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Preliminary Design of Passive Tilting System for Amcoach

Volume 1. Description of Tilting Truck Currently Used by JNR

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16. Abstract

A description of the tilting truck currently used by Japanese National Railways (JNR) is presented. JNR 381-series electric railcars with passive tilting device were manufactured to aim at speed-up in curves, and have been operated in Chuo-sai line between Nagoya and Nagano, and Kisei-line between Tennoji and Shingu.
This report presents the background of tilting truck manufacture, an outline of 381-series electric railcar, a construction of tilting truck and an operational experience and future plan of tilting truck.

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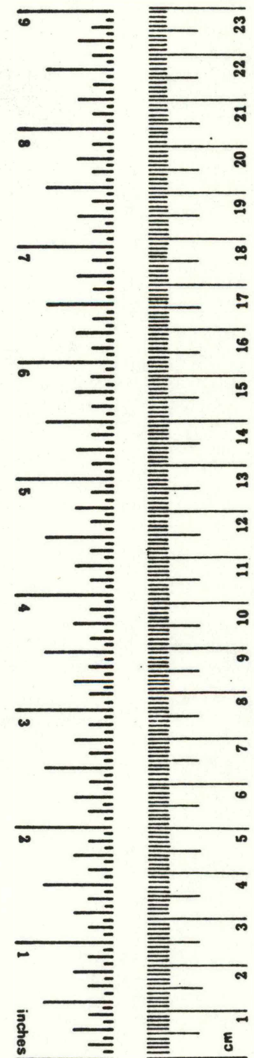
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

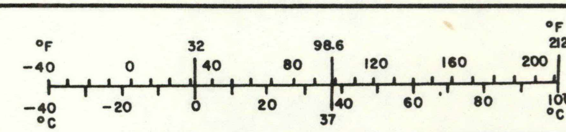
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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DESCRIPTION OF TILTING TRUCK CURRENTLY USED BY JNR

1. BACKGROUND OF TILTING TRUCK MANUFACTURE

The passenger transport by railroad was conventionally characterized by its capability of mass transportation and low cost. For the interurban transportation, the qualitative improvements for higher speed and more comfortability have come to be recognized as indispensable in order to have a chance in a competition with other transportation media. Now is the time, in which the transportation media are evaluated by the required time and comfortability for passengers to reach their destination.

In Japan, the Shinkansen runs the country from north to south like a spinal column and local lines are combined like so many ribs. With the high-speed network thus formed, the speed-up of Japanese railroad transportation is intended through the nationwide spread of high-speed effect of the Shinkansen.

This basic concept was used as a basis for the technological development activity which started in 1968 to speed up the local lines.

The speed-up here means solely to reduce the time required to reach the destination, and not necessarily the raising of maximum speed. This purpose can be achieved by any of following methods:

(a) Increase in the curve passing speed
(b) Increase in the turnout passing speed
(c) Increase in the maximum speed
(d) Increase in acceleration/deceleration
(e) Reduction in stopping time

To what extent each of these methods is effective varies depending on various track conditions (e.g., curve, grade, etc.). The run curve simulation on various railway lines shows that the above methods can effectively reduce the time roughly in the order of (a), (b), ... (e).

Apart from this analysis in terms of software, the below listed developments were made:

(a) 1968 Development of High-speed Turnout
(b) 1970 591-Series Electric Railcar with Tilting Device for High-speed Operation
(c) 1972 391-Series Gas Turbine Railcar with Tilting Device for High-speed Operation

Using the test railcars in above (b) and (c), the in-depth study was made on the effectiveness of tilting device, effect on the improvement of ride quality, relationship between the tilting device and side wind, effect on the lateral force between the wheel and rail, safety against derailment, etc.

The study result proved that the tilting device can be put into practical use and it was concluded to start the manufacture of mass production type 381-series electric railcars with tilting device for commercial use in 1973.

The electric railcar with tilting device can achieve the speed-up without a substantial change of ground facilities (i.e., without adjusting the curve on alteration or super elevation). Also from the viewpoint of investment effect, this is a big success.

2. OUTLINE OF 381-SERIES ELECTRIC RAILCAR WITH TILTING DEVICE

The series 381 limited express d.c. electric railcar train (Fig.-3) is the first practical version of the series 591 prototype a.c./d.c. electric railcar with tilting device. About 200 cars have been built so far, they have been operated on Chuo-sai line (252 km, between Nagoya and Nagano in the mountainous regions of the central part of Japan) and on Kisei-line (262 km, between Tennoji and Shingu along the coast of Kisei peninsula, in the middle of Japan)

Take the Chuo-sai Line as an example to see the time reduction effect of the electric railcar with tilting device. In this line, the curve occupies more than 45% of the entire division, as shown in Table 1. In particular, the section with a radius less than 600m runs up to 23.9%. As is evident from Table 2, the introduction of electric railcars with tilting device in this line full of curves contributed to shortening the time required, achieving the time reduction of about 14%. The trial calculation generally shows that this type of electric railcar reduces the time by about 8% to 20%.

Table 1 Chuo-sai line

Curve or straight line		Length (percentage)
Curve	R ≦ 400m	31.7 km (12.5%)
	400m < R ≦ 600m	28.8 km (11.4%)
	600m < R ≦ 800m	18.6 km (7.4%)
	R > 800m	36.0 km (14.3%)
	All curves	115.1 km (45.6%)
Straight line		137.2 km (54.4%)
Total		252.3 km (100.0%)

Table 2 Time reduction effect of electric railcar with tilting device in Chuo-sai line

		Limited express diesel railcar without tilting (181 series DC)	Limited express electric railcar without tilting device (181 series EC)	Limited express electric railcar with tilting device (381-series EC)
Operating section (Nagano—Nagoya)		252.3 km		
Operating condition	Nagoya — Nakatsugawa	Max. speed 120 km/h Curve passing speed +5 km/h	Max. speed 120 km/h Curve passing speed +5 km/h	Max. speed 120 km/h Curve passing speed +20 km/h
	Nakatsugawa — Nagano	Max. speed 110 km/h Curve passing speed +5 km/h	Max. speed 110 km/h Curve passing speed +5 km/h	Max. speed 110 km/h Curve passing speed +15 km/h
Running time		3 hr. — 52 min.	3 hr. — 45 min. (Δ7 min.)	3 hr. — 20 min. (Δ32 min.)

Lines other than Shinkansen of JNR are narrow gauge, i.e., 1,067 mm in track gauge; and the maximum running speed of trains for service is set at 120 km/h. A speed-up over this limit would be hard to realize, because the emergency braking distance is set at less than 600m. For the purpose of increasing the scheduled speed of trains with the maximum speed remaining at 120 km/h, it would be effective to raise the turnout speed, but there is a solution that can be obtained with the vehicle alone, that is, a reduction of axle load, which would enable speed-up over curves and speed-up on gradients. Lines of JNR, even trunk lines, are full of 300m curves and 25% gradients.

Speed-up on gradients can be effectively realized through electrification of the line, and speed-up on curves can be realized by providing the car with a tilting device and lowering the gravity center of the car body without any sacrifice of ride quality or increasing the chances of the car overturning.

Tilting device adopted by JNR

The most outstanding feature of this railcar is its tilting device. This device gives good riding quality even when the curve-passing speed is increased by 20 km/h over, the speed of the conventional electric railcar. Moreover, since the gravity center of the car body is set low to enhance the effect of tilting, an increased curve-passing speed does not cause an overturning of the car. It has been confirmed with the series 591 prototype electric railcar with the tilting device that good riding quality under centrifugal force, and running safety can be assured up to an increase of 30 km/h over conventional curve-passing speed.

The device adopted by JNR is a passive tilting system with rollers, which utilizes the centrifugal force working on the car body as it passes a curve. For the purpose of passive tilting, the gravity center of the car body has to be located below the tilting center. Thus, all the electrical equipment, excepting the pantograph, the braking system and the air conditioning equipment, are mounted under the floor of the body, thereby making the gravity center far lower than the tilting center. Namely, the tilting center is about 2,300 mm above the rail level, while the gravity center is about 1,300 mm. The maximum tilting angle is set at 5°. At low speeds the tilting effect is suppressed so that the swing of the car body is prevented when passengers get on or off the car. (See Fig. 1)

To abate the swivelling lateral force acting in the passage of curves, a pivot-shifting device and a link device to transfer the pivot position were tested with series 591 prototype electric railcars. But they were discarded because they were complicated in structure and were not so effective as expected in passing curves at speeds faster by about 20 km/h than the conventional electric railcar. The fact that the lateral force could be reduced by the tilting effect alone was another reason for discarding them.

Table 3 Main feature of the series 381 electric railcar train

		Tc	M	M′	Ts
Car body	Body length (mm)	20,800			
	Length over couplers (mm)	21,300			
	Distance between truck center (mm)	14,400			
	Minimum width of car body	2,900			
	Floor height (mm)	1,105			
Seat capacity (Psngs)		60	76	72	48
Tare weight (t)		(approx)36	(approx)39	(approx)39	(approx)35
Truck	Type	TR 224	DT 42	DT 42	TR 224
	Rigid wheel base (mm)	2,300			
	Wheel diameter (mm)	860			
	Power transmission system		Parallel cardan drive with hollow shaft		
	Gear ratio		4.21		
	Tilting device	Passive tilting by roller			
Maximum speed (km/h)		120			
One-hour rating	Out-put power (kW)	960			
	Tractive effort (kg)	4,460			
	Speed	77			
Traction motor	Type Number per unit		MT 58 x 8		
	One-hour rating		120 kW, 375V, 360A		
Control system			Series-parallel connection and weak field control. Dynamic brake for stop and for speed control on on the gradient		
Brake system		Dynamic brake, electro-magnetic air brake and additional straight air brake			

Section of car body

The maximum tilting angle of the car body is set at 5° and under the tilting effect, a car with standard cross-sectional dimensions begins to violate the car construction gauge. Therefore, the bottom width of the car body has been reduced and the equipment mounted under the floor has been made small. (Under the tilting effect the pantograph is heavily inclined, but it has been confirmed with the series 591 prototype electric railcar that a pantograph of the stationary type can suffice if only the current-collecting area is enlarged; thus a pantograph of the stationary type with a simple structure has been adopted. (See Fig. 2)

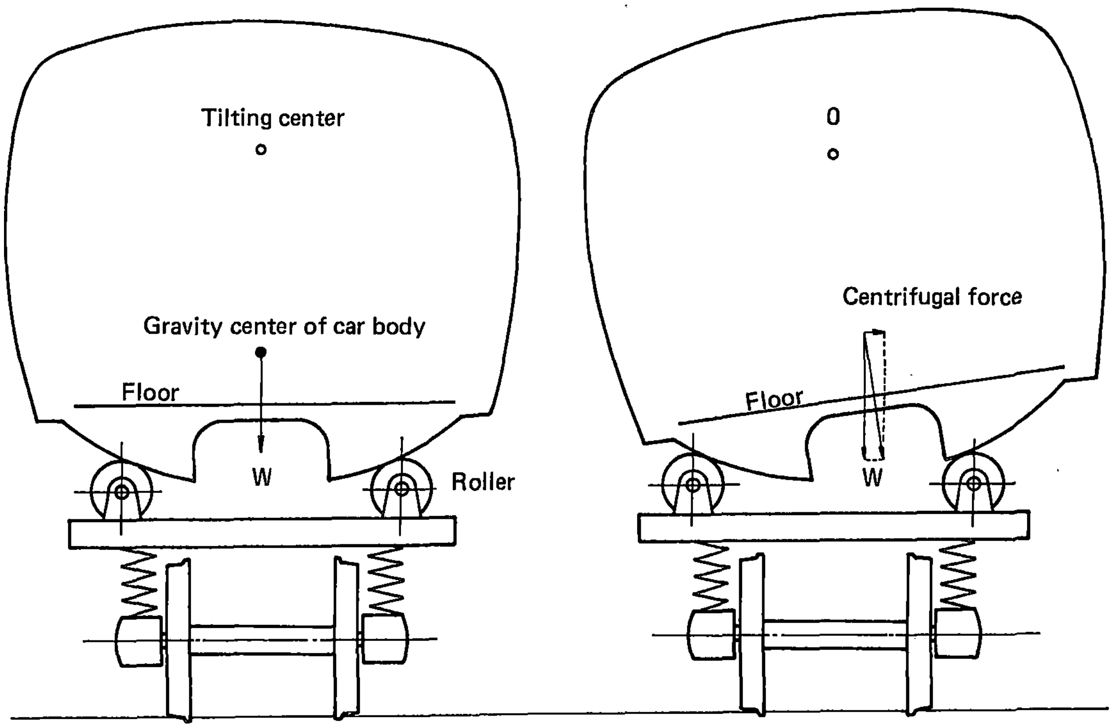


Fig. 1 Explanation of tilting device

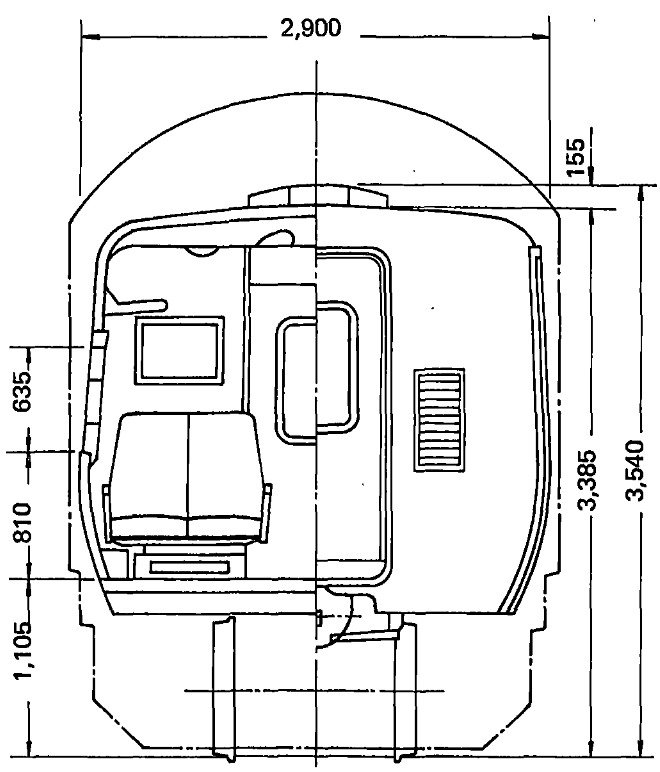


Fig. 2 Section of car body

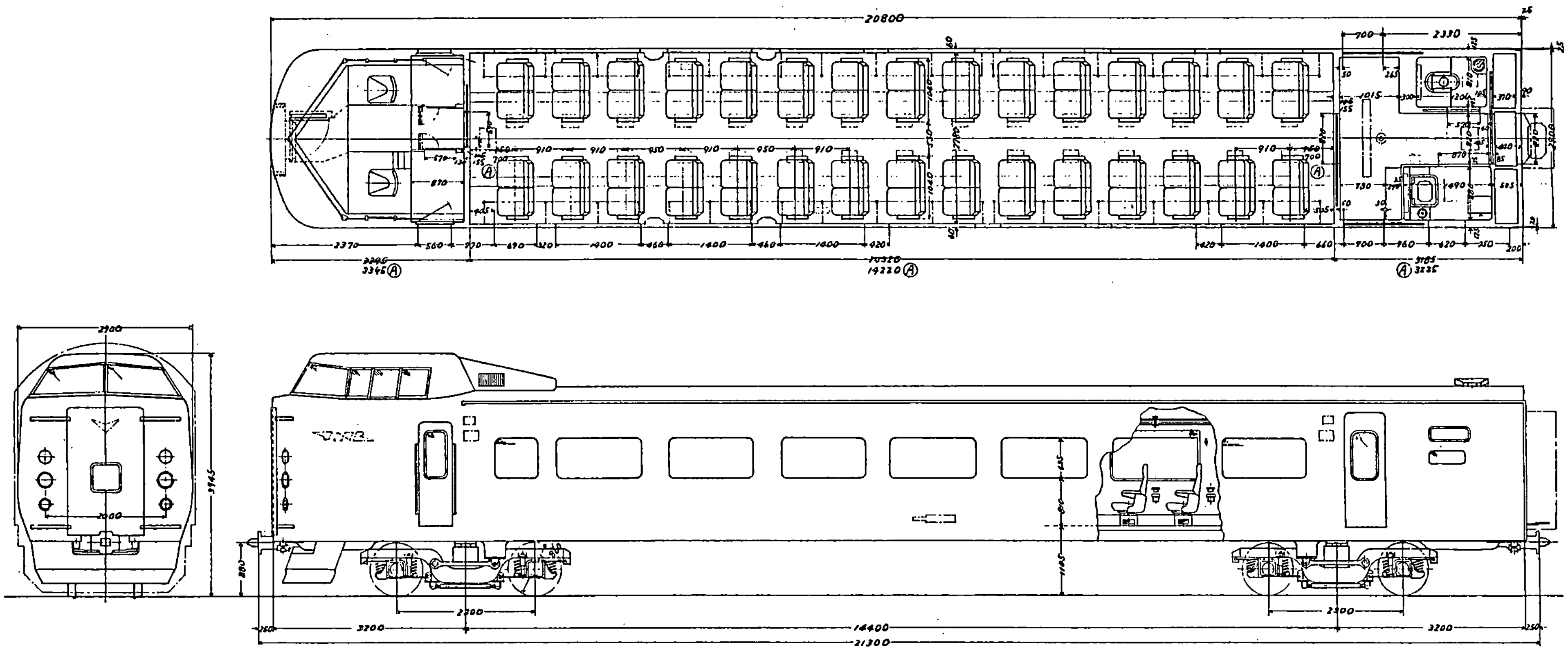


Fig. 3-(1) General view of 381 series electric car, control trailer

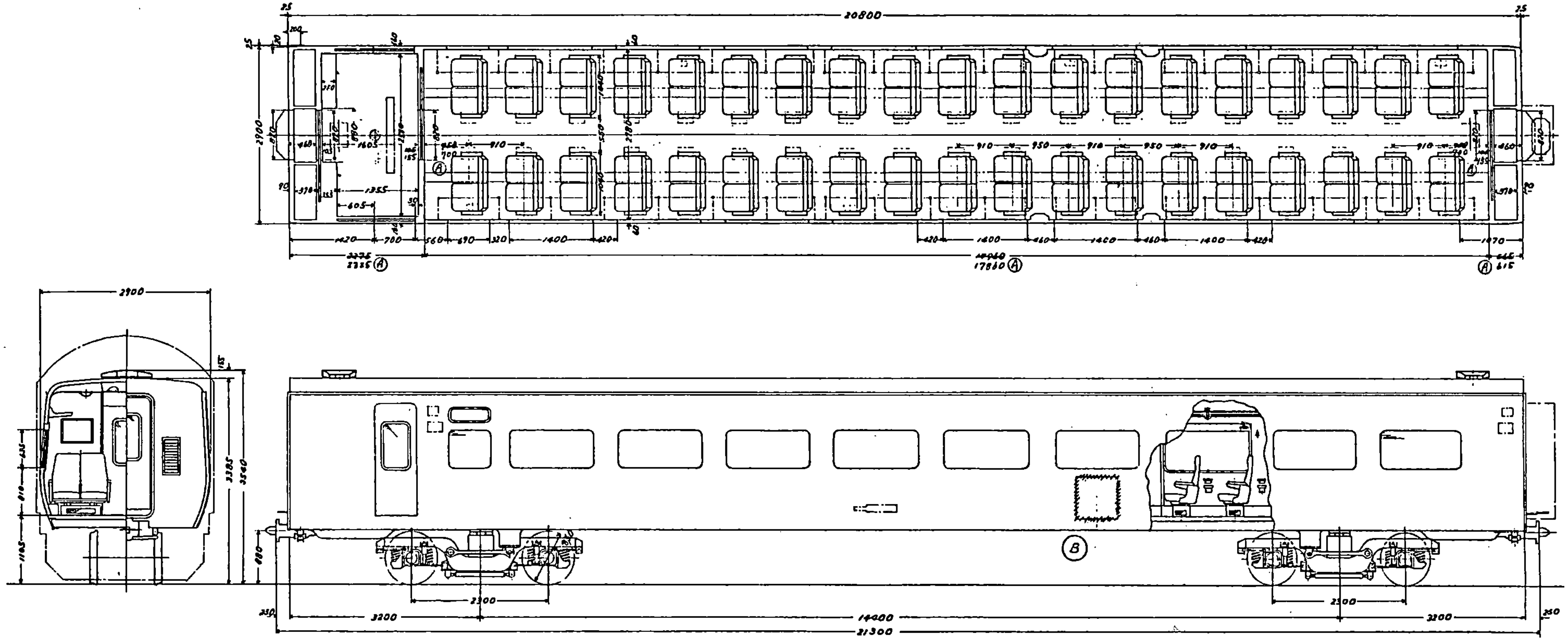


Fig. 3-(2) General view of 381 series electric car, electric motor car

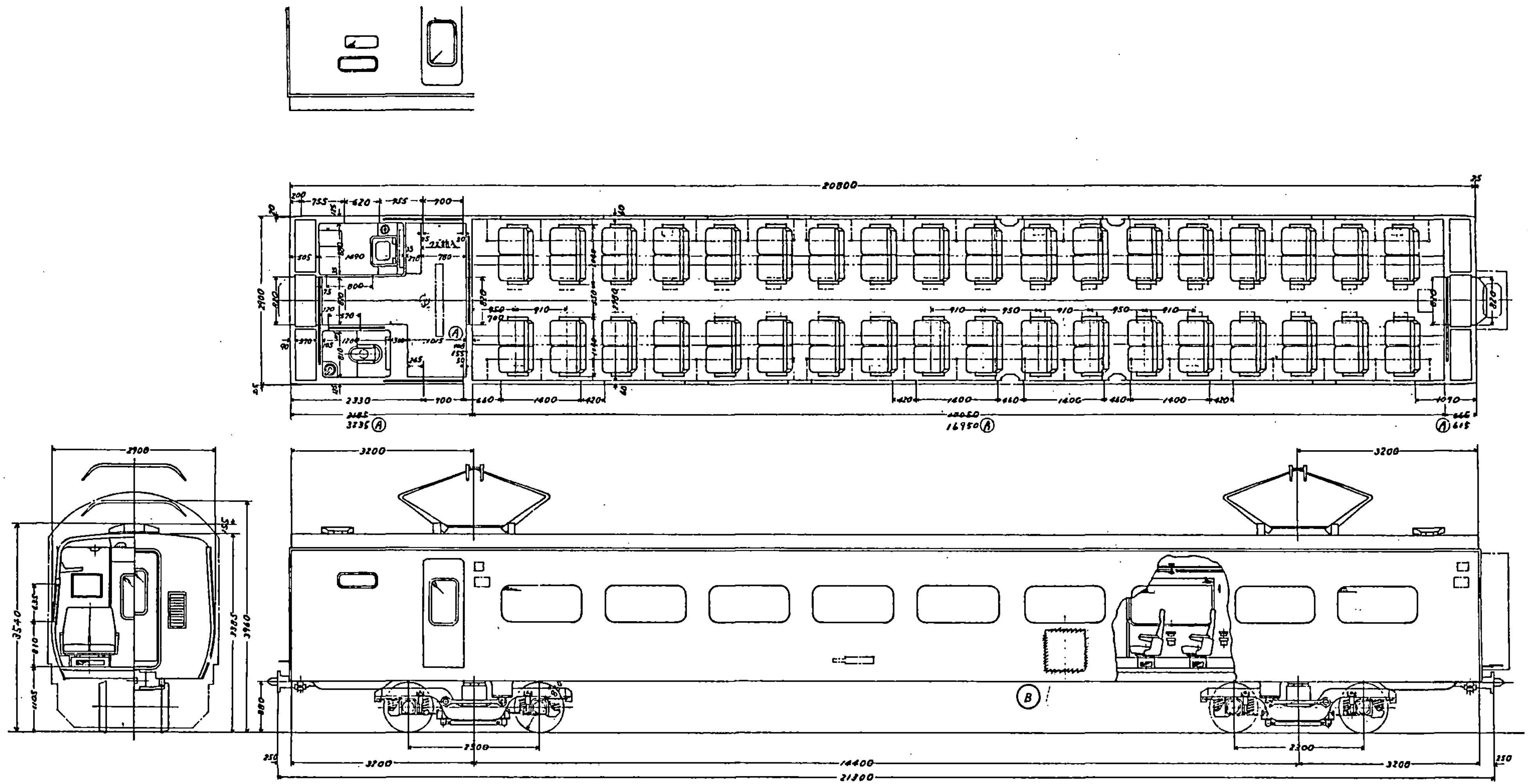


Fig. 3-(3) General view of 381 series electric car, electric motor car

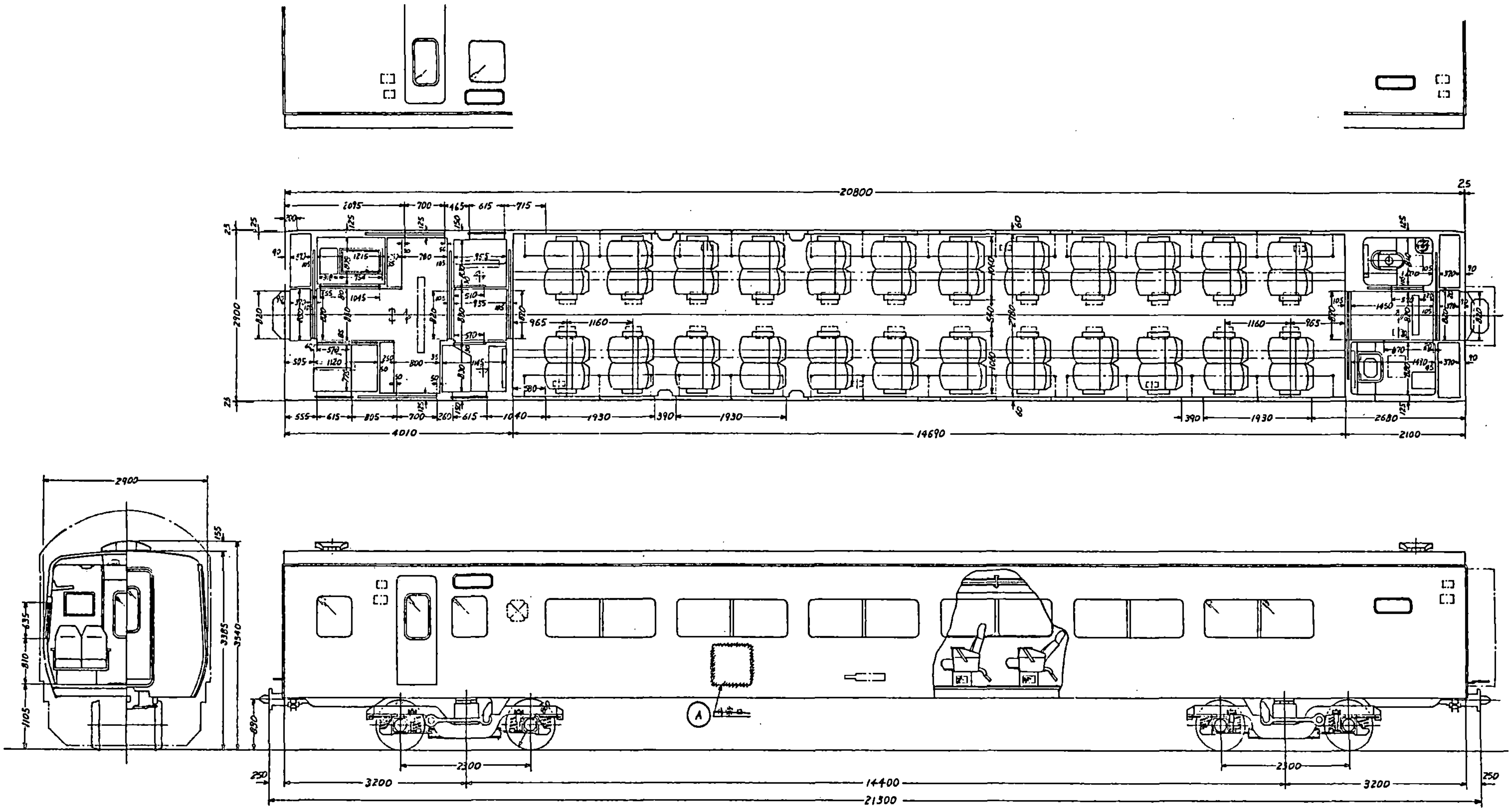


Fig. 3-(4) General veiw of 381 series electric car, trailer

3. CONSTRUCTION OF TILTING TRUCK (TR 224) OF 381-SERIES ELECTRIC RAILCAR

This truck is of a construction appropriate for the running on the roadway full of curves. As compared with conventional trucks, this roller type passive tilting truck has a curve passing speed higher by 25 km/h, and its maximum speed is 120 km/h.

Principal features are as shown below:

(1) To improve the ride quality during the running along the curve, the roller type passive tilting device is provided. The center of tilting is located 2,305 mm above the rail surface: the max. tilting angle is 5°.

(2) Smaller axle load and lower lateral force, which are favourable for the prevention of derailment and protection of track from adverse effect.

(3) The vertical load is supported on both side bearers of the truck. Reasonable rotation resistance is provided to the truck to prevent hunting.

(4) The air suspension is directly coupled to the car body to improve the anti-rolling performance.

(5) The wheel tread cleaning device is provided to stabilize the adhesion between rail and wheel.

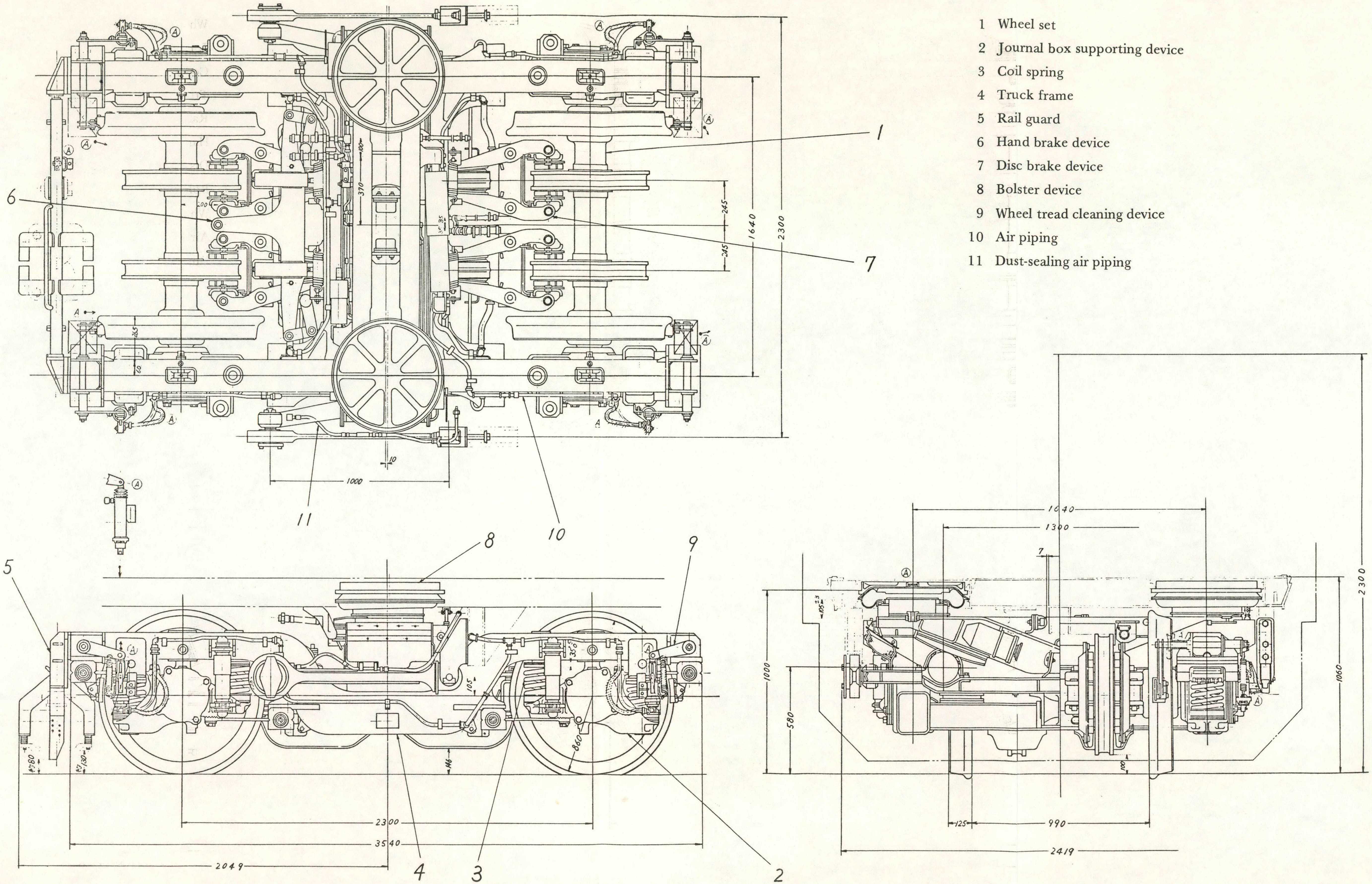
(6) Extensive surface treatment and dust-sealing are made to prolong the service life of roller device and to reduce the friction resistance.

Major technical data of tilting truck (TR 224) are as follows.

Table 4 Technical data of truck

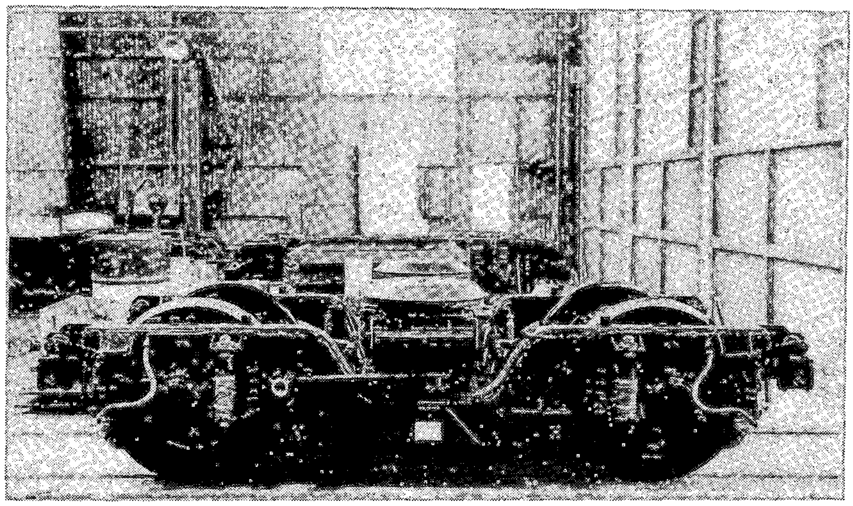
Item	TR224
Wheel base	2,300 mm
Bearing center distance	1,640 mm
Wheel diameter	860 mm
Max. truck length	3,540 mm (3,819 mm with rail guard)
Max. truck width	2,419 mm
Height of side bearer (above rail surface) of empty car	424 mm
Side bearer center distance	1,100 mm
Air spring mounting height (above rail surface) of empty car	861 mm
Air spring center distance	1,640 mm
Air spring effective radius	487 mm
Roller center height (above rail surface) of empty car	580 mm
Roller center distance	1,300 mm
Tilting center height (above rail surface) of empty car	2,305 mm
Brake system	Disc brake, 4-rubber cylinder double-operating type with resin lining
Brake leverage	2.16
Gross weight per truck	6,554 kg
Sprung weight	156 kg
Intermediate weight	3,106 kg
Unsprung weight	3,292 kg

The view (Fig. 4) and the external view photo (Photo 1) are shown below.



1 Wheel set
2 Journal box supporting device
3 Coil spring
4 Truck frame
5 Rail guard
6 Hand brake device
7 Disc brake device
8 Bolster device
9 Wheel tread cleaning device
10 Air piping
11 Dust-sealing air piping

Fig. 4 Tilting truck



Photo—1 External view of tilting truck (called TR224 by JNR)

3-1 Wheel Set and Axle Box

The wheel is a solid-rolled rim-quenched wheel with a wheel diameter of 860ϕ. The brake disc is of two-piece construction and mounted with 12 bolts.

The journal bearing is a double-row cylindrical roller bearing with ribs and the inside diameter of innerlace is 130ϕ. The thrust load is supported on the ribs of bearing.

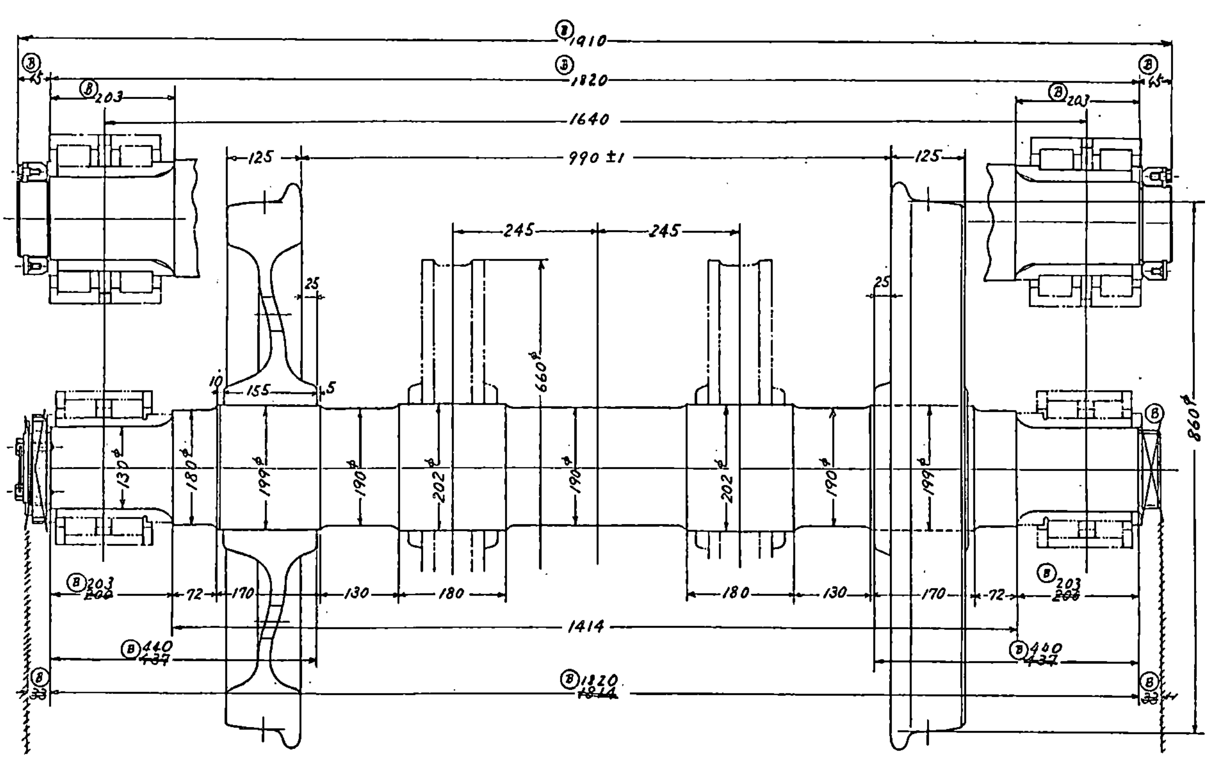


Fig. 5 Wheel set

3-2 Suspension system

The axle box is elastically suspended by the suspension plate and rubber bush. To prevent hunting, the axle box is provided with the wheel set suspension stiffness in the longitudinal and lateral directions, as listed in the table below.

Table 5 Wheel set suspension stiffness

Loading direction	Spring constant per axle box
Longitudinal	2,500 ~ 3,000 kg/mm
Lateral	750 ~ 1,000 kg/mm

The axle spring and secondary suspension have a spring constant as shown below:

Table 6 Spring constant of primary and secondary suspension (kg/mm)

		TR224	
Axle spring	Coil spring	56.52x8=452.16	Total 425.62
	Rubber	906x8=7248	
Empty car	Secondary suspension	34.7x2=69.4	
	Total spring constant per truck	59.4	
At seating capacity	Secondary suspension	38.9x2=77.8	
	Total spring constant per truck	65.8	

The axle spring is of a wing type comprising double coil spring of metal. One oil damper is provided to each axle box and its damping force is 200 kg at a 5 cm/s piston speed and 400 kg at 10 cm/s.

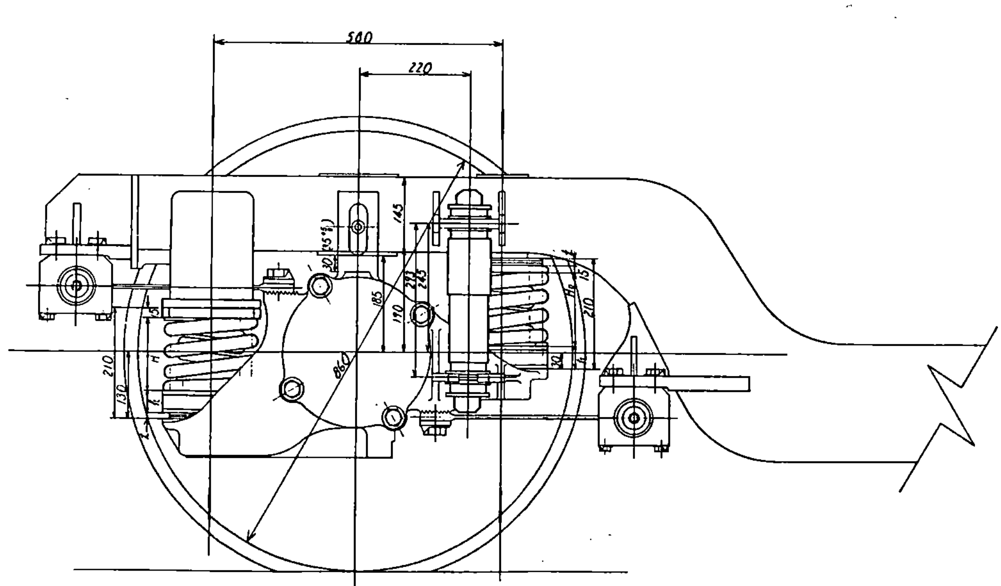


Fig. 6 Suspension system

3-3 Truck Frame

The truck frame is of 9 mm H-shape steel plate welded construction. The cross beam has a center pin bush to receive a center pin (used as a center of truck rotation) in a center. On either left and right side, a side bearer wear plate is provided at a 1,100 mm distance. These side bearers carry all of swing bolster loads. The wear plate has a friction coefficient of 0.09, and the rotating friction force offers the truck rotation resistance to prevent hunting.

3-4 Swing Bolster Device

The swing bolster device is on the side bearers of truck frame, supporting the car body via the air suspension.

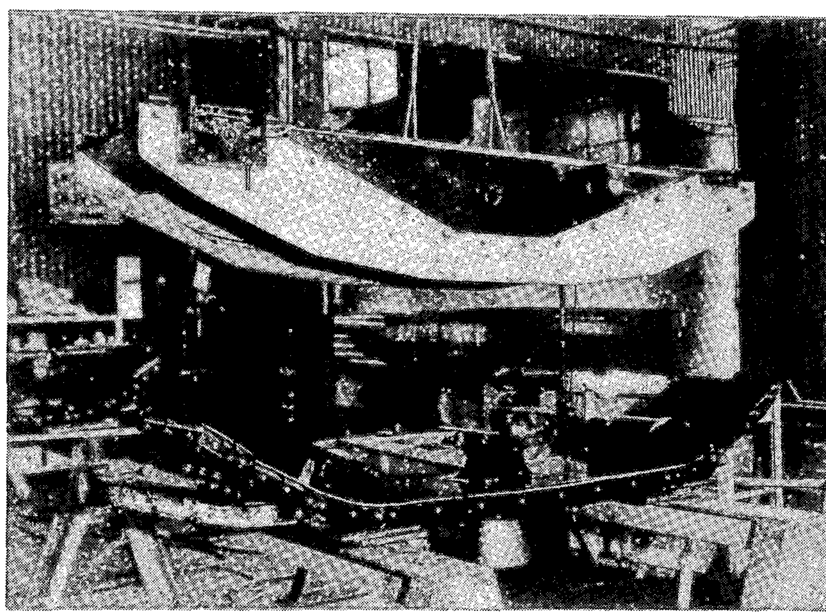


Photo 2 Swing bolster device
The device has an upper swing bolster on the top, lower bolster which does not swing, and intermediate roller device on each side.

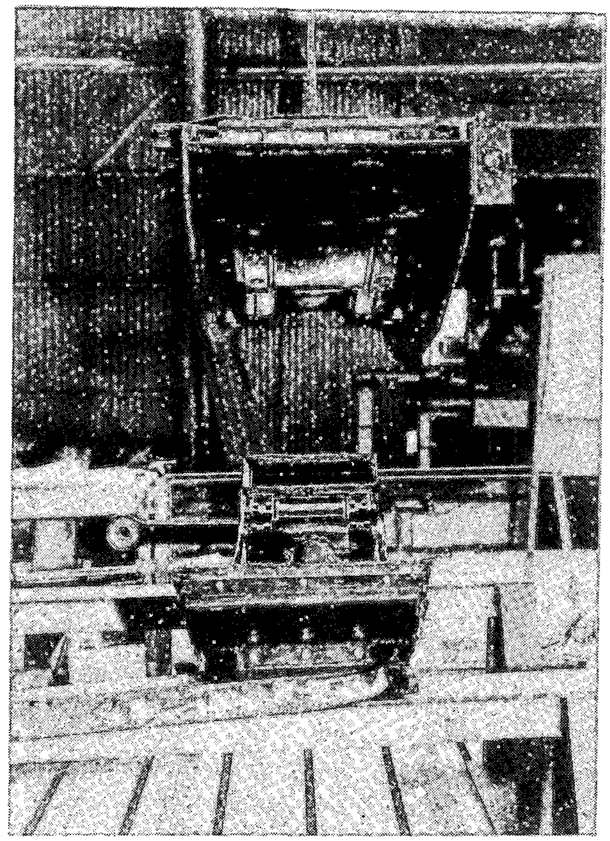


Photo 3 Swing bolster device

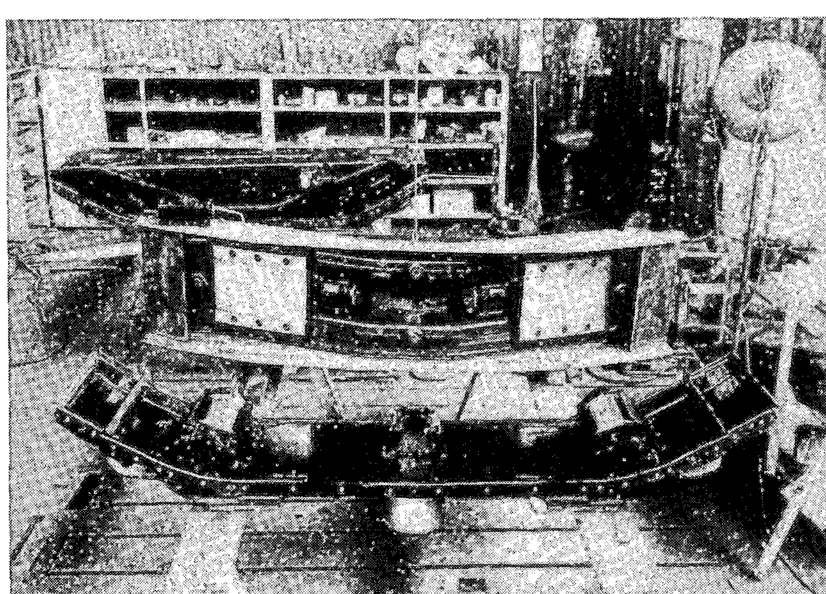


Photo 4 Swing bloster device (upper bolster and lower bolster)

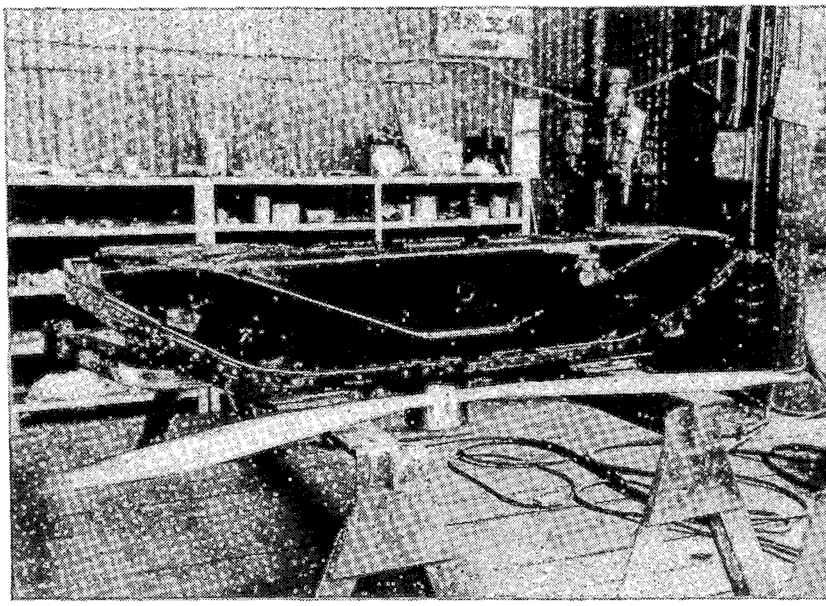


Photo 5 Swing bolster device

The swing bolster device, which makes the tilting motion, is made up from the tilting upper bolster and non-tilting lower bolster. The roller device is provided between these bolsters. The lower bolster is connected to the car body with the bolster anchor so as to transmit the forward and backward force between the car body and truck frame without hindering the vertical and lateral play of air spring as well as without hindering the car body tilting movement.

The non-tilting lower bolster is on the side bearer wear plates of truck frame. The center pin in the lower surface goes into the center pivot bush on the cross beam, allowing the truck frame to rotate. On both sides of lower bolster, the roller is mounted which is supported by the bearing on both ends. The stopper rubber for tilt restraint system is mounted in the center of lower bolster. On either end, the bolster anchor is attached. The dust-sealing air of roller device flows inside the lower bolster. (Photos 2, 3, 4 and 5)

The roller device comprises the roller supported at both ends by the bearing on the lower bolster and the roller guide plate mounted on the upper bolster. The roller guide plate rolls over the roller. Since the car body and lower bolster are connected via the bolster anchor, the longitudinal force is not applied on the roller device. Both the roller and roller plate are made of carburized and ground nickel and chromium steel. The roller diameter is 170 mm, the roller support radius is 1,754 mm, and the car body tilting center is located 2,305 mm above the rail surface (Photo 6 and 7).

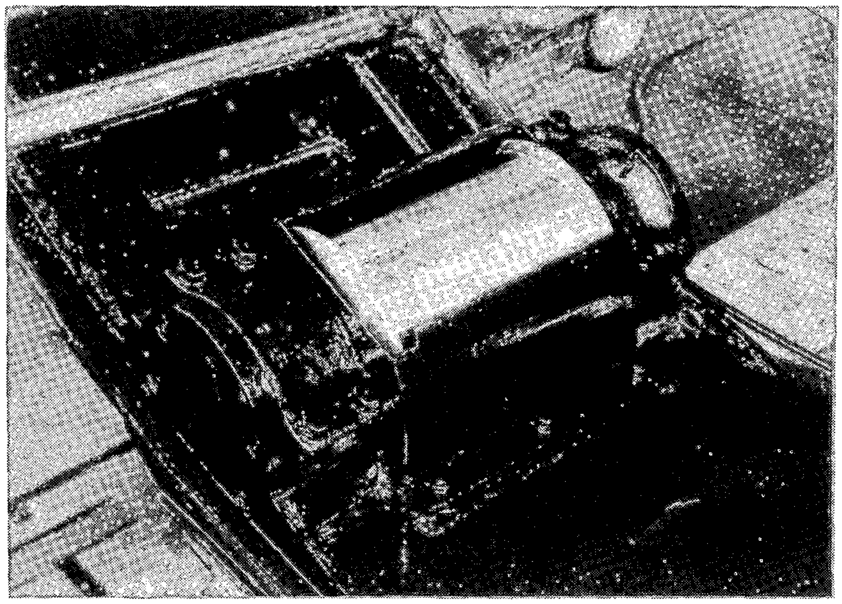


Photo 6 Roller device

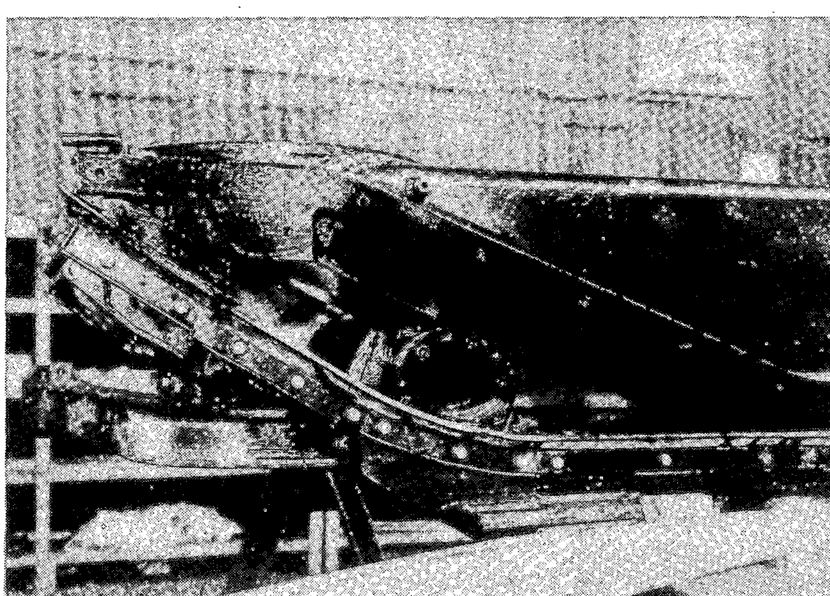


Photo 7 Roller device

On the bottom surface of upper bolster, the roller plate is mounted and rolls over the roller. The air springs are mounted on the top surface on either side at a distance of 1,640 mm to support the car body. The inside of swing bolster is designed as an auxiliary air chamber. (34ℓ per air spring) The swing bolster has a tilt restraint system, leveling valve device for air spring, differential pressure valve, lateral stopper, lateral damper, tilting damper, etc.

The tilt restraint system is to restrict the tilting movement at a speed below 50 km/h, thus limiting the swing of car body along the curved platform, the car body tilting when the passengers get on or off the train, and excessive tilting at a time of passing the turnout. Under the air pressure of 8 kg/cm^2, the piston is put into a stroke of 145 mm to lock the tilting. When the air pressure is released, the piston returns to an original position under a force of spring.

To ensure smooth tilting operation, the tilting damper is provided between the upper swing bolster and cross beam of truck frame. The damping force is about 20 kg·s/cm. The lateral stopper rubber provided in the center of upper swing bolster limits the lateral play between the car body and upper swing bolster. The 7 mm/side clearance is provided.

Particular care is paid on the dust sealing of roller device. The space between the upper swing bolster and lower bolster is covered and filled with the compressed air (3 kg/cm^2).

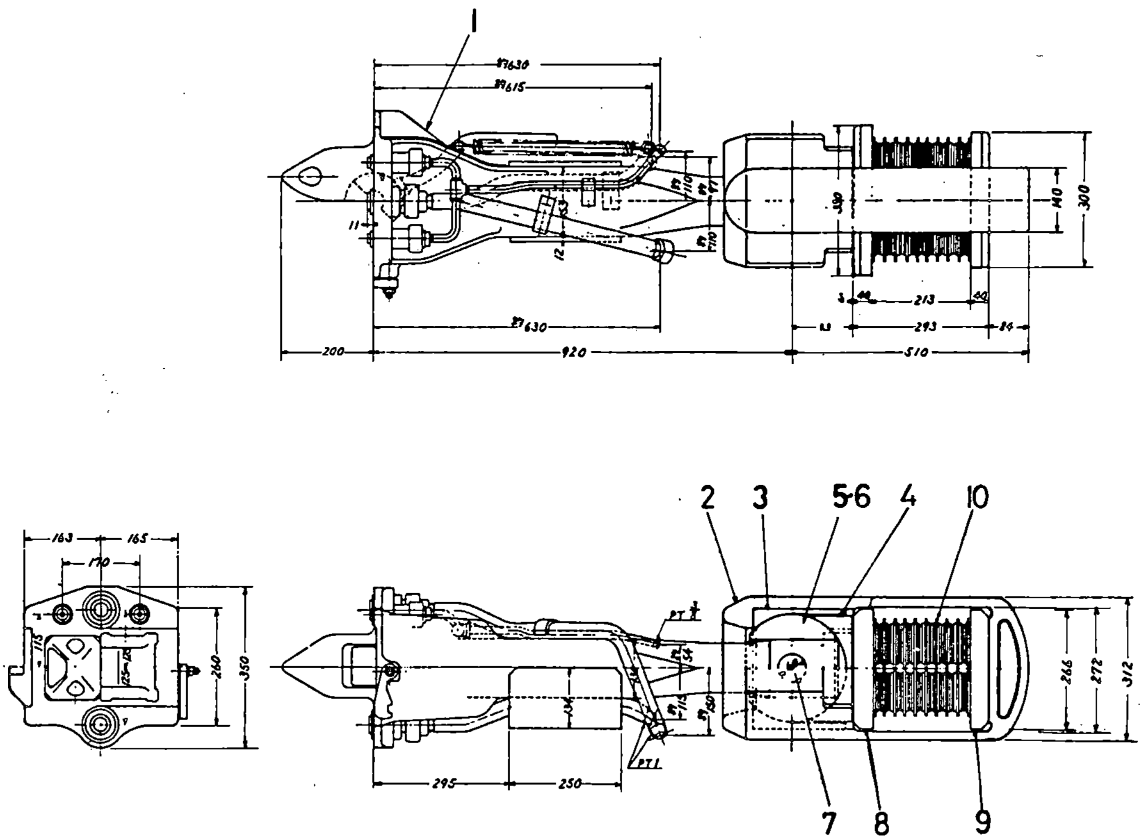
3-5 Brake system

A disc brake is used, which is operated by the 200ϕ x 100 rubber diaphragm brake cylinder.

The brake leverage is 2.16 and the brake ratio is 32.7% at the pressure increase (brake cylinder pressure 4.2 kg/cm^2). The cleaning shoe is interlocked with the operation of brake and pressed against the wheel tread. With a pressing force of 25 kg this shoe removes dust, rust, etc. from the tread to ensure sufficient adhesion and to prevent skid.

3-6 Coupler

The coupler and coupler yoke are coupled via a ball joint in such a manner that the car body tilting is not affected, thus ensuring the smooth and free movement of coupler in all four directions. Namely the ball joint is fixed to the end of coupler via a pin joint, a wear plate (anti-wear resin) with spherical inside surface is placed before and after this ball joint, and the whole assembly is incorporated into the yoke.



1	Coupler
2	Coupler yoke
3, 4	Anti-wear resins
5, 6	Ball
7	Pin joint
8, 9	Follower plate
10	Rubber plate

Fig. 10 Coupler for tilting car

4. OPERATIONAL EXPERIENCE AND FUTURE PLAN OF TILTING TRUCK

JNR has already eight-year experience in the commercial operation of tilting truck.

The tilting trucks are introduced principally in the Chuo-sai Line (252 km) and Kisei Line (262 km), where about 200 units of 381-series electric railcars with tilting device are currently operating.

The operation diagram of this type of railcars in the Chuo-sai Line is shown in Fig. 7. The running kilometerage per day is averaged at above 700 km and the averaged operation time per day is more than 11 hours, indicating that the operating factor here is very high.

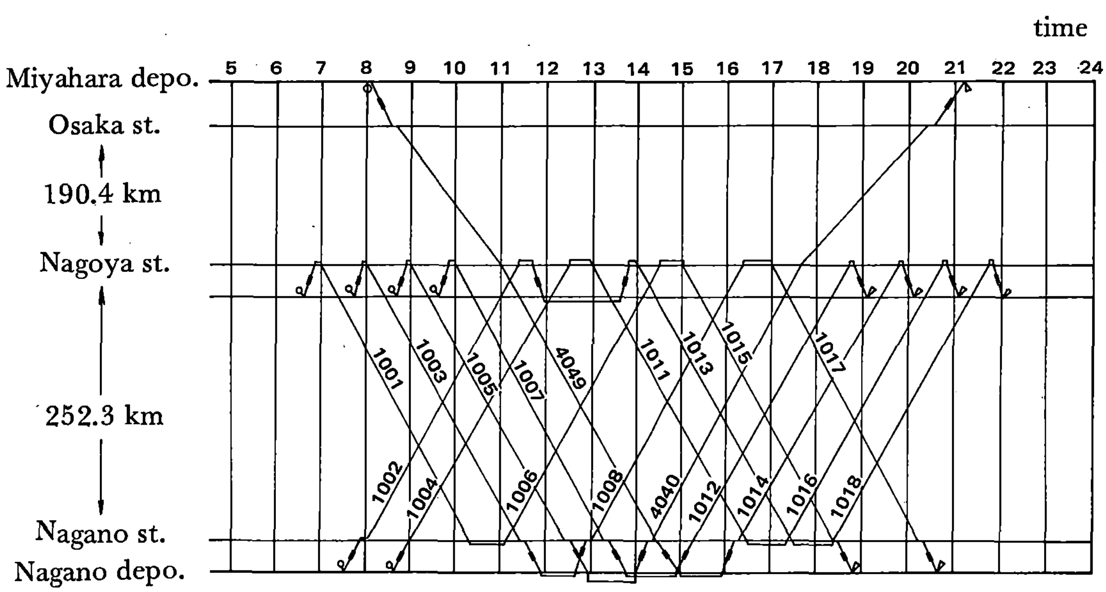


Fig. 7 Operation diagram

As far as the tilting movement is analyzed from the ride quality, its lateral vibration acceleration is not so critical. Actually our running test result shows that this acceleration is at most 0.04g, which is less than conventionally alleged limit of 0.05g. There ia a report, however, that the difference in vibration mode (the center of rotation does not make a pendulum motion in conventional rolling stocks) causes nausea to standing passengers. Though this does not deteriorate the ride quality heavily, it is planned to make a study on the relationship between the ride quality and the vibration acceleration and jerk. Both the vertical and longitudinal vibrations are almost similar to those of conventional rolling stocks, ensuring satisfactory ride quality. Generally, this type of truck retains a good ride quality if the curve running speed limit is raised by 20 km/h, enabling the realization of intended time reduction.

In terms of maintenance of tilting truck, the tilting device has extremely high reliability. Actually, the roller device which was most concerned with initially have not developed trouble at all, without wear in roller and fault in bearings. Up to the presnet, the trouble was reported only on the spherical bearing of bolster anchor. The trouble was abnormal wear due to large displacement during tilting movement, but this is now eliminated by redesigning the bearing to the one of Teflon composite resin. Althouhg the maintenance work may require an additional manpower corresponding to the extent of complicatedness of truck construction due to addition of tilting device (roller device), no trouble of work difficulty, etc. is reported. Besides no special technology and facility are needed for the maintenance work.

The future plan consists of the performance test of electric railcar with tilting truck as scheduled on the commercial line this fall. The purpose of this test is to obtain various data, which will be utilized in the atempt to reduce the lateral pressure, and thus to reduce the effect of lateral force on the rails for minimization of investment and maintenance of truck. This test is also to make investigations with an aim at the improvement of the ride quality by comparing the result of tilting motion sumulation with actual measurement. JNR intends to design a new tilting truck on the basis of results thus obtained and this new truck may have a new tilting device which is added artificial power such as pneumatic cylinder between upper swing bolster and lower bolster to make sure of tilting motion against friction force and to obtain good ride quality by control of artificial power.

It is also intended to expand in future the railway division to run the electric railcars with tilting truck. In addition to the present 381-series electric railcars with tilting truck (DC electric railcars), the development of this type of electric railcars is also planned for the AC electrified division.

Now the study is under way to develop the tilting type rolling stocks for the Shinkansen. The minimum radius of curvature in the roadway is originally standardized at above 2,500m, and, if the higher speed is to be attained with this radius of curvature, the tilting type rolling stock will have to be introduced into the Shinkansen.

Specifically a large amount of 381-series electric railcars with tilting device will be introduced into the Hakubi Line, in the near future, along with its electrification whose completion is scheduled for the next year.