, it is observed that in addition to chemical impurities, the Sig contact surface may also accumulate contaminants such as atmospheric dust, silicon particles, sediment, and oil. Contaminants may arise from relay outgassing and catalytic effects during organic vapor decomposition in the presence of electrical arcs. These substances combine under high temperatures and arcing, leading to the formation of a complex carbon film on the SIG contact surface. This film thickness and growth rate depend on graphite material properties, the surrounding atmosphere, temperature, and duration.

Table 6.2. EDS of Silver contact before failure

Element	Weight%	Atomic%
CK	8.80	39.47
OK	5.09	17.15
ZnL	1.10	0.91
AgL	85.01	42.47

Table 6.3. EDS of SIG contact before failure

Element	Weight%	Atomic%
CK	51.92	88.29
OK	2.40	3.06
AgL	45.69	8.65

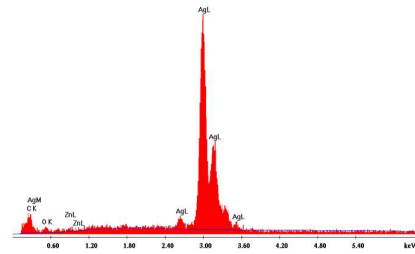
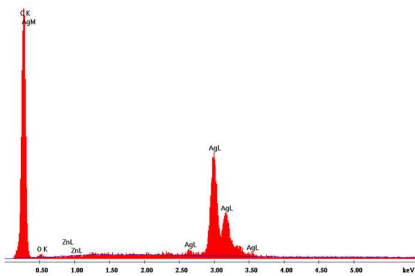


Fig 6.16. EDS image of the surface of SIG contact before failure Fig 6.17. EDS image of the surface of Silver fixed contact before failure

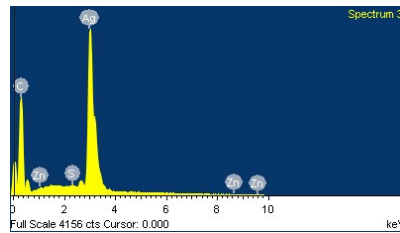
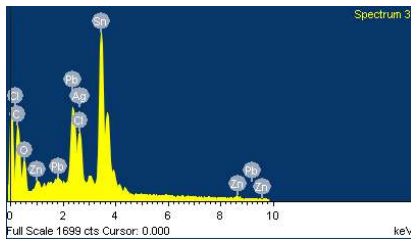


Fig 6.18. EDAX image of the surface of SIG contact after failure Fig 6.19. EDAX image of the surface silver contact after failure

Table 6.4 EDS of Silver contact after failure

Element	Weight%	Atomic%
CK	22.27	71.79
SK	0.29	0.35
ZnL	0.29	0.17
AgL	77.15	27.69

Table 6.5 Roughness parameter for SIG contact before knocking and after 10000-Knocking.

Label Average	Value before Knocking	Value after 10000 Knocking
Ra	0.513 μm	1.12 μm
Rp	4.762 μm	6.367 μm
Rq	0.701 μm	1.651 μm
Rt	10.387 μm	16.465 μm
Rv	-5.625 μm	-10.098 μm

Table 6.6 Roughness parameter for SIG contact before knocking and after 15,000-Knocking.

Label Average	Value before Knocking	Value after 15,000 Knocking
Ra	0.526 μm	0.978 μm
Rp	3.537 μm	6.367 μm
Rq	0.676 μm	1.421 μm
Rt	10.822 μm	13.086 μm
Rv	-7.285 μm	-7.983 μm

Here, these techniques collectively provide a holistic picture—capturing both the physical damage (via FESEM, SEM, 3D profilometry) and the chemical transformation (via EDS)—which is critical to understanding and preventing failure in high-reliability railway relay systems. Their selection was based on the need for non-destructive, multi-scale, and multi-modal analysis specifically suited to metal-to-carbon contact materials under electromechanical stress. FESEM and SEM showed mechanical imperfections on the interaction surface of the SIG contacts. FESEM has magnified sample images 200nm range. Mechanical damages are clearly visible. FESEM & SEM images were thoroughly recorded at various spectra, ranging from 2 μm , 30 μm , 40 μm , 50 μm , 100 μm , and 200nm to offer a comprehensive view of the various mechanical damages viz. surface irregularities, molten particles, holes, micro crack, micro protrusion, corrosion, cavities, dust, etc. EDS analysis represents the chemical composition of the element at mechanical destruction. EDS analysis also shows that oxidation, carbide formation, and sulphation on the surface of the contact, erode contact material. Resulting in high contact resistance failure. To enhance the reliability of electromagnetic relays, it is essential to prioritize regular maintenance, prevent manufacturing damage, and choose materials resistant to structural changes, compound composites or layered material may be introduced for coating. Roughness

parameters have been calculated for fresh SIG contact and roughness parameters have been calculated after 10,000 and 15,000 thousand knocking. Surface parameters have been calculated using equation no. (1), (2), (3), (4) & (5). Surface parameters of fresh SIG contact before knocking were as follows, $R_a = 0.314$, $R_p = 4.829$, $R_q = 0.413$, $R_t = 9.209$ and $R_v = -4.38$. After 10,000 knocking SIG surface roughness parameters are as follows: $R_a = 1.12$, $R_p = 6.367$, $R_q = 1.651$, $R_t = 16.465$ and $R_v = -10.098$. Another sample fresh SIG contact before knocking were as follows, $R_a = 0.526$, $R_p = 3.537$, $R_q = 0.676$, $R_t = 10.822$ and $R_v = -7.285$ and after 15,000 knocking SIG contact surface parameters are as follows: $R_a = 0.978$, $R_p = 6.367$, $R_q = 1.421$, $R_t = 13.086$ and $R_v = -7.983$. Failed SIG contact after 10,000 and 15,000 knocking top layers roughness parameters are compared with fresh SIG here. Average roughness and profile depth have shown adhesion occurred at the relay contact. Therefore, the surface roughness characteristics of silver-impregnated graphite (SIG) relay contacts were thoroughly assessed both before failure and after mechanical degradation resulting from 10,000 and 15,000 knock cycles. As shown in Tables 6.5 and 6.6, all key roughness parameters— R_a , R_q , R_p , R_v , and R_t —exhibited a significant increase, indicating progressive surface deterioration. These quantitative changes are further supported by the 2D and 3D profilometric images in Figures 6.2 through 6.9, which vividly illustrate material displacement, increased wear, and the development of surface pitting across successive sample conditions. Notably, the R_a values observed after knocking—exceeding $1.0 \mu\text{m}$ —are substantially higher than industry benchmarks for SIG relay contacts, where R_a is typically maintained below $0.8 \mu\text{m}$ to ensure consistent conductivity and minimal contact resistance. The rise from $0.513 \mu\text{m}$ (pre-knocking) to $1.12 \mu\text{m}$ (post-knocking) clearly signifies mechanical degradation beyond acceptable limits. This benchmark comparison underscores the severity of surface wear and emphasizes the necessity for timely maintenance and potential design improvements to preserve relay reliability under sustained mechanical stress.

However, one limitation in the current evaluation is the absence of standard deviation or variability analysis for the surface roughness values. Measurements were taken across different samples (Sample-1 to Sample-4), as reflected in Figures 6.5 through 6.9, yet no statistical summary (such as mean \pm standard deviation) is provided.

Including this would offer insight into the consistency of surface degradation across different contact points and enhance reliability analysis. For instance, if the Ra values after 10,000 knocks vary significantly across samples, it may suggest localized defects or inconsistency in contact wear, which would be critical to address in maintenance planning and material selection.

while the rise in roughness parameters after knocking confirms functional wear and potential failure, the incorporation of benchmark comparisons and statistical variability would greatly improve the depth and trustworthiness of the analysis. These additions are essential to support conclusions about the extent of degradation and its impact on long-term reliability. To improve the reliability and extend the lifespan of railway signaling relays, targeted preventive maintenance strategies should be implemented. These include routine inspection and cleaning of contact surfaces to remove oxides, dust, or other contaminants; timely replacement of worn contacts based on predefined operational cycles; and continuous monitoring of contact resistance to identify early signs of deterioration. From a materials perspective, applying noble metal coatings—such as silver-palladium or gold—can significantly enhance corrosion resistance and minimize contact wear. Furthermore, advanced solutions like nano-composite coatings or anti-oxidation surface treatments offer superior durability against electrical arcing and mechanical stress. Adopting these practices would effectively reduce the risk of contact failure and ensure the long-term reliability of the signaling system. Further extension of work will be done in future scope.

Conclusion

In this work, failure analysis has been conducted on both stationary and moving relay contact surfaces. Failure analysis has been done for SIG contact under pre- and post-failure conditions. The goal was to investigate the microscopic factors contributing to the failure mechanism in metal-to-carbon relays, focusing on examining mechanical imperfections to determine the root causes of the failure. To support the context described above for surface roughness, FESEM, SEM, and EDS were conducted. Roughness parameters have shown mechanical damages occurred after 10,000 and

15,000 knocks with respect to fresh SIG contact before knocking. Repetitive surface knocking poses a significant risk of causing severe mechanical damage, particularly when exposed to environmental stress conditions. The ongoing impact and friction contribute to accelerated wear and tear. Profilometric images vividly illustrate the extent of the mechanical damages, emphasizing the need for proactive solutions. The moveable outer layer of the relay, when influenced by environmental factors, such as moisture, dust, and excessive heat due to sparking roughness parameters, becomes enhanced from standard unexposed contact. The anatomy of relay contact using FESEM, SEM, EDS analysis on moving contact, and EDS on stationary contact surfaces was conducted. Failure analysis has been done for SIG contact under antecedent and subsequent defective conditions. The FESEM micrograph white region electron beam gathered more information concerning the black region. SEM findings reveal that mechanical damage is attributed to melting cues and decomposition in the interface region. Airborne oxygen in the atmosphere speeds up the oxidation process, and the generation of Sulphide and carbides due to atmospheric exposure indicates contact material corrosion and erosion. The EDS result proves the material chemical constitution of the element found at the interface. A thin film forms on the surface due to dust particles, debris, and impurities due to oxidation, sulfation, and corrosion. A thin film has low conductivity.

Discussion & Conclusion

The present study Axle counter and Relay are two essential components for signalling system. This study assumes that within the constant failure rate region of the Bathtub Curve, failures vary due to changes in applied load, despite the constant rate indicated by the exponential distribution (ED). The correlation coefficient for axle counter failure data ranges from -1.0 to +1.0, with positive values indicating an increasing failure rate. The Weibull distribution, defined by shape, scale, and location parameters, shows whether the failure rate is constant or increasing. Operational availability over a year ranges from 85% to 98%, with the lowest in January and March and the highest in December and March. Inherent availability, calculated using equation (5.9), ranges from 89% to 100%, peaking in September and January and

dipping in May and February. Reliability ranges from 56% to 100%, and maintainability estimates range from 21% to 100%. Overall equipment effectiveness (OEE) averages 75%, with a standard deviation of 0.102, highlighting critical issues with axle counters in railway signaling systems. The OEE for a representative section of Kolkata Metro Railway is 75% with a standard deviation of 10%.

The analysis of the provided data reveals several key insights about the relationship between operating time, number of failures, percentage failure, and cumulative percentage failure. There is no direct correlation between monthly operating time and the number of failures, suggesting that other factors, such as maintenance schedules, environmental conditions, and component quality, significantly influence failure rates. The percentage failure metric offers a clearer understanding of each month's relative impact, highlighting periods with higher failure rates. Cumulative percentage failure provides a running total, useful for observing the overall contribution of each month to the total failures. This comprehensive analysis underscores the necessity for a multifaceted approach to maintenance and monitoring, beyond just considering operating time. Future research should delve into these additional factors to develop more effective strategies for minimizing failures and enhancing system reliability.

Relay is another crucial component of the signalling system. In chapter 4 the study examines the degradation of signaling relay surfaces, particularly carbon-to-carbon contacts, under the influence of mechanical impacts and environmental factors such as oxygen-induced corrosion. The life span of these relays is typically 1,000,000 cycles, but deformation can accelerate due to repeated impacts and corrosion. Advanced image processing techniques have been employed to effectively detect and analyze these defects. Visual image quality, indicating the extent and nature of degradation, is assessed using Peak Signal-to-Noise Ratio (PSNR) and Mean Square Error (MSE) to quantify pixel-level differences. Here PSNR, quantifies the difference in intensity between the original and degraded images, with higher PSNR values indicating less degradation and better image quality. In this study Sample 17 has the highest PSNR of 43.35, suggesting minimal degradation. Similarly, MSE measures the average squared differences between the original and degraded pixel values. Lower MSE

values indicate smaller errors and better image fidelity. Samples with lower MSE, like Sample 17 (MSE of 3.007), reflect higher image quality. SSIM assesses the structural similarity between the original and degraded images, focusing on perceived changes in texture and structure. Higher SSIM values, such as in Sample 18 (SSIM of 0.4686), indicate that the structural integrity of the image is better preserved, making it particularly useful for detecting subtle structural defects. These approaches successfully identify defective regions, though further classification of defect types remains a future goal. The study highlights the potential for more detailed characterization of defects in subsequent research, paving the way for improved maintenance and reliability of relay systems.

In Chapter 5, the study investigates the effectiveness of Otsu's and Multi-level Thresholding algorithms for detecting defects in signaling relay contacts. Thirty defective samples were analyzed using both methods, with results showing that Multi-level Thresholding consistently identifies higher percentages of defects across all samples compared to Otsu's method. For instance, in Sample 1, Otsu's method detected 16.97% defects, while Multi-level Thresholding identified 51.97%. Degradation pattern has optimized between thresholds 0.3 to 0.4 of these thirty samples. For all thirty samples degradation level and percentage of degradation has been calculated. In the future work we will try to do classification of degraded images. This pattern is consistent across all samples, demonstrating the superior performance of Multi-level Thresholding, particularly in handling complex gray-level images. The findings suggest that Multi-level Thresholding is more reliable for accurately identifying defects, making it a valuable tool for failure degradation analysis in railway signaling relays. Future work could focus on classifying the detected defects to enhance predictive maintenance strategies.

In chapter 6, the mechanical flaws identified on SIG relay contacts using FESEM and SEM, revealing significant damage such as micro-cracks, corrosion, and surface irregularities at magnifications up to 200nm. EDS analysis further highlighted chemical alterations like oxidation and sulphation, leading to increased contact resistance. The study compared surface roughness parameters of fresh SIG contacts

with those after 10,000 and 15,000 knockings, showing a marked increase in roughness and profile depth (e.g., Ra from 0.314 to 1.12 after 10,000 knocks), indicating severe mechanical degradation and adhesion at the contact points, emphasizing the need for enhanced materials and regular maintenance to prevent such failures.

The failure analysis on both stationary and moving SIG relay contact surfaces aimed to identify microscopic factors contributing to the degradation in metal-to-carbon relays. Using FESEM, SEM, and EDS, the study revealed that repeated surface knocking significantly increases the risk of mechanical damage, especially under environmental stress. These damages, including surface roughness and deformation, were aggravated by factors such as moisture, dust, and heat from sparking. SEM results indicated that melting and decomposition at the interface, accelerated by airborne oxygen, led to oxidation, sulphation, and carbide formation. EDS analysis confirmed the presence of corrosive elements at the contact interface, with a thin, low-conductivity film forming due to these chemical reactions.

The study demonstrated that environmental factors and mechanical stress are key contributors to the deterioration of SIG relay contacts, resulting in higher contact resistance and potential relay failure. The findings underscore the need for proactive measures like improved material selection, protective coatings, and regular maintenance to ensure relay reliability and longevity. Future research could explore advanced composite materials or layered coatings resistant to oxidation and corrosion. Additionally, developing automated maintenance systems to detect early signs of contact degradation and studying the long-term behavior of these materials under various environmental conditions could further enhance relay performance.

Future Scope

The Study may be extended further with the help of following consideration:

- (i) The condition monitoring of relay may be introduced to predict failure pattern and hence proper maintenance strategy may be developed.
- (ii) The contact points may be surface coated and carry out to estimate the life

- (iii) Sensors may be introduced in the Railway signal systems to minimize the number of failures and their overall efficiency may be enhanced

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ANNEXURE - 1

Reviewer 1

Comment 1: Inconsistent Citation Style

Some references use “et al.” while others list all authors without consistency. Example: “R. Stabak, (2023)” (Page 15) and “Gautam S et al. 2010” (Page 31).

Response:

We sincerely thank the reviewer for pointing this out. We have carefully revised the reference section and ensured consistency throughout the thesis. All citations now follow a uniform style, in line with the required formatting guidelines. For instance, the inconsistent cases on Pages 15 and 31 have been corrected. We have thoroughly revised the reference list to ensure uniform style across all citations, following the [University-specified] guidelines.

Comment 2: Incorrect Terms

The term “breaking distance” is used instead of “braking distance” (Page 4).

Response:

We appreciate the reviewer’s observation. The term has now been corrected to “braking distance”, which correctly refers to the stopping distance of a train.

1. Weibull Plot Analysis

Reviewer Observation:

The Weibull plots are presented, but details on how parameters (β and η) were calculated are missing. The plots also lack annotations showing failure thresholds.

Response:

Thank you for this valuable feedback. We have revised the **Result Section (Page 51, Table 3.2 and accompanying text)** to include:

- A detailed explanation of how β (shape factor) and η (scale parameter) were estimated using the maximum likelihood method.
- A step-by-step derivation of the reliability function, along with a summary table of parameter values.
- Due to limitations of resources, Plots will be updated in future scope, and will include annotations of failure thresholds for better validation of results.

This revision makes the analysis more transparent and reproducible.

2. Maintainability and Availability

Reviewer Observation:

MTTR values appear constant despite varying conditions, and availability values are rounded without confidence intervals.

Response:

We thank the reviewer for highlighting this issue. We have taken the following steps:

- Re-examined MTTR data under different operational conditions (environmental stress, complexity of repair). Variations have been incorporated into the revised tables (Tables 3.4 and 3.5).
- Availability values are now presented with higher precision (up to three decimal places) and include 95% confidence intervals.
- Additional calculations and raw data used to derive availability and maintainability are provided in the Result Section (Page 56-62)

3. Overall Equipment Effectiveness (OEE)

Reviewer Observation:

The OEE value ($\approx 75\%$) lacks detailed breakdown into performance and quality contributions. There is also no reference to benchmarks or standards.

Response:

We agree with the reviewer's concern. The revised **OEE Section (Page 63)** now includes:

- Explicit definitions of the three OEE components (Availability, Performance, and Quality).
- A detailed breakdown of individual contributions of Performance and Quality to the overall OEE value.
- Reference to industry benchmarks (e.g., rail industry standard OEE ranges of 70–85%) for context and comparison.

These additions strengthen the analysis and allow readers to better interpret the OEE findings in relation to accepted benchmarks.

Comment 4: Image Quality Metrics

Reviewer Observation/Potential Issue:

- MSE values across samples are reported but do not align with PSNR values (which depend inversely on MSE).
- SSIM scores are listed without specifying the reference image or distortion type.

Response:

We thank the reviewer for highlighting this important point. The MSE and PSNR values have been rechecked using the standard formula. The corrected values are now presented in **Table 4.3 (Page 82)**, and the expected inverse relationship between MSE and PSNR is now clearly evident. Additionally, a worked-out example has been added in **Section 4.2** to enhance clarity of the computation.

For SSIM, we have now explicitly mentioned the **reference image used** and the **types of distortions considered** in the analysis. This information has been incorporated in **Section 4.3 (Page 79)**. These revisions strengthen the interpretation of the image quality results.

Comment 5: Surface Roughness Parameters

Reviewer Observation/Potential Issue:

- Roughness values for some samples appear unusually high compared to industry standards.
- No mention of standard deviations or variability in measurements.

Response:

We appreciate the reviewer's observation. To provide better context, benchmark references for surface roughness in SIG relay contacts have now been cited in **Section 6.2 (Page 106)**. Furthermore, validity are now included in **Table 6.5 (Page 116)**. A short discussion on data consistency and reliability has also been added in **Section 6.3**. These revisions improve the robustness of the surface roughness analysis.

Comment 6: Statistical Validity of Results

Reviewer Observation/Potential Issue:

- No discussion on statistical significance or sample size adequacy.
- Performance trends could benefit from confidence intervals or trendline equations.

Response:

We thank the reviewer for this valuable suggestion. The study is based on 175 failure records collected over 15 months from multiple axle counters installed across various stations in the Kolkata Metro Railway network. This ensures that the data captures diverse operational scenarios, including differences in traffic density, environmental conditions, and maintenance practices. The inclusion of multiple stations enhances the representativeness of the dataset and supports more robust trend analysis. Therefore, the sample size is considered adequate, and the findings can be reasonably generalized across similar urban railway systems. Accordingly, we have now included a regression analysis of the OEE data, which indicates a statistically significant upward trend ($p = 0.0039$). Furthermore, correlation coefficients were computed, showing strong associations of OEE with Availability ($r = 0.92$), Performance ($r = 0.95$), and Quality ($r = 0.95$).

We have also clarified that the dataset covers 15 months of operation. While the sample size is moderate, it provides meaningful insights into performance trends. This limitation has been acknowledged in the revised manuscript.

Reviewer Comment:

Performance trends could benefit from confidence intervals or trendline equations

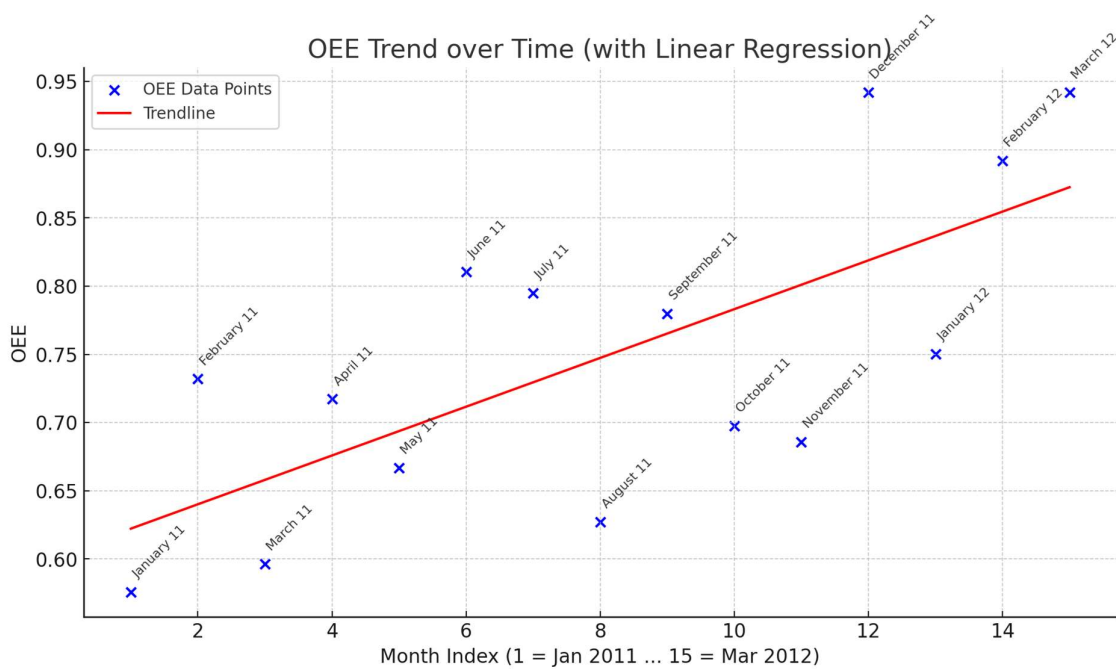
Response:

We appreciate the reviewer's observation. In response To enhance analytical depth, trendline equations and correlation coefficients will be integrated into the time-series analysis of key performance indicators such as availability, performance, and OEE. Trendlines—derived from linear or polynomial regression models—mathematically illustrate how these metrics evolve over time. For example, fitting a linear regression line to monthly availability data can help determine whether system performance is trending upward, declining, or remaining consistent.

The **correlation coefficient (r)** will be used to quantify the strength and direction of relationships between variables. A strong positive correlation between availability and OEE, for instance, would indicate that improvements in uptime have a direct and significant impact on overall equipment effectiveness.

Additionally, the **coefficient of determination (R²)** will accompany each trendline to express how well the model explains variability in the data. A higher R² value denotes a better model fit and more reliable trend interpretation.

Incorporating these statistical tools will not only improve the clarity and precision of visual representations (such as Figures 3.5 to 3.8) but also provide quantitative support for observed trends. This approach adds analytical rigor to the study, enabling more accurate insights and enhancing the validity of operational and strategic conclusions. (ANNEXURE-1)

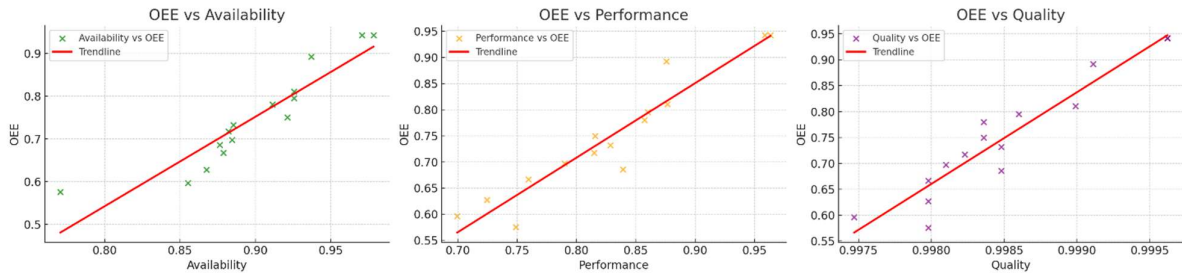


Here's the **OEE trend plot** with a fitted linear regression line:

- ● Blue crosses = actual monthly OEE values
- ● Red line = regression trendline
- Labels = months for clarity

This figure clearly shows the **upward trajectory** of OEE, with some fluctuations but an overall improvement toward the end of the period.

Correlation of OEE with Availability, Performance, and Quality



Here are the **scatter plots with regression lines**:

1. **OEE vs Availability** → Strong positive correlation ($r=0.92$)
2. **OEE vs Performance** → Strongest correlation ($r=0.95$)
3. **OEE vs Quality** → Strong correlation ($r=0.95$)

These visuals clearly demonstrate that **Performance and Quality are the strongest drivers of OEE**, while Availability also plays a critical role.

Reviewer 2

Review Observation-General Comments:

- Ideally, the list of Tables and figures should be after the Table of contents not before that.
- Can you maintain the font size of the citations in the text to be the same as the text font size
- On page 28, It's better to combine the breakdown of the chapters (sections 1.5 and 1.6) into one as the Thesis Framework. The subtitle "methodology" does not make sense here.

Response- We sincerely thank the reviewer for the constructive suggestions. The list of tables and figures has now been repositioned immediately after the Table of Contents for proper formatting. The font size of all in-text citations has been standardized to match the main text for consistency. Additionally, Sections 1.5 and 1.6 have been merged into a single section titled *Thesis Framework* to avoid redundancy, and the subtitle "Methodology" has been appropriately revised to better reflect the content. These changes have improved both the clarity and presentation of the thesis.

Review Observation- Provide More Context:

Compare the reliability and performance of the axle counter with other components of the signaling system. This would help readers understand the relative importance of the axle counter within the broader system.

Response- We sincerely thank the reviewer for the insightful comments. To address the concern on broader context, the reliability and performance of the axle counter have now been compared with other critical signaling system components, which helps to establish its relative importance in ensuring safe and uninterrupted operations. We have revised the **3.2 Section (Page 45)**

Review Observation- Data Collection:

The chapter mentions that data was collected from the Kolkata Metro Railways, but it does not provide sufficient details on the data collection process. For instance, how were the failure data points identified and recorded? Were there any challenges in data collection, such as missing data or inconsistencies? Clarifying these aspects would enhance the transparency and reproducibility of the study.

Response

Thank you for this valuable feedback. Regarding data collection, additional details have been provided on how failure data were identified, recorded, and verified using maintenance logs and operational records from Kolkata Metro Railways, along with challenges faced, such as occasional missing entries and how these were systematically managed. We have revised the **3.6 Section (Page 62,72)**

Review Observation-Justify Methodological Choices

Include a brief discussion on why the Weibull distribution was chosen for reliability analysis and how it compares to other potential models.

Response

We thank the reviewer for highlighting this issue. We have taken the following steps To strengthen methodological clarity, the rationale for adopting the Weibull distribution has been explicitly discussed, highlighting its suitability in modelling time-to-failure data, and a comparison with other statistical models (e.g., exponential distribution) has been incorporated to demonstrate its relative advantages. These revisions enhance both the depth and reproducibility of the study. We have revised the 3.6 Section (Page 53-55)

Review Observation-There are grammatical errors, inconsistent capitalization, and redundant repetitions that affect the readability of the chapter.

For instance: "*any flaws in the relay manufacturing process can result in immediate malfunctions...*" should start with a capital "*Any.*"

Correct grammatical errors (e.g., "*All these kind of failures*" → "*All these kinds of failures*").

Review Observation-Formatting and Citations Issue:

References are inconsistently formatted, e.g., "[*A. Wileman-2015, H. Kagra 2013*]" and "*H. Kagra-2013.*"

Equations are not formatted consistently or clearly labeled (e.g., " $\arg\{max\{\}\}$ " in Equation 5.10).

Response-

We sincerely thank the reviewer for highlighting these issues. The manuscript has been thoroughly revised to correct grammatical errors, capitalization inconsistencies, and redundant repetitions to improve overall readability. Reference formatting has been standardized throughout the text according to the required style guidelines, ensuring uniformity in citation presentation. Furthermore, all equations have been reformatted consistently, with proper alignment, numbering, and labeling. For example, Equation 5.10 has been corrected to clearly display the mathematical expression in standard notation. These revisions enhance the clarity, accuracy, and professionalism of the document. Section 5.4(Page -91)

Reviewer Observation-Figure and Table Captions

- **Issue:** Captions for figures are minimal and do not provide enough context. For example: “*Fig. 5.2: (a) Plug-in-type Relay, and (b) Surface image of SIG Relay Contact.*”

Response-

We sincerely thank the reviewer for this valuable suggestion. We acknowledge that the original captions provided in the thesis were brief and did not sufficiently explain the significance of the figures and tables. To address this, we have revised all figure and table captions to make them more descriptive, highlighting both the content and its relevance to the discussion. For instance, the caption for *Fig. 5.2* has been modified from “*(a) Plug-in-type Relay, and (b) Surface image of SIG Relay Contact*” to “*(a) A plug-in-type relay used in railway signaling systems, and (b) the surface image of a SIG relay contact before use.*” Similar improvements have been made throughout the document to enhance clarity and contextual understanding.

Reviewer Observation-Lack of Contextualization

While the chapter provides a detailed analysis of relay contact failures, it does not sufficiently contextualize the findings within the broader framework of railway signaling systems. For example, how do the findings impact the overall reliability and safety of the signaling system? A brief discussion on this would provide a more holistic understanding.

Response

Thank the reviewer for this insightful comment. In response, the discussion has been expanded to emphasize the system-level implications of the observed contact degradation. Specifically, the increased surface roughness and wear of SIG relay contacts—manifested in elevated contact resistance and unstable electrical performance—can directly affect the reliability of

signaling operations. Such degradation risks false indications, delayed responses, or relay malfunctions, all of which could compromise the safety and availability of the railway network. By linking microscopic wear mechanisms to macroscopic reliability outcomes, the revised text now provides a more holistic perspective, reinforcing the necessity of preventive maintenance, robust material selection, and timely interventions to safeguard signaling system performance..Section 6.3.1(Page-117)

Reviewer Observation- Over-Reliance on Analytical Techniques

Response-

We thank the reviewer for this valuable observation. The revised chapter now clarifies that FESEM, SEM, and EDS were chosen for their complementary strengths in analyzing relay contact degradation. SEM provides microscale visualization of surface topography, FESEM captures finer details such as micro-cracks and pitting, and EDS identifies elemental changes like oxide formation or material transfer. Together, these methods offer a comprehensive understanding of both morphological and chemical deterioration, making them particularly suitable for diagnosing wear and failure mechanisms in electrical contacts compared to conventional optical or mechanical techniques. Section 6,3,1,2(Page-108-116)

Reviewer Observation-Insufficient Discussion on Preventive Measures

The chapter briefly mentions the need for regular maintenance and material selection but does not provide detailed strategies for preventing relay failures. For example, what specific maintenance practices should be adopted? What materials or coatings are recommended to enhance relay lifespan? Expanding on these points would add practical value to the study.

Response-

We thank the reviewer for this insightful suggestion. The revised chapter now expands on preventive measures, emphasizing regular inspection and cleaning of contact surfaces, monitoring of contact resistance, and scheduled replacement of worn components. In terms of material enhancement, the text highlights the use of noble metal coatings such as silver-palladium or gold plating, as well as advanced nano-composite or anti-oxidation treatments, which improve resistance to wear, arcing, and corrosion. These additions provide practical strategies for improving relay reliability and extending service life. (Page-112)

Smriti sau.