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# How to Deal with Revolutions in Train Control Systems

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ABSTRACT

Train control systems ensure the safety of railways. This paper begins with a summary of the typical train control systems in Japan and Europe. Based on this summary, the author then raises the following question regarding current train control systems: What approach should be adopted in order to enhance the functionality, safety, and reliability of train control systems and assist in commercial operations on railways? Next, the author provides a desirable architecture that is likely to assist with the development of new train control systems based on current information and communication technologies. A new unified train control system (UTCS) is proposed that is effective in enhancing the robustness and competitiveness of a train control system. The ultimate architecture of the UTCS will be only composed of essential elements such as point machines and level crossing control devices in the field. Finally, a processing method of the UTCS is discussed.

## 1. Introduction

Many train control systems have been developed and introduced to date. Although such systems have been invented in compliance with the railway requirements of the countries and railway lines for which they were developed, as well as in accordance with the technologies available at the time, they have a common fundamental architecture. More specifically, such systems are manufactured from fundamental components, including block systems for controlling train-to-train spacing for trains running between stations and traffic direction control in a single-track section, automatic train protection (ATP) systems affiliated to the block systems, and interlocking devices for performing route control in station premises.

The systems vary depending on how they perform train detection and how they realize ATP. However, although these systems range from low-safety systems with only an automatic warning system (AWS) to the most advanced radio train control systems (communication-based train control (CBTC) systems), they are the same in that interlocking devices are responsible for route control and safety assurance for trains running in station premises.

Current train control systems, which have gone through continuous improvements as described above, constitute solid systems composed of many hardware devices and subsystems. The key question is: What approach should be adopted in order to enhance the functionality, safety, and reliability of train control systems and assist in commercial operations on railways? Rather than persisting with conventional architectures, I have spent considerable time pondering desirable architectures that are likely to assist in the development of new train control systems based on current information and communication technologies. Among these architectures, I propose a new unified train control system (UTCS), in which all safety devices are regarded as devices for securing train paths so that trains are informed of an available path through unified processing by a common processor placed at the center. A description of the background story and advantages of the UTCS follows.

## 2. The evolution of train control systems in Japan

In Japan's ATP systems, automatic train stop (ATS) control, in which the driver's brake operation is given priority so that the train is forced to stop if the situation is determined to be dangerous, is differentiated from automatic train control (ATC), in which

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the brake operation itself is automated with a system to prevent train accidents from occurring due to the driver's negligence. Hence, the evolution of Japan's ATP systems will be surveyed in comparison with Euro-American ATP systems in order to examine the requirements for the UTCS.

### *2.1. From automatic warning system (AWS) to automatic train stop (ATS)*

In its early days, ATS began with the development of an AWS that was intended to prevent negligence in brake handling by notifying the driver of stop signals. The Mikawashima train crash that occurred in 1962 was a large-scale accident caused by a driver not only driving through a stop signal but also breaking through a safety siding, resulting in derailment, obstruction of the adjacent line, and 160 casualties. ATS was developed to prevent such accidents. It notifies the train of a stop signal from the ground in order to call it to the attention of the driver using an alarm sound (bell), as well as automatically actuating emergency braking, unless the driver responds with a confirmation operation within 5 s, irrespective of the issued alarm sound. This device, called the S-type ATS, can be regarded as the least functional backup device that has evolved from the AWS. The Japanese National Railways (JNR) decided to install ATSs of this type in all railway lines and completed installation in 1966. Although this device contributed to a great reduction in the number of accidents, ATS was far from a perfect system because it still could not prevent accidents caused by delayed brake handling and so forth after the confirmation operation. (Note that the "confirmation operation" means that the brake handle is shifted to the brake position, and the confirmation button is pressed.)

### *2.2. Instruction from the Ministry of Transport and advanced ATS of private-sector railways*

In January 1967, one year after the JNR reported that the installation of ATS was completed on all JNR lines, the Ministry of Transport (currently the Ministry of Land, Infrastructure, Transport, and Tourism) issued a notification (Government Notice No. 11) that obligated public-sector/private-sector railway companies to install ATS systems. Unlike the JNR's S-type ATS that was developed assuming the confirmation operation, this type of ATS could provide some speed check function. As a result of this notification, ATS was advanced one step further, in that no alarm sound was issued as long as normal operation was performed, and braking was actuated only if the result of a speed check indicated danger.

In response to the notification from the Ministry of Transport, public-sector/private-sector railway companies developed and introduced an ATS system in accordance with their individual conditions. Typical ATSs of the speed check type employed by public-sector/private-sector railways are as follows [1]:

(1) Speed is checked on the basis of the time that the train takes to pass two ground coils placed on the ground.

(2) A continuous speed check pattern is selected on the basis of ground coil information in order to continuously check the train speed until the train stops.

(3) A modulation signal corresponding to the speed to be checked is transmitted to the track circuit and is checked against the train speed.

(4) The track circuit current is instantaneously interrupted for a certain period of time according to the speed to be checked, in order to check the running speed.

### *2.3. ATSs capable of delivering train performance*

While the JNR's S-type ATS was plagued by accidents due to driver failure after the confirmation operation, various other ATSs developed by public-sector/private-sector railway companies in accordance with the notification from the Ministry of Transport demonstrated their effects without bringing about severe accidents. Against the backdrop of this situation, in the early 1970s, the JNR started to examine how to realize ATSs that were as superior in functionality as those used by private-sector railway companies. However, the hardest task was to develop an ATS system that could be commonly applied to railway lines where trains that greatly differed in brake performance, from limited express trains to freight trains, ran together at high density. Conversely, the brake performances of trains running in applicable railway lines of public-sector/private-sector railways were almost identical, so that controlling trains even on the basis of a uniform speed check did not cause a major problem.

To solve this difficult problem of developing an ATS that could be applied to railway lines where trains with greatly differing brake performances ran together, the JNR decided to provide information on the distance to the stop signal, rather than performing speed control from the ground. This was a novel idea, in that a speed check pattern according to distance information from the ground is generated by counting the brake performance on the train. This system was named the P-type ATS.

Because the P-type ATS could generate a speed check pattern according to the brake performance, not only could the most reasonable speed check be realized for each train, but also unwanted braking could be avoided. Furthermore, because the P-type ATS used a transponder, which is a device capable of transmitting multiple items of data bi-directionally, it possessed three advantages listed as follows. Using the P-type ATS, it became possible:

- To perform protection in response to stop signal aspects;
- To perform control by notifying the train of information according to speed restriction points; and
- To perform detailed level crossing control by the use of passing/stopping information from the train.

In addition, the concept employed in the P-type ATS—that is, control information from the ground being given to the train, just like information about simple running limit points, so that highly effective train control could be performed by counting data stored on the train—enormously influenced subsequent train control, such as digital ATC. Digital ATC and the P-type ATS have another advantage in that it is not necessary to upgrade the system even if the train speed is enhanced.

A key factor in the development of the UTCS is what information should be transmitted to the train; the UTCS to be developed needs to fully deliver train performance on the basis of actual achievements in the P-type ATS and digital ATC.

### *2.4. Emergence and advancement of automatic train control (ATC)*

ATS is a human-centered system in which the driver primarily operates the train according to signals, and the brake is actuated in the event of a dangerous situation. In subways and Shinkansen trains, where it is difficult to install a ground signal, ATC is employed, which totally mechanizes brake control for safety without entrusting it to human determination. The first ATC employed a method in which a speed signal (an ATC signal) that is made to flow through rails is received by an on-board antenna, and an on-board ATC device then compares the actual speed with the speed signal value. If the actual speed is higher, the brake is automatically actuated to slow down the train to a specified speed. Thus, ATC, as a machine-initiative system, solved safety problems due to human errors by eliminating human operation.

In ATC, an ATC signal that indicates a limit speed, instead of a trackside signal, is displayed in the cab. ATC was also installed in subway sections where signals are difficult to see, and in conventional high-density railway lines, and demonstrated a high level of safety. However, because this method forces a speed check to be performed according to the ATC signal, it is disadvantageous in that it is necessary to add a new signal to increase the speed. As a result, a problem occurred with passenger comfort due to repeated motion, such as the brake being actuated, released, and actuated again, until the train stopped.

A measure taken as a solution to these problems was to give information about a limit section for a running stop by applying the concept of the P-type ATS, rather than transmitting a speed signal from the ground for safety control. If a speed check pattern was generated on the train in conformance with the brake performance and so forth of the train, and according to the distance to the stop limit point, a continuous single pattern was generated. For this reason, transmission information was transferred from the ground to the train using a digital telegraph, causing the system to be referred to as digital ATC.

The CBTC system, which sends the control telegraph to the train via radio waves and acquires the running position from the train, was introduced in October 2011 on the Senseki Line under the name Advanced Train Administration and Communications System (ATACS) and has shown stable operation [2]. ATACS established a radio closed-loop control system with a level crossing controller to generate a pattern to allow the train to pass through the level crossing only after confirming that the level crossing gate has been closed and that there are no obstacles. This system enhances safety and has also realized a 10 s reduction in closed time. In considering UTCS functions, it is also necessary to explore smart solutions to key challenges; namely, examining interface information and level crossing control. Fig. 1 shows the evolution of these ATP systems in Japan.

### 2.5. Features of train control systems in Europe

Typical train control systems in Europe include the French transmission voie-machine (TVM) (TVM-300 and TVM-400), the German Linienzugbeeinflussung (LZB), and the European Train Control System (ETCS), as Europe-wide specifications. Although these systems are important in ensuring the safety of modern high-speed railways, systems up to TVM-300, TVM-400, and ETCS (Levels 1 and 2) build their safety control logic on the basis of train position detection information from conventional track circuits. Furthermore, as TVM-430, which performs control with a smooth speed check pattern, was developed from TVM-300, which performs a step-like speed check, the mainstream approach for the speed check method is to use a single speed check pattern. A speed check with a smooth speed restriction pattern is also used for the automated train protection function of the ETCS. The features of each system are listed in Table 1.

However, for Japan's digital ATC, ATACS, and so forth, fixed railway data, such as speed restriction along with a curve section and gradient, and data such as train brake performance are stored on the train to generate a reasonable speed check pattern on the train. In contrast, many of the European systems receive data such as a brake profile from the ground in order to realize ATP control with on-board logic. This is one of the issues that requires further research when considering the form of future train control systems, including tilting control for the performance of vehicle tilting control and safety data collection.

## 3. Proposal of the unified train control system (UTCS)

### 3.1. Background of the UTCS proposal

The fundamental functions of a train control system are the block function and the interlocking function. Aside from the role of route arrangement, the most important mission of both functions is to avoid accidents such as train-to-train collisions and rear-end collisions. Thus, the principle of ATP, as discussed in the

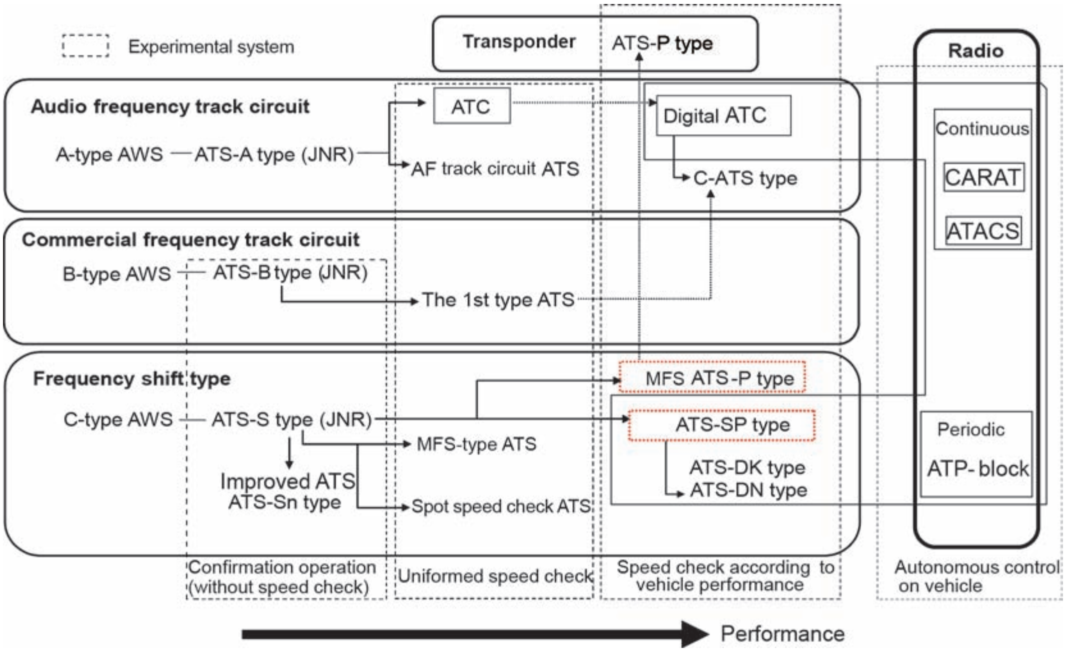

**Fig. 1.** Evolution of automatic train protection (ATP) systems in Japan. AF: audio frequency; ATACS: Advanced Train Administration and Communications System; ATC: automatic train control; ATS: automatic train stop; AWS: automatic warning system; CARAT: Computer and Radio Aided Train Control System; JNR: Japanese National Railways; MFS: multiple frequency shift.

**Table 1**
Typical ATP systems in Europe.

| | SNCF(1) (France) | SNCF(2) (France) | SNCF(3) (France) | DB AG (Germany) | FS (Italy) | RENFE (Spain) |
|---|---|---|---|---|---|---|
| Name | TVM-300 (Paris–Lyon) | TVM-300 (Atlantique) | TVM-430 (LGV Nord) | LZB-80 | BACC | CAT (LZB-80) |
| Back-up | Crocodile | — | — | INDUSI | | ASFA 200 |
| Max. speed (km·h$^{-1}$) | 270 | 300 | 300 | 250 | 255 | 270 |
| Headways (min) | 5 | 4 | 3 | 3 | 5 | 3 |
| Bidirectional operation | Existence | Existence | Existence | Existence | Existence | Existence |
| Cab indicator for driver | Existence | — | — | Existence | Existence | Existence |
| Speed limit | Existence | — | — | Existence | Existence | Existence |
| Over run protection | None existence | — | — | Existence | None existence | Existence |
| ATO | None existence | — | — | Existence | None existence | Existence |
| Insulation of track circuit | None insulation | — | — | None insulation | None insulation | None insulation |
| Data transmission | Code track circuit + barise | — | — | Loop | Code track circuit | — |
| Code | 1 of 18 | 1 of 18 | 27 bits | Max 83 bits | 1 of 9 | Max 70 bits |
| Modulation | FM | — | — | FSK | 50/178 HZ (AM) | FSK |
| Fail safety of ground device | — | — | 2 out of 2 | 2 out of 2 | Code-MPU | 2 out of 3 |
| Fail safety of cab equipment | Fail safe circuit | Fail safe circuit | Code-MPU | 2 out of 3 | Code-MPU | 2 out of 3 |

AM: amplitude modulation; ATO: automatic train operation; FM: frequency modulation; FSK: frequency-shift keying; MPU: micro processing unit.

previous section, has been built on the basis of exclusive control for eliminating contact with another train. In the mechanisms of various types of ATP, technologies that have been cultivated through bitter lessons have accumulated—lessons that have been learned through accidents since vehicle transport first began. The history of this technological advancement represents the current situation of train control systems—in other words, the intricate and complete modern block system and interlocking devices that have evolved through repeated improvements in a bottom-up manner.

Processes commonly included in many devices have proliferated in the course of developing individual facilities, whereas processes that will disappear some day as systems advance have also been unveiled. Furthermore, for the purpose of solving problems, including the prevention of level crossing accidents, some systems should be subject to radical and innovative changes in order to be effective. In existing signal systems, while train control is transmitted via signals, signs, and indicators, train operation itself is performed on the basis of information about routes and block signals, as well as according to supplementary information such as speed restrictions. Of these, information about routes and block signals is transmitted to the train in the same information format as those of signal aspects and ATC signals; therefore, processes can be standardized. I propose the UTCS based on this way of thinking. The UTCS includes not only processing for path allocation but also a function for controlling the point machines and level crossings required for path allocation.

### 3.2. Architecture of the UTCS

Fig. 2 shows the system architecture of the UTCS. The UTCS is a hierarchical train control system composed of a central processor placed in the center (functional layer), an interface-to-device unit placed in the field (terminal layer), and a transmission unit for information exchange between them (network layer). In the UTCS, the logical processing of devices, such as the interlocking device, the block system, and the ATP, is aggregated and unified in a central processor in the functional layer. As a result, processors placed in the field are eliminated. In addition, as a result of processes being unified in the UTCS, similar functions that are currently included in multiple devices, such as the train tracking function, are also unified, and the logic can be simplified.

### 3.3. Outline of the UTCS processes

In the UTCS, the concept of a "path" (labeled "authorized route" in Fig. 3) for a train is introduced for the standardization of processes. A path means a "limit position to which running is possible," and is derived from an associated preceding train, a point machine, and the states of a level crossing for each train. For this reason, train processes by unified processors are realized by train tracking, path searching (or "route searching"), and control processes that are initiated by route searching processes in order to control level crossings and point machines.

When paths for trains (Train k and Train j in Fig. 3) are determined, a run command (authorized command$_{k/j}$) with additional speed restriction information in a path is also generated and sent to the corresponding terminal device of the terminal layer.

Path searching creates a search for a limit point to which running is possible (a path) in the train movement direction. In the case of station premises, however, a search is made according to a scheduled running path acquired from the running control device (or "traffic control system") on the functional layer. The path at this time is based on the terminal end of the running path and is determined by the state of point machines existing in between and at the tail position of a possible preceding train (including the safety margin).

On the other hand, in the case of a midway point between stations, the tail position of the preceding train or the state (labeled "status" in Fig. 3) of an existing level crossing is associated with the determination of a path. If the level crossing is controlled by the relevant train and the status indicates "passing allowed," which means closing completion and no obstacle, the search is extended up to a further remote position.

Although on-board devices are responsible for on-board safety processing, a continuous speed check according to a pattern is

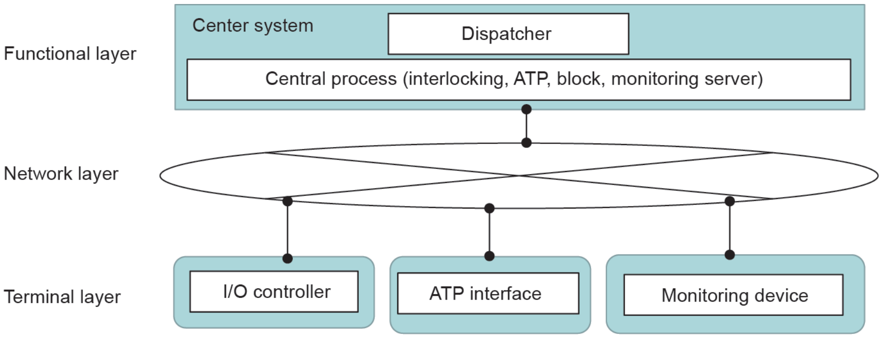

**Fig. 2.** The architecture of the unified train control system (UTCS).

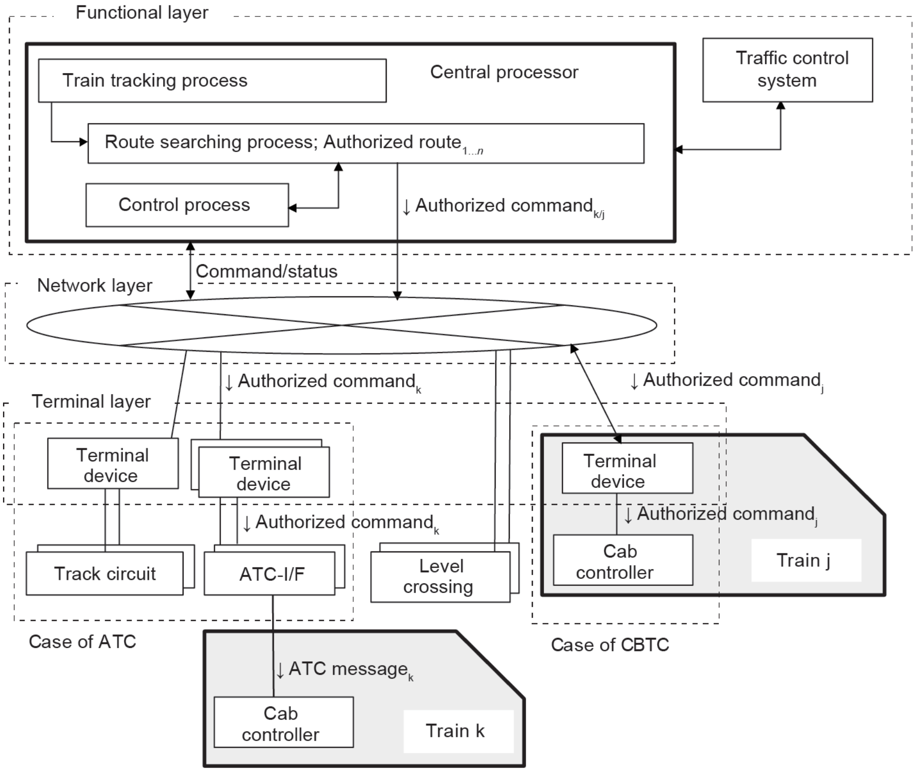

**Fig. 3.** An outline of the UTCS processes. CBTC: communication-based train control.

realized on the train anyway. Moreover, in the case of the CBTC, a high-level speed check function can be realized by installing a terminal device on the train, rather than providing an ATP terminal device on the ground.

## 4. An Internet Protocol (IP) network responsible for the network layer

In realizing the UTCS, the network layer plays an important role. An Internet Protocol (IP) network is used as a network for the UTCS. Performance requirements for the IP network differ depending on the railway section to be used. Because an information transmission period of time needs to be guaranteed in a fast and highly reliable manner in a high-density railway section, a performance-focused network designed specifically for train control is necessary. In the case of a low-density railway section, on the other hand, for which high reliability is required while keeping introduction and maintenance costs under control, it is necessary to consider using a cost-focused general-purpose network. In addition, even in a case where a high-density railway section and a low-density railway section are connected, easy connection is possible because of the connections between IP networks.

### *4.1. An IP network for high-density railway lines*

An IP network for high-density railway lines loop-connects a transmission node developed solely for train control via an optical line. Each device and a transmission node are then connected via an Ethernet line. This IP network can also guarantee a communication time between transmission nodes and the longest communication time in a short time period equal to or smaller than 1/10 of the relaying time period. As a result, each device can realize processing with responsiveness equal to or higher than that of a relay interface without being conscious of the device-to-device physical distance.

Although the IP network is basically built in the form of a single configuration, two or more IP networks can be redundantly configured in order to enhance the availability factor. Because individual IP networks are completely independent of each other, forming a parallel dual configuration, the center processor and a terminal device can freely select the route for communication. Because the availability factor of an IP network is directly connected to the system availability factor, attention must also be paid to reliability. Hardware for transmission nodes is under development, following the signal local area network (LAN) technology that has in fact been used in many systems, including the Tokaido Shinkansen trains.

### *4.2. An IP network for local railways*

Because introduction and maintenance costs are important in local railway line sections, a cellphone line, for example, can be used as the IP network. Although cellphone lines can reduce high cable routing costs, facility costs, and maintenance costs, it is necessary to consider the constraint of a communication time that cannot be guaranteed, as well as the communication cost.

When using a cellphone line in a local railway, continuous communication becomes difficult. However, a train control system that has a function beyond the current level can be realized even if the point at which information exchange is performed with the center is limited to a neighbor of the station premises in a single line section. This has been demonstrated by the development of an automatic train protection and block (ATPB) system [3].

## 5. The UTCS serving as an advanced system

The UTCS can realize not only CBTC at low cost but also existing signal systems, such as the digital ATC, in a simple manner. Therefore, an advanced strategy in which digital ATC would be temporarily realized under the UTCS and then someday switched to the CBTC becomes feasible.

### *5.1. Changing digital ATC into the communication-based train control (CBTC) by the UTCS*

Thus far, in order to realize digital ATC, it has been necessary to prepare machine rooms in the field, equip the machine rooms with large-scale digital ATC ground devices, and connect the machine rooms via a network. In order to subsequently evolve digital ATC into the CBTC, the logical units of the CBTC would be installed separately, and information would be exchanged with on-board devices via radio waves. If this was the case, most digital ATC ground devices (including the logical units in the machine rooms) and interlocking devices (including the interfaces to the digital ATC) would become obsolete.

On the other hand, for a design taking a future transition to the CBTC into account, it would be appropriate to standardize on-board devices with a patterned safety control processing function. In other words, such on-board devices could be commonly used to handle data, whether digital ATC telegraphs from a power receiver or telegraphs from an on-board radio device.

In contrast, in the case of the UTCS, a run command for a train is generated as a result of unified processing by the central processor at the center. If digital ATC is to be realized under the UTCS, the ATC terminal unit should amplify an ATC telegraph on the basis of a train run command distributed from the central processor and transmit it to the track circuit, as well as performing train position detection.

For the purpose of a future transition from digital ATC to the CBTC under these conditions, ground radio units connected to the IP network would perform radio communication with on-board devices via a terminal device mounted on trains, and would transmit and receive a run command and train position information from the functional layer. Consequently, the terminal units that would become obsolete are limited to the amplifier (AMP) and the train detection (TD) for each track circuit, in addition to ATC terminal units.

### *5.2. Effects of the introduction of the UTCS*

Because the UTCS allows a large number of facilities to be reduced, not only can the facility cost and running cost required for the train control system be reduced, but the maintainability, reliability, and safety can also be enhanced. For the aggregation of logic units, the renovation range at the time of function changes and function additions is based on the center; hence, it becomes easy to change a train control system into an evolvable system that flexibly adjusts to changing needs. Although it is possible to maintain the control configuration of the present signal protective devices under the UTCS, transition to, for example, the CBTC becomes easy by placing terminal devices on the train.

The CBTC realized by the UTCS is a system without a base-point control device at a line wayside; therefore, train hand-over (hand-over processing) between base-point controllers becomes unnecessary. In short, the UTCS also serves as a strategy for introducing the next-generation CBTC and can receive the full benefit of the CBTC as-is.

For example, in order to realize the conception of dual-mode vehicles (DMVs) and rail buses that can run on both rails and roads under the current signal system, it is necessary to harmonize UTCS with the track circuit method by using rail clamping via wheels and shafts. Stable train detection with a track circuit is also indispensable for realizing free-gauge trains that can freely run on Shinkansen lines and conventional railway lines. The UTCS becomes a safety system that does not depend on a track circuit, removing these constraints simultaneously and allowing a practical discussion about DMVs and rail buses.

In addition, in order to enhance running density and running speed using the current signal system, the division of block sections, the addition of signal aspects, changes in the aspect system, changes in the positions of level crossing controllers, and so forth are necessary. However, such enhancement is not possible with the current state of things, presenting an obstacle to enhancing rail's competitiveness with automobile transportation and so forth. Fortunately, train-based position detection and the realization of cab signals that do not depend on a track circuit, as well as radio control of level crossings, will eliminate these difficulties simultaneously, leading to free enhancement of speed and running density, and will easily realize performance enhancements of traffic systems.

Because the UTCS becomes autonomous on a train, it includes on-board continuous position detection as an essential element. Track diagnosis information collection with a commercial vehicle becomes possible by using this elemental technology, blazing a trail for modernized maintenance work [4,5].

With the UTCS, field facilities are reduced compared with those of existing train control systems; for example, interlocking devices in station premises are eliminated. Furthermore, interface reduction is advanced, such as integration of the block system and the ATP and elimination of the interface units between components such as a signal device and the ATP. Equipment savings such as these will enhance reliability and maintainability. In addition, because the probability of malfunctions caused by human error at interfaces is reduced, safety advantages are anticipated. Thus, the UTCS will contribute to the robustness of railway systems.

The ultimate architecture of the UTCS will be composed of only essential elements such as point machines and level crossing control devices in the field. This approach has been summarized under the concept of “essential control.” Application of this concept will conceivably serve to improve reliability, safety, and maintainability, as well as enabling the construction of railway systems at low cost.

## 6. Conclusions

This paper proposes a new UTCS, in which a train control system is realized in a hierarchical structure of a functional layer, a network layer, and a terminal layer, and discusses its processing method. It has been demonstrated that an existing signal system can be flexibly evolved into an ideal CBTC that does not have a base-point controller. While the CBTC will start, for the time being, with an ATP block system in the form of a minimal system for local railway lines, in order to demonstrate its advantages, I will endeavor to realize this proposal as soon as possible, as it will be effective in enhancing the robustness and competiveness of railway systems. The ATP block system is a good example of realizing the essential control concept.

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