The Current Status of Signal Control Systems, and Research and Development

Yoshinori Kon
Advanced Railway System Development Center, Research and Development Center of JR East Group

The signal control system, having been developed over the long history of railways, involves several problems. To solve these problems, the signal control system needs to be reconfigured using state-of-the-art technologies.
This paper discusses the wide-ranging signal control system by describing the transition and history of the related technologies up to the current status in order to give an understanding of the general image of the signal control system. This will be followed by a discussion of the problems involved in the current signal control system, and by an introduction of the development concept of the new system for which we are currently making research and development efforts. Finally, this paper will describe part of "the future signal control system" that we envisage.

1 Introduction

Railways are comprised of rolling stock such as electric trains and locomotives, and wayside equipment such as tracks, power systems, and signal control systems. It is a gigantic total system that does not work if any one of such various devices fails. Among others, the signal control system is an essential system for the railway in order to ensure punctual and safe operation of trains.

However, the signal control system, having been developed over the long history of railways, involves several problems. It has become necessary to reconfigure the signal control system using state-of-the-art technologies.

This paper will command a bird's-eye view of the signal control system as a whole and will discuss the direction that the East Japan Railway Company is heading in the research and development of a signal control system.

2 Transition and overview of the signal control system

So far we have used the collective term "signal control system." In practice, however, the signal control system consists of a great variety of equipment. Before describing the research and development of each component of the signal control system, we will discuss the transition and history of the related technologies up to the current status so that the general image of the signal control system can be understood.

2.1 Signals, track circuits, and switch machines

The operation of railway trains started with the transportation of commercial cargo by "the Stockton and Darlington Railway" in England in 1825. In 1830, passenger transportation started on the Liverpool and Manchester Railway.

When the train speed was slow, a flagman riding a horse preceded the train to ensure safety. However, as train speed and the number of track branches increased, "railway policemen" had to be stationed at specified positions to ensure safety of the route, and manual signs were used. For example, "Safe (to proceed)" was indicated by raising one hand in the horizontal position, "Caution" by raising one hand upright and "Danger (stop)" by raising both hands upright. This is the beginning of the railway signal. After that, the "ball signal" (Fig. 1) and other devices appeared. In England, they were followed by the advent of a semaphore signal (Fig. 2), where a wire or steel pipe was used to indicate "Proceed," "Stop," and in some cases "Caution," by means of the angle of a cross arm.

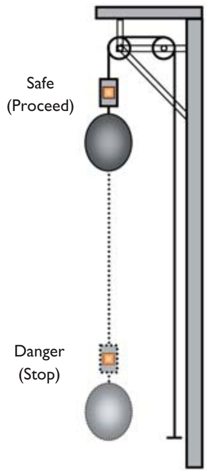

Fig.1: Ball signal

Fig.2: Semaphore signal in Japan

Incidentally, in the ball signal a ball was suspended by a string. The ball positioned at a higher place (high ball) indicated "Proceed," while the ball at a lower position (low ball) indicated "Stop." The high ball in the sense of whisky and soda is said to be derived from engine-men crying out "High Ball" (Proceed) when they drank a toast in a pub. In an alternate story, the name is said to have derived this way: Passengers used to disembark from the train and have a drink while the locomotive was being supplied with coal and water. When the ball signal indicated a "high ball," soda water was added to their whisky, and the passengers finished their drinks, "bottoms up," and then boarded the train.

Fig.3: Colored light signal

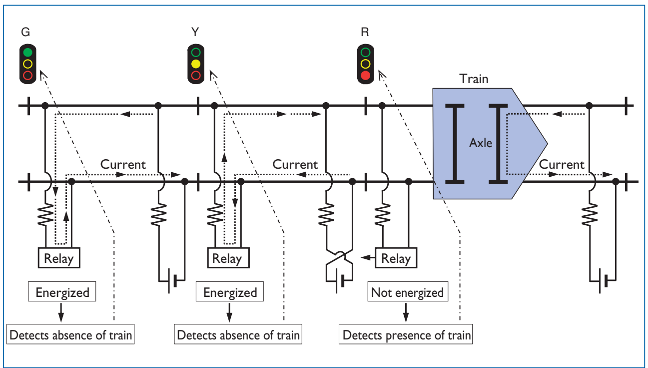

Fig.4: Mechanism of track circuit

Incidentally, this track circuit was originally patented by Dr. William Robinson (the United States) in 1872. Needless to say, the current device is much more sophisticated than the original one. However, the basic principle discovered more than 130 years ago is still utilized even today. This demonstrates how simple the structure is and how reliable the system is.

Unlike the automobile, the train has no steering wheel. The train advances only in the direction of the open track ahead. Accordingly, the track must be switched in such a way that the train can run in the desired direction. A device that changes the direction of the train is a turnout (point). The turnout used to be switched manually, but is now switched by motor. A device used for this switching operation is called a switch machine (Fig. 5).


Fig.5: Switch machine (left) and turnout (right)

The aforementioned signal, track circuit, and switch machine are collectively called a wayside device.

2.2 Interlocking device

To change the route of the train in early days, the station staff in charge went to the turnout to select the route. However, when trains pass by each other in opposite directions, several turnout points must be operated simultaneously, and a sign must be given to the trains. This work cannot be done by one person alone. If two or more persons are to do this work, accurate communication and confirmation are an absolute necessity. In the case of a small station or a route where the traffic density is low, careful attention by humans is sufficient to assure safety, but at a large station or a heavily travelled route, the power of human concentration alone is not enough to assure safe operation. And so to solve this problem and assure the safety of trains, it became necessary to devise a mechanism whereby the operation of the signal is coordinated, or interlocked, with the direction of the turnout opening. This is done by an interlocking device.

This interlocking device was configured as follows: While the signal and turnout were mutually operated by wire or steel pipe in the initial stage, a mechanical lock (Fig. 6) was operated to ensure that the signal could issue a proceed sign only when the turnout was open, thereby ensuring safety. This device was operated by mechanical means, and was called a mechanical interlocking device. It was invented by John Saxby in England in 1856.

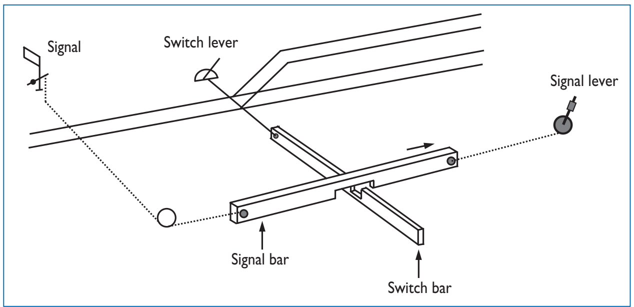

Fig.6: Mechanism of mechanical Lock

A relay circuit was used to ensure this safety function. Through the "relay interlocking device" (Fig. 7), this device developed into a computer-based "electronic interlocking device" (Fig. 8) introduced at Kanagawa station on the Keihin-Tohoku Line in Japan in 1985.

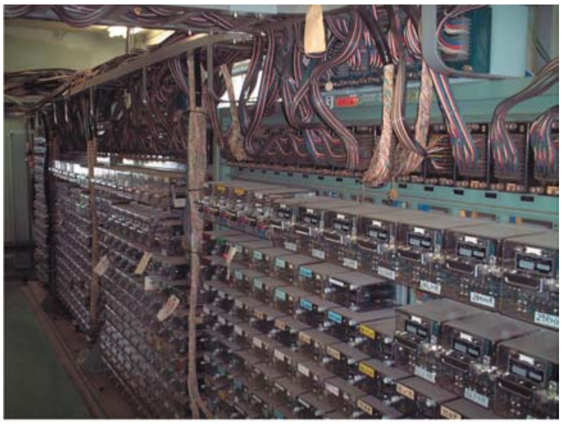
Fig.7: Relay interlocking device


Fig.8: Electronic interlocking device

Although there is a time difference, you may notice that the transition of this interlocking device is very similar to the history of the computer: Namely, the first mechanical digital computer called the "Difference Engine" was designed and developed by Charles Babbage in England in 1839. It was then developed into a relay based computer, which was further developed into the current electronic computer. To put it another way, the functions of an interlocking device are basically the same as those of a computer.

The interlocking device discussed so far and the "new route controller" currently being developed by JR East are generically called "route control system."

2.3 CTC and PRC

Since the interlocking device was installed at each station, operators had to be assigned to each station. In the meantime, it was also necessary to appoint a train dispatcher to provide traffic control by accurately comprehending the "big picture" of the entire train operation status of a line section. Then, in 1927 the Centralized Traffic Control (CTC) system whereby the dispatcher could remotely control the interlocking devices of multiple stations from the dispatch control center was put into commercial use in the United States. In Japan, this system was first introduced on the Tenri Line of Osaka Denki Tetsudo Co., Ltd. (current Kinki Nippon Railway Co., Ltd.) in 1936.

In the scheduling of train runs, almost all train operations run according to a fixed pattern, except that there is a distinction between weekdays and weekends/holidays and there are some special train runs. In 1964, with the advancement of computer technology, train dispatchers started using computers to control CTC route settings on the Tokaido Shinkansen with a system called Programmed Route Control (PRC), which was later introduced to other existing lines.

Assisted by CTC and PRC, the dispatch center was able to provide centralized control over train operations for an entire line section. To meet the recent needs for providing information on train operations to passengers and station staff at any given time and restore normal scheduling after a disruption, the Autonomous Decentralized Transport Operation Control System (ATOS) was introduced in the metropolitan area in 1996.

The aforementioned CTC and PRC are collectively called "Traffic control system" (Fig. 9).


Fig.9: Dispatch center and traffic control system

2.4 Transport operation control system

In the metropolitan area, the introduction of ATOS has brought about a substantial improvement in the transmission of information and workability, as compared with conventional CTC and PRC. However, traffic control and the logistics of managing train crews are still done manually in the event of a calamity that disrupts schedules. Thus, in the event of transport disruption, a great deal of human labor is required in the operations section and dispatch center in charge of management of rolling stock and staff. In this field, moreover, in relation to places, staff, and trains, the information becomes very complicated, and processing by computer is therefore very difficult, and little progress has been made in systemization in this regard.

When quick recovery in the event of a transport disorder is taken into account, immediate computerization is essential. Fortunately, computer processing speed has been dramatically increased in recent years and a great number of suitable computer algorithms have been developed, making this the right time to introduce computerization.

A system for crew operation support, rolling stock operation support, and forecasting train schedules at the time of recovery from an accident is called the "transport operation control system."

2.5 Train control system

In the past, train operators operated their trains by applying the brakes or raising a notch (equivalent to an automobile accelerator) in accordance with the signals they observe. This method relies solely on the operator's focus of attention, and cannot be considered sufficient. To solve this problem, the ATS (Automatic Train Stop) for automatically stopping the train in response to a stop signal was introduced some time after the Second World War.

Further, ATC (Automatic Train Control) which automatically controls train speed without depending on the attentiveness of the operator was put into practical use in 1964. At present, this system is used on Shinkansen as well as other conventional existing lines such as Yamanote line. Incidentally, there has never been an accident on Shinkansen since commencement of its service. This is largely attributable to ATC.

It should be pointed out that the "train control systems" include the aforementioned ATS and ATC as well as systems based on digital technology such as Digital ATC (D-ATC) for conventional lines, Digital Communication and Control for Shinkansen ATC (DS-ATC), and Advanced Train Administration and Communications System (ATACS) that we are currently developing.

3 Overall configuration of signal control system

Fig. 10 shows the configuration discussed so far of the signal control system as a whole.

The configuration of the system varies somewhat for each line section. Basically, the system can be classified into three levels; "wayside devices," "route control system," and "traffic control system" levels.

Here control safety is guaranteed for the wayside devices and route control system levels. The high-order level of traffic control is not directly related to safety. To put it another way, even if the CTC and PRC should give an erroneous instruction, the system is configured in such a way that safety is ensured by the route control system and wayside devices.

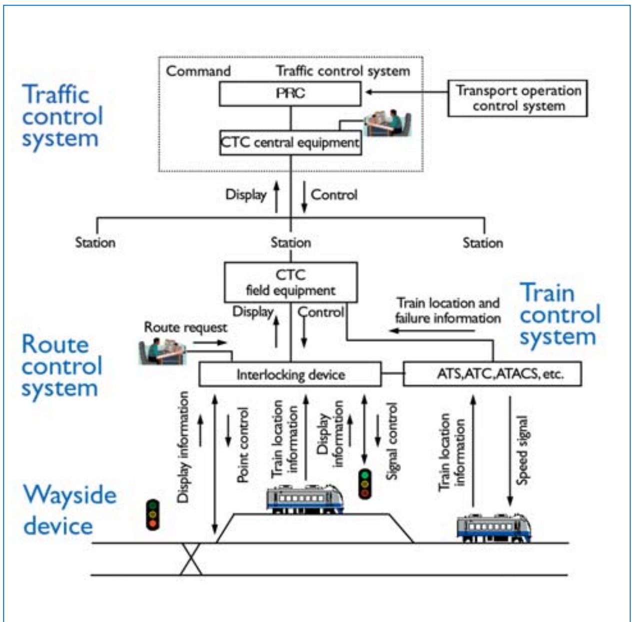

Fig.10: Overall configuration of signal control system

4 Problems with current signal control system

As described above, the transition of the signal control system is railway history. It reflects the long-term experience and the state-of-the-art technology of each period. The state-of-the-art technology in each period may have been the best technology when it was adopted, but various problems become evident when reexamined from the viewpoint of the current level of technology. Further, from the viewpoint of railway business operations, it has become necessary to implement improvements.

4.1 Signal control system – similar to building blocks

The configuration of the signal control system, starting with wayside devices, was not based on the ideal concept of a total railway system design. This system has been configured, like building blocks, according to the needs and technologies at different periods throughout the years. Accordingly, when the railway system is viewed as a whole, the current signal control system cannot necessarily be considered as the best solution.

4.2 Massive amounts of cables and other wayside devices

Each wayside device is connected by means of cables with the interlocking devices installed in the equipment room. A current is sent through the cable, and control is provided directly by voltage and current. In the case of a signal, control is carried out by a cable conductor for each electric bulb and LED. The total cable length adds up to 120 kilometers at a station of the same scale as that of Ofuna station on the Tokaido Line. For example, the electric bulbs used in signals operate at 30 V and 1.5 A. When consideration is given to a possible voltage drop, a very thick cable must be used.

Thus, in the signal control system as a whole, cable laying and connection work account for an enormous proportion of the construction period and cost (Fig. 11).

Fig.11: Cable conditions in the current machine room

4.3 Enormous amount of manpower and extremely long construction period required for installation and improvement of facilities

When station facilities are to be installed or improved, a great number of employees having expert knowledge and skill and other workers must be assigned for the construction and testing of the logic of the interlocking devices responsible for safety in train operations.

If a new line is to be introduced into a station, a period of one to two years is required, though it may vary according to the scale of the station and construction project. However, this fails to meet passenger needs or speedy railway business operation requirements.

4.4 Need for reducing construction and maintenance costs

Japan has entered an era of having a growing number of senior citizens and a falling birthrate. The railway transport industry is gradually feeling the influence of this trend, as exemplified by sluggish growth in the sales of commuter passes for students. To stabilize operation of the railway business under this condition, a substantial reduction in railway construction and maintenance costs is essential.

To succeed in this reduction effort, it is necessary to downsize the facilities of the railway control system. Further, it is also urgently necessary to promote adoption of a centralized monitoring system of possible equipment failures and introduction of a maintenance free system, instead of the current maintenance where each piece of equipment is checked.

4.5 Low reliability of wayside device

Trains run on tight schedules on a daily basis, and are usually right on time, but delays sometimes occur, causing inconvenience to passengers. There are several reasons for such delays. One of the major reasons is what is often called "signal trouble." This is the problem with a wayside device such as a signal, track circuit, or switch machine.

To eliminate this problem, efforts have been made to create a maintenance free system and to reinforce equipment. However, these wayside devices and the cables used to control the wayside devices are basically standalone systems that have no backup, and therefore, a low degree of reliability is simply not acceptable.

5 Direction in the development of a signal control system

To solve the problems with the current signal control system, it is necessary to introduce state-of-the-art technologies and to carry out bold and innovative changes.

The railway system, and the signal control system in particular, is a matter of basic safety in railway transport. So far we have been extremely cautious about introducing new technologies and implementing system changes. In fields other than railway such as the nuclear power generation and aircraft industries, gigantic systems directly related to safety have appeared. In addition to the previous approach based on empirical engineering alone, a theory of "system safety" has also been established in the world.

Further, there has been remarkable development in current information communications technology, computer technology, digital processing technology, and software engineering. Much of what could not have been realized previously is now within reach.

We believe that the target of our development effort is to catch up with the state-of-the-art technologies of the world and to innovate and reconfigure the signal control system at the earliest possible date.

6 Concept in the development of a "new signal control system"

The development of a new signal control system is based on the three major concepts of:

(1) departure from track circuit, (2) system simplification, and (3) improvement of safety and reliability of the signal control system.

6.1 Departure from track circuit

The track circuit system used in the train position detection system functions simply and is based on a long history. The limitations of this system have been manifested.

For example, a 4-wire cable is required for each track circuit in order to apply voltage to the track circuit and to check if a train is present or not. This is one of the reasons why the station is full of cables.

Sometimes the train detection is disabled due to rust on the rails, volcanic ashes, and fallen leaves gathered by strong winds of typhoons and so on.

To solve this problem, the following methods are available:

- Use of geodetic technologies such as GPS and others
- Counting the number of revolutions of the wheels and determining the position of a train
- Installation of a wheel sensor between the wayside and car

Of these, the GPS method is considered to be difficult to implement for the time being, because of the following problems:

- Use of the GPS system is still too expensive to ensure a high degree of accuracy in determining the train location.
- The required number of satellites cannot be acquired in the presence of a great number of tunnels or buildings.

For this reason, the D-ATC, DS-ATC and ATACS systems in use by JR East count the number of revolutions of the wheel to determine the train's location. Especially ATACS does not use the rail at all to transmit information on the train location. This is an epoch-making system radically different from the D-ATC, DS-ATC and other conventional systems.

We are also making efforts in the research and development of using detectors between the wayside and car in the line sections where D-ACT, DS-ATC and ATACS are not in use.

6.2 System simplification

In the signal control system which is comprised of the three levels of "wayside devices," "route control system," and "traffic control system," improvement of the "route control system" and "wayside devices" and the cables connecting them is urgently required. To meet this requirement, we are proceeding with research and development of a new route control system and network-based signal control system.

6.2.1 New route control system

In the mechanical interlocking system, a number of operators handled the turnouts and signals individually. An algorithm was created according to the basic concepts to ensure that serious accidents such as collisions or derailments would be prevented, despite possible handling error by these operators. This long-standing basic concept has been inherited by the current electronic interlocking device.

If processing is limited to within one computer, it is not necessary to perform mutual checking among events, which would be required in the case of handling by a number of operators, and there would be no need for an algorithm for preventing human errors. When a new route control system is developed, processing can be made very simple.

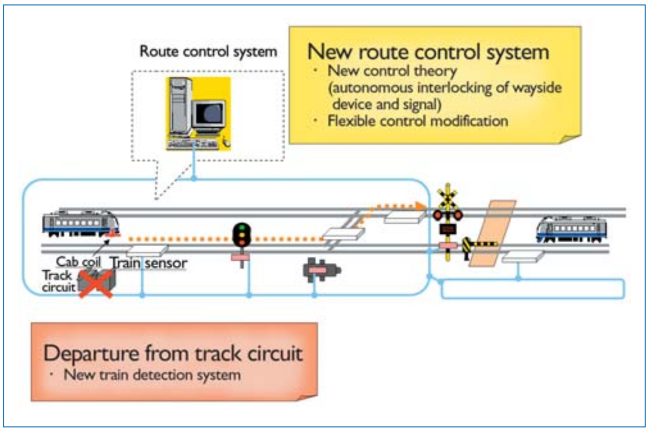

Fig.12: New route control system

The current interlocking device needs to be formed into a system conforming to the particular conditions of each station, and is currently produced in a form that is customized uniquely to each station. By introducing the state-of-the-art achievements of software engineering, it has become possible to configure a system that easily allows one basic system to be customized to suit each station. This will make a significant contribution to a reduction of the signal facility construction period and construction cost, and to preventing software failure in the early phase since bugs in the software configuration can be minimized.

6.2.2 Network-based signal control system

The current signal cable in railway compounds is used to transmit control information and to supply driving power to the wayside device. This dual function is separated into two; power supply function and control information transmission function. In the case of control information, the current cable is replaced with a fiber-optic cable for multiplex transmission of control information (Fig. 13).

This network-based signal control system is mainly intended to reduce the massive length of cables from the route control system to the wayside device. At the same time, it is intended to improve high-capacity transmission and noise resistance and to connect each of the facilities to terminal equipment by means of fiber-optic cables. Another advantage of this system is that development and testing of the route control system and construction and testing of the wayside network can be implemented in parallel, because of functional separation between the network devices and route control system, with the result that the time required for construction can be reduced. Each terminal has a self-diagnostic function for its electronic devices and wayside devices. And, as maintenance will be improved if they are placed under centralized monitoring and control, we are working toward that goal.

The wayside device must perform stably even under severe wayside conditions. So our principal objective is to configure a duplex system. We are making further development efforts to design an intelligent wayside device in such a way that, in addition to the current self-diagnosis function, the device will recognize the warning signs of possible failures and issue an alarm before train operation has to be suspended due to a failure.

Further, the cable is formed into a loop. This structure improves resistance to breakdown, and ensures upgraded reliability.

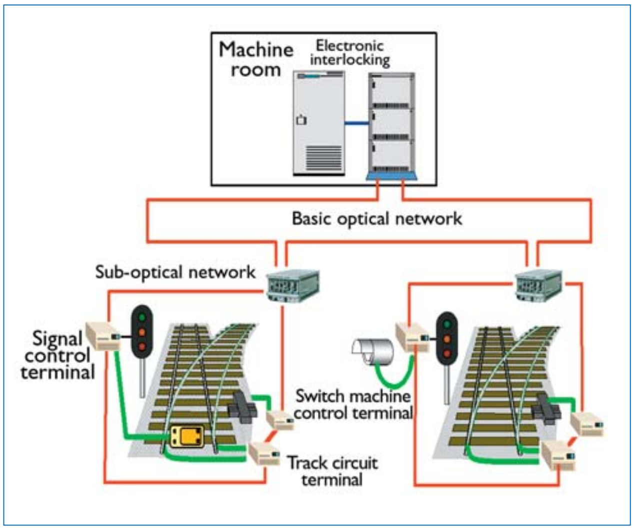

Fig.13: Network-based signal control system

6.3 Improvement of safety and reliability of signal control system

Today's high level of safety in the signal control system has been achieved by long experience and lessons learnt through the sacrifice of human lives. For the details of the signal control system technologies, expertise and experience are stored inside the heads of individual engineers in the form of "implicit knowledge." At present, the passing down of this expertise and experience and the training of young engineers is getting more and more difficult. Not only that, the system covers a great number of extensive fields, with the result that the knowhow gained from troubles in one system cannot easily be reflected to other systems. To solve this problem, the RAMS (Reliability Availability Maintainability Safety) document system, which is currently being established in Europe, needs to be introduced in such a way that the "implicit knowledge" will be formulated when signal control systems are introduced.

Further, in the system construction up to now, it has been difficult to share detailed knowledge of the specifications and the like that should be conveyed to related sections and organizations, and the cores of problems cannot be easily identified. Accordingly, in constructing the system, it has been difficult to create "common knowledge" for the project team as a whole, consisting of the manufacturers and our company. As a result, initial failure occurred at system startup. To solve this problem, we are thinking of using the UML (Unified Modeling Language) for the description of the specifications.

Introduction of these methods will minimize bugs and will further improve the system safety and reliability.

7 Future signal control system

As described above, the signal control system up to now has been configured, like building blocks, in accordance with the needs and state-of-the-art technologies at different periods of time. Accordingly, the signal control system is not a system that was created as a total comprehensive system from the beginning. This means that the time is ripe for creating an entirely new system instead of partial modification of the existing system.

So then, if a new signal control system is created based on cutting-edge technologies, what sort of a system will it be? The responsibilities and mission of those of us who are engaged in the research and development project are to draw up a master plan for such a signal control system.

We have just started this work. The following is a partial introduction to it:

7.1 Introduction of intelligence into rolling stock rather than mere improvement of wayside devices

The signal control system so far consists of wayside devices alone, which has supported the traveling of trains. However, if an intelligent system is introduced aboard the rolling stock so that the train location can, at any given time, be identified from aboard the train itself, autonomous travel of trains can be achieved by using an arrangement that allows each train running fore and aft to exchange information on their respective locations.

To put it another way, trains have been running according to the instructions from the dispatcher and according to predetermined train scheduling. This has been a very effective system so long as there is no accident or trouble. However, such a system has difficulty coping with abnormal situations when traffic is very congested. Accordingly, if the trains can identify their positions to each other for autonomous running, train operations will become flexile and it will allow quick recovery from confusion when traffic is congested.

Further, if trains are provided with a database of the operating plan, slopes, curve radius, speed limit, and other information for each section of the line, the efficiency of train performance can be maximized. It will also be possible to ensure the optimum train acceleration and deceleration, as well as minimizing energy consumption and travel time. Further, it will be possible to materialize the dream of an on-demand operation or platooning (electrical coupling, not mechanical) operation that will ensure flexible train operation by adjusting the number of train runs according to the number of passengers using the train service (Fig. 14).

Such a system configuration will change the conventional concept of the entire line section being controlled by a dispatcher. Accordingly, the function and role of the operation control system will also undergo changes.

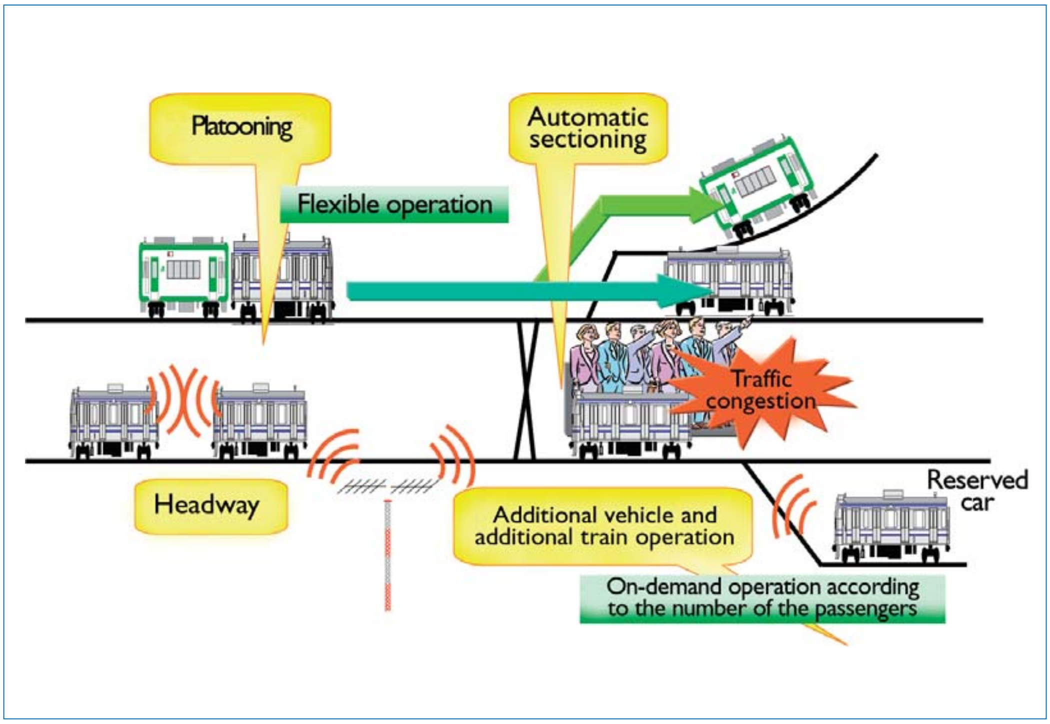

Fig.14: Flexible train operation

7.2 Simple route control system

When an intelligent system is introduced into the rolling stock to permit entirely autonomous train operation, the wayside devices will determine the route according to the route request by the train. If decentralized control is adopted by providing each wayside device with intelligent functioning, the entire system can be configured into a very simple "route control system."

8 Conclusion

Looking back on the transition of the signal control system, we have discussed the direction of the development of the future system of our research and development target.

The current signal control system technologies have been created by the ceaseless development efforts of our predecessors at the high cost of the sacrifice of human lives caused by major accidents. You will have understood that there are many problems requiring system change. Namely, the current signal control system was not created as a total system from the beginning. As a result, the facilities are large and cumbersome and do not employ cutting-edge technologies are not fully adopted in the system as a whole. Each section of this paper has introduced a part of our efforts to overcome these problems.

Innovations in the future signal control system cannot be achieved by the East Japan Railway Company alone. To ensure a world's top level railway system and greater safety, your support and assistance are indispensable.

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