Breakthroughs in Japanese Railways 2

Learning from Past Railway Accidents—Progress of Train Control

Masayuki Matsumoto

Introduction

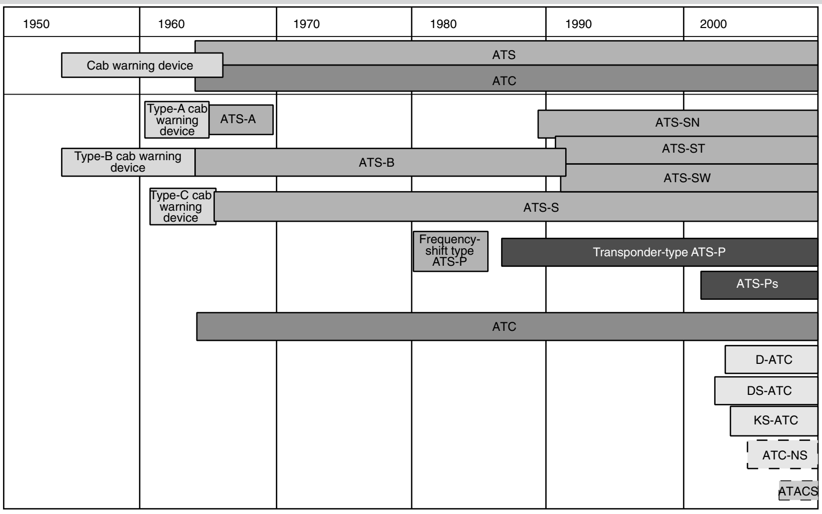
The earliest railways had no signal systems, so station employees had to use hand gestures to train drivers indicating whether to stop or go on. Even so, there were still many train collisions because drivers missed or ignored the hand signals due to human error. The race was on to develop fool-proof signalling system that could prevent train accidents. However, it was more like an arms race because as soon as a new system was introduced to prevent one type of accident, another accident caused by another type of error required yet another new system. This race has culminated in today's almost accident-proof train-control systems, but even so, new train control systems are still being developed with the focus on improving operation efficiency and passenger services quality.

This article describes the development and improvement of train control systems to prevent train accidents, with a focus on the train operation mode and related technologies.

Overview

Figure 1 shows the progress of train control systems. Since it was quickly realized that directing trains using signals (hand, semaphore, lamp, etc.) alone could not stop train accidents, cab warning devices indicating to the train driver that the train was approaching a stop signal soon came into common use but even so, train accidents ascribable to driver oversight occurred from time to time. To solve this problem, automatic train stop (ATS) systems—which took the driver partly out of the equation by adding the ability to stop the train automatically—were added to the cab warning system. In this design, the ATS halts the train by automatically applying the service brakes if the driver overlooks or disregards a warning signal in the cab. But there was one clear drawback, once the driver acknowledges the in-cab warning (usually by pressing a confirm button), the automatic stop system is overridden and the train can proceed, so if the driver confirms the warning by mistake, a collision can still occur.

Figure 1 Progress of Train Control Systems



To solve this drawback, a new ATS-P system was brought into service. With ATS-P, the train speed is constantly checked against a speed pattern to bring the train to a halt at a stop signal. The ATS-P sends digital data about the distance to stop signals by transponder to on-board equipment which checks the train speed pattern against a reference model and automatically applies the train brakes if the train speed exceeds the pattern. Since the system reduces the number of braking stages, train headways can be shortened to improve train operation efficiency.

However, on high-speed sections with trains operating at very short headways, failure to respond to any signal aspect for any reason can lead to a very serious collision within seconds. Therefore, another system that continuously displays permitted speeds on an in-cab monitor and automatically applies the service brakes was needed. Today, this is called automatic train control (ATC); it was introduced first in late 1960s on the Tokaido Shinkansen where trains were running faster than 200 km/h because drivers could not safely recognize trackside signal aspects and could not respond quickly enough even when they saw the signals.

Some time slightly before the debut of ATC on the Tokaido Shinkansen, the Hibiya subway line in Tokyo introduced a trackside signal-based ATC system—the result of R&D into automatic train operation—to improve train safety and operational efficiency. Then an in-cab signal-based ATC system to prevent driver mistakes was put into service on the Nagoya subway. This was soon followed by an installation on the Joban Line of Japanese National Railways (JNR) to support through operation with the Chiyoda subway line.

ATC is a continuous control system that has improved the safety of train operation much more than ATS, which is an intermittent control system. This is largely because ATC assures safe train operation even if the driver misreads a traffic signal. In ATC, the trackside equipment transmits an ATC signal matching the control train speed to the track circuit and the on-board equipment receiving the ATC signal displays the signal on the monitor and slows the train according to the signal. However, ATC is relatively old technology that was developed during the early stages of the Tokaido Shinkansen and has problem, including inability to cope with increasing numbers of trains.

The ideal train control system would determine the distance to the position where the train must stop—the only information needed to prevent a collision with the ahead train—and stop the train there safely. In this case, the basic required system information is the current exact train position and exact position where the train must stop. Reconsideration of the purpose of conventional train control systems led to new decisions on the basic functions of a new train control system where the trackside equipment transmits the position where the train must stop to the on-board equipment, which determines the current position of the train and calculates the distance to the stop position. The system applies the train brakes as necessary at curves and on down grades. These are the operation principles of the newly developed digital ATC (D-ATC).

Existing train control systems have been in long use and boast high degrees of safety. At the same time, they have contributed to better track utilization. However, some of the technologies, such as detection of train position using track circuits and transmission of data to the on-board equipment via the rail, are very old. There has been recent remarkable progress in mobile communications and computer technologies which can be used for train control systems to reduce the amount of ground equipment and cut costs. Therefore, we are developing a new wireless train control system (ATACS) using digital radio, computer and information technologies (IT) that adopts a new framework for trackside and on-board equipment functions.

Railways and Signals —Human Errors

In 1804, the Cornishman Richard Trevithick built the first steam locomotive to run on rails, marking the start of railways. In 1814, the English engineer George Stephenson built an improved steam locomotive and spent a great deal of effort constructing a 40-km line from Stockton to Darlington. The line was finally completed in 1825 with the successful operation of *Locomotion* hauling freight trains. The world's first commercial passenger railway was opened in 1830 between Liverpool and Manchester. A signal system was introduced years later to passenger lines to secure safe train operation and handled increasing traffic volumes.

Japan's first 29-km government railway opened between Shimbashi and Yokohama in 1872. It was soon followed by rapid expansion throughout the country—despite some local opposition—and railways played a leading role in the government's 'rich country, strong arms' policy.

Early railway signals

In the first days, a man on horseback rode in front of the train waving a flag to warn people that the train was approaching. As speeds increased along with more junctions, a guard was stationed at each critical point to ensure safety using three hand gestures: danger (both hands raised above head); caution (one arm raised above head); and safe (one arm stretched out sideways). Some time later, a permanent signal consisting of an upright pole, crosspiece and lamps was installed at each critical point. The crosspiece was set at right angles to the line (unseen from the train) to indicate danger, and parallel to the line to indicate safe. This device evolved into the three-aspect semaphore signal, indicating danger, caution, and safe by setting a rectangular board at various angles. The semaphore signal soon became widespread in Japan.

Various other safety devices were invented in quick succession, including equipment preventing entry of more than one train into a tunnel at one time, the fixed block for preventing train collisions, and the track circuit for detecting trains. All contributed to much-enhanced train safety and many present signal systems are still based on the core concepts of those 19th century technologies.

When Japan's first railway opened between Shimbashi and Yokohama, 16 semaphore signals of two types were installed: station semaphores (one pole with two arms), and distant semaphores (one pole with one arm), each with three aspects. The arm face was red and the back was white. An upright aspect (with white lamp at night) indicated safe, a 45° downward tilt (with green lamp at night) indicated caution, and a horizontal position (with red lamp at night) indicated danger.

Operations mistakes and accidents

The world's first railway accident occurred at Parkside Station in England in September 1830 when a Member of Parliament who had helped establish the railway company was hit by a train as he trespassed on the track. Many accidents occurred in following years. In Japan, the first railway accident was a derailment and overturned train caused by some problems with a turnout in the Shimbashi Station yard on 11 September 1874. In those days, train operation were controlled by telegraph communications between stationmasters. After a head-on collision caused by one train departing before the stationmaster gave the departure signal, the staff-and-ticket block system, which permits only one train in one-track section, was introduced earlier than planned. In another accident, a train ran from a side track onto the main track of a single-track section to collide with another train. This accident led to the development of the safety siding system, which derails an over-running train rather than let it trespass onto the main track—a system that is still used today. After another head-on collision between opposite trains in a single-track section was caused by the illegal issuance of a tablet, the block equipment was modified to prevent tampering.

As described, each of the many railway accidents in the 19th and early 20th century was followed by an improvement to the signal system. Nevertheless, railway accidents still occurred from time-to-time.

Evolution from Cab Warning to ATS-P

Early cab warning devices

The 1920s to 1940s in Japan saw testing and development of cab warning devices that eventually evolved into ATC devices. In 1921, the magnetic induction type ATS (using permanent magnets on sleepers) developed in the United States was tested on the Shinagawa–Shiodome section of the Tokaido Line. Some time later, similar ATS tests were made on the Tsukaguchi–Kanzaki (now Amagasaki) section of the Amagasaki Line belonging to Hankyu Railway, and the Kikuna–Kozukue section of the government railway's Yokohama Line. Around 1930, to meet the need for higher-density train operations, the government railways considered operating trains at a headway of 90 s on the Tabata–Tamachi section shared by the Keihin Line and the Yamanote Line. To that end, the trip arm type ATS, which mechanically transmits the signal aspect to the on-board equipment, was tested at Yurakucho Station in January 1933. However, there were also plans to increase capacity by quadrupling this section, so the ATS project was abandoned.

Following this, the government railways tested a cab signal system on the Kikuna–Kozukue section of the Yokohama Line and the Hodogaya–Totsuka sections of the Tokaido Line. In February 1937, a simpler cab warning system was tested on the Tokamachi Line. It issued a warning to the train crew when the home or distance signal could hardly be seen in heavy fog or snow.

When a 3-minute headway was planned for the Kanmon Tunnel (opened June 1942), a combination of a closing-in system and ATS system was tested on the Shonan section of the Tokaido Line in July 1940. After good results, in December 1942, it was decided to introduce the combined system on the Tokaido, Sanyo, and Kagoshima lines as well as several electric railways in Tokyo and Osaka. However, after most of the ground equipment and scores of on-board units had been installed, they were destroyed by air raids and the project did not come to fruition.

In January 1947, testing of the same magnetic-induction type intermittent cab warning system tested in 1937 was resumed at Minakami Station on the Joetsu Line. The on-board equipment was composed of a pickup coil excited by a DC power supply and a main relay connected in series with the pickup coil and operating at all times. The trackside equipment was a coil called an inductor. The pickup coil and inductor were arranged so that they coupled outside the track gauge. When the pickup coil coupled while the inductor coil was open, the main relay tripped, issuing a warning to the driver. However, MacArthur's General Headquarters (GHQ) rejected a request for permission to continue construction and work had to stop.

Accident at Rokken Station and cab warning system

Rear-end train collisions were common after the war, especially on electrified sections. The April 1947 collision between commuter trains near Tabata Station on the Tohoku Line caused 118 casualties. Many of those accidents were ascribed to stop-signal violations by careless or overstrained crews. Clearly, development of a cab warning system was an urgent priority. Around 1950, studies were started on devices for preventing rear-end collisions on electrified sections. The study showed a cab warning system would be effective for preventing rear-end collisions on commuter sections characterized by short block lengths and high-density operations.

Therefore, the newly formed JNR developed a cab warning system using current in the track circuit at commercial frequency. A relay circuit is connected to the sending end of a conventional track circuit. When the relay detects that a train is approaching the braking point side of a stop signal, the current from the track circuit is interrupted, issuing a warning to train crew. Consequently, when the track circuit becomes 'no current,' the main relay of the on-board equipment opens and a warning is issued to the crew. The system was called the continuous induction Type-B cab warning system using vacuum tubes. It was put into use in December 1954 on the electrified sections of the Yamanote Line and Keihin Tohoku Line.

About 2 years later on 15 October 1956, a collision between trains at Rokken Station on the Sangu Line killed 42 passengers and injured 94. The accident occurred because the driver of the down train misunderstood that his train, which had already passed Rokken Station—the station where it passed the up train—had been changed from Matsuzaka Station to Rokken Station and entered the safety siding where it collided with the up train.

Since many of the victims were school students on a trip, the accident was a great shock to Japanese society. In the accident's wake, JNR decided to adopt a new cab warning system that gave an audible stop signal to the driver. At the same time, JNR pressed ahead with automation of signal devices and use of coloured lamps for signalling.

The Type-B cab signal system developed for electrified sections with a fixed braking distance is unsuitable for sections serving trains with different braking distances. As a result, JNR studied two new types of cab signal systems: the Code Type using several different code currents obtained by turning an AC current off and on, and the Track Circuit Type, passing a frequency of about 1 kHz to the track circuit. Eventually, the latter type was adopted due to its advantages. This device was called the Type-A cab warning device in which a 1300-Hz AM waveform is superimposed on the track circuit at commercial frequency to issue a stop-signal warning to the train crew. Since transistor reliability was still poor, vacuum tubes were used for the circuits (Fig. 2). The system was introduced on the 689-km section between Tokyo and Himeji and entered operation in July 1960.

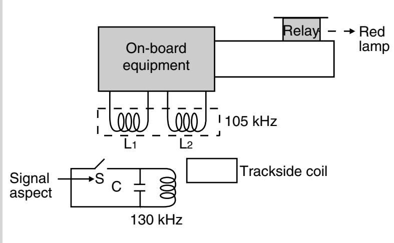
On the other hand, JNR developed a system using the change in magnetic flux that occurs when a ground-based inductor couples with the on-board pickup coil. There are two system types: the frequency-shift type, and the absorption type.

The former type consists of a ground-based resonance circuit and an on-board special feedback oscillation circuit. It utilizes the phenomenon in which the normal oscillation frequency (105 kHz) changes to the resonance frequency (130 kHz) of the trackside coil when the pickup coil couples with the trackside coil as the ground circuit is short-circuited or opened.

The latter type uses the same trackside coil as the frequency-shift type, but is based on the principle that the oscillation stops when the trackside coil couples with the pickup coil. Prototype systems were subjected to various tests and the frequency shift type was found to be superior in terms of stability, sensitivity characteristics, etc. This system was called the Type-C cab warning system and it was adopted in August 1957. From early 1958, about 1100 trackside coils and about 450 pickup coils were installed over a total track length of 957 km on the Hokuriku, Shin'etsu, Uetsu, and Ou lines, but because there were some instability problems only thoroughly checked steam locomotives were operated between Maibara and Aomori in June 1961.

In 1958, two different prototypes of the Type-B cab warning system with added ATS capability were tested. One was a prototype of the ATS-B put into practical use later. It had a function to apply the train brakes automatically unless the driver pressed the confirm button within 3.5 s after the warning. The other had train identification and speed check functions; both were tested on the JNR Chuo Line in March 1959 with good results (Table 1). In particular, the operation principle of the latter prototype was applied to the design of an ATS for implementing through services on the Keihin Electric Express Line, Tokyo Metro Asakusa Line and the Keisei Line. It became the prototype of the later so-called ATS-1.

Figure 2 Operating Principle of Cab Warning System

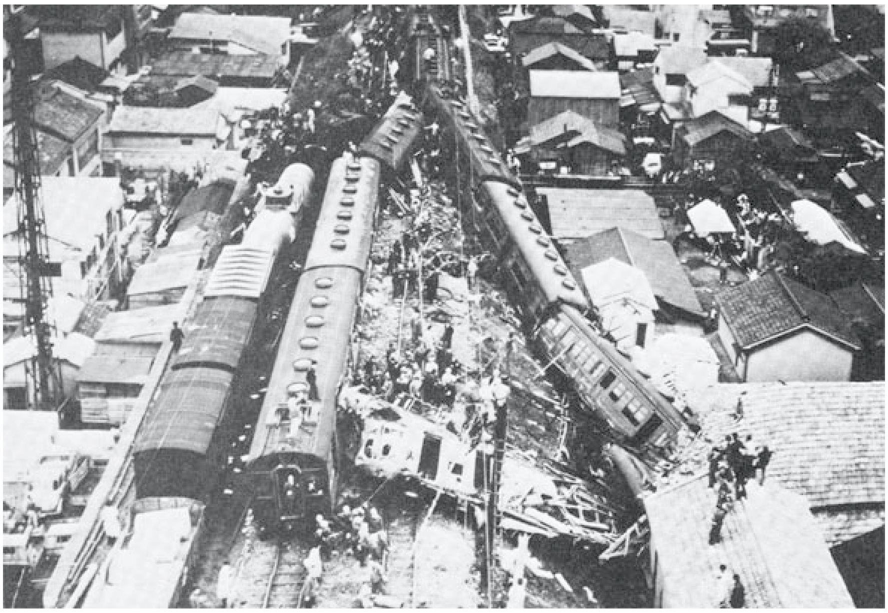


Mikawashima disaster and ATS

In January 1960, a train with the Type-A cab warning system collided with the preceding train near Yurakucho Station. After this accident, the need to add an ATS capability to the cab warning system was discussed and 18 plans were studied as the result. In 1961, four promising types were prototyped for performance and endurance tests. They were the PM type using permanent magnets installed on the ground; the loop type using a loop coil; the frequency-shift type using the

Table 1 Types of Cab Warning Systems

	Type-A		Type-B	Type-C		
Type	Track circuit	Code		Type C-1	Type C-2 (frequency shift)	Type C-2 (absorption)
Application	Important trunk lines		Electrified sections	Quasi-trunk lines		
Operating principle	Signal current passed to track circuit, from which modulated signal current transmitted to on-board equipment		When arrival of train at braking point detected by relay, track circuit current interrupted for specified time to transmit warning signal to on-board equipment	Trackside coil exciter current switched on and off to transmit warning signal to on-board equipment	On-board equipment frequency changed by resonance with trackside coil	On-board equipment oscillating energy absorbed by trackside coil
	Amplitude modulation of 1300-Hz fundamental wave	Code generated by turning on and off 1300-Hz fundamental wave				



Scene of Mikawashima disaster (JNR CPH)

change in coupling resonance frequency of the trackside coil and pickup coil; and the oscillation-stop type using the phenomenon in which the impedance of the pickup coil changes and the oscillation stops when the pickup coil couples with the trackside coil. The PM type malfunctioned frequently and could hardly secure the required S/N ratio while the oscillation-stop type had practical problems (difficulty in securing trackside coil resonance frequency appropriate to pickup coil oscillation frequency). Therefore, only the frequency-shift type and loop type were subjected to long-term tests with the former on the Shin'etsu and Joban Lines, and the latter on the Hachiko Line.

As tests continued, the worst railway accident in JNR's history occurred in 1962 at Mikawashima Station, killing 160 passengers and injuring 296. A down freight train in the Mikawashima Station yard on the Joban Line, entered the safety siding when the driver missed the stop signal. The locomotive and one freight wagon derailed, blocking the main track of the down line. A following down train hit the freight train and derailed blocking the main up line. Six minutes later, an up passenger train collided with the previously derailed cars, derailing its first four cars. This disaster prompted the decision to introduce a new ATS, combining a cab warning system and ATS. As a result, the frequency-shift type ATS was introduced on all JNR lines by April 1966. It was called the Type-S cab warning system (ATS-S). Trackside coils were installed at about 43,300 points on the ground and pickup coils were installed on about 13,000 carriages.

As shown in Figure 3, the ATS-S system warns the driver of red signals and stops the train automatically if the driver fails to apply the brakes properly. When the train approaches a stop signal, the system warns the driver by a bell, chime and red lamp, prompting the driver to confirm the signal. If the driver does not confirm the signal within 5 s, the system automatically applies the emergency brakes to stop the train. As long as the driver confirms the signal properly, he can continue operating the train himself. However, if the driver makes a mistake in the confirmation procedure, it can lead to an accident. This is a weak point of ATS-S.

On the other hand, a detailed study of ATS-A, which is a modified version of the Type-A cab warning system, was carried out. As a result, a system that makes good use of the advantage of continuous control was put into use in July 1965. However, since ATS-S had already become widespread and the Type-A system employing vacuum tubes had a short life, the Type-A system was retired in 1970.

A study on modification of the Type-B cab warning system into an ATS was started in 1963. While the trackside equipment was kept unchanged, the method of handling the warning by the crew and the connection of the warning system with the brake system were modified and a new receiver using transistors in place of vacuum tubes was developed. The introduction of the new ATS was started in September 1964.

Accidents at Hirano and Nishi Akashi Stations and ATS-P

After a derailment at Hirano Station on the Kansai Line in December 1973, it was decided to add a speed check ability to ATS-S because of the following three problems.

- No ability to check train speed
- After train driver confirmed warning within 5 s, subsequent safe operation dependent entirely on him.
- Ground equipment transmitted information to on-board equipment only when train at some specified point ahead of stop signal.

In addition, since the warning point was set at a point where even a train with brakes with the poorest performance could stop before the stop signal, the warning was issued even to trains with good brake performance. Therefore, the warning did not always indicate a critical condition. And because warnings were issued too frequently the effect was less than initially expected.

To solve these problems, it was necessary to transmit the signal aspect and distance to the signal to the on-board equipment, meaning an increased volume of information transmitted to the on-board equipment. Therefore, considering

Figure 3 ATS-S Operating Principle

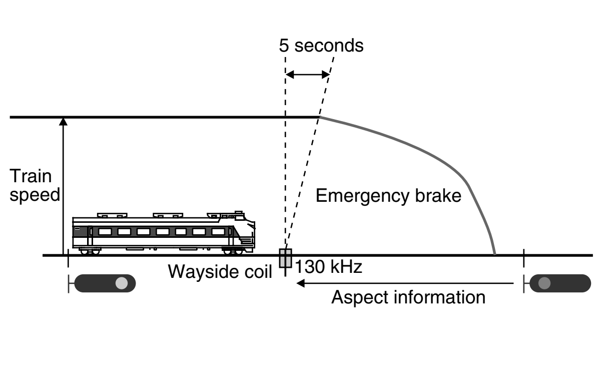
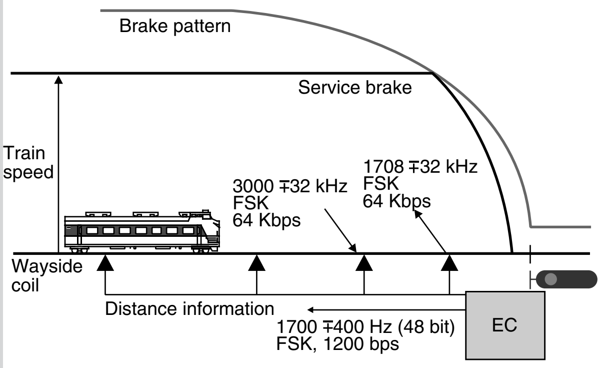


Figure 4 ATS-P Operating Principle



compatibility with existing Type-S systems, JNR started development of a new multi-frequency shift-type ATS, allowing a wider range of frequency shift. This new system provided on-board equipment with a speed check pattern to eliminate the need for crew confirmation and added the ability to generate a speed check pattern based on information supplied by a trackside coil some distance before the signal. The system was tested on a train running between Nara Station and Minatomachi Station on the Kansai Line. After satisfactory test results, the system was installed on the Nara–Minatomachi section and entered operation in May 1980.

Nevertheless, on 19 October 1984, the *Fuji* limited express sleeper derailed at Nishi Akashi Station on San'yo main line, injuring 32 people. Although the speed that the train could pass the turnout in the station yard had been regulated, due to a change in course from the main track to the sub-track for track maintenance, the driver operated the train at the normal speed of about 100 km/h, hitting the platform. The accident was due partly to the inability of ATS-S to check speed.

Those days saw massive increases in the number of trains, especially express and limited expresses, and in train speeds. Because more accidents were being caused by stop signal violations, it was realized that ATS functions could not completely prevent this kind of accident. Therefore, there was an urgent necessity to introduce an advanced new ATS with full compatibility with actual JNR operation conditions. The multi-frequency shift-type ATS-P described above had about 10 applicable frequencies, which was insufficient for the large volume of information required to implement the function, so it was decided to develop a transponder-type ATS-P with transponder for exchanging 48-bit data between the trackside and on-board equipment, permitting the on-board equipment to control the train speed to the prescribed speed pattern. In developing the new system, it was decided that the train operation should be kept unchanged (the driver would still operate the train according to the signal aspects), that the new system should be used as a backup facility, and that the new system should have the following functions:

- If the train approaches a stop signal and the driver fails to apply the brakes correctly, the system automatically applies the emergency brakes to stop the train after the signal.
- Even if the driver starts the train by mistake through misreading a signal, etc., the system automatically applies the service brakes.
- The system maintains the ATS functions at all times.
- As far as possible, the system offers measures to prevent violation of speed limits at turnouts and curves and violation of shunting signals on the main track.
- The system does not interfere with efficient rail transportation even in sections in which trains are operated densely.

The basic ATS-P operation principle is that when the signal aspect is stop, the trackside coil ahead of the signal causes the on-board equipment to generate a speed check pattern (brake pattern) based on the distance to the signal and train speed (Fig. 4). The service brakes are applied automatically to stop the train safely after signal only when the train speed exceeds the brake pattern. Therefore, the ATS system never intervenes in train operation as long as the train speed is within the brake pattern. If the train speed exceeds the brake pattern due to driver operation error, the brakes are applied immediately. Consequently, ATS-P has a very sophisticated man-machine interface compared to ATS-S.

Technically, the receiver is a compact, reliable simplex system achieved by stabilized circuit characteristics, use of ICs, introduction of a newly developed ceramic filter, compact electromagnetic relay, and wet reed relay, self-diagnostic functions, logic circuit for troubleshooting, etc. The compact trackside coil with stable and reliable characteristics can be installed on a wide sleeper.

ATS-P prevents accidents due to signal violations and over-speeding at turnouts, curves and down grades. It also speeds up signal indications for high-deceleration trains. The information about whether a train has high, medium, or low deceleration is transmitted from the on-board equipment to the trackside equipment, so the signal aspect can be changed as required. The train number and some other information can also be transmitted to the trackside equipment. Consequently, ATS-P has a wider application scope, such as constant warning time control of level crossings based on train control and train speed and passenger broadcasts.

Accident at Higashi Nakano and ATS-P promotion

In September 1988, JR East planned to introduce ATS-P to the Chuo Line, Joban Line, etc., but it was introduced to the entire line on 1 December 1988, when the Keiyo Line opened. A rear-end collision occurred at Higashi Nakano Station on the Chuo Line just a few days later on 5 December, killing two passengers and injuring more than 100, when a local train collided at about 40 km/h with the ahead local train stopped near Higashi Nakano Station. The accident can be ascribed to ATS basic functions. Although ATS does issue an audible warning, the warning is reset when the driver presses the confirm button and the driver can then continue operating the train without ATS intervention. Since the train was running on a tight schedule, the driver could have violated the red signal to try to make up time but some experts think that the driver could have failed to detect the ahead train early enough to stop safely because the site is on a sharp left curve on a down grade.

After this accident, JR East brought forward the planned introduction of the new ATS-P system. At the same time, the company increased the sections where the new system would be introduced. In May 1989, the ATS-P system was first introduced to Ueno Station on the Tohoku Line. By late 1991, it was introduced on the main sections (totalling 240 km) of the Tohoku, Chuo, Sobu, Joban Line, etc., in the Tokyo area; expansion continued and also introduced the system on the Yamagata Shinkansen and Akita Shinkansen. Today, some 1500 km in the Tokyo Metropolitan area are protected by ATS-P.

ATS-S Improvements

Although the newly developed ATS-P system was introduced on major trunk lines, other sections still used ATS-S, so the new companies in the JR group studied ways to correct defects in ATS-S.

One method was to install a 123-kHz trackside coil at the absolute signal to actuate the emergency brakes when the signal aspect is stop, preventing signal violation. This is JR East's ATS-SN.

Another method was to implement both a speed check function in which the on-board equipment measures the time that the train takes to pass two 108.5-kHz trackside coils and actuates the brakes when the train speed is higher than the prescribed limit, as well as a function informing the on-board equipment of a stopped ahead train. This is JR Central's ATS-ST. JR West has introduced ATS-SW with very similar functions to ATS-ST but using microcomputer-based on-board equipment. All these systems use frequency multiplexing and transmission frequency overlapping developed for the multi-frequency shift-type ATS-P system.

Road to Cab Signal —ATC Development

Tokaido Shinkansen

The Tokaido Shinkansen started revenue operations Tokyo and Osaka in October 1964 just before the 1964 Tokyo Olympics. It used an ATC system with cab signalling to display a speed signal on the driver's console for automatic speed control. ATC played an important role in assuring the safety and stability of high-speed railways. ATC development required research on AF track circuits and an AF cab warning device in 1955.

The Tokaido Shinkansen was a remarkable innovation in railway signalling. Although introduction of electronic signalling typified by ATC and CTC underlies the shinkansen system, the concept of ATC with cab signalling dates back to 1938 when the first 'bullet train' project was planned. Technically, the kilocycle track circuit (introduced on the Hokuriku Line in 1957) and the Type-A cab warning device (introduced on the Tokaido Line in 1957) provided the foundation for ATC with cab signalling.

In developing the shinkansen, engineers realized that a continuous ATC would be indispensable to high-speed trains running at 210 km/h and that such signalling systems could be implemented most efficiently by a cab signal with automatic brake control based on the kilocycle track circuit (later AF track circuit) and Type-A cab warning device that had just been developed and put to practical use. The ATC was characterized by use of many newly developed transistors and a triple-redundant circuit to build a very reliable system as well as use of a signal device concentration method to facilitate signal installation and maintenance.

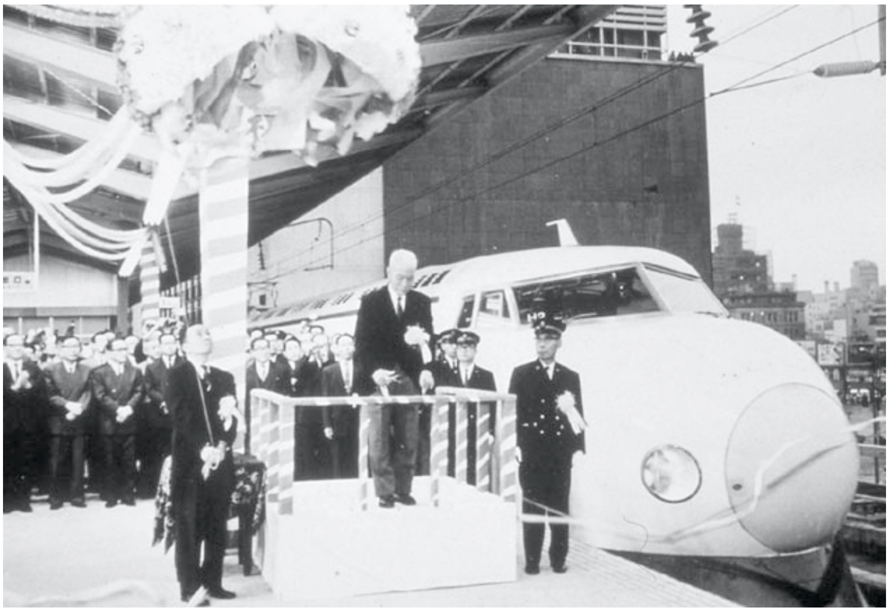
The 1955 research on AF track circuits and AF cab-warning device was followed by testing on the Senzan Line and high-speed testing on the *Kodama* commuter limited express in 1958. In July 1962, the first practical ATC was installed in the Kamonomiya signal box for general testing before the opening of the Tokaido Shinkansen.

After the opening, the ATC system continued to operate stably while other signal systems suffered teething troubles. Improvements to signal aspects, etc., were made when extra speed limit levers were installed for 160 and 110 km/h. About 10 years after the opening, the electrolytic capacitors had become so deteriorated that they were all replaced.

Just about the same time, ATC-related accidents occurred in Osaka and Shinagawa. In February 1973, a train ran on an unopened route to the main track in the Torikai carriage depot in Osaka, making the turnout trailable. In September 1974, at the Shinagawa carriage depot, a false proceed signal was caused by harmonic electromagnetic induction from a car-wash machine. These two accidents challenging the fundamental safety of ATC caused great shock to JNR, which soon established an investigation committee. As a result, the conventional single-frequency system was modified to a dual-frequency system to prevent false signals caused by spurious harmonics. This was the most important improvement to ATC. The modified system was first introduced on the Tohoku Joetsu Shinkansen. Subsequently, the Tokaido Shinkansen and Sanyo Shinkansen also introduced dual-frequency ATC system when renewing the obsolescent ATCs.

Introduction of ATC on private and municipal railways

The first subway in Asia was opened on 30 December 1927 between Asakusa and Ueno in Tokyo. As urban transportation, the subway incorporated various new technologies. Adoption of the trip-arm-type ATS is worthy of special mention in the history of Japanese signalling systems. This type of ATS was developed to improve safety on subways with high density operation at a minimum headway of 90 s. It was later adopted by many other subways. The trip-arm-type ATS transmits a stop signal to the train by mechanical contact between a trip arm on the ground and a trip switch on the leading carriage. When the train is allowed to proceed, the trip arm is forced down by compressed air, so it does not touch the trip switch. This type of ATS was used mainly by subways, because it could be a hindrance on level crossings, etc.



Tokaido Shinkansen opening ceremony (Transportation Museum)

Eventually, as it became necessary to review safety systems for train operations at higher speeds and shorter headways, introduction of a cab warning system was discussed. By that time, JNR had already prototyped a cab warning device. Looking at private railway companies, Tokyu Corporation began using a cab warning device similar to JNR's Type-B on the Toyoko Line in November 1957. Next, the company introduced the device on all its lines. In July 1964, Hankyu Corporation adopted a cab warning device for its Kobe Line.

However, an electric ATS was adopted for the first time by the Tokyo Metropolitan Government (TMG) Subway No. 1 Asakusa Line (between Asakusa and Oshiage) on 4 December 1960. Train protection systems were an important problem because the subway has through operations with Keisei Electric Railway and Keihin Electric Express Railway. Therefore, the three parties carried out joint R&D on signal systems, and decided to use an electric ATS based on JNR's Type-B cab signal system with a speed check ability. This was a great stride forward and the electric ATS was called ATS No. 1.

The Teito Rapid Transit Authority's (TRTA) Hibiya Line opened in March 1961 using ATC based on plans for through services with suburban lines. The ATC system and not ATS was adopted because the TRTA realized that any system should allow for future automatic train operation. Therefore, ATC was chosen because it permits automated braking and improves operation efficiency. Eventually, ATC was introduced on the Tozai Line and municipal subways in Osaka as well. Since these ATC systems were a backup to prevent driver mistakes, they were all trackside signalling types. The easier-to-handle ATC cab signalling was introduced first when Nagoya Subway No. 2 opened in October 1965 and has been introduced on many public and private railways.

Introduction of ATC on JNR narrow-gauge lines

In the 1960s, JNR had plans to add more tracks to the Joban Line. At the same time, it was planning through operations on Subway No. 9 (today's Chiyoda Line) planned by the TRTA. According to the plan, the Joban quasi-express line and the Joban local line would be considered independent revenue lines, so through service between them should not be implemented even in emergencies.

Figure 5 ATC Operating Principle

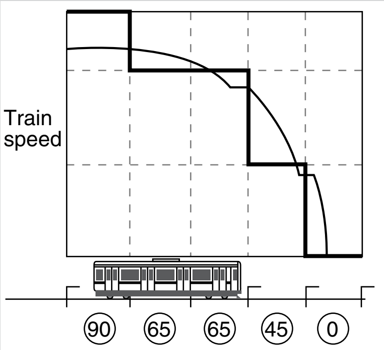
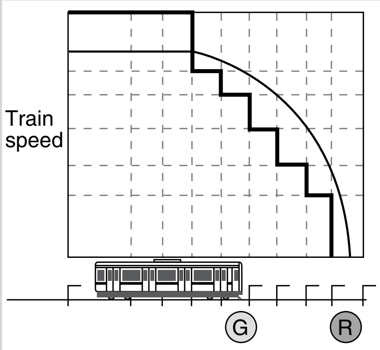


Figure 6 ATC with Continuous Braking Control Operating Principle



Therefore, JNR decided to use the same signal systems as Subway No. 9 to implement through service and install ATC and cab signalling systems. When through service started in 1971 between the Joban Line and the Chiyoda Line, JNR introduced the first ATC for a narrow-gauge railway. Specifications for the system were discussed with reference to shinkansen in Japan and several other systems at home and abroad. For a commuter train, the primary issue is reducing headways as far as possible. Ultimately, the 'overlap & half-overlap' system was adopted in view of transportation demand, vehicle performance, and technical problems.

Several accidents occurred before and after introduction of the ATC system, including a rear-end collision due to a mistake by the driver of a following train at Ochanomizu Station on the Chuo Line (July 1968: 210 injured) as well as at Funabashi Station on the Sobu Line (March 1972: 758 injured), and at Nippori Station on the Yamanote Line (June 1972: 158 injured). After these accidents, introduction of ATC on high-density operation sections in the Tokyo Metropolitan area was discussed in earnest, resulting in a decision to introduce ATC to the Yamanote and Keihin Tohoku lines. Although quick deployment was planned, the global oil crisis postponed the work which was not finished until 1981.

How exactly does ATC work? As shown in Figure 5, an allowable train speed in each block sections is pre-calculated from data on the presence of a train in a section. The ATC central logic unit transmits a signal indicating the allowable train speed to the track circuit. Since the wheels short the track circuit, the presence or absence of a train can be determined by monitoring the level of the receive signal. Therefore, the ATC signal is also used for train detection. The relationship between the track circuit boundary and allowable train speed is set to maintain the headway required for train control. The ATC central logic unit is almost exclusively responsible for controlling the interval between trains—the role of the on-board equipment is simply to apply the train brakes according to instructions from the ground equipment.

The ATC controls the train speed in each block by applying a frequency-modulated signal (10 frequencies from 16 to 77 Hz) allocated to each specific speed stepwise (90–65–65–45–0) to limit the speed carrier signal (one of four frequencies from 2850 to 3750 Hz) passed to the track signal and decelerate the train to that speed.

Although the present ATC has improved train safety and enhanced the transportation efficiency there are problems. The stepwise braking requires extra braking/releasing, making it difficult to improve traffic density; the sudden, automatic actuation of brakes at entry into a low-speed section reduces ride quality; and a system consisting of many trackside devices and track circuit cables is large and costly. These are all hindrances to further improving transportation efficiency and efforts have been made to solve the problems.

ATC with continuous braking pattern

In 1983, Tokyu Corporation launched a movement to solve the inability of ATC to greatly reduce headways. The company's Den'entoshi and Shin Tamagawa lines link Tokyo to the western suburbs and rising passenger numbers year by year forced the company to find a way to increase capacity. At that time, Tokyu was using an ATS system and could not shorten headways any more without making the job more difficult for its drivers. Therefore, it was decided to introduce an ATC system with continuous braking to minimize braking distances by reducing headway losses due to idle running. In continuous braking control, after the brakes are applied, they are not released until the train stops. However, although the speed indication steps transmitted from the ground equipment to the on-board equipment are subdivided, the basic ATC operation principle remains unchanged. Consequently, there was the problem that the train speed did not decline to the specified speed. The company consulted with the then Ministry of Transport and obtained a special permit for the new brake control system (Fig. 6). The system started service on both the Den'entoshi Line and Shin Tamagawa Line in March 1991.

The TRTA, which had been using the trip-arm-type ATS system since 1927, began updating its system by improving the efficiency and safety of train operation as it introduced new vehicles around 1983. Eventually, the TRTA developed CS-ATC with continuous braking based on the system on the Chiyoda Line. The new system entered service on the Ginza Line in July 1993 and was then introduced on the Marunouchi Line in March 1998 and the Chiyoda Line in November 1999. Today, it is the basic system of the Tokyo Metro. The ATC system of the Joban Line providing through service on the Chiyoda Line was replaced by CS-ATC in 1999.

Reducing Headways —Digital ATC

The Yamanote Line and Keihin Tohoku Line—JR East's important arteries in metropolitan Tokyo—must maintain stable, high-density transport. The existing ATC systems came into use in 1981 and had become obsolescent after 20 years, making renewal important. In renewing the old systems, rather than simply replace the old ATC with new ATC systems of the same type, JR East decided to undertake a comprehensive review and develop a system based on an entirely new concept compatible with the basic purpose of ATC (controlling the headway between trains safely).
Interval control is one approach to train control. As long as the distance between preceding and succeeding trains is known, it is possible to secure safety by controlling the train speeds. Implementing interval control required accurate train position detection and high-speed communication between train and ground. Clearly such an on-board intelligence system is very different from conventional ATC.

What is digital ATC?

The only data required to stop a given train at the rear of a block with a stop signal aspect is the position where train must stop and the distance to that position. Based on this concept, JR East decided to develop a new on-board digital ATC in which the ground equipment transmits only the stop position as digital information to the on-board equipment, which recognizes the train position and continuously calculates the distance between the train position and stop position and applies the brakes at the right moment, taking into account relevant factors such as curves and grades.
The characteristics of the digital ATC system are as follows:

- Continuous braking control and recognition of train position by the on-board equipment, reducing headway and allowing high-density operation
- Comparatively compact and economical ground equipment by using general-purpose IT devices and distributed system configuration
- On-board equipment with sufficient flexibility to support improved train acceleration/deceleration and permit reduced headways without modifications to ground equipment
- System informing crew of route conditions and with precision brake control, thereby improving train manoeuvrability

The new ATC system is less costly than the existing ATC system and has reduced headways of 150 s to 120 s with stop times of 50 s and a deceleration of 3 km/h/s. In addition, the new system has much lower construction costs.

How it works

The digital ATC functions are outlined below (Fig. 7).

- Train detection
  A train detection (TD) signal is transmitted constantly to the track circuit. As soon as a train enters the track circuit, the ATC logic unit detects the train.
- Stop point information transmission
  Based on the train position information supplied by each track circuit and the route setting information supplied by the interlocking device, the ATC logic unit calculates the section permitting train entry, and transmits it as a digital ATC signal to the on-board equipment via the track circuit.
- Own position recognition
  While the train is running, the on-board equipment constantly determines the train position (specific position in specific track circuit) by counting tachometer pulses from an axle generator. The train receiving the ATC signal retrieves the relationship between the stop point information given by the signal and the train position from the on-board database, calculates the distance to the stop point from that relationship and generates a braking pattern.
- Brake control
  The on-board equipment checks the train speed against the braking pattern and applies the brakes if the train speed exceeds the pattern. Immediately after the brakes are applied and immediately before the train stops, the on-board equipment also applies weak braking to minimize the shock of the braking action. Also, before the on-board equipment applies the brakes, it indicates that the train is approaching the brake pattern by flashing a lamp. Furthermore, a monitor displays the condition of the route ahead to improve the train manoeuvrability.

Improving safety

Due consideration is given for the safety of digital message transmission, train position recognition by the on-board equipment, and other functions that the conventional ATC system does not have. The ground equipment transmits an MSK-modulated, 80-bit ATC signal (64 bits for text and 16 bits for CRC) using an HDLC-compatible transmission protocol to the on-board equipment, which performs a CRC check on the received ATC text. It also validates the serial number, content, etc., of the ATC text and invalid ATC texts are not used in control of train operation.
In the digital ATC system, the on-board equipment must find the train position

Figure 7 Digital ATC Operating Principle

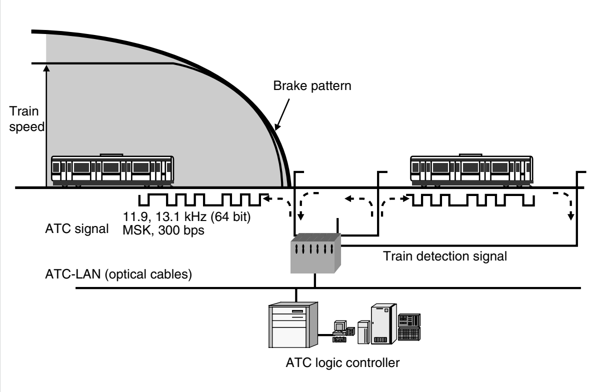
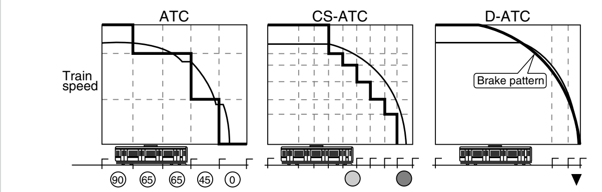


Figure 8 Performances of Train Control Systems



	ATC	CS-ATC	D-ATC
Characteristics	Ground equipment type	Ground equipment type	On-board equipment type
	Intermittent braking	Continuous braking	Continuous braking
High-density train operation	Headway: 2 minutes and 30 seconds	Headway: 2 minutes and 10 seconds	Headway: 2 minutes
Train manoeuvrability and ride quality	Sudden braking	Front brake warning lamp	Monitor on driver console
		Auxiliary brake	Auxiliary brake
			Feedback control

accurately, using a tachometer generator. Even if the tachometer generator error is on the large side, the data is processed on the safe side. In addition, to prevent accumulated error, correction-position transponders are installed between stations at intervals of about 1 km. The transponder also performs distance correction while the train is running at a low speed or during slide detection to ensure safe position detection. If the train position becomes unknown, the system immediately applies the emergency brakes.

The digital ATC system is configured to secure both higher safety and reliability; the ground equipment is triplex and the on-board equipment is parallel duplex, lowering the critical failure rate of the entire system by 10% to 12% or less, compared to the electronic interlocking system.

Putting digital ATC to practical use

For about 6 months from October 1998 before putting the system into practical use, comprehensive final testing (32 night tests and about 180 days of day tests) was carried out with new ATC ground equipment installed between Minami Urawa and Omiya on the Keihin Tohoku Line and the new on-board equipment mounted on a Series 209 train set. Since the component technologies of the new system had already been validated by the 1995 on-track testing, the emphasis was on confirming and evaluating system functions, performance, constants, etc., required during revenue operation from the system startup to changing driver's cab, shunting, etc.

JR East planned to introduce digital ATC called DS-ATC, with 'S' standing for shinkansen as the control system for the soon-to-be-opened Morioka–Hachinohe section. Testing started near Koriyama Station in 1999 with good results. In 2002, JR East decided to introduce D-ATC on its narrow-gauge railways and DS-ATC on its shinkansen. Both projects went smoothly with the DS-ATC system introduced on the Hachinohe section of the Tohoku Shinkansen in December 2002, and the D-ATC system introduced on the Minami Urawa–Tsurumi section of the Keihin Tohoku Line in December 2003. Then, in November 2005, the DS-ATC system was introduced on the Furukawa–Morioka section of the Tohoku Shinkansen. Presently, construction is under way to introduce the DS-ATC system on the Joetsu Shinkansen by late FY 2008 and the D-ATC system on the Yamanote Line in 2006, and on remaining sections of the Keihin Tohoku Line in 2007 (Fig. 8).

Next-generation Train Control using Radio

JR East is now developing a train control system using radio communication. Existing train control uses the track circuit to detect the train position and displays the appropriate signal according to the detected train position. However, this control system requires many trackside facilities and huge investment in construction and maintenance. The recent great progress in IT has now made it possible to build a train control system called ATACS (Advanced Train Administration and Communications System) in which each train determines its position and exchanges data with other trains by radio (Fig. 9). It is an innovative new train control system that uses IT and autonomous distribution technology.

Why develop new train control system?

Conventional train control systems using track circuits for train detection require huge investment in equipment and maintenance. There are several reasons: various ground facilities must be installed on and around the track; train positions cannot be detected very accurately; many signal cables are required to connect ground facilities; etc. In addition, because train control is implemented by block, conventional systems cannot effectively support changes in transportation mode, such as development of new, high-performance vehicles.

However, by utilizing IT as the core and redesigning the distribution of functions between the ground and on-board equipment, it is possible to configure an ideal control system in which individual trains exchange train position information with each another to control train intervals. This new train control system utilizing IT has the following purposes:

- Cutting costs
  Reducing the number of ground facilities cuts construction and maintenance costs. In addition, the costs of large-scale improvement and signal installation works during renewal of train control systems can be cut.
- Facilitating system renewal
  Since the system does not depend on ground facilities, it can easily support changes in transportation mode, such as higher train speed and shorter headway.
- Improving safety and reliability

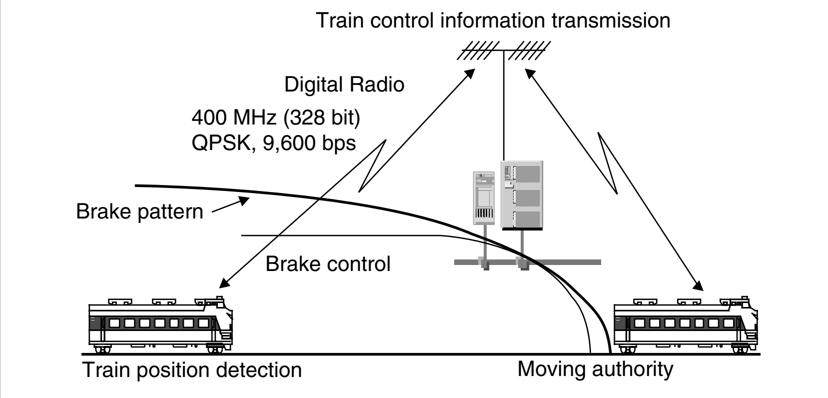
The system does not depend on the train crew for control. It improves safety by positively preventing entry of trains into a closed section and by providing a protective pattern for brake control at level crossings. In addition, the fewer ground facilities reduce problems, contributing to improved transportation reliability.

Using radio in train control

ATACS has many function; the main functions—train interval control and level crossing control—are described here.

- Train interval control
  The train speed is not controlled directly—it is controlled by calculating the allowable speed from the limit of movement authority (LMA) for each train. Control of the interval between trains begins with transmitting the train positions to the trackside control equipment. Next, the control equipment determines the LMA for each train from the train position and route information and sends it to each train. Then, the on-board computer of each train calculates the allowable running distance. Taking into account the brake performance, grade, curves, speed limit and all other relevant factors, the system prepares a braking curve to stop the train before the LMA and performs braking control.
- Level crossing control
  ATACS controls level crossings by exchanging data between the ground and on-board equipment. To adjust the warning time of an approaching train, the system uses the train speed and train performance to estimate the time when the train will arrive at the crossing, and transmits it to the ground control equipment to actuate the crossing signal. Then, the system transmits the information to the train and recalculates the brake curve. If the crossing signal is not actuated, the system stops the train before the crossing.
- Other functions
  The other functions include track-work safety management, switch control, bidirectional distance control, and temporary speed regulation.
  The distributed ground equipment are linked by a network. Each on-board system performs autonomous brake control according to LMA data. The ground equipment consists of a traffic control system and a train control system, and each device is configured, so that it works independently and even the failure of one device does not affect any other device. Consequently, the system can be built on a step-by-step basis where appropriate. If one radio station goes down, the neighbouring station automatically backs it up, keeping the system functioning.

Figure 9 Outline of ATACS

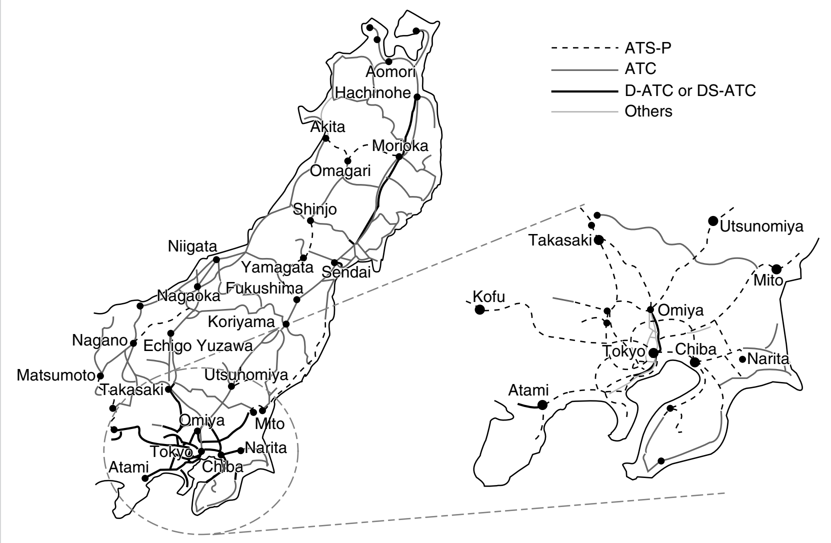


Toward pratical application

An ATACS system configuration and specifications were prototyped with future practical application in mind. Seven radio stations were installed on the 17-km Aobadori–Higashi Shiogama section of the Sengoku Line and on-board ATACS was installed in each of 18 train sets. The test section is divided into several control areas, each of which has control equipment and a radio station. The control equipment has a number of functions, including train detection, train interval control, switch control, level crossing control, and track-work safety management. The radio stations exchange information with the on-board computer and are installed at appropriate intervals according to radio area; some are linked to the control equipment. The on-board computer controls the train brakes according to data received from the ground control equipment. It also transmits train position information to the control equipment.

First, the on-board equipment determines the accurate train position. The initial train position is obtained when the train passes the trackside coil installed at the boundary between train departure section and train entry section. Next, the on-board equipment continues recognizing

Figure 10 JR East's Network of Train Control Systems



the train position using the cumulative running distance calculated from the train speed. The distance is corrected each time the train passes each trackside coil installed at appropriate intervals. The train position is allocated as a unique number to the associated control equipment, and data about train positions in virtual sections (divisions of control area), related sections, etc., is processed by the ground and on-board computers. Radio stations are installed at intervals of about 3 km (varies according to reach of radio wave). To avoid mutual interference between adjacent radio stations, four different frequencies are used so stations in individual control areas can select a suitable frequency. Each station communicates with trains in its area every 1 s. Since transmission errors can occur, space diversity and Reed-Solomon error correction are used to improve transmission quality.

Day running tests (cumulative distance of more than 1 million km) and night control running tests (28 times) were performed from October 2003 to February 2005. Since the test results showed no functional or safety problems with the prototype system, R&D has started into practical application.

Conclusion

The former JNR and now JR East have continually developed and refined train control systems, which have evolved from the cab warning system to ATS-S to ATC (Fig. 10). As a result, the number of train accidents, especially rear-end collisions, has dramatically decreased.

Recently, an innovative new train control system using IT technology is being developed from dual standpoint of preventing railway accidents and improving passenger services.

With the successful completion of ATACS testing, we expect to see it in practical use in the near future as a 21st century control system replacing more conventional signalling. Autonomous distributed train control will permit individual trains to exchange information with each another to control their own speeds. I believe that train control systems will continue developing in the years ahead driven by improvement in transportation needs and progress in communications and information technology. ■

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Masayuki Matsumoto

Dr Matsumoto is General Manager of Facilities Department at JR East. He joined JNR in 1972 after obtaining masters degree in physical electronics from Tokyo Institute of Technology. After joining JR East in 1987, he held posts such as Deputy Senior Manager of Tohoku Construction Office and General Manager of Transport & Rolling Stock Department. He was Executive Director of Railway Head Office at Hoan Kogyo Co., Ltd. before taking present post in 2004. He obtained his doctorate degree in computer science from Tokyo Institute of Technology in 2003. He is the author of *Electric Railway* published by Morikita Shuppan in April 1999.