Interpretive Article

History of JR East Commuter Trains

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Since JR East started mass production of the Series 209 type trains in 1994, more than 3,000 commuter type and suburban type train cars based on this series have been put into use. This policy was taken to improve services, including alleviating overcrowding, and to reduce costs in commuter transportation within the greater Tokyo area, which has one of the world's highest population densities. These cars have been developed according to principles that differ greatly from those adopted when JR East was still a part of the Japan National Railways. This paper describes the basic concepts involved in the development of these cars, and specifics concerning the development of the systems and equipment.

1 Concepts Concerning the Development of Commuter Trains

JR East owns about 8,000 cars used for commuter transport in the greater Tokyo area. The number of cars has been increasing every year in order to increase carrying capacity. Since the privatization of the JR companies, however, there has been a need to replace older cars and further increase carrying capacity. The life expectancy of a railway car is roughly between 20 to 30 years, depending on the degree of maintenance. In other words, with 8,000 cars, there is a need to replace from 300 to 400 cars every year or else cars that have exceeded their service life will be in use.

Although a large number of commuter cars must be produced every year, in order for a company to maintain its long-term fiscal health, it needs to provide better services, keep control of capital investment, and reduce costs for maintenance and operations.

In order to cope with this problem, JR East started the development of a new commuter train in 1991. The concepts that were applied were: "Half the cost," "half the weight" and "half the service life." "Half the cost" was in reference to controlling the initial investment. "Half the weight" was about reducing operating energy costs, and controlling running costs by reducing maintenance for wayside facilities. "Half the service life" had to do with improving the level of service to meet improved standards of living, introducing the latest technology in a timely manner, and drastically reducing maintenance costs by shortening the service life of cars. Embodying these concepts, JR East completed its first totally new commuter train, the Series 901 (which was later modified into the Series 209), in 1992.

Starting in 1994, the Series 209 type train, which is the mass production version of the Series 901, went into production. Ten years have passed since then. During this period, additional versions have been introduced and modifications have been made. The latest model is the Series E231 type train. Over 3,000 cars from this series are in use, and their number is being added to again this year.

The most recent Series E231 type train is a highly polished product, because it reflects our experience from the Series 209 and because it uses the latest technology. When contemplating future commuter trains, however, more breakthroughs are required for further reduction of costs and functional improvements. The Series E993 "AC Train" is our answer. We are currently developing this train, and it includes many system changes as described later in this paper.

Table 1: List of Technology Introduced for Commuter and Short-Distance Trains

(Legend ○ :Introduced in all cars △ :Introduced in some cars — : Not introduced)

Item \ Car type		Series 901 (209-900)	Series 209	Series E217	Series E501	Series 209, serial #500	Series E231, commuter model	Series E231, suburban model	Series E231, serial #500
Completed		1992. 3	1993. 2	1994. 8	1995. 3	1998. 11	2000. 2	2000. 3	2002. 1
Mainly used on		Keihin-Tohoku line	Keihin-Tohoku line Nambu line	Yokosuka line Sobu/Narita line	Joban Express line	Chuo/Sobu local lines	Chuo/Sobu local lines	Utsunomiya Line Shonan-Shinjuku Liner	Yamanote line
Main features		Comparative assessment of innovative technology	Drastic weight reduction; reduction of power consumption	Adoption of impact absorption construction	AC/DC cars; vector control	First expanded-width body for commuter trains	Adoption of TIMS automatic departure inspection	Common performance for both commuting and suburban travel	VIS (information guidance device) introduced
Two-sheet steel body		△	△	△	△	△	△	△	△
Wide body car		—	—	○	—	○	○	○	○
Impact absorbing construction		—	—	○Leading car	—	—	—	○Leading car	—
AC motor		○	○	○	○	○	○High-speed models	○High-speed models	○High-speed models
Inverter	(GTO element)	○	○	○	○	○	—	—	—
	(IGBT element)	—	—	—	—	—	○	○	○
Vector control		—	—	—	○	—	○	○	○
Controlled transmission device		○	○	○	○	○	—	—	—
TIMS		—	—	—	—	—	○	○	○
Light-weight, bolsterless trucks		○	○	○	○	○	○	○	○
Brake air supplement control	(in units)	○	○	○	○	○	—	—	—
	(as systems)	—	—	—	—	—	○	○	○

2 Overview of Commuter and Suburban Trains Developed by JR East

In order to allow readers to better understand the types of commuter and suburban trains that we have developed, we shall provide short descriptions of the features of the various series.

2.1 Series 209 (901) type train (Figure 1)

This was the first commuter train developed by JR East. New concepts were implemented in all aspects of development of this train, including the body, truck, main circuit equipment, control equipment, brakes, interior and design.

In the three car configuration prototype Series 901, different specifications were used for the main circuit equipment, body construction, interior, air conditioning equipment, air compressors, main control equipment, and other equipment. This was done in order to determine the optimum systems for the mass production version.

The mass production Series 209 type train has a weight that is only 70 percent of its predecessor Series 103, and only consumes 47 percent of the power. This series has become the JR East mainstay for commuter and suburban use. In 1998, a wide-body version (serial #500) was introduced to help alleviate overcrowding.

Fig.1: 209 Series type train

2.2 Series E217 type train (Figure 2)

This series is a suburban train based on the Series 209 type train. The main circuit equipment and control equipment are the same as those used in the Series 209. The gear ratio in the drive train has been modified to allow a maximum operating speed of 120 km/h. In addition, the body width was increased to the same 2950 mm as other suburban trains, and some of the cars have semi-cross seat layouts despite having four doors per car. Because these trains will use long tunnels, the end cars have been designed to allow passengers to pass through in case of emergencies. In addition, impact-absorbing construction based on detailed analyses of railroad crossing accidents was adopted. These trains were also the first commuter/suburban trains with lavatories that are accessible to wheel-chair users when they were introduced in 1997.

Fig.2: Series E217 type train

2.3 Series E501 type train (Figure 3)

This series, based on the Series 209 type train, was developed in 1995 as an AC/DC train for the Joban line. A German unit is used for the main circuit equipment. This equipment allows for greater control of the drive by using "vector control." Imported equipment was adopted because there were no domestic manufacturers producing this type of control system at the time. Today, "vector control" is no longer rare, and the Series E231 also uses it. The Series 501 also automated switching for AC/DC sections, which were manually switched until then, by utilizing the transponder function of ATS-P units. This series is designed for commuter use with cars with four doors and long seats. It is used between Ueno and Tsuchiura on the Joban Express line.

Fig.3: Series E501 type train

2.4 E231 Series type train (Figure 4)

In order to improve the functionality of commuter trains, the Series 209, serial #950 was developed by introducing "intelligent" control units, increasing the maximum rotational speed of the main motor, and achieving a maximum operating speed of 120 km/h with the same gear ratio. The mass produced version of this train is the Series E231 type train, and this is the first train that does not differentiate between the commuter and suburban categories. However, depending on the lines on which this series is used, there are suburban cars with semi-cross seats and lavatories, and that have impact-absorbing construction. The different versions are distinguished by their serial numbers. The biggest feature of the Series E231 is the introduction of the "TIMS" car information control unit. Most of the instructions sent to the trains are sent digitally, thereby reducing the amount of wiring necessary. In addition, departure inspections have also been automated.

Fig.4: Series E231 type train

3 Innovations in Train Bodies

This section will introduce the various technologies that have been adopted in JR East commuter trains by the area where the technology was applied. The first area to be covered is body construction. The main points of interest with regard to bodies have been reducing weight and manufacturing costs, and making bodies more maintenance-free. The development of computer strength analysis technology now allows us select materials that are suitable to the distribution of stress. In the development of impact-absorbing construction, we have utilized dynamic crash analysis technology.

3.1 Body Construction with Consideration given to Industrialization

Conventionally (when we were still part of the Japan National Railways), commuter train bodies were usually made of inexpensive, ordinary steel. Towards the end of the JNR era, however, the adoption of light-weight stainless steel construction was considered because of its resistance to corrosion, even though initial costs would be higher. The use of stainless steel bodies became the standard in 1986 with the introduction of the Series 205.

Stainless steel has continued to be used with the birth of the JR companies, and the "half the weight" concept has led to further reduction of weight. Table 2 shows a comparison of the weights of commuter trains.

Table 2. Comparison of the Weights of Commuter Trains

Unit: tons

Item \ Series		Series 103 (steel)	Series 205 (stainless steel)	Series 209 (stainless steel)
Structural weight		9.5	6.5	5.4
Empty weight	M cars 1)	39.7	32.6	27.7
	T cars 2)	28.8	23.6	22.2
Gross weight (10 cars)		359 (6M4T)	290 (6M4T)	241 (4M6T)

1) Motorized 2) Non-motorized

Also, as a new way of thinking, we allowed the adoption of body construction that was suited to the manufacturing facilities of each manufacturer, as long as the basic dimensions of the bodies were the same. During the JNR era, there was a division of labor for the design of trains among the manufacturers, and all of the manufacturers were required to make the same trains. With the Series 901, however, we allowed each manufacturer to adopt their own construction. This helped to further reduce costs.

One of the body structures that was adopted for the Series 901 type train was the "two-sheet construction" for which industrialization for mass production was a prerequisite. In conventional body construction, sheeting is applied to a framework. This method requires considerable labor for the construction of the frame. Therefore, a construction method similar to that used for automobiles was developed that maintains strength by combining stamped sheet metal with the external sheeting. This structure is used on the sides of the bodies. (Figure 5)

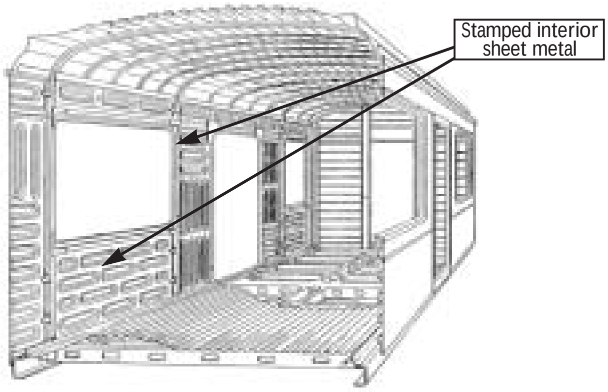


Fig.5: Two-Sheet Construction Body

This manufacturing method requires large stamping presses, however. Therefore, it is not a method that can be immediately adopted by all manufacturers.

3.2 Development of Impact-Absorbing Construction

The railroad crossing accident on the Narita line in 1992 involved an overloaded dump truck, and the crushed engineer compartment of the train led to the death of the engineer. This led to the consideration of crash countermeasures for trains. The goal was to, in a similar accident, reduce the force of impact to which passengers are subjected, and to secure a survival zone for engineers.

The first matter at hand was to take detailed measurements of the crushed sections of the train (Series 113) that was involved in the accident. Next, the accident was recreated using a computer crash analysis program, in order to determine the forces involved in the accident.

Based on these results, a leading-car model with a new structure under consideration (Figure 6) was subjected to the same conditions in the crash analysis program to determine the degree of damage and crash acceleration. This led to the strengthening of the survival zone through changes in the structure of the framework and allocation of impact-absorbing material. The construction of the leading cars of the Series E217 was determined in this manner, and the suburban Series E231 type train uses this same construction.

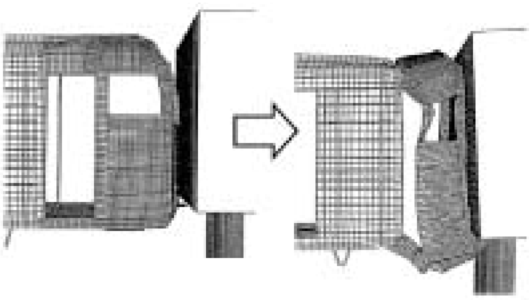


Fig.6: Crash Analysis Diagram

4 Innovations in the Main Circuits

In trains, the high voltage circuits that are used to drive the motors for operation are referred to as the "main circuits," and the running motors are referred to as the "main motors." Since the birth of electric trains, these main motors have been DC motors, but they have their disadvantages, such as the high amount of maintenance involved. With the recent developments in power electronics, however, light-weight and maintenance-free AC motors have become available, and these have led to major changes in the configuration of main circuits.

4.1 The Adoption of Induction Motors

DC motors have been used as the main motors because they are suitable for trains because they produce a large amount of torque when activated and they allow a wide range of speed control. However, because DC motors apply a current to the rotating section (armature), they have a commutator and brushes. Because the brushes are made of carbon, they become worn and need to be replaced. In addition, the carbon leads to dirtying of the interior of the motor, which in turn leads to malfunctions and other problems. In addition, there are other structural problems involved: The commutators do not create any rotational force, so that motors with the same output tend to be larger; and commutators are made up of thin pieces of copper which are a mechanical weak point.

In comparison, induction motors, a type of AC motor, have many advantages, such as: There is no need to supply power to the rotating unit; the rotating unit has a simple construction and can withstand high rotational speeds; the entire rotating unit contributes to the production of rotational force so that the motor can be made smaller; etc. In order to use induction motors as the main motor, however, the frequency and voltage of the alternating current applied to the motor must be varied continuously over a wide range. In the past, it was difficult to vary the frequency of alternating currents, however, this problem was solved by the development of power electronics that controls large amounts of power with semiconductors.

4.2 Improvements in Semiconductors

The first field to utilize power electronics was chopper control that was used to control DC motors. "Thyristor devices" were adopted for this. Although this device allows currents to pass through with gate signals, once a current starts flowing, a separate, parallel "commutation circuit" is required to stop the current.

For street cars and other relatively small motor controls, controlling alternating current frequencies with chopper devices and similar thyristors is an option. For trains that require large amounts of torque and wide ranges of speed control, however, semiconductor devices that allow faster switching (turning the current on and off) and that do not require a commutation circuit were necessary. In the latter half of the 1980s, GTO (gate turn off) thyristor devices that can turn off currents with gate signals were developed, and devices that could handle larger currents and higher voltages gradually became available. The devices were still expensive, however, so that cheaper devices would be necessary for use in commuter trains which would require many of them.

Fig.7: GTO Device (External view and internal view of the gate electrode)

4.3 Considering the Configuration of Inverter Units

Before we could develop the Series 901 type train, we had to develop the main circuit that would be necessary to use AC motors in trains. Innovations for the devices and circuitry to be used in VVVF inverters (variable voltage, variable frequency inverters that convert direct currents to alternating currents) that control AC motors were necessary in order to reduce the price of the inverters. To that end, we tested the following three types of main circuits, one on each train configuration, in the development of the Series 901 type train to compare their properties. (Figure 8)

1) High capacity transistors were used in control circuits that controlled one motor each, and four of these circuits were connected in a series.
2) Small GTOs were used in control circuits that controlled one motor each, and these circuits were connected in parallel.
3) Low voltage, high current capacity GTO modules were used to change the voltage in two stages, and four main motors were controlled at once.

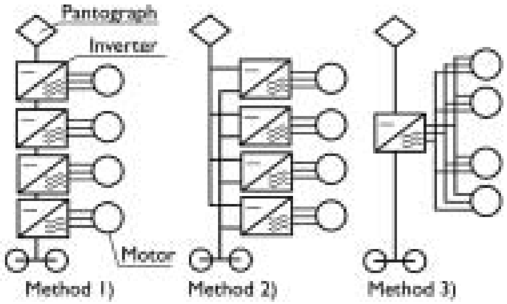


Fig.8: The Three Circuits that were tested with the 901 Series type train

As a result of the performance tests, we selected method 3) because it has the most stable operation, and it would simplify the configuration of the main circuit. This became the basic system used in our commuter and suburban trains.

4.4 The Development of Devices for Inverters

When we were developing the Series 901 type train, GTOs were the main type of control devices used in VVVF inverters. Because GTOs use gate signals to stop currents, the gate electrodes are located on the top of devices in a manner resembling branches on a tree. Because it is difficult to manufacture these devices, there was a limit to reducing costs.

Recently, devices referred to as Insulated Gate Bipolar Transistors (IGBT) (Figure 9) are starting to replace GTOs. This is a type of field effect transistor that controls a current by the strength of the gate signal. Therefore, it allows even faster switching than a GTO. This makes the output current of a VVVF inverter unit even smoother, and because the frequency of the sound during switching (turning on and off the current) is higher, it is less audible to the human ear. Inverters using IGBTs were used starting with the Series E231 type train.

Fig.9: IGBT Device (External view)

5 Innovations in Control Units

Although so-called "intelligent" cars are in the mainstream now, intelligent control systems for trains were being developed even before systems for providing information to passengers was started. Monitoring of various systems through multiplex transmissions was developed towards the end of the JNR era. The improved performance of microcomputers and the great strides in the development of digital transmission technology have led to the addition of even more functions. Furthermore, the integration of instruction circuits has helped to greatly reduced the amount of wiring required in trains.

5.1 Digital Transmission of Control Instructions

In the past, the circuits used to accelerate trains, apply the brakes, turn on and off the air conditioning and heating, open and close the doors, and light the various lamps used to monitor equipment were all independent systems. These systems had to be independently wired from the front to the back of the entire train in order for instructions and information to be sent back and forth. Therefore, the adding of functions to trains led to the need for more wiring to be installed.

When the Series 651 type train (Super Hitachi) was being developed as the first new train after the privatization of the JR companies, it was decided to install "monitoring units" that would use serial transmission of digital signals to handle equipment monitoring functions and service related instructions, such as those for air conditioning and heating. With respect to power and brake instructions that were directly related to the operation of the train, and door open/close instructions that are an important safety related item, the conventional one-line-per-signal system was used.

When developing the Series 901 type train, important train control instructions, such as those for power and braking, were also converted to serial transmission in order to reduce the number of lines necessary throughout a train. At the same time, the equipment monitoring functions were also improved with the MON8 system. In order to assure the reliability of the system, two control instruction transmission lines are used. When an instruction is received, the instructions sent over the two lines are compared and confirmed before an instruction is executed. (Figure 10)

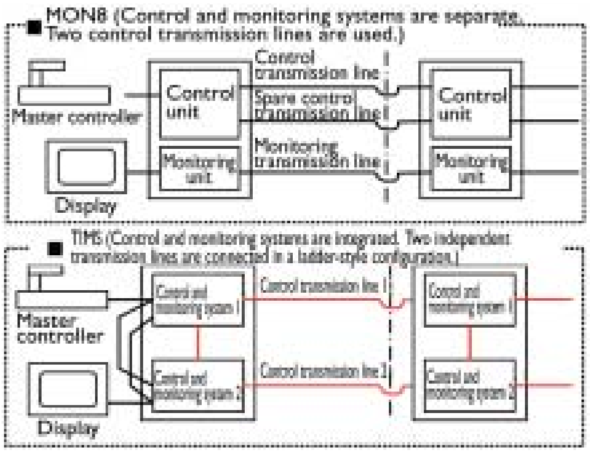


Fig.10: Comparison of MON9 and TIMS Transmission Configurations

5.2 Development of TIMS

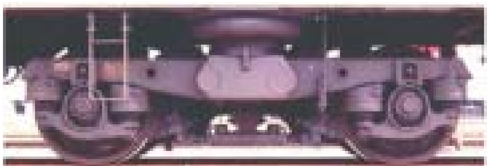
The transmission rates and processing speed of information transmission devices that are computer based have improved significantly. The Train Information Management System (TIMS) utilizes these advances in technology to create a computer network in trains. This system was initially installed in the Series 209, serial #950 trains in 1998. After confirming the operation of the system and improving the control logic, it was officially introduced in the Series E231 type train. Transmission rates were improved by 65 times (38.4 kbps to 2.5 Mbps) in TIMS. In addition, the transmission units in each train were made up of two independent nodes, and these nodes were connected in a ladder-style configuration. These changes helped to improve reliability, increase transmission rates, and helped to circumvent any malfunctioning sections (even if one system is down, transmission is possible over the other). Furthermore, it also became possible to daisy-chain the terminal units in each car to transmit instructions. This made it possible to even further reduce the amount of wiring required in trains.

The biggest feature of TIMS from the point of view of usage is that pre-operation inspections (departure inspections) can be automated. Power and braking tests, door open/close states, the condition of the public announcement systems in each car, and other systems can be checked automatically with a series of inspection programs. With regard to brakes, in the Series 209 and E217 type trains, a predetermined sequence of motorized and non-motorized cars gives priority to regenerative braking, and if that is insufficient, the air brakes in the non-motorized cars is used. TIMS allows overall control of this braking system for entire trains. This leads to a better ride, and prevents the brake pads in any one car from becoming more worn than the others. (Details will be explained later.)

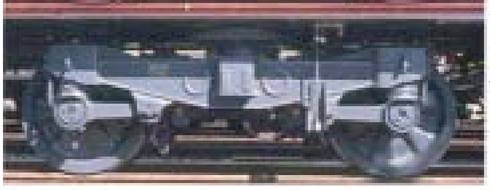
6 Simplification of Truck Construction

Unlike electrical circuits, it is difficult to make trucks fail-safe because they are mechanical in nature. Therefore, any changes in construction must be made with great care. Because of this, it is harder to see changes in trucks when compared with electrical circuits, but improvements have been made. The most recent major change started in the latter half of the 1980s. This was the introduction of the "bolsterless truck" in which the body of a car is placed directly on the frame of the truck. Trucks have to cope with the various differences in attitude between the tracks and the body of a car, and they have many moving parts to absorb shock. In addition, they have many friction points because they need to transfer power and bear the weight of the cars. As a result, they required a great deal of maintenance. One of the major points in improving trucks is reducing the number of these friction points, and the adoption of bolsterless construction is one means to that end. Bolsterless construction was first adopted in the Series 205 type train during the JNR era. Bolsterless construction uses air springs with low horizontal rigidity. This allows them to better cope with the rotational angles between the bodies and trucks that are created when a trains goes around a curve. Because of this, innovations were necessary in the construction of the center pin unit that transmits the drive. In the Series 205 type train, four rubber bushings and an intermediate body were placed between the truck cross beam and center pin, and the lower part of the intermediate body was inserted over the center pin. In this case, there is still a friction point at the bottom of the center pin. In the bolsterless truck used in the Series 209 type train, the "single-link method" was used in which the center pin and the truck cross beam are connected with a link with a rubber bushing.

In the Series 205 type train, an axle box support is used. There are rubber springs on the left and right of the axle box. Because rubber springs are subject to secular distortion and because height adjustment is difficult, the axle beam system was adopted for the axle box support in the development of the Series 901 type train. In addition, a metal coil spring was used for the axle spring to reduce secular distortion, and the structure was designed to eliminate any friction points. The adoption of axle beam construction also allows the shortening of the truck cross beam, which helps to reduce weight. Placing the air springs as close to the wheels as possible will reduce rolling. After considering cost and roll rigidity for the Series 901 type train, it was decided to place the air springs directly above the vertical beams of the truck in order to simplify the design. In the Series E217, the location of the air springs was widened because of the wider body. The current Series E231 type train has a truck design similar to that of the Series E217 type train. (Figure 11)



The Series 205 truck axle boxes are supported by the left and right rubber springs.



The truck axle beam system used in the Series E231 allows for a shorter axle box support length, and the location of the air springs is inside of the body.

Fig.11: Comparison of the Series 205 and Series E231 Type Train Trucks

7 Improved Brake Functions

When electric trains had resistors and used generative braking, a constant braking force was available. The air brakes of electric trains were closed off, when electric brakes were used. After regenerative braking was introduced with chopper control, the amount of braking continuously changes depending on the load. Braking is provided by what is called blending control in which air brakes are used to supplement regenerative braking. With the introduction of induction motors, regenerative braking increased in force, so that supplementary braking also changed dramatically.

7.1 Adoption of Air Supplement Control

In the regenerative braking of trains that used conventional DC motors (the Series 201, Series 205, etc.), it was difficult to attain sufficient braking from the regenerative brakes alone. Therefore, air brakes were used to supplement braking. In the Series 901 and later trains that use AC motors, the efficiency of regenerative braking was improved, so that more braking force than is necessary to stop an electric train is available. In order to efficiently use this braking ability, the brakes in non-motorized cars are controlled to apply less braking. This is referred to as "air supplement control." In the Series 209 and E217 type trains, the non-motorized cars to be paired with the motorized cars are predetermined and brake instructions are sent to the brake control units in the motorized cars. These units calculate the maximum regenerative braking force depending on the load, and send instructions to the inverter. Next, the regenerative braking force (a signal returned from the inverter) is subtracted from the braking force necessary to stop two cars, and any insufficient amount is applied by the non-motorized car after an instruction is sent to the brake control unit in that car.

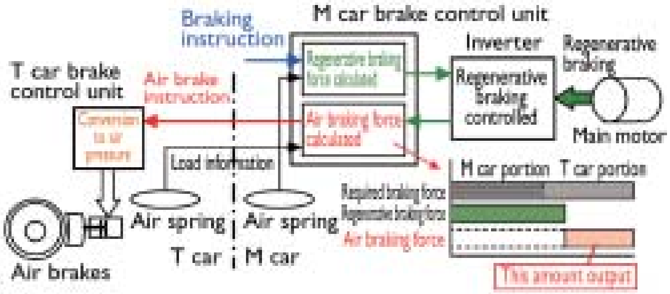


Fig.12: Conceptual Diagram of Air Supplement Control

7.2 Development into Full Train Control

As we described in the section about TIMS, braking in the Series E231 type train is controlled at the whole train configuration level. Each motorized car sends TIMS the amount of regenerative braking force that can be output, then TIMS calculates the amount of braking force necessary for the entire train from the brake instructions and load status. The amount of regenerative braking is subtracted from this sum, and any insufficient amount is divided evenly among the non-motorized cars.

8 Summary

Ten years have already passed since JR East started development of commuter trains based on its own concepts. During these ten years, we have continued discussions in order to improve our trains. The development of the AC Train was one of the achievements of those discussions, and the results have been fed back into the production of the current Series E231 type train.

Since the development of the Series 209 type train, improvements have been made leading to the Series E231 type train, and this has led to great increases in cost performance. There are a number of train models used by private railway companies that have been based on the Series E231 type train, so that it has become the de facto standard for commuter trains.

We believe that it is our duty to continue improving commuter trains in order to improve their performance and make them friendly to both man and the environment through close relations between our R&D division and operations division.