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Shinkansen Bogies

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In the previous issue we discussed some of the main features of bogies, and looked at bogie structure for various carriages, specific bogies for trains carrying commuters and other passengers over short distances, tilting carriages using pendulum mechanisms, and steering bogies. Such trains run mainly on narrow-gauge track in Japan, at maximum speeds of 120 to 130 km/h. This next article examines some of the characteristics of bogies required for high-speed trains, particularly shinkansen that travel at maximum speeds over 200 km/h. I will also discuss the past and present development of shinkansen bogies, focusing particularly on their structure.

Technical Innovations

The first scheduled shinkansen run was on 1 October 1964 but many prior technical developments were necessary before trains could travel at high speeds. The following summarizes some of the important advances made in bogie development in the 1950s.

- Incorporated springs and oil dampers in bogie suspension, significantly reducing vibration
- Mounted traction motor on bogie frame instead of using nose suspension system and also used parallel Cardan drive system (see *JRTR* 18, p. 58) to transmit power to wheelset via flexible couplings and gears, greatly reducing bogie weight, in turn permitting faster speeds on shinkansen and other electric trains
- Adopted press-welded structure for bogie frames, reducing frame weight considerably
- Introduced disk brakes, increasing braking power, in turn permitting faster speeds
- Used air springs in carriage suspension to improve ride comfort

These important technical innovations raised bogie performance, lowered weight and reduced vibrations. As a result, bogies could run at faster speeds, making rapid shinkansen services possible.

Bogie Performance

Because shinkansen run at high speeds, their bogies and carriages must not be subjected to serious lateral vibrations, called hunting. As a train runs faster, hunting can increase to such an extent that the bogie vibrates severely side to side, which creates passenger discomfort, damages the track, and can even derail the train in extreme cases. To achieve operating speeds higher than 200 km/h, bogie developers tried to solve the hunting problem through theoretical calculations and trial runs using scale models and actual carriages. These tests helped discover effective ways to raise the speed at which bogie hunting becomes a problem. Here, I will summarize the steps used to solve these problems and produce a new bogie design for shinkansen.

Graded wheel tread gradient

The outer rim of the wheel in contact with the rail is called the wheel tread (see *JRTR* 18, pp. 52 and 57). The wheel tread generally has a gradient to help the train negotiate curves more easily, and to maintain the carriage in a central position on straight track. If the main aim is to achieve high speeds, the wheel tread gradient is kept low. On the other hand, if the main aim is to maintain high performance on curves, the wheel tread has a higher gradient. The wheel tread gradient for shinkansen bogies takes into account both the need for high speed and the need to ensure that wheels do not continually run on one side of the rail. The gradient used to meet these conditions was 1:40 using a conical wheel tread configuration.

However, circular wheel tread configurations were developed for the shinkansen in the mid 1980s, and recently almost all bolsterless shinkansen bogies use this type of wheel tread. The circular configuration which is shaped like a large number of arcs aligned next to each other, supposes a wheel tread that has already been subjected to wear. This configuration reduces contact bearing forces between the wheel tread and the running surface of the rail. This means less wheel tread wear, which in turn means better running performance. The effective gradient of shinkansen circular wheel treads is about 1:16, which meets demands for both stability at high speeds and excellent running performance on curved track.

Axle box suspension ridigity

Important factors affecting bogie running performance are: the structure of the axle box suspension system supporting the wheelset on the bogie frame; the structure of the axle bearings; and the rigidity of the axle box suspension. In other words, the axle box suspension system must be constructed so that it prevents play due to wear over many years of operation. Moreover, the axle bearings must be designed so that they prevent, as much as possible, any play at all especially in the axial direction. The rigidity of the axle box suspension can be determined mainly by theoretical calculations and tests using actual bogies. In the case of bogies for older shinkansen, the rigidity required of the axle box suspension depends on the carriage type (Table 1).

Bogie rotational resistance

Previously, it was thought that bogie hunting could be prevented effectively by using friction to resist bogie rotation relative to the car body. However, calculations and test results showed that this bogie hunting can be prevented more effectively by using rotational moment obtained from springs to resist bogie rotation. However, such springs increase wheel lateral pressure on curved track and make the bogie structure more complex, so Series DT200

Table 1 Axle Box Suspension Stiffness

Series 0 and 200 carriages	Longitudinal: 3,000–4,000 kgf/mm per axle box Lateral: 1,500–2,000 kgf/mm per axle
Series 100 carriages	Longitudinal: 1,500–2,000 kgf/mm per axle box Lateral: 3,000–4,000 kgf/mm per axle

bogies use the frictional resistance obtained from side bearers that support the entire load of the car body.

Bogie Development

About 35 years have passed since the shinkansen began carrying passengers in 1964. Over the years, three types of bogies have been used on shinkansen carriages (Table 2). These are:

- Series DT200 bogies used for many years after start of shinkansen
- Bolsterless bogies introduced in 1992 for new types of shinkansen
- Bolsterless bogies for Yamagata and Akita Shinkansen (running on both shinkansen and conventional tracks converted to standard gauge)

The following three sections describe the development of these three bogie types and their structure.

Development of Series DT200 bogies

When the shinkansen started operations, it was the first train in the world to attain operating speeds of more than 200 km/h. Safety at such speeds can only be achieved if the bogies perform properly, so bogie designers and manufacturers focused on the need to prevent the wheelsets and bogies from hunting dangerously, and the need to prevent failure or other damage in important parts like bogie frames, wheels, axles, axle bearings, and springs. In mid-1962, before the actual shinkansen cars were manufactured, six test cars were built each using a different type of driving bogie (DT9001 to DT9006) and axle box suspension types (e.g., Minden, IS and Schlieren, etc.). Data from trial runs on the Kamonomiya test track (on part of the Tokaido Shinkansen line) were used in the design and manufacture of Series DT200 bogies. For the axle box suspension, the Series DT200 bogie combined the advantages of the Minden system with an improved IS system developed by the now defunct Japanese National Railways (JNR). The bogies that actually went into service were lighter than the test models, and were easier to manufacture and maintain (*JRTR* 18, p. 56).

Spurred by the success of the Tokaido Shinkansen, JNR built new shinkansen lines to other parts of the country—first the Sanyo Shinkansen, which began operations to Hakata [Fukuoka] in 1975, and next the Tohoku and Joetsu shinkansen, which opened between Omiya and Morioka, and between Omiya and Niigata in 1982. Carriages also saw changes. The pioneer Series 0 shinkansen was improved with the introduction of the Series 100 that began operations on the Tokaido and Sanyo shinkansen in 1985, and Series 200 on the Tohoku and Joetsu shinkansen in 1982. The Series 100 shinkansen use DT202 driving bogies and TR7000 trailing bogies. The Series 200 use DT201 driving bogies and TR7002 trailing bogies. Compared to the DT200 bogies for Series 0 shinkansen, the newer bogies are lighter and easier to maintain. The bogies for Series 200 trains on the Tohoku and Joetsu shinkansen lines have also been adapted to cope with the prevailing cold snowy winter conditions.

Despite these improvements, the basic structure of the new bogies for those new series shinkansen carriages was the same as that of the DT200 bogies used by the

Table 2 Shinkansen Bogie Series

Bogie Types	Carriage Types
DT200 Bogies from start of shinkansen (2,500 mm wheelbase)	Series 0 Series 100 Series 200
Bolsterless bogies for new shinkansen (1992〜) (2,500 mm wheelbase)	Series 300 Series 500 Series 700 Series E1 Series E2 Series E4
Bolsterless bogies for Yamagata and Akita shinkansen (2,250 mm wheelbase)	Series 400 Series E3

Series 0. In other words, although they have undergone some modifications over about 30 years, shinkansen bogies continue to use a design based on the DT200. During the same time frame, shinkansen operating speeds rose to 220 km/h on the Tokaido and Sanyo shinkansen in 1986, and then to 230 km/h on the latter line in 1989. The Tohoku Shinkansen saw an increase to 240 km/h in 1985, while speeds on part of the Joetsu Shinkansen rose to 275 km/h in 1990.

Development of new shinkansen bolsterless bogies

The success of the shinkansen prompted European countries to develop their own high-speed trains in the 1980s. In 1988, the German ICE achieved 406.9 km/h, and then the French TGV posted a new world record of 515.3 km/h in 1990. These impressive advances spurred Japan to further effort. In addition, better expressways and improvements to domestic airports in Japan had resulted in faster road and air travel, posing another challenge for the railways. Shinkansen designers realized that they would have to come up with a new type of train capable of running at operating speeds of 270 to 300 km/h.

They knew that this target could only be met by development of a light, high-performance bogie. Over the years they had experimented with many test models, trying to develop a lighter shinkansen bogie that would permit higher speeds and greater ride comfort. But none of the test models were good enough to go into production. Realizing they would need a different approach, in about 1980, JNR designers began to develop a bolsterless bogie for shinkansen. Just before JNR was privatized in 1987, they built a number of trial bogies (DT9022 to DT9026) and then conducted experimental runs. However, these test designs could not meet the required performance levels. As a result, after JNR was privatized and split into the seven JRs, the Railway Technical Research Institute (RTRI) was given the task. The Institute chose the DT9023 trial bogie as the basis for further development.

JR Central, one of the JR group, participated in new development trials by mounting trial bogies on a Series 100 shinkansen and subjecting the train to long-term experimental runs to test endurance levels. The company was trying to find a suitable bogie for the Series 300 shinkansen being developed at the time. Their efforts paid off in 1992 when the *Nozomi* Series 300 shinkansen entered operation. *Nozomi* uses a bolsterless electrically driven TDT203 driving bogie and TTR7001 trailing bogie. It is smaller and lighter than the DT200 bogie, and offers far greater stability at high speed, more dependable performance on curves, and better ride comfort. As a result, it has been adopted for all new shinkansen (Series 300 and later). For example, in 1997, JR West adopted this bogie technology for its Series 500 shinkansen that were designed to reduce aerodynamic noise and achieve a maximum operating speed of 300 km/h, thereby bringing Japan into the age of rail travel at 270–300 km/h.

The three shinkansen operators (JR East, JR Central, and JR West) realized that higher shinkansen speeds create environmental and other problems, including noise, micro-pressure waves in tunnels, ground vibration, and aerodynamic problems in tunnels when trains pass each other at high speed. To resolve these problems and obtain data that could be used to raise performance and ride comfort, each company built a high-speed experimental train (STAR21, 300X, and WIN350) for running tests. The bogies for these trains were based on the same design principles as the above-mentioned bolsterless bogie. During high-speed tests, WIN350 ran at 350.4 km/h (August 1992), STAR21 reached 425 km/h (December 1993), while 300X outran them both at 443 km/h (July 1996).

Development of bolsterless bogies for Yamagata and Akita shinkansen

We have looked at two different types of shinkansen bogies—the DT200 bogie for the first and early shinkansen trains, and the bolsterless bogie for more recent shinkansen. A third type is a bogie for trains running on shinkansen tracks with through operations on conventional tracks converted to shinkansen standard gauge. Examples are the Yamagata Shinkansen trains that began operations between Fukushima and Yamagata in 1992, and the Akita Shinkansen that began operations between Morioka and Akita in 1997. These are the so-called mini-shinkansen operated by JR East. For these trains, the bogies have to be capable of stable running at about 270 km/h on shinkansen tracks, as well as be able to negotiate sharp curves of approximately 400-m radius on conventional tracks.

After the JNR privatization, RTRI obtained funding from the national government to develop a trial DT9027 bogie for experiment. The result of this research was a bogie with a shorter wheelbase of 2250 mm, the first time a shinkansen bogie had varied from the 2500 mm wheelbase. The Institute proposed giving the axle box suspension system optimum rigidity and the wheel tread optimum shape, to ensure an ideal balance between stability at high speeds and excellent running performance on curved track. JR East manufactured trial bogies (DT9028, DT9029, DT9030) that also adopted hollow-bored axles and a wheel diameter of 860 mm for Series 400 trains to Yamagata. These trial bogies were made lighter using techniques obtained during development of the shinkansen bolsterless bogie. For example, they used an aluminium gearbox, and three different axle suspension systems. After many trials, the company decided to base its bogie design on the DT9030, which had a rubber/leaf spring system for the axle box suspension system. The new DT204 bogie was made for Series 400 shinkansen. A trial run in 1991 on the Joetsu Shinkansen using bogies with the same smaller wheelbase of 2250 mm achieved 345 km/h.

Structure of Series DT200 Bogies for First Shinkansen Trains and Some Subsequent Models

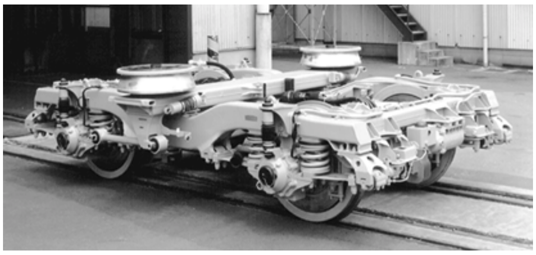
Figure 1 shows the composition of the DT200 bogie for shinkansen trains. The bogie has a bolster with air springs mounted on its upper surface. These air springs support the carriage body directly. As I will explain later, the bolster has been eliminated from recent shinkansen bogies in order to lighten the bogie and gain extra performance.

The main characteristics of the DT200 bogie are shown in Table 3. The main components of the DT200 bogie—the axle box suspension, bolster system, bogie frame, wheelset, and driving gear box are described briefly below.

Axle box suspension

After comparing results from tests of several types of axle box suspension systems mounted on trial shinkansen bogies, the IS type was chosen. The IS axle box suspension system had been developed previously by JNR. A supporting plate (leaf spring) is attached to the front and rear of the axle box, with rubber bushings mounted on the front and rear ends of the supporting plates. The positioning of the rubber bushings ensures that the wheelset and axle box are suspended from the bogie frame in a relatively rigid manner longitudinally, yet in a relatively flexible manner laterally. Two advantages of this axle box suspension system are that the vertical movement of the axle springs is not obstructed, because vertical movement deflects the supporting plates and rubber bushings, and that the various parts have no play and are not subject to abrasion or wear. However, one disadvantage is that the bogie must be made longer than

Figure 1 DT200 on Series 0 Shinkansen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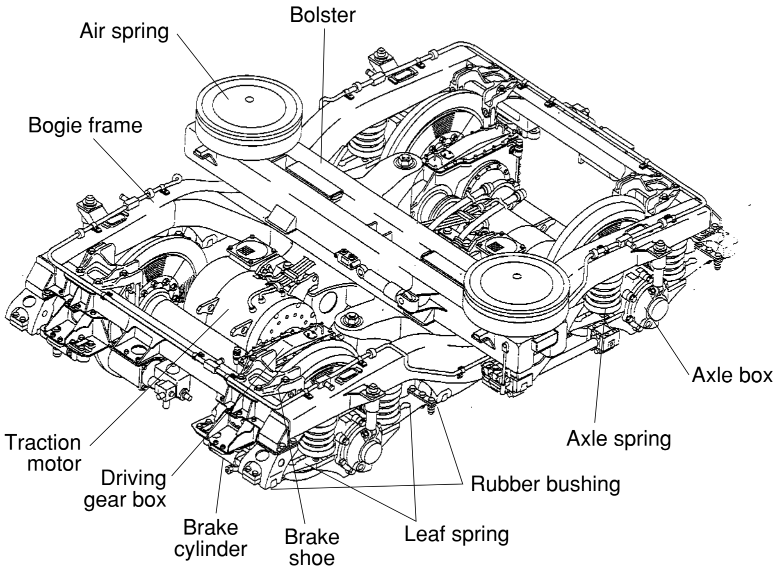



(Japan Overseas Rolling Stock Association)

Table 3 Characteristics of DT200

Bogie wheelbase	2,500 mm
Wheel diameter	910 mm
Bogie weight	10,100 kg (unsprung mass, 4,660 kg) for Series 0 shinkansen 9,870 kg (unsprung mass, 4,630 kg) for Series 100 shinkansen
Traction motor	DC 180 kW for Series 0 shinkansen DC 230 kW for Series 100 and 200 shinkansen

ideal, because the supporting plates are arranged in series. This type of axle box suspension system was adopted for Series 0, 100, and 200 shinkansen.

Bolster system

The main components of the bolster system are: a bolster that supports the carriage body, air springs, lateral dampers, side bearers, a bolster anchor that transmits tractive force between the bogie and the carriage body, and the centre pin. The centre pin allows the bogie to rotate relative to the body on curved track, while the side bearers apply frictional resistance to prevent hunting. The bolster is made by pressing 9-mm thick steel plates and then welding these plates together into a box. The hollow part of the box serves as an auxiliary air chamber for the air springs. The experimental version of the bogie used a triple-folded bellow-type air spring, but the bogies installed on actual bodies have a special diaphragm self-sealing air spring. This type of air spring permits lateral rigidity, so designers could eliminate the swing bolster hanger found on conventional bogies at that time. The air spring is mounted as high as possible to control carbody rolling.

Bogie frame

The DT200 bogie frame consists of two side beams (left and right), a central cross beam, and end beams. The beams are formed by pressing 9-mm thick SS400 (rolled steel for ordinary structural purposes) steel plates, then welding them into box sections. These beams are then welded together to fabricate the bogie frame. The end beams were originally 6-mm thick, but this was later increased to 9 mm. Since 1976, SM400B steel plates have replaced the SS400 steel plates, which tend to contain layers of impurities embedded during rolling. SM400B steel plates are very suitable for welding purposes.

Wheelset and driving gear

Axles for the DT200 bogie are made of S38C (carbon steel suitable for mechanical structures) that has been heat-treated by induction hardening. This process changes only the surface into hard martensite, and at the same time generates residual compressive stress at the axle surface, raising the fatigue strength of the material to extremely high levels. Induction-hardened axles are used for all shinkansen bogies, to ensure greater strength in mating parts that are prone to fretting corrosion.
For safety, the bogie uses solid rolled wheels. Designers were concerned about wear and tear on the wheel tread over daily long-distance travel, so they performed tests on three different types of candidate wheel materials. However, in the end, they chose STY-80 that had already been used for many years.
The driving gear used a parallel Cardan system. The basic technology of this system was being put to practical use as early as the *Kodama* limited express on the old Tokaido main line. The designers were concerned that the gears might not be able to withstand the higher speeds and that lubrication problems could develop, but no problems were found in different tests using prototypes.

Structure of Bolsterless Bogies for New Shinkansen Trains

Bolsterless bogie development

As explained, the DT200 bogie was used for many years on shinkansen, but a new type was needed to meet the demands of trains travelling at maximum speeds of 270 to 300 km/h. The required improvements included:

- Greater stability at high speed
- Higher running performance on curves
- Less vibration and greater ride comfort
- Smaller size and lower weight to reduce track wear and tear

Development of a bolsterless suspension system began in earnest in about 1980. After the JNR privatization, efforts focused on the DT9023, a bogie type that JNR had tested. It was realized that a number of improvements would be required, including:

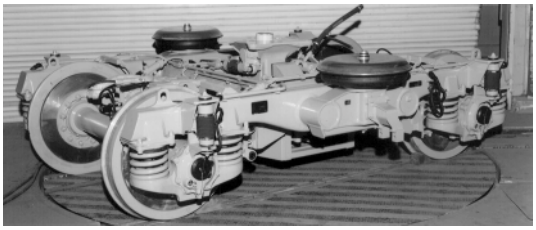
- Reduce high-frequency chatter in car floor immediately above bogie
- Reduce car vertical and rolling oscillations to improve ride comfort
- Achieve superior stability at high speeds while ensuring excellent running performance on curves
- Eliminate end beams on bogie frame and reduce bogie size to reduce weight of bogie between beams
- Reduce unsprung mass of bogie (e.g., mass of wheelset, axle box and gear system)

When the improved trial bogie was tested at RTRI, no stability problems were found even at extremely high speeds of 450 to 500 km/h, and the bogie also proved effective in reducing oscillations. Later two endurance tests of the bogie on a Series 100 shinkansen of JR Central each covering about 300,000 km, validated the result of the running test. By about 1990, it was clear that bolsterless bogies were suitable for shinkansen and they are now used for all Series 300 and later shinkansen.

Structure of bolsterless shinkansen bogie

Figure 2 shows the structure of a bolsterless shinkansen bogie. Like its DT200 predecessor, each bogie has two air springs that support the carriage body directly. However, unlike the older bogies, these air springs are not supported by a bolster. Instead, they are mounted directly on the upper surface of the bogie frame.
The main characteristics of this bolsterless bogie are shown in Table 4.
Some important features of the components of the bolsterless bogie for Series 300 shinkansen are described below.

Figure 2 Bolsterless Bogie on Series 300 and Later Shinkansen



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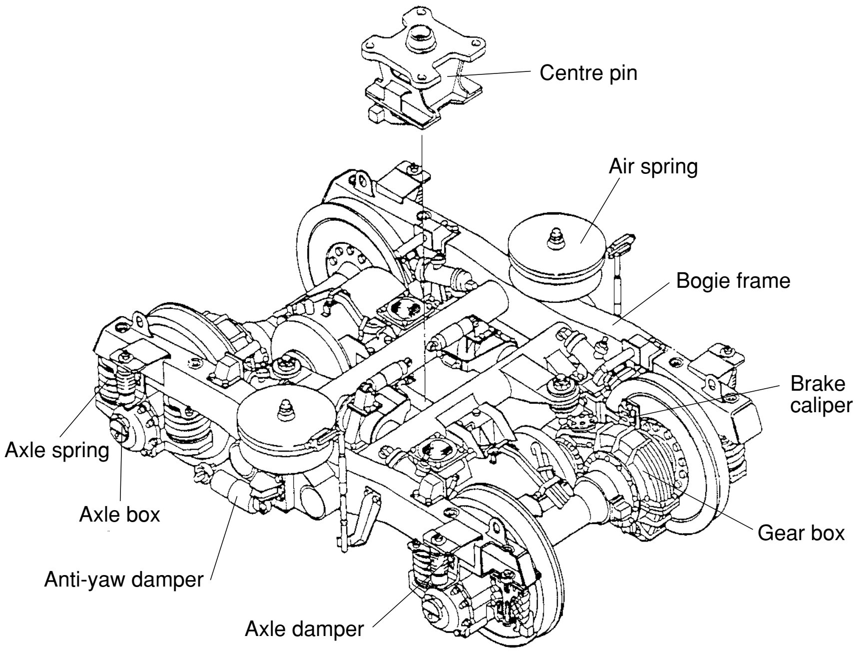

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Axle spring and axle box suspension

The axle spring and axle box suspension of the trial bogie included a conical laminated rubber structure. This would have made construction easy, but it was unsuitable for high-speed rolling stock, because the dynamic spring constant of the axle spring was too high. Therefore, the designers decided to use coil springs and a cylindrical laminated rubber/wing-type spring system. In this system, the vertical load on the axle springs is borne mainly by coil springs that have linear deflection capabilities; the longitudinal and lateral loads are borne mainly by the cylindrical laminated rubber parts, which also support and guide the axle box. Because the coil springs and cylindrical laminated rubber parts are arranged symmetrically (in a wing shape) at the front and rear of the axle box, the support and guidance of the axle box is smooth. Moreover, because the optimum degree of longitudinal and lateral support rigidity was given to the cylindrical laminated rubber parts, stability is achieved even at high speeds and running performance with reduced lateral pressure remains high on curves. The axle damper works in both directions and the increase in damping force reduces vertical vibrations in the bogie.

A number of axle box suspension systems are used to simplify the structure and permit easier maintenance. Some systems for bolsterless shinkansen bogies have an axle beam type of construction, while some others have a rubber/leaf spring type of construction.

Carriage body support system

The carriage body support system has no bolster so it is described as bolsterless. Instead, the body is supported directly by air springs, thereby permitting considerable horizontal displacement. When the bogie rotates relative to the car body on curves, this relative angular displacement is absorbed through horizontal distortion of the air springs. Longitudinal forces between the car body and bogie are transmitted via the monolink or Z link, which is mounted at the virtual rotational centre of the bogie.

As explained above, side bearers are used on DT200 bogies to prevent hunting at high speeds. However, in the case of bolsterless bogies, rotation relative to the body is controlled by anti-yaw dampers

Figure 3 Axle Box Suspension of New Shinkansen Bolsterless Bogies

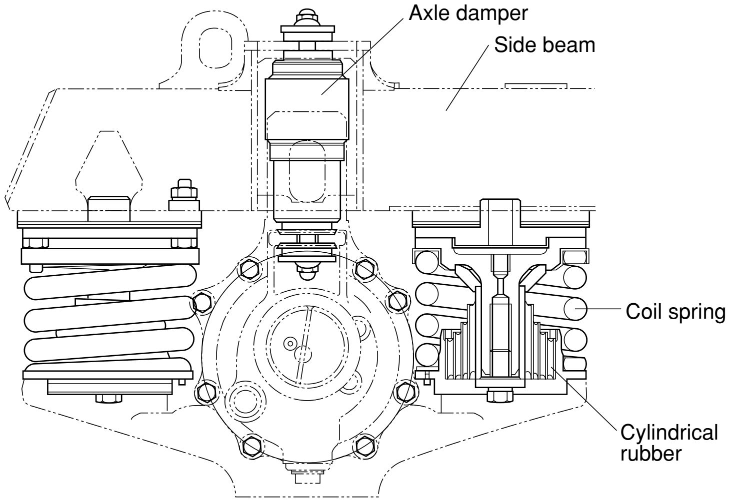


Table 4 Characteristics of Bolsterless Bogie

Bogie wheelbase	2,500 mm
Wheel diameter	860 mm
Bogie weight	6,600 kg (unsprung mass, 3,500 kg) for Series 300 shinkansen
Traction motor	AC 300 kW for Series 300 shinkansen

mounted between the car body and bogie frame outside of and parallel to the side beams of the bogie frame. The damping force of the anti-yaw dampers and the rigidity of the rubber bushings at both ends of the damper both greatly improve the stability of bogies running at high speeds.

Bogie frame

The bogie frame is constructed in an 'H' shape. The two side beams (left and right) made of 8-mm thick rolled steel (SM490YA killed steel suitable for welded structures) are welded to a cross beam made of 9-mm or 12-mm thick seamless steel pipe (STKM18B). The top of the side beams is made as flat as possible and the cross beam is made of seamless pipe to keep the bogie frame structure simple and to prevent welding defects. The cross beam is hollow, permitting creation of an auxiliary air chamber for the air springs.

The DT200 bogie frame has end beams on which brake parts and other equipment are mounted. For the newer bogie frame, small caliper disk brakes were developed and mounted on the cross beam located across the bogie centre. This design eliminated the end beams. As a result, the bolsterless shinkansen bogie is about 80 cm shorter than the DT200 bogie, and it weighs about 3.3 tonnes less, although the wheelbase is the same (2500 mm).

Wheelset, driving gear, etc.

The wheels and axles of the bolsterless bogie are basically the same as those of the DT200 bogie but the wheel diameter was reduced from 910 mm to 860 mm, and a 60-mm straight hole was bored longitudinally through the centre of the axle to reduce the unsprung mass as much as possible. Furthermore, at fabrication, the vector sum of the dynamic unbalanced mass in the wheelset is set below 5 kgf•cm to ensure that when the wheels rotate at high speed, any centrifugal force created by unbalanced weight distribution will not cause high frequency vibration in the carriage body, or ride discomfort.

The DT200 bogies use two types of axle bearings simultaneously: cylindrical roller bearings designed to bear radial loads, and ball bearings designed to bear thrust loads. More recent versions of the cylindrical roller bearings have had a thrust collar, to bear thrust loads at the same time. When bolsterless shinkansen bogies were first produced, they used collared roller bearings, because it was thought this would minimize the lateral play of the roller bearings. The bolsterless axle box was also made smaller and lighter. However, it was later discovered that tapered roller bearings could actually reduce lateral play themselves, so tapered roller bearings are now used for bolsterless shinkansen bogies.

The axle box and gearbox of DT200 bogies are made of cast steel, but on the bolsterless bogie they are made of aluminium alloy to reduce the bogie unsprung mass. There were fears that track ballast might fly up and damage this lighter material, but tests using flying stones proved these fears unfounded, permitting its introduction.

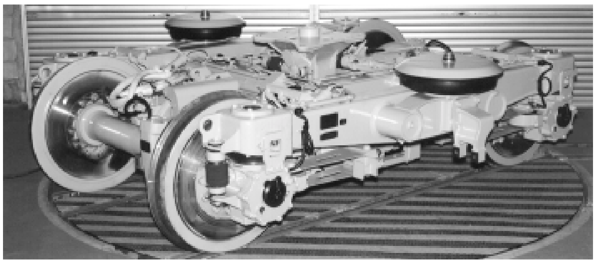
Future Possibilities for Shinkansen Bogies

Over more than three decades of shinkansen operations, no passenger lives have been lost because of a defective bogie. This excellent record is largely due to the extremely high reliability and standards of the bogies' structure and maintenance.

To meet the demands of passengers today and in the future, Japan's shinkansen operators will have to make further improvements—for example, higher speeds, better running performance on curved track, greater ride comfort, less running noise, and better labour-saving maintenance methods. At the same time, every priority must be placed on safety and reliability. The areas requiring further efforts are as follows:

- Research into bogie structure and manufacturing techniques to develop greater precision in components
- Considerable reduction in bogie weight between primary and secondary springs and unsprung mass by developing smaller lighter bogies
- Development of simpler bogie structure with fewer welded parts and greater reliability of welded parts
- Improvements of semi-active and active suspension systems, and their more widespread use
- Development of pendulum tilt system for shinkansen
- More effective use of dampers, particularly anti-yaw dampers between cars
- Further study of aerodynamic causes of carriage vibration when high-speed trains pass in tunnels ■

Figure 4 Bolsterless Bogie on Series E2 Shinkansen



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