The JR East Group developed an AC Train prototype (Series E993 type train) towards the formation of the next generation of commuter and suburban trains. With this adoption, in order to compare operational performance and the structure of the articulated part, two types of articulated methods were developed; the articulated bogie that utilizes the four point spring suspension type system and the articulated bogie that utilizes the two point spring suspension type system. As a result of the evaluation through operational tests, it has been confirmed that both bogies have no problems from the perspective of operational safety and that the articulated bogie that utilizes the four point suspension type system is advantageous with respect to run on derailment at the spiral transition curve at the exit of curves. Moreover, assuming cases in which there are significant differences in the number of passengers in each compartment, tests to measure operational safety under offset load conditions were conducted and it has been confirmed that there is no difference in operational safety from traditional bogies. With respect to ride comfort, the articulated bogies were found to be equivalent or superior to the current Series E231 type trains and the outlook is that further improvement of ride comfort may be attained.

**Keyword**: AC Train, articulated bogie that utilizes the four point suspension type system, articulated bogie that utilizes the two point suspension type system, operational safety, offset load

### 1 Introduction

The JR East Group developed an AC Train prototype (Series E993 type train) towards the formation of the next generation of commuter and suburban trains. This train was the first commuter and suburban train for the JR East Group to employ the articulated method, a method that was adopted in order to improve passenger services and reduce the life cycle cost. In contrast to the traditional bogie in which the train body is supported by two bogies, with the articulated method 1), the bogie is deployed at the coupling of the train body to support the fore and aft vehicles. In Japan, major examples of use have been in the express trains of Odakyu Electric Railway (Romance Cars), Enoshima Electric Railway, and Hiroshima Electric Railway and JR East Group employs the system for the Shinkansen high speed test train (Series 953: STAR21) that was developed in 1993.

The articulated bogies of the past generally employed a method of supporting the train laterally with an indirect mount method 2) used for the bolster spring. In contrast to this, in order to improve ease of maintenance and achieve lighter weight, the sliding parts have been eliminated and a bolsterless method has been used for the articulated bogie of the AC Train. In order to compare operating performance and the structure of the articulated part, two types of articulated bogies, a two point air spring suspension type system and a four point air spring suspension type system were developed. This paper will present the overview and structure of these articulated bogies and the results from operational tests on measurement of operational safety, operational safety under load offset conditions assuming a significant difference in the number of passengers in each compartment, and ride comfort.

### 2 Overview of the Articulated Bogies Manufactured for Testing on the AC Train

The AC Train was tested using two types of articulated bogies. Figure 1 is an overview of both these bogies and Table 1 provides the principal specifications of the two types of bogies. Figure 2 is a diagram of the train configuration. Figure 1 (a) is the articulated bogie that utilizes the four point air spring suspension type system (hereafter referred to as “four point suspension type system”; the model codes are DT958 and TR915) and Figure 1 (b) is the articulated bogie that utilizes the two point air spring suspension type system (hereafter referred to as “two point suspension system”; the model codes are DT957 and TR914). The DT957 and DT958 models are electric bogies that are adaptable to direct drive motor (DDM) used to obtain traction.
2.1 Matters that Both Types of Articulated Bogies Have in Common

This section will explain the matters that the four point suspension type system and the two point suspension type system have in common. Moreover, matters that are characteristic to the four point suspension type system will be explained in section 2.2 and matters that are characteristic to the two point suspension type system will be explained in section 2.3.
(1) Strengthening of the Bogie and Braking Device through the Adoption of the Articulated System

Since the number of bogies per train configuration is small with the AC Train, the load and braking power that each bogie needs to assume increases. For this reason, the wheels, axles, axle springs, and bogie frame were all made to withstand a maximum axle load of 16 tons. Moreover, the wheel tread brake system has been adopted for the break gear of the motor bogies and the combined wheel tread brake and 1 axle 1 disk system has been adopted for the carrying bogies as in the past while the diameter of the cylinder diaphragm and the lever ratio have been increased to cope with the reduction in the number of brake axles.

(2) Installation of the DDM

Since the AC Train employs DDM, the structure of the electric bogie has been made appropriate for installing the DDM. As shown in Figure 3, the rotational movement of the rotor is directly conveyed to the wheel axle via the joints on both sides of the motor. While there is concern that a negative impact on operational safety may be generated as a result of the increase of unsprung mass, deterioration of operational safety has been prevented by inserting rubber as buffer strips between the joints. Moreover, in order to prevent the DDM itself from rotating, a reactive force absorber has been installed.

2.2 Articulated bogie that utilizes the four point suspension type system

The articulated bogie that utilizes the four point suspension type system has four air springs per bogie and supports both sides of the articulated part with two air springs each (Figure 1 (a)). While the number of parts related to the air spring such as the air springs themselves and the leveling valve (hereafter referred to as "LV") increases, since the body bolster that thrusts out between train bodies in the case of the two point suspension type system about which explanation will be provided later becomes unnecessary, it is possible to simplify the structure of the train body. Such articulated bogies that utilize the four point suspension type systems are used overseas in the commuter and suburban train Series ET423 of the German railway system with several other examples of use. On the other hand, the track record of use in Japan is limited to partial test use in the Series 953 type Shinkansen high speed testing train and this is the first adoption for commuter and suburban trains.

(1) The Articulated Structure and the Central Pin

The structure of the articulated part is shown in Figure 4. The train body with the central pin (lower train body) is placed on the articulated bogie that utilizes the four point suspension type system and the central pin and the bogie are connected using a single link in order to provide traction. The top part of the central pin has a bush for connecting the coupling device and the coupling device on the other train body is placed here and anchored using bolts. A rubber buffer is pressed into the body of the coupler on the upper train body and the movements of the two train bodies are allowed with this buffer acting as the node. In the case of this bogie, since the weights of the various train bodies are borne by the air spring that supports each train body, this coupling device will not be continuously subjected to the vertical weight of the train body. With this system, since the air spring may be installed immediately below the head stock, it is not necessary for the head stock to protrude to the connecting train body and the structure of the end of the train body may be made relatively simple. When a comparison including the body and the bogie is made, the advantage is in the simplicity of the structure and the ability to achieve a lighter weight.

Fig.3: Installation of the DDM

Fig.4: Structure of the Articulated Part (Four Point Suspension Type System)
(2) Spacing of the Air Springs in the Direction of Travel of the Train
In the case of the articulated bogie that utilizes the four point suspension type system, the spacing of the air springs in the direction of travel of the train is believed to influence the wheel load balance and ride comfort and for this reason, the spacing of the air springs in this direction is important. With this bogie, in order to mitigate such influence to the extent possible, the spacing has been significantly reduced to 840 mm that is within the scope that enables configuration with a distance of 400 mm between the coupling surfaces.

(3) Communicating Mechanism of the Air Spring and Control of Height
Control of the height of the air spring for maintaining the height of the floor of the train body uniformly when the train body is full and when the train body is empty is undertaken separately for each air spring. Accordingly, an LV has been installed on the air spring. In order to prevent the generation of an unbalance in the wheel load in the unlikely event that an air spring develops a leak, in addition to connecting the air spring in the left and right directions via a differential pressure valve as in the case of the communicating mechanism of traditional bogies, a communicating mechanism that uses a differential pressure valve has also been installed in the direction of travel of the train. Accordingly, even in the event one air spring in the bogie develops a leak and a significant pressure differential is generated among the air springs, wheel load unbalance can be prevented as a result of loss of all air from all the air springs in the relevant bogie.

2.3 Articulated bogie that utilizes the two point suspension type system
Since the articulated bogie that utilizes the two point suspension type system used for the AC Train has a structure whereby the weight of the air spring is borne by the bolsterless bogie at the center between the articulated train bodies, the body bolster on the train body that is attached to the air spring protrudes from one of the train bodies to the articulated side. This body bolster must be installed in a position that is lower than the bottom of the train body in order to avoid interference with the other train body to which the train body with the body bolster is coupled when passing through curves. The air spring must be installed below this body bolster and for this reason the frame member of the bogie frame has been significantly bent and the height of the top of the air spring has been reduced to 830 mm (Figure 1 (b)).

(1) Articulated Structure
The status of the attachment of the train body is shown in Figure 5. A train body with a body bolster (lower train body) is placed on the articulated bogie that utilizes the two point suspension type system and the central pin at the center of the body bolster is connected to the bogie using a single link for traction. The top part of the body bolster has a bush for connecting the coupling device and the coupling device on the other train body (upper train body) is placed here and anchored using bolts. A spherical roller bearing is incorporated in the coupling device with consideration given to rotational movement and this becomes the node that allows movement between the two train bodies. For this reason, with this bogie, the support of one train body is through three points made up of the two air springs and the coupling device.

Fig5: Structure of the Articulated Part (Two Point Suspension Type System)

(2) Increase of the Lateral Spacing of the Air Springs
As explained in the preceding section, in this method, the train body is supported at three points and for this reason, the rigidity borne by one bogie in the direction of roll must be increased. Increase in the vertical rigidity of the air spring can increase the roll rigidity but this is disadvantageous from the perspective of ride comfort and for this reason, increasing roll rigidity has been attempted by enlarging the left to right spacing of the air spring to 1980 mm.

3 Results of Operational Tests
Operational tests on safety and ride comfort were conducted on the Saikyo Kawagoe Line between Sashiogi and Akabane and on the Tohoku Line between Omiya and Utsunomiya due to the fact that curves of appropriate radius required for the tests and testing at the maximum speed of 120 km/h that is the standard for the new trains.
recently built by JR East Group are available in these sections. The
testing speed was a maximum speed of 120 km/h and the speed
when passing through curves was the basic speed +15 km/h for the
(Saikyo Kawagoe Line) and +45 km/h for the (Tohoku Line).

3.1 Operational Safety
(1) Results of Measurement in General Circular Curves
In terms of safety, the derailment coefficient was 0.95 or less on the
entire course at the maximum speed of 120 km/h and a curve
coming in speed of +15 km/h of the basic speed and the dynamic
reduction in wheel load was 80% or less indicating that there are no
problems. The maximum value of the lateral pressure did not exceed
the guideline value for any of the curves. The relationship between
the speed and the derailment coefficient and the maximum lateral
pressure in a curve with a radius of 800 m and cant of 95 mm is
shown in Figure 6. The various elements having to do with
operational safety did not exceed the guideline values confirming that
there is no problem with respect to operational safety. With respect
to the motor bogie that adopted the DDM method, there was no
negative impact on operational safety such as the generation of a
significantly large wheel load or lateral pressure. It is believed that
this is because the buffer rubber installed in the DDM joint proved to
be effective.

(2) Status of Reduction of Wheel Load when Traveling in a Spiral
Transition Curve
Figure 7 shows the comparison of the state of reduction of the wheel
load between a traditional bogie and an articulated bogie that utilizes
the four point suspension type system. With the bogie, the load on
the spring suspension in one diagonal of the train is prone to
decrease as a result of the change in the cant (1) and the wheel load
in one diagonal of the bogie is prone to decrease as a result of such
change (2) and there is a tendency for loss of wheel load to be large
at places where (1) and (2) coincide. On the other hand, with the
articulated bogie that utilizes the four point suspension type system,
there are no points at which (1) and (2) coincide and an effect that
limits loss of wheel load can be expected compared to bogies. Figure
8 shows an example of a simulated comparison of the load on the
suspension air spring and the axle spring load on the high side of the
curve when traveling through a spiral transition curve for a bogie
and for an articulated bogie that utilizes the four point suspension
type system. In the case of the bogie, since the air spring load
decreases when traveling through a spiral transition curve, the
reduction in the load of the axle spring also becomes large. On the
other hand, in the case of an articulated bogie that utilizes the four
point suspension type system, since the load of the air spring
increases in a spiral transition curve, it can be seen that the load on
the axle spring decreases.

Fig.6: Results of Measurement of Operational Safety
(R = 800 m; C = 95 mm)

Fig.7: Comparison of the Reduction of Wheel Load
(a) Bogie (non-articulated)
(b) Articulated bogie that utilizes the four point suspension type system

Fig.8: Comparison of the Air Spring Load and Wheel Load (Simulation)
Figure 9 is the result of operational tests that compared the wheel load on the high side of the curve when traveling through a curve with radius of 405 m and cant of 105 mm at a speed of 48 km/h for a leading bogie, articulated bogie that utilizes the two point suspension type system and articulated bogie that utilizes the four point suspension type system. From these tests, it was found that loss of wheel load is small at the exit of the spiral transition curve for the articulated bogie that utilizes the four point suspension type system. This is believed to be the effect of the limitation of loss of wheel load that was considered in Figure 7 and Figure 8.

(3) Operational Safety under Offset Wheel Load Conditions
In order to confirm that operational safety is assured even when there is a significant difference in the number of passengers from one compartment to another, operational safety was verified under offset wheel load conditions. Verification through simulation was undertaken in advance to confirm safety in terms of derailment and the actual operational test was undertaken after this.

i) Results of the Simulation
The simulation involved a model with a train configuration of three articulated compartments and a model of a bogie train compartment. Figure 10 shows the overview of the models and in the simulation, the conditions for the articulated train configuration under full and empty conditions were calculated for four cases as shown in Figure 10.

Figure 11 shows the results of the simulation with respect to derailment coefficient and lateral pressure in a curve with radius of 300 m. From this figure, it is seen that:

- For the articulated bogie that utilizes the four point suspension type system, under “empty, full, empty” and “full, empty, full” conditions that represent offset wheel load for the front and back wheel loads, the operational safety showed no difference compared to operations under “all empty” or “all full” conditions.
- With respect to lateral pressure, the pressure is low for all empty conditions and high for all full conditions. In the empty, full, empty and full, empty, full conditions in which the front and back wheel loads become offset for the articulated bogie that utilizes the four point suspension type system, the lateral pressure is between those of all empty conditions and all full conditions.

From the above, it has been confirmed that no significant change in operational safety occurs even when there is a difference in the load from one compartment to another.

ii) Operational Test
The operational test with respect to offset weight was conducted by mounting weights in the compartment of the train and by moving the position of these mounted weights, a condition in which an offset in the load of the front and back wheels was created.

The actual conditions for mounting the weights are shown in Figure 12 and the load setting conditions are shown in Figure 13. The load condition A is when the number 3 compartment is extremely heavy (left side of Figure 13) and load condition B is when the number 2
compartment is extremely heavy (right side of Figure 13) and PQ measurements were undertaken for the number 3 compartment. The results of the operational test are shown in Figure 14. In both load conditions, the derailment coefficient was about 0.2 for the scope of speed in which measurements were taken and it was seen that the derailment coefficient became lower as the load increased.

3.2 Ride Comfort

Measurements were taken with the articulated bogie that utilizes the four point suspension type system, articulated bogie that utilizes the two point suspension type system, and Series 209-500 type train as an example of the bogie. Figure 15 shows the results of measurement of ride comfort levels in various speed zones. Ride comfort was about the same for the articulated bogie that utilizes the four point suspension type system as for the Series 209-500 type train on bogies while for the articulated bogie that utilizes the two point suspension type system, the ride comfort was superior to the Series 209-500 type train. With the train on articulated bogies, since there is no overhang at the end of the train, there is no position that has inferior ride comfort as is seen at the end of a bogie type train.

With respect to the articulated bogie that utilizes the four point suspension type system, tests are being conducted under such conditions as improved characteristics of the dynamic damper on the left and right and forced limitation of yawing towards improving ride comfort and through review of the rigidity of the axle spring suspension, the outlook is that ride comfort may be made equivalent to trains with the articulated bogie that utilizes the two point suspension type systems.

Development work has been undertaken with respect to two articulated bogies (two point suspension type system and four point suspension type system) that employ the bolsterless system for AC Trains. As a result of operational tests, it has been confirmed that both types of articulated bogie trains have superior operational safety. Moreover, with respect to the loss of wheel load in spiral transition curves, it was found that the articulated bogie that utilizes the four point suspension type system is an effective method.

In the future, measures for improving ride comfort identified through the tests will be applied to existing AC trains and the results of such implementation will be evaluated and verified.

References:
2) The Dynamics of Railway Trains, Denki Sha Kenkyu Kai (1994), p. 56