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COMMUNICATION BASED TRAIN CONTROL: TRANSFORMING MODERN RAILWAY SYSTEM

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Abstract – *The importance of rail transportation in sustainable transport is mainly due to their safe, trustworthy, high capacity, and energy-effective characteristics. Urban rail transit, which has witnessed rapid global development in recent years particularly among developed and developing countries alike, is faster, safer, more convenient, and offers large capacities with the application of Communication-Based Train Control (CBTC) system. This study explores the principles of a CBTC system that defines its working mechanism; it also identifies subway lines using CBTC systems. It provides an understanding of the benefits associated with CBTC focusing on automation of train control systems essential to contemporary railways that offer new approaches to expanding urban populations through advanced enthralling efficient secure solutions. Therefore, CBTC utilizes high precision train positioning methodology and has two-way communication between trains and wayside equipment for complete automated train operation systems in large continually expanding towns. This paper illustrates the advantages of CBTC technology, showing that it can safely increase capacity and efficiency on busy urban lines, hence developing train signaling systems to accommodate increasing demand as well as traffic capacity*.

Key Words: **CBTC, Urban rail transit, Sustainable transport, Train positioning methodology, Automation of train control.**

List of Abbreviations

ATO: Automatic Train Operation, ATP: Automatic Train Protection, ATS: Automatic Train Supervision, CBTC: Communication-Based Train Control, LTE: Long-Term Evolution, GSM-R: Global System for Mobile Communications – Railway, TETRA: Terrestrial Trunked Radio, MA: Movement Authority, RCS: Radio Communication System, VOBC: Vehicle On-Board Controller, ZC: Zone Controller, RATP: Regie Autonome des Transports Parisiens (Autonomous Paris Transport Authority), MTR: Mass Transit Railway, SMRT: Singapore Mass Rapid Transit, ERTMS: European Rail Traffic Management System, IoT: Internet of Things, IEEE: Institute of Electrical and Electronics Engineers, ATS: Automatic Train Supervision, MA: Movement Authority, ZC: Zone Controller, ATP: Automatic Train Protection, ATO: Automatic Train Operation, ATS: Automatic Train Supervision, AP: Access Point

1.INTRODUCTION

Traditionally, railway signaling systems employed in India, like the Absolute Block and Automatic Block systems were using fixed-length blocks with downtime between a train and another one moving in the same direction. These mechanisms ensure safety but fail to enhance track capacity. Consequently, alternative approaches such as Communications Based Train Control (CBTC) have been implemented in some countries. CBTC is an advanced wireless communication-based signaling system that offers high-resolution real-time train control information, enabling reduced headways between trains on the same line and reducing the need for extensive track-side equipment. Currently, this system is being installed on Metro Railways across India where each metro uses different communication technologies such as LTE, GSM-R, and TETRA resulting in some differences between them [13,8].

In CBTC systems, trains continuously compute and transmit their status which includes their exact positions, speeds of trains travel directions and braking distances to the distributed along wayside equipment through radio communication. This constant exchange of information allows for precise calculation of areas occupied by trains thus defining safe points on the track that must be avoided by other trains [11]. If each train keeps getting updated about the distance of the other, then all trains can control their speed and keep at a safe distance between them for passengers to feel safe as well as comfortable [4]. Increasing railway transportation efficiency is about speed and capacity. Speed is limited but capacity can be increased by shortening the headway between trains. The two-way communication in CBTC systems allows to move from a fixed-block to a moving-block system where trains are separated by an absolute braking distance. But trajectory prediction which considers the leading train movement is key to safety and efficiency.

Active communication in CBTC means frequent exchange between control center and trains about dynamics and characteristics. Trajectory prediction in CBTC means calculations are made with the actual leading train movement, not as a static object. It avoids emergency braking and is safe driving.

A dynamic headway system based on predicted trajectories is another big thing in CBTC. It uses future information to calculate safe distance between trains and updates it in real-time [1]. It also has contingency for communication disruption, so it can safely switch to more conservative mode without safety compromise.

Overall, CBTC is good for efficiency and safety of railway. It replaces fixed block signaling with continuous real-time data transmission. Real-time monitoring means trains can run faster, scheduling is more accurate and collision risk is reduced. That's why it's key for modern urban rail [3].

In short, CBTC is a big thing in signaling technology, electronic, communication and automatic control. As population grows and transportation demand increases, CBTC will be needed for safe, efficient and high-capacity railways everywhere. Research is ongoing and will bring even more solutions for future rail challenges [8].

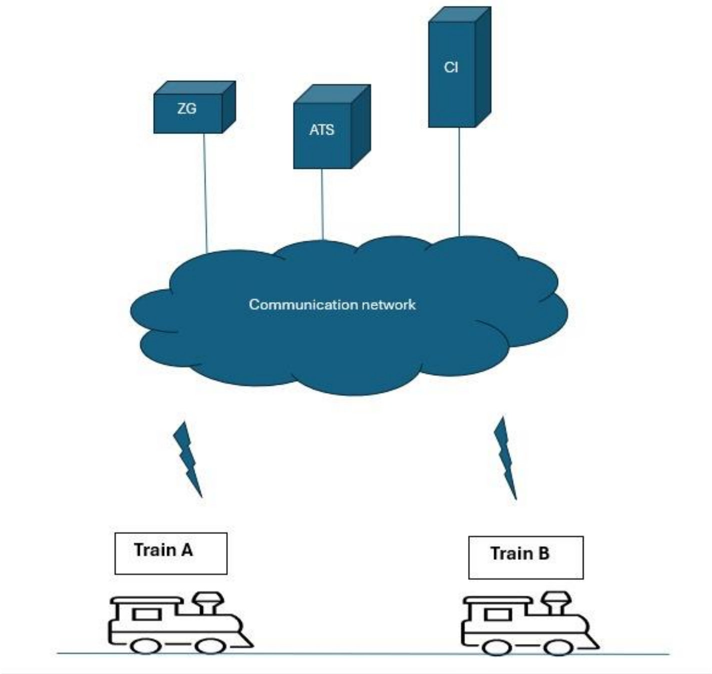

Fig -1: Basic Structure of Communication in CBTC

2.TECHNICAL OVERVIEW OF CBTC

2.1 Basic Principles

CBTC is a sophisticated signaling technology meant to be used in increasing the effectiveness and safety of rail-based transport. CBTC can be specified based on IEEE 1474[13]. CBTC relies on high resolution train location determination in contrast to track circuits, bidirectional data communication between the train borne and wayside equipment in a continuous manner, as well as both train borne and wayside processors for the provision of ATP, ATO, and ATS functions [13,15,8].

The chief concept of CBTC is that information is shared between the train and equipment on the ground in real-time. This real time communication helps in a precise grip by calculating the intervals between two trains moving on the same track with the consideration to speed and the braking distance and hence does not require separate blocks. This variable increase in the safety margins enables the trains to be closer increasing operations efficiency without compromising safety thresholds [1,2].

2. 2 Components

CBTC systems consist of four major subsystems: CBTC systems consist of four major subsystems:

1. Automatic Train Supervision (ATS) Equipment: ATS equipment, located at central and wayside facilities, is required to recognize the trains, monitor and indicate them, perform manual/automatic route establishing, and control the operations to conform with the schedule [2].

2. Wayside Equipment: This also entails the processor-based controllers located at central as well as at the wayside in relation to the train borne equipment's external interlocking and ATS. MA settings, ATP, ATO, and ATS are also accomplished by these controllers that consist of track-bound equipment required for chief specific absolute reference positioning's [1,2].

3. Train-Borne Equipment: Including processor-based controllers and sensors for speed measurement as well as location determination, train borne equipment communicates with train subsystems, wayside equipment and/or ATS equipment. Also, it addresses train location identification, speed and MA limit management, as well as other functions of ATP and ATO [1].

4. Data Communication Equipment: Situated at the wayside, centrally as well as aboard the trains, this equipment is useful for two-way data communication and inter-train communication which makes the exchange of information swift and efficient [10,13].

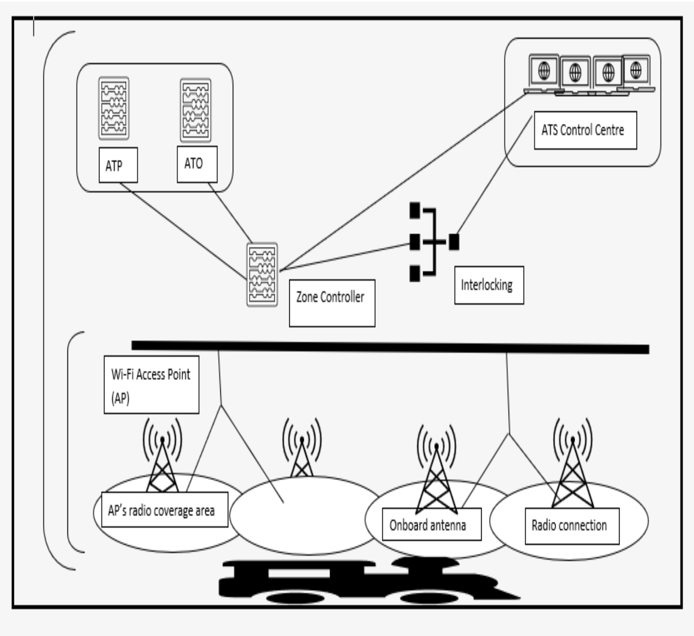

Fig -2: Wayside Components of CBTC

2. 3 Communication Technologies

In CBTC, signaling communication of trains as well as with other train borne wayside equipment is done through radio-based control facilities. The Vehicle On-Board Controller (VOBC) sends periodic control information to the wayside, cooperates or is linked with the onboard ATP and ATO systems. An onboard ATP subsystem is responsible for safety issues, whereas the ATO subsystem is charged with the running of the train. The main idea of the communication is based on Radio Communication System (RCS) that consists of radios and antennas and software that provides the possibility of permanent data transfer [10,11,12,13].

Within the zone, the wayside zone controller (ZC) is responsible for train separation, calculating the movement authority and is further made up of necessary ATP and ATO subsystem. Train to track side interface is made through aps which act as interface points letting formation of a network for continuous data transfer [11,12,13].

In operation, CBTC involves several stages:

- real-time accurate identification of the train location without the use of track circuits [11,12].

- Communication from the train of the location and status of the train to the wayside controllers [11,12].

- Transmission of MA to train-borne systems and generation of MA [10,12,13].

- Adherence to ATP profiles and the activation of MA by systems mounted in trains.

- Communications between wayside controllers and other external interlockings concerning commands and the status of those interlockings, as well as data exchange between sets of train-borne communication equipment.

This is a principle of CBTC to calculate safe separation in real time to enable reduced train separation and increased capacity as it eliminates the fixed block sections and enables trains to run safely at closer distances to one another.

CBTC is considered as a key advancement in current signaling system as it utilizes continual and high-capacity communication technologies to make advancement in the railway operations with detailed train control, better safety, and this increases the track capacity.

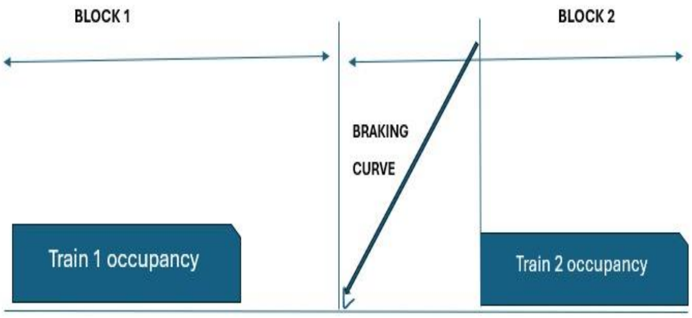

Fig -3: Fixed Block Working

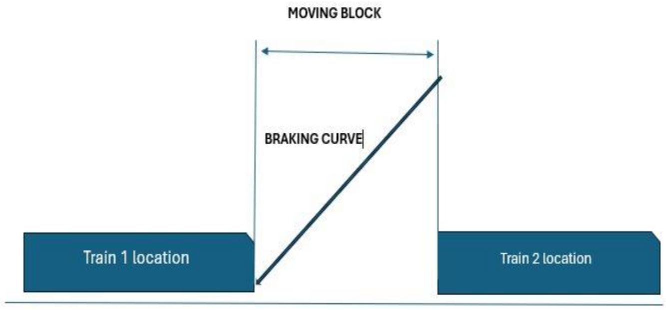

Fig -4: Moving Block Working

3. KEY FEATURES AND FUNCTIONALITY

3.1 Real-time Communication

CBTC system is built on a very reliable, real-time two-way wireless communication train-to-trackside equipment and vice versa. This real-time data exchange forms one of the core enablers of CBTC's high-end functionality. First, wireless networks are high capacity and low latency to establish continuous communication between the trains and the control center through accurate positioning of trains, updating speed and status of the trains, and controlling commands' transmission in real time. CBTC systems use several types of wireless technologies such as Wi-Fi, LTE, and future 5G interfaces [16]. The decision on the new technology to be adopted is informed by among others the bandwidth needed, the coverage needed and the general system specifications. CBTC solutions are designed to have at least one backup mode of communication, as well as provide auxiliary communication systems to guarantee conversation if primary means of signaling is compromised. It is evident that communication systems must be designed to address such factor as tunnels, urban canyons and high-speed movement of the rail. Proper design and optimization of the radio network are critical for the proper coverage of the network throughout the network. Mitigation of interferences and ways of operating with potential interference sources are some of the major aspects of implementing CBTC [13].

3.2 Automatic Train Control

CBTC system incorporates a full range of Automatic Train Control functions which assist in minimizing the dependency on the drivers and improving the overall systems performance. The three main components of automatic train control in CBTC are: The three main components of automatic train control in CBTC are:

1. Automatic Train Protection (ATP): This safety critical consists of several functions that are vital in preventing dangerous interaction between trains, managing the train speed and ensuring that the train movements conform to the granted authorities. Key ATP functions are constant speed check and control, calculation of safe braking profile, and checking the interlocking between the routes [8,12,13,14].

2. Automatic Train Operation (ATO): ATO deals with the real-time control of operation of a train through aspects such as acceleration and braking, stopping at ordinal platforms, opening and closing of the doors as well as energy utilization. ATO can however exist at different levels of automation ranging from level three where the vehicle is driven by the operator with some assistance to level four where the vehicle is mostly self-driven [12,13,14].

3. Automatic Train Supervision (ATS): ATS holds the overall responsibility for all rail networks and the control of operations by providing live schedule management, automatic setting of routes, traffic control, and dealing with abnormal conditions and services.

These three components are mutually integrated to achieve the high level of automation and thereby increase the train operations efficiency and safety [12,13,14].

3.3 Safety Mechanisms

Safety plays a very crucial role in rail business and so CBTC systems contain various layers of safety to help protect against these potential failure modes and business operational risks. It is noteworthy that CBTC systems incorporate a fail-safe concept; that is, in case of a failure, the immediate state is safe; decision critical functions are protected by duplication; and the integrity of the whole system is continuously checked.

In addition to generic speed exceedance protection, CBTC-ATP provides other safety features such as rollback protection, safe door control interlocking, work area protection and level crossing protection whenever necessary. The train location and speed specifics plus the fact that it is a real-time system enables the system to compute braking distance, hence improving the safety of the whole system.

One of the most important issues that need specific attention and protection within the framework of CBTC operation is cyber security. Since these systems depend on data communication, effective and efficient cyber security measures must be put in place. Such measures include encrypting of all safety-critical data which are transmitted through a particular line, provisions of a safe means of authenticating the users, controlling for security intrusions and identification of such intrusions and prevention of their occurrence, and periodic security checks and upgrade of security provision [9].

CBTC systems are also implemented with redundancy for partial system failings; they transition to more conventional modes of operation or switch to backup systems and comes with very organized steps and guidelines for additional manual intervention when necessary.

3.4 Efficiency and Capacity Improvements

It is pertinent to mention that one of the main reasons for integrating CBTC is to improve the productivity and ability of the rail systems, especially in the urban areas. CBTC helps to improve the acceleration and braking curves, manage the car's speed to consume less energy and find the most effective way of coasting.

Moving block signaling is one of the aspects of CBTC efficiencies, but it is the major one because it can quadruple the line capacity compared to the fixed block system. In moving block operation, distance between trains is arrived at in real-time; thus, a train can be closer to the next one behind it than the train in front of the control point, meaning shorter intervals between trains and optimum usage of tracks. Some of its features include the Moving block operation as well as precise train control, that leads to a headway movement of 60-90 seconds in some systems depending on complexities hence enhance through put without having to add track structures [12,15].

CBTC also helps in achieving energy beneficial driving patterns, the synchronization of acceleration and deceleration of number of trains, and the use of regenerative energies of brakes. Often, disasters are unexpected, and due to the real-time management and adaptability of the given system, it is possible to quickly react to disruptions and, therefore, does not significantly affect the network's performance.

3.5 Scalability and Flexibility

CBTC systems come in as versatile with modularity and scalability where CBTC may be fitted in different environments of a rail. These are the wayside systems that involve interlocking, zone controllers, onboard systems that involve train control computers, communications system and central control system that involves ATS. This flexibility enables staged installations, improvements and enlargements, plus interfacing with currently installed signaling equipment.

CBTC can be implemented in metro/subway systems, light rail & trams, commuter rail, and even some mainline ones. The flexibility of CBTC makes it possible to be adopted on small single line operation or very large multi-line operations, as well as very complex networks.

The modularity of CBTC also applies to the fact that it is applicable on a train operating spectrum from trains manned by drivers to completely driverless trains. Such an advantage provides rail operators with flexibility to increase degrees of automation as per the flow of operations [12,15].

3.6 Advanced Supervision and Management

The CBTC systems are equipped with a special feature known as Automatic Train Supervision (ATS) that helps to define many instruments helping to manage the general network interchange. Development ATS systems can have capabilities, which change the schedule depending on the current situation, define automatically the route for the train and optimize the work in the junctions and terminals.

Advanced traffic control models include the current position of the train, schedule, passengers' demand, and limitations of the system to work efficiently. ATS presents application tools for quick identification and deployment of the occurrence, the immediate executive of contingency plans, as well as integration of crisis responses [5,8].

In addition to real time performance variables, CBTC-ATS systems are equipped with an historical data acquisition feature as well as built-in automatic reporting capabilities vital in meeting instituted regulatory reporting requirements for data. A huge amount of operational data has the potential to enhance the system performance and make well-aimed decisions about the network's further development.

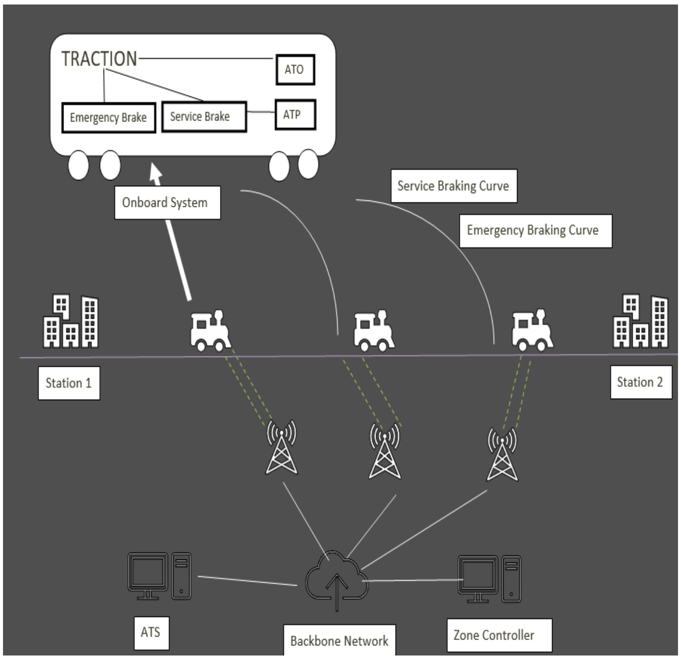

Fig -5: CBTC system

Grade of Automation	Type of Train Operation	Setting Train in Motion	Stopping Train	Door Closure	Operation in Event of Disruption
GoA 1	ATP with Driver	Driver	Driver	Driver	Driver
GoA 2	ATP and ATO with Driver	Automatic	Automatic	Driver	Driver
GoA 3	Driverless	Automatic	Automatic	Train Attendant	Train Attendant
GoA 4	UTO	Automatic	Automatic	Automatic	Automatic

Fig -6: Level of Automation

4. BENEFITS OF CBTC

CBTC (Communications-Based Train Control) technology has several advantages over the previous train signaling technology especially with regards to the effectiveness, security and carrying capacity of the existing and future rail networks. These systems therefore optimize the use of infrastructure through what is known as headway convergence to enhance carrying capacities within the network. CBTC offers higher range and control which enhances the operational rail quality and brings about continuous safety in train separation and over speed in utilization of the tracks.

Maintenance costs are lower with CBTC because these systems can run trains without drivers; thus, lowering operation costs. Also, CBTC has fewer physical components and thus, substantially requires less wayside equipment and hence their maintenance. This, added to the fact that modern CBTC systems are much more reliable than two decades ago, means that CBTC systems keep track of when certain components need to be replaced or serviced, therefore allowing the CBTC system to service the needs of the signaling system and proactively fix any problems, which reduces costs and leads to less system down-time.

CBTC enhances the capacity of rail systems as it allows for short headway thus improving the carrying capacity. CBTC systems greatly help in safety. Moreover, such measures are applied by means of ATP and ATO that mitigate the potential human error. For example, Marmaray stated that no worker lost his/her life or sustained an injury after they adopted CBTC while the company witnessed 22 accidents in 2012, which were attributed to motorist errors under the old management system [8].

Another advantage of CBTC systems is energy saving for the system users. They allow more efficient driving compared to manual interventions and employment of regenerative braking energy. This not only helps to save energy, but it also entails environmental sustainability as well.

CBTC systems are known to enhance passengers' experience through better and variable information transmission and updates. Other facilities like announcements, doors and timetable information make traveling more comfortable and less strenuous for the passengers.

Hybrid systems also reduce the influence of human error since they incorporate automatic control reducing the chances of an accident due to a human factor. Moreover, these systems can be integrated with other modern control systems like ERTMS as seen in Marmaray and this improves the flexibility as well as functionality of the systems [9].

Inter-car and inter-train communication is always a critical part in CBTC systems, as it is necessary for proper, seamless sharing of information between trains and control centers. This enhances the scheduling, planning, and execution that takes place in any organization, thus heightening the effectiveness of its operations. The use of security features, especially in the aspect of the blockchain helps to make CBTC systems secure from hacking and other cyber-related incidents hence keeping the rail operations safe.

CBTC roadmap also provides the efficiency and the orderly running of trains thus promoting orderliness thus the satisfaction of passengers. The adaptability to increase operation automation also helps to cut down on the need for human intervention and thus improves the stability of train services.

Finally, CBTC is an emergency proof solution as the progress in the field of data communication and control techniques proved that it is a sound and long-term strategy for contemporary rail systems. Therefore, the sustainability is guaranteed, and the ongoing progressive enhancement of the rail transit systems can be established.

Consequently, CBTC systems are a safer, faster, more efficient, more capacity-utilizing system overall, achieving higher levels of operational performance. The successful implementation in systems like Marmaray has provided them with an attractive role to transform the present course of the urban rail transit making them effective assets for the modern rail networks.

5. CHALLENGES AND LIMITATIONS

Judging by the complexity of solving various problems when creating CBTC systems, it can be noted that the existing rail networks face a lot of difficulties in upgrading to these systems. Maniacal processes like implementation of new technologies require specialty and proper planning, which may take time and lot of effort. The scholar also stated that the initial capital cost which is needed to establish as the CBTC systems also pose challenge with railway operators for a wider acceptance.

Integrating different CBTC system from different vendors may pose some problems of compatibility which makes it necessary to standardize the CBTC system. Due to these issues of non-interoperability, integration of CBTC system within the existing network might be a costly affair as it may need more resources. Furthermore, the daily, weekly and timely maintenance and technical support that are required for the CBTC systems to operate as expected cost a lot of money and manpower from the transportation authorities.

Security threats are also another major issue with the CBTC systems by they rely on digital communication networks. The integration of these systems is high coupled with the digital aspect; these systems are prone to hacking hence requiring high-security features for defense. While putting into practice and when ensuring these security measures, there can be certain challenges that exist, and these challenges can include the trade-off between maintaining higher system security and having optimum operational efficiency and speed of train control mechanisms [7,13].

Other issues that training entails for the operating and management of CBTC systems are also challenging since appropriate training for the personnel is needed. This can take ample time, and this depends on the number of qualified people thus can result in scarcity of skilled workforce in the rail business. While the employment of CBTC systems promises safer and efficient operations, training staff on how to handle such systems is important and could be demanding; therefore, it would require other things such as training expenditures, time, and resources to ensure that the system is run efficiently. And solving these problems is crucial to ensure the effective application and functioning of CBTC systems in today's railway infrastructure [7,12].

6. CONCLUSIONS

CBTC systems are an impressive step in the development of rail transport that gives safer, more efficient, and higher capacity solutions to urban railways. CBTC integrates real time data communication, accurate positioning of trains, and automated operations which improves operation productivity, used track time, and overall customer satisfaction. There are some issues that are imposed by CBTC like; initial and later implementation expense, compatibility, and security concern that may be considered as negative impacts of CBTC but the positive impacts of headway, low maintenance cost, enhanced safety make it a vital technology for modern urban rail transit. In the progression of the cities as well as the rising need for transportation, CBTC will be the key driver for future sustainable rail.

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