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A Review of the Japanese Train Control Systems

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Abstract—**Train control is an important component of railway systems that improves safety and operational efficiency. Several different types of control systems have been developed in many countries. Challenges have always existed in train control systems, and the need to solve some of these challenges has influenced the evolution of the systems over the years. Some of the challenges include the need to reduce human error and the amount of equipment required. There is also the need to increase operational efficiency and passenger comfort. This paper reviews the Japanese train control systems. A survey of the literature on Japanese train control systems was performed. The review shows how the train control systems have evolved over the from the early generation ATS-S system to the current ATACS system. The improvements that have been made that include the reduction of human driver control in unsafe conditions, the reduction of ground equipment by leveraging newer technologies amongst other improvements are shown. It also shows the benefits of the improvements that include increased safety, operational efficiency, ride comfort and revenue for the operators amongst other benefits.**

Index Terms—. **Advanced Train Administration and Communication System, Automatic Train Control, Automatic Train Stop, Operational efficiency, Safety, Signaling, Train control system**

I. Introduction

Trains have been playing a major role in the provision of on land transport for goods and people. Their increased use resulted in increases of traffic, loads carried and operating speeds so as to increase capacity. However, this increased the chances of accidents because trains have low adhesion to the rail and a huge inertia resulting in long braking distance. In the early days of railway transport there were no signaling systems. Therefore, to reduce accidents signaling systems were developed that would inform train drivers whether it was safe or not to travel in a given section and also advice on recommended speeds [1]. Gestures by a station attendant were initially used to signal go or stop instructions. However, human error occurred resulting in accidents. Signaling systems were developed in order to efficiently prevent accidents. Train signaling and control systems vary from country to country. One of the variations is the Japanese train signaling and control system. One of the earliest signaling system in Japan was the Automatic Traffic Stop (ATS-S) system. The system was capable of stopping the train automatically if a train was moving dangerously and the driver failed to respond to an alarm [2]. However, drivers were also susceptible to human errors thus it became necessary to automate the control system to reduce or eliminate human error. Missing a signal can lead to serious accidents, therefore there is need for an automated system that continuously displays the permitted speed and applies brakes automatically relative to the situation [1].To increase the efficiency of the ATS-S, the ATS-P was introduced. A transponder was used to send and receive data about the distance to the next stop via the track. This information was used by the train to generate a train speed checking pattern. The Automatic Train Control (ATC) was then developed to solve some of the challenges on the ATS-P. The ATC performed safety procedures in the event that a driver made mistakes. With the advancement of technology, the Advanced Train Administration and Communication System (ATACS) was then introduced to meet some of the short falls of ATC and meet the requirements of the modern massive high-efficient transportation [2]. This paper reviews the various control systems that have been used in Japan over the years.

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II. The Evolution Of Train Control Systems In Japan

Train control and signaling systems are systems that ensure safety and increase the operational efficiency of the train. The first passenger railway started operating the UK between Manchester and Liverpool in 1830.A signaling system was developed afterwards to improve the safety and enable increased traffic volume. The development of electronic communication helped progress the signaling technology starting with development of telegraph in 1837. Four years later telegraph communication equipment was installed at the two ends of the North Midland Railway tunnel to help prevent the entry of more than one train into the tunnel at the same time. This was the beginning of the fixed block signaling system. The interlock system for ensuring safety by locking routes was developed in 1856. In 1872 the track circuit for train detection was invented. The improved safety of the railway system is mainly attributed to all these devices. Modifications have been made after the inventions however most of the present signaling systems are based on these inventions [3].

Various control systems have been introduced over the years. Most of the systems are developed relative to the requirements of the countries and railway line where they operate. However, fundamentally their architectures are similar. These include fundamental components like block systems for controlling train to train spacing and traffic direction control for single track operation, automatic train protection systems and interlocking devices [4]. The systems differ in terms of how they may perform train detection or implement train protection. The control systems range from low safety systems like automatic warning systems to the most advance communication-based train control systems (CBTCs). The Japanese train control system is one of the systems that has evolved over the years. The first system was the ATS-S, followed by the ATS-P, the ATC and finally the ATACS.

III. AUTOMATIC TRAIN STOP – S

The first generation of the control system was the ATS-S. In this generation the automatic warning system was developed which warned the driver about stop signals in order to prevent accidents due to negligence in brake handling. The ATS was developed by the Japanese National Railways (JNR) to prevent accidents like the Mikawashima train crash in 1962. The accident was caused by a driver who drove through a stop signal and braked in a safety siding resulting in a derailment and 160 deaths. The ATS-S was introduced by the JNR to reduce train collisions. When a train is in a given track the track circuit detects and turns the signal light to red. This aspect will indicate that no other train is allowed in this block section. Trains are supposed to stop before this section. When a signal is green or yellow, they train can move into the section. There is a relationship between a given signal aspect in a section and the position of a train. The permitted speed depends on the distance to the red signal section. The ATS-S system uses the fixed block system that mainly depends on the track circuit and signal lights [2]. The ATS-S warns the driver of a stop signal from the ground by ringing an alarm bell and automatically engaging the emergency brakes if the driver fails to respond to the warning within 5s. The driver responds by shifting the brake handle to the brake position and pressing the confirmation button. The ATS-S was installed by the JNR in all its railway lines by 1966. The ATS-S contributed to a reduction in accidents, however it was not a perfect system because it could not prevent accidents due to delayed braking handling[4].

In 1967 the Japanese Ministry of Transport issued a notification that mandated all railway companies to install ATS systems. This ATS was different from the JNR's ATS because it was required to provide some speed check function. There was no longer need for alarm sound if the train operation was normal. Brakes were only engaged if the speed check indicated danger [4]. The railway companies responded to the notification by introducing ATS systems with the following characteristics:

1) Speed was checked based on the time a train took to pass two ground coils.
2) The speed pattern was continuous to check the speed train until the train stopped.
3) A speed signal corresponding to the required speed was sent to the track circuit, to be compared against the actual speed.

IV. AUTOMATIC TRAIN STOP – P

The JNR's ATS-S was plagued by more accidents compared to the other railway companies ATSs. Therefore, in the 1970s the JNR started to research on how to improve the performance of their ATS-S. One of the most challenging factors for JNR was that their lines were used by trains that had different braking characteristics. These varied from limited express trains to freight trains. This was different from the other railway companies whose trains had almost identical braking characteristics thus their systems could use uniform speed check systems without many problems. A solution to this problem was to provide the distance information to the stop signal instead of performing speed control from the ground. The idea was novel because a speed checking pattern relative to the distance information from the ground is generated by computing the brake performance on the given train. The system was named ATS-P. Because speed check patterns were now generated using the trains braking performance, reasonable speed check for each train would be realized and unnecessary braking could be avoided.

The ATS-P used a transponder that was capable of transmitting information bi-directionally[4].The transponder transmits signal aspects and distance to stop signal from the trackside to the train. The data is used to generate a train speed check pattern. The onboard computer compares the actual speed and the speed pattern. Where the actual speed exceeds the pattern, the brakes will be engaged. In contrast to the ATS-S, the ATS-P alarms the driver in case of danger but does not need the verification of the driver to stop it from engaging the brakes. The brakes are engaged at maximum power when in danger [2]. The ATS-P was first tested in 1980 on the Kansai line. It was then introduced to other lines including the Keiyo and Chuo lines in the following years[5]. The ATS-P advantages include protection in response to stop signal aspects, control through train notification according to speed restrictions, level crossing control using passing and stopping information from the train, and no need to upgrade the system if the train speed is enhanced

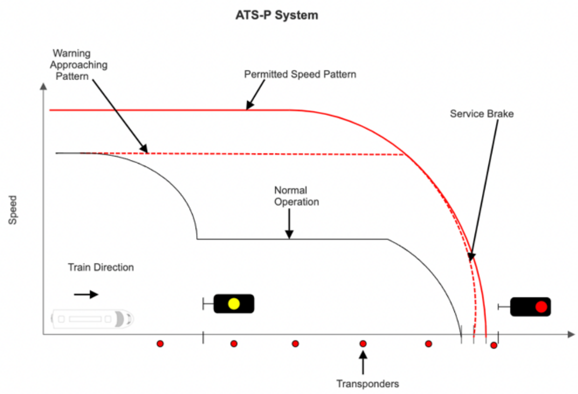

Fig 1 : ATS-P system.

V. AUTOMATIC TRAIN CONTROL

A. Conventional Automatic Train Control

ATS is human-centered and depends on the performance of the driver relative to signals, and only brakes in dangerous situations. However, super-high-speed trains like the Shinkansen are difficult to control and ensure safety using conventional control systems where the driver applies brakes while watching trackside signals. It is also difficult to install ground signals in subways and Shinkansen super-high-speed trains. Therefore, conventional/analog ATC was used which mechanizes the brake control safety without relying on human determination [6]. The first generation used a method in which a speed signal was continuously transmitted from the ground control. The speed signal current is applied to each section of the rail (track circuit). The transmission is done using electromagnetic induction between the current and a pick-up coil on the train [6]. The signal is received by an onboard antenna for the onboard ATC system. An onboard display in the cab shows the driver the permitted speed. This is important in subways where it is difficult to see the trackside signals [4].

The signals are also used to detect the train's location. The train location can be detected by monitoring the level of signal power received as the train shorts the track circuits. The onboard ATC system compares the speed signal to the actual speed. If the actual speed is higher, brakes are engaged to slow down the train to the specified speed[7]. This helps lessen human error. The speed control performed by the ATC is only related to safety. Speed control related to operations i.e., starting, accelerating and stopping at stations were performed by the driver [6]. The permissive speed data is discrete, thus train stopping control is performed using multi-level braking control as shown in fig 2. There are two types of conventional ATC. The first one is called the Half-Overlap system which performs speed control in stages by reducing the speed as instructed in each section. The second system is called the Closing-In system which allows exceeding the permitted speed if the train can be stopped before the stop signal. The Closing-In systems helps to reduce headway[5].

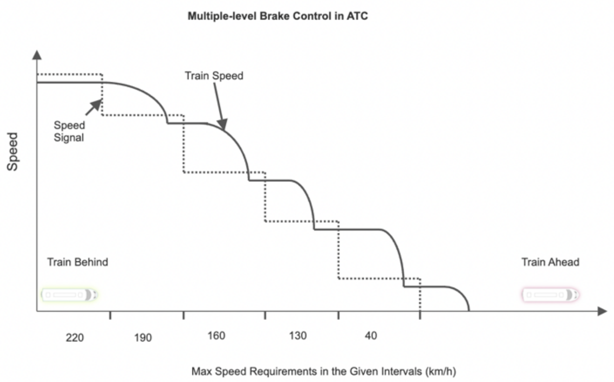

Fig 2: Multi-level braking in conventional ATC

The ATC helps establish safety and stability in high-speed trains. It enabled operation at high speeds above 200km/h, resulting annual transportation of 17.7 billion passenger-kilometers, average delays of one minute or less per day for the East Japanese Railway (JR East) company Shinkansen lines. The revenue was almost 30% of the entire revenues of the JR East company thus it enabled stable revenues [6]. Costs due to ground equipment are lowered by the use of general information equipment. The system is flexible thus when the train performance is improved, adjustments can be made without changing the ground equipment [2]. The ATC was first introduced to support the Japanese Shinkansen to travel safely at superspeed. It was then introduced to traditional railway systems in order to reduce the distance between trains. It was first used on the Tokaido Shinkansen. It was later introduced on the heavily-used commuter route in Tokyo like the Yamanote and Keihin-Tohoku lines [8].

B. Digital Automatic Train Control

The conventional ATC is safe and reliable. However, the conventional ATC had some limitations due to technology constraints [2]. It was developed using technologies of the 1970s which used electromagnetic relays. In addition, improvement in the way of life of the Japanese society also influenced the demand for comfortable rides on public transport[5]. The use of multilevel braking is not good for ride comfort and operation efficiency. Therefore, there was need for improvement [6]. In 1998 a decision was made to develop a new ATC system because the old one was aging and also to address some of its short comings. Therefore, the D-ATC (autonomous decentralized/digital ATC) was developed by JR East for Shinkansen. The D-ATC is based on the autonomous and decentralized system (ADS). D-ATC uses data communication and each train uses the data to calculate its own speed. In the Shinkansen it is called DS-ATC [2],[5].

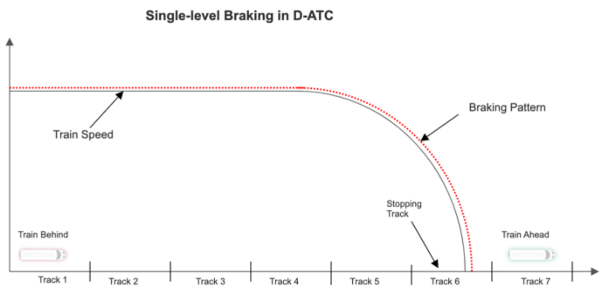

Fig 3: Single level braking in D-ATC.

The disadvantage of the conventional ATC system was that the method forces a speed check relative to the ATC signal, and a new signal is required to increase speed. This resulted in passenger comfort problems due to repeated braking and releasing until the train stopped. A solution was to give information about a limit section for a running stop like the ATS-P. A speed check pattern is then generated relative to the brake performance and the distance to the stop point. This results in a single continuous pattern. Transmission information was transferred to the train from the ground using digital telegraphy thus this was known as digital ATC (D-ATC)[4]. The JR East company developed the DS-ATC for the Shinkansen which utilizes digital communications control. The DS-ATC uses the on-board equipment thus it allows for reduction of trackside equipment. The braking system is changed from step wise to one-time command control thus it improves passenger comfort. The system also reduces arrival time and the time between train intervals. The system incorporates the use of technologies like microcomputers, digital radio communications and databases. The amount of communication between on-board computer and trackside computer is increased. Cost and construction processes are reduced because of fewer system components required[6]. The track circuits are detected by the ground equipment depending on the present positions of preceding trains and signal conditions. Necessary information is transmitted to the onboard equipment. The onboard equipment checks from the database the braking pattern for a single-level brake control that enables the train to stop at the detected stopping track.

The determination and control of distance between trains is important in ensuring safety and operating optimally. Functions like exact positioning and high-speed communication between the onboard and ground equipment are required [7],[8]. The major difference between the conventional ATC and D-ATC is that the D-ATC is an on-board intelligent control system. Every train computes its permitted speed according the stopping information it receives from the central control. The benefits of D-ATC include increased traffic density, reduction of ground equipment costs due to the use of general information equipment, increased safety and reliability, improved passenger comfort and also flexibility to change headways without changing the ground equipment. The D-ATC reduces construction costs by 20% and decreases traditional operating interval from 2 minutes 30 seconds to 2 minutes [2]. The DS-ATC was first introduced to new lines that were extended on the Tohuku Shinkansen line in December 2022. The old Tohoku-Joetsu Shinkansen ATC were than replaced. The rest of the system was replaced with DS-ATC after that [6].

C. D-ATC System Functions and Equipment Composition

The ground equipment is composed of the following devices:

1) ATC Logic Device

The ATC logic device collects data about trains on the line, train routes and site equipment. It monitors the trains using this data and prepares ATC telegraphs that are transmitted to each track circuit.

2) Transmission Control System (TCS)

The TCS translates ATC telegraphs it received from the ATC logic device and transmits the information to each transceiver. It also detects trains based on information it received from each transceiver.

3) Transceivers

Each track circuit has one transceiver. ATC telegraphs are transmitted to a track circuit by the transceiver after modulation. In reverse the transceivers demodulate signals from the track circuit and transmit the to the TCS for train detection. The Minimum Shift Keying (MSK) modulation technique is used.

4) ATC Monitor

The ATC monitor records the signal currents that flow in the track circuits as maintenance information.

5) Gateway

The gateway interconnects ATC devices installed in adjacent equipment rooms.

The on-board equipment is composed of the following devices:

1) Receive and Control Unit

This unit uses the stopping position information from the ground equipment to find the braking patterns stored in the database. It compares the braking pattern with the current position of the running train and issues braking patterns accordingly. It shows the permissive speed on the speedometer.

2) Inspection and Recording Unit

The unit records inspection and performance history. It also shows performance conditions on the monitoring device.

3) Transponder

The transponder gives position information it receives from the wayside coils installed at every three kilometers to the receive and control unit

4) Speedometer

It indicates the permissive speed signal and train speed.

D. Advanced Train Administration and Communication System (ATACS)

Traditional signaling systems used a lot of ground equipment that included track circuits for train detection, wayside signaling equipment for train control, level crossings etc. [9]. The equipment is often installed in rough condition extreme temperatures or excess vibrations that results in frequent breakdowns. Maintenance and replacement costs are often very high. The maintenance work is also labor intensive and prone to staff injuries. In order resolves these challenges the ATACS was introduced. The Research and Development Center of the JR East started developing the ATACS in 1995. The aim was to put intro practical use the Computer and Radio Aided Train control system (CARAT). The Railway Technical Research Institute had been researching the CARAT system[10]. It is a controlling system that uses radio transmissions and onboard equipment. This reduces trackside equipment [11].

ATACS is similar to the European ERTMS/ETCS level 3, CBTC and the North American Positive Train Control. It is different from traditional systems because it determines train position using onboard equipment instead of track circuits. The ground equipment and train communicate using digital radio communication. The train onboard display shows the transmitted signal[3]. ATACS enables full moving block signaling. The onboard computer computes the train's location and transmits to the ground controller. The ground controller continuously transmits the Limit of Moving Authority (LMA) to the trains relative to the locations of all the trains on the network. A parabolic braking profile is calculated by the onboard computer for the train based on the LMA sent by the ground controllers [11]. The ATACS system has a closed loop control system with a level crossing controller. The level crossing controller generates a pattern to permit the train to go through a level crossing only when it has confirmed that there are no obstacles and the gate is closed. The system is safer and it increases the efficiency of the train operation [4]. ATACS was first installed for commercial operation on the Senseki Line in October 2011. After that it was introduced in the Tokyo metropolitan on the Saikyo Line [4], [11].

Table 1: Comparison of ATACS and traditional systems.

Traditional Signaling Systems	**ATACS**
Many trackside facilities Color signal (every several hundred meters) Balises for each signal Signal box Multiple cables	Few trackside facilities. Radio base station (Every 3km) Balises for location refreshment (Every 3km) Reduction of cables

The advantages of implementing ATACS include improved railway safety, stable transportation, cost reduction, and improved follow-up to changes

1) Improved railway safety

The speed profile of the train is always being calculated by the on-board controller. If braking is necessary the system automatically engages the brakes. This reduces excessive speed and accidents due to human error. If a car breaks down on a level crossing, it is detected and the control stops the train before the crossing.

2) Stable transportation and cost reduction

The railway system is divided into a number of control areas. Ground equipment and radio base stations are installed accordingly. The purposes of the ground equipment are train positions tracking, distance between trains control, switching control and level crossing control. Radio base stations share information with the onboard equipment[3]. The intervals between the ground equipment and radio base stations are determined by the service area of each set of equipment. The onboard controller engages brakes and sends train position information to the ground controller. The initial step is to determine the train position as measured by the onboard controller. When a train enters the boundary of a section its position is recorded. The onboard controller detects the trains speed and use it to track position. When the train passes another position device its position will be corrected [2]. The detected position is structured into the identification numbers of the ground device in the given relevant area of control. The control area is divided into virtual blocks. The onboard controller and ground equipment determine the appropriate virtual block and the position in the given bock. Depending on the radio restrictions for transmission distances two base stations are usually set three miles apart.

Four different frequencies are used in order to prevent interference between neighboring base stations. Every base station must connect trains as they pass it. The communication with each station is in 1 second cycles. To compensate for mistakes during communication the space difference system and Reed-Solomon code are used [2]. One onboard control and the radio system replace the large number of complicated trackside equipment like the conventional track circuits. This minimizes and simplifies the trackside equipment. This results in reduced failure and stabilizes the transportation system. This also lowers operation and maintenance costs [11].

3) Improved follow-up to changes

The need for signaling system follow up changes after rail track changes or rolling stock performance enhancement are reduced.

E. Main Features ATACS

In ATACS there is interactive radio communication between trackside and onboard control equipment. The trackside equipment gets train position and the onboard equipment receives routing and safety information in real time [9],[11].This enables efficient train interval control (moving block), more efficient test runs using actual cars and control of level crossing using radio communication.

1) Efficient train interval control (moving block)

In ATACS, onboard devices detect the positions of all trains. The rear point of the train ahead is used to calculate the position to which the train following may run (stop limit). Therefore, the intervals may be efficiently controlled.

2) More efficient test runs using actual cars

Simulations of the actual running conditions may be performed in the factory before actual tests runs are performed. This helps improves the actual test runs.

3) Level crossing control by radio

ATACS enables control of level crossing using radio communication. Level crossing control for commercial service using ATACS was started on Senseki Line in December 2014 [11].

F. Main Components ATACS

In the ATACS system running trains detect their own position and control their operations based on interactive communication between the trackside and onboard control devices. It departs from the track circuits detection method that has been used for more than a century. It consists of onboard devices, trackside devices and radios that are responsible for the radio communication between trackside and onboard devices [10].

Wayside equipment

1) Ground controller

The ground controller is the main control equipment of the trackside devices that is responsible for the identification of train positions using information from onboard control devices, control of routes to ensure safe required routes, control of train intervals and establishment of boundaries. It also performs boundary control whereby entry and exit of trains is controlled at the system boundary.

2) Train existence supervision equipment

The train existence supervision equipment is responsible for managing the IDs of all on-board control devices present in the ATACS system, and also backing up the ground controller in case of system failure.

3) Field controller

The field controller connects ground controllers with field equipment like switches, level crossings and radio base stations.

4) Balise

A balise transmits train location to onboard controllers to help enhance onboard controllers' accuracy in train positioning. It is placed every one kilometer.

Onboard equipment

Onboard equipment for ATACS is made up of the onboard controller that controls the train and the in-cab indicator that provides the driver with information . The onboard controller detects the trains position, sends the position information to the ground controllers using radio communication. It then receives the stop limit from the ground controller. Using the stop information, track gradient and speed limit the onboard controller generates a braking pattern to perform speed checks and braking control. Control units are concentrated at the lead car.

Radio system

The radio system is comprised of the radio base station (connected to a ground controller) and the onboard radio station (connected to an onboard controller). Both are in duplex for back-up. The system conforms to the narrow band digital radio standard required by the Japanese Radio Law. It employs the four-frequency reuse to protect against interference from other radio base stations and also efficiently use the radio signals. Each radio station is placed at positions where it can control an area of 2-3 km [11].

VI. Conclusion

Train control is an important component of railway systems that improves safety and operational efficiency. Several different types of control systems have been developed in many countries. This paper reviewed the Japanese train control systems that have been developing over the years. The first-generation control system was the ATS-S. The system enabled automatic braking when the driver did not respond to warnings in dangerous situation. The system helped reduce accidents however it had challenges like its susceptibility to human error. To improve the ATS-S, the ATS-P was developed. The ATS-P helped reduce the susceptibility of the ATS-S to human error. However, the ATS-P also had its challenges especially for use in the control of high-speed trains like the Shinkansen. To enable better control at high speeds the conventional ATC was introduced. The system provided onboard speed display and automatic speed control. However, the system used multilevel braking which caused ride discomfort. The D-ATC was introduced which was more intelligent and could compute a single level speed pattern that improved the comfort of the ride. Finally, the ATACS system was introduced. The system takes advantage of the improved radio communication technology. The system uses radio communication to detect the speed and location of the train. It then also uses the radio communication to send control instructions to the onboard control system on the train. The system reduced the amount of ground equipment required.

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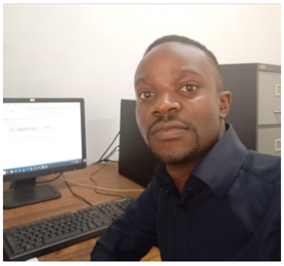

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