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# Development of the New Concept Steering Bogie

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# Abstract

As for railway vehicle, there are many problems in sharp curve negotiation such as large lateral force, squeal noises and excessive wear of wheel flange and rail gauge corner. To solve these problems, single axle steering bogie has been developed by Tokyo Metro and Nippon Steel & Sumitomo Metal Corporation, and Tokyo Metro adopted this newly developed steering bogie for the new train series 1000 for Ginza-line. The series 1000 has started commercial operation in April 2012 and silence of cabin is highly appreciated. In this paper, the design concept and outline of steering bogie for series 1000 are described. And curving performance of steering bogie for series 1000 is evaluated based on the result of field test.

## 1. Introduction

Subway lines have many sharp and transition curves of small cant transition factors because of restrictions on the route plan, and as a result, problems occur at curves such as large lateral force on rails, high-frequency noises, severe wear of wheel flanges, and significant wheel load change at transition curves. To solve these problems, improvement in axle box suspension and pneumatic spring systems,<sup>1-3</sup> reappraisal of truck bolsters,<sup>4</sup> spray of friction control agents,<sup>5</sup> and other measures have been studied, developed and put into practice.

Aiming at solving these problems related to the curve negotiating ability of railway vehicles, Nippon Steel & Sumitomo Metal Corporation, jointly with Tokyo Metro Co., Ltd., has developed a new type of steering bogie truck capable of steering a wheel set according to curves. Different from other types of steering bogies, the developed one is characterized by improving its turning attitude at curves by steering only the wheel set in the rear.<sup>6,7)</sup>

Since steering bogies allow displacement of wheel sets, the drive system inevitably tends to be complicated, and for this reason, their use has been limited only to a comparatively small number of cars for superior services. In contrast, the developed steering bogie uses a conventional drive system for the non-steered axle, and therefore, it is excellent in reliability and maintainability.

In appreciation of the good curve negotiating ability and reliability, the new steering bogies were adopted for the new Series 1000 trains for Tokyo Metro's Ginza Line and Type SC101 steering bogie (see Figs. 1 and 2).

This paper presents the outlines of the developed steering bogie, the results of their trial runs on the real lines as well as those of the



Fig. 1 Series 1000 train for Tokyo Metro's Ginza Line



Fig. 2 Type SC101 steering bogie for Series 1000 vehicles

measurements of wheel loads, lateral force noises, etc., during commercial operation.

## 2. Concept of New Steering Bogie

2.1 Behavior of railway wheels at curves

The treads of railway wheels are tapered as shown in **Fig. 3**. When passing a curve, wheel sets shift to the outer rail side, and as a result of the taper, the effective diameter of the outer wheel increases

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Fig. 3 Self-steering characteristics of wheelset



Fig. 4 Behavior of non-steering, conventional bogie in sharp curve

and that of the inner wheel decreases. Thanks to this difference in the effective diameters and consequent self-steering function, railway vehicles turn curves without having to use steering mechanisms like those of automobiles.

On the basis of the above, **Fig. 4** explains what happens when a common two-axle bogie goes along a curve. A conventional bogie tends to take an understeer attitude, or to turn outwards with respect to the tangent of the curve, and as a result, the front axle has an angle of attack to the curve, which gives rise to a lateral creep force pressing the outer wheel to the outer rail. On the other hand, the rear axle stays near the track center, and consequently, the differential wheel diameter is insufficient, and there occurs a longitudinal creep force (tangential force) between the rear wheels and the rails. These forces act as anti-steering moments on the bogie, and cause high lateral force of the front wheel set toward the outer rail.

### 2.2 Problem of curve negotiation and function of steering bogies

As explained above, the problems with railway vehicles at sharp curves are large lateral force and high derailment coefficient, an indicator of running safety defined as the lateral force of a wheel on the rail divided by the vertical load. In addition, because the wheels turn at sharp curves with their flanges contacting the gauge corner of the outer rail, there are other problems arising from the wheel/rail contact such as high-frequency noises and the wear of the wheel flanges and the gauge corner of the rail.

In view of the large lateral force and high derailment coefficient, derailment is prevented physically by providing anti-derailment angles or rails along the inner rail.

Since the above large lateral force, high-frequency noises, and the wear of the flanges and the rail gauge corner result from wheels contacting the rail, they have been taken care of by providing oiling facilities to the tracks or wheels for lubrication control. Oiling, however, often leads to wheel spinning during power running or slipping







Fig. 6 Problems with sharp curve passing of railway vehicle and function of steering bogie

during braking, and thus is not adequate for curves. Spray of a special friction control agent<sup>5)</sup> has been developed and introduced recently to enable both smooth power running and braking at curves, but further improvement is required.

Steering bogies can solve all these problems. As **Fig. 5** shows, the idea of steering bogies is to steer a wheel set or wheel sets such that the wheelbase on the outer side of a curve becomes longer than that on the inner side, and the wheel axles turn radially in the direction of the curve. The problems of vehicles' negotiation with sharp curves and the function of the steering bogie are sorted out in **Fig. 6**.

#### 2.3 Concept of new steering bogie

The mechanism by which the developed steering bogie negotiates a curved track is illustrated in **Fig. 7**. The rear axle of the developed bogie is steered, and consequently, the angle of attack of the rear axle increases, which leads to a lateral creep force toward the outer rail, and accordingly the axle shifts toward it. As a result, the insufficiency in the differential diameter between the rear wheels is alleviated, and the longitudinal creep force of the axle in the antisteering direction decreases. In addition, the shifting of the rear axle toward the outer rail improves the attitude of the bogie from understeer to a radial turn. As a result, the angle of attack of the nonsteered front axle decreases, and so does the lateral creep force. The decrease in the longitudinal creep force of the rear axle and that in the lateral creep force of the front axle reduce the anti-steering moment of the bogie, as well as the lateral force of the front wheel on

#### the outer rail.

#### 2.4 Outlines of developed steering bogie

The configuration of a Series 1000 vehicle equipped with the new bogies is given in **Fig. 8**. While only the rear axle is to be steered, since railway vehicles run in both directions, the Nos. 1 and 4 axles on the body-end sides are not steered. The intention in the design is to steer the Nos. 2 and 3 axles to improve the curve negotiation performance of the leading axle of each vehicle in either direction of travel.

In the case of the rear bogie of a vehicle, its front axle, or the No. 3 axle, is steered. The turning attitude of a rear bogie in a curve is illustrated in **Fig. 9**. Since the leading axle of the bogie is steered, its angle of attack decreases, so does the lateral creep force, and consequently, the lateral force on the outer rail decreases.

The illustration in **Fig. 10** shows the outlines of the Type SC101 steering bogie designed for the Series 1000 cars of Tokyo Metro's Ginza Line. The axle boxes of the non-steering (Nos. 1 and 4) axles on the body-end sides are connected to the bogie frame using conventional mono-link suspensions. To realize high reliability, the

traction motor, the gear box, and the tread brake systems, which have been time-proven with conventional bogies, are used for the bogie.

With the steering (No. 2 or 3) axle on the body-center side, the brake systems pose a problem: since the wheels change their positions with respect to the bogie frame, common tread brake systems are not applicable. To solve the problem, disc brake was applied to the steered axle to allow for its displacement with respect to the bogie frame.

#### 2.5 Steering mechanism

The steering mechanism used for the SC101 bogie and its movement are shown in **Fig. 11**: it is a link-type steering mechanism wherein the swing bolster, the truck frame, and the axle boxes are connected with rods and levers. When a vehicle enters a curve and the bogie truck changes its angle to the vehicle centerline, the linkage members change their positions such that the axle boxes change



Fig. 7 Behavior of single-axle-steering, front bogie in sharp curve



Non-steering axle Steering axle Non-steering axle Fig. 8 Configuration of Series 1000 vehicle for Ginza Line



Fig. 9 Behavior of single-axle-steering, rear bogie in sharp curve



Fig. 11 Behavior of steering device



Fig. 12 Type FS576 prototype steering bogie



Fig. 13 Running test on test line

their positions in proportion to the curvature. Because of this passive actuation, the link-type steering is highly reliable.

Since conventional steering bogies change the positions of both wheel sets, the mechanism tends to be bulky. In contrast, the developed new steering bogie manipulates only one wheel set, and therefore, the mechanism can be designed compact and light-weight, and fits into the space of an ordinary axle-box suspension.

#### 3. Development of New Steering Bogie

The development work included numerical simulations using mathematical models and assuming the running conditions of real trains, and test runs on the curved test line in the premises of Nippon Steel & Sumitomo Metal's Osaka Steel Works.

For tests on commercially operated trains, trial units of the Type FS576 steering bogies were manufactured (see **Fig. 12**). They were tested in terms of the basic running performance, and in addition, running safety was confirmed through tests simulating unusual situations such as sticking and failure of the steering mechanisms. The photograph in **Fig. 13** shows a scene of the test run on the test line of the Works.

After the test runs in the Works, the prototype FS576 bogies were fitted to the Series 02 vehicles of the Marunouchi Line of Tokyo Metro for trials to confirm the performance on commercial lines (**Fig. 14**). Then, the bogies were used for commercial runs on the Marunouchi Branch Line from February 2010 to August 2011, through which stable and reliable functioning of the steering was confirmed.

In appreciation of the above results, introduction of the steering bogies to the Series 1000 trains for the Ginza Line was finally decided.

#### 4. Tests on Real Vehicles

#### 4.1 Test conditions

A six-car train of the Series 1000 equipped with the steering bogies was subjected to field test runs on the Ginza and Marunouchi



Fig. 14 Series 02 train for Tokyo Metro's Marunouchi Line

Lines in December 2011.

To compare the developed bogies with conventional ones in terms of curve negotiating performance, the test runs were conducted without loading the vehicles, a condition under which the derailment coefficient is high. The composition of the test train is given in **Fig. 15**. The car No. 1401 was used for comparative tests of steering and non-steering bogies: after test runs under steering conditions, the steering mechanisms were removed from the bogies to modify them into ones with non-steering, mono-link primary suspensions, and the tests were resumed on the same lines.

#### 4.2 Evaluation of curve negotiation performance

The wave forms of the lateral force of steering and non-steering bogies taken at a sharp curve are compared in **Fig. 16**; the curve radius is 197 m, the superelevation of the outer rail 109 mm, and the gauge widening 13 mm. While the steady lateral force by the non-steering bogie was 28 kN, the same by the steering bogie was 19 kN, which shows an improvement of 32%.



Fig. 16 Comparison of lateral force applied to outer rail by No. 1 axle

The graphs in **Figs. 17-19** compare the steering and non-steering bogies in terms of lateral force by the No. 1 axle on the outer rail, the angle of attack of the same axle, and the loads on the suspension linkages (which corresponds to the longitudinal creep force) of the No. 2 axle boxes, each measured at curves of different curvatures at normal running speeds. Each of the plotted points represents the average of the reading along a 10-m portion at the center of each curve.

It is clear from Fig. 17 that the lateral force by the No. 1 axle of the steering bogie on the outer rail is lower than that by the nonsteering bogie at all the curves. In addition, Figs. 18 and 19 show that the angle of attack of the No. 1 axle and the loads on the sus-



Fig. 17 Comparison of lateral force applied to outer rail by No. 1 axle at different curve



Fig. 18 Comparison of angle of attack of No. 1 axle



Fig. 19 Comparison of load on linkage between axle box and bogie frame of No. 2 axle



Fig. 20 Comparison of lateral force applied to outer rail by No. 3 axle



Fig. 21 Comparison of angle of attack of No. 3 axle

pension linkages of the No. 2 axle boxes are also lower with the steering bogie. These results evidenced that the steering mechanism explained in Sub-section 2.3 above effectively decreased the lateral force that the No. 1 axle exerted.

Likewise, **Figs. 20** and **21** show the measured lateral force on the outer rail and the angle of attack of the No. 3 axle, respectively, of the steering and non-steering bogies. The graphs show that the lateral force on the outer rail and the angle of attack of the No. 3 axle are smaller with the steering bogie than with the non-steering one, which demonstrates that the steering mechanism explained in Sub-section 2.4 above is effective at decreasing the lateral force by the No. 3 axle.

#### 4.3 Evaluation of under-car-body noise

The 3-D graphs in **Fig. 22** compare the steering and non-steering bogies in terms of the under-car-body noise during passage through a curve 172 m in radius having a cant of 111 mm and a gauge widening of 13 mm at the speeds of normal operation. The noise of the steering bogie is significantly lower than that of the non-steering one in the low frequency range of 1 kHz or less as well as in the high frequency range from 4 to 7 kHz.

## 5. Measurements on Commercial Lines

# 5.1 Performance verification with Series 1000 cars during normal commercial operation

Strain gauges and accelerometers were attached to the rails at a constant-radius curve of the Ginza Line, and wheel load, lateral force, and lateral vibration acceleration on rails were measured during commercial operation of the Series 1000 trains with steering bo-



Table 1 Measuring conditions on commercial line

	Item
Track data	Curve radius: 120 m
	Superelevation: 95 mm
	Gauge widening: 12 mm
Period	2012/9/11 - 2012/10/3
Measurement item	1. Lateral force on outer rail applied by leading axle
	2. Lateral acceleration of inner rail applied by
	leading axle
Axle load in	Series 1000 with steering bogies: 65 kN
empty condition	Series 01 with conventional bogies: 65 kN

gies and the Series 01 trains with conventional bogies. In order to make the measurement conditions (loading, wheel/rail lubrication, etc.) as equal as possible between the trains, the data of the Series 1000 trains were compared with those of the Series 01 trains that ran immediately before or after. **Table 1** shows the conditions of the track where the measurement was performed, and **Figs. 23** and **24** show the measurement results.

It is clear from Fig. 23 that the lateral force on the rails during commercial operation was lower and more stable with the steering bogies of the Series 1000 trains than with the conventional bogies of the Series 01.

Likewise, Fig. 24 shows that the lateral acceleration applied to the inner rail of the curve by the Series 1000 trains was markedly lower. This is presumably because of the smaller angle of attack due to steering. Thus, it was made clear that the loads of steering bogies on tracks are milder than those of conventional non-steering bogies. **5.2 Survey of flange wear with Series 02 cars of Tokyo Metro's** Marunouchi Line

As stated in Section 3, the FS576 steering bogies were used for commercial operation on the Marunouchi Branch Line for a year and a half. The difference in the wear of wheel flanges between the steering and non-steering bogies was measured over a long period during the time; **Fig. 25** shows the composition of the train used for the measurement.

The graph in **Fig. 26** shows the wear of the wheel flanges during commercial runs starting from the initial tread shape. The advance



Fig. 23 Comparison of lateral force applied to outer rail by leading axle



Fig. 24 Comparison of lateral acceleration of inner rail applied by leading axle



Fig. 25 Train set in which the steering bogie was installed



of the flange wear slowed down after running roughly 4000 km as a result of additional measures to suppress the flange wear such as application of lubricant to the flanges, and comparison became difficult. Nevertheless, with the steering bogies, the flange wear during

the initial period was roughly half that with the non-steering bogies. Since this indicates that steering bogies are also effective at reducing the wear of rails,<sup>8)</sup> follow-up investigation will be conducted for further periods.

# 6. Closing

A new type of steering bogie having improved curve negotiating performance has been developed on the basis of the idea of steering the rear axle, and the developed steering bogie has been adopted for the Series 1000 cars for Tokyo Metro's Ginza Line.

In the tests on real trains, the developed bogies were found to impose significantly lower lateral force on the rails and emit less noise at curves than conventional non-steering bogies did.

It was also found that the steering markedly decreased the lateral vibration of the rails, and thus was effective at reducing loads on tracks.

Long-term measurement of the wear of wheel flanges on the commercially operated trains on the Marunouchi Branch Line made it clear that the steering decreased the wear to a half; the wear of rails is also expected to decrease. Further investigation into the wear of wheel flanges and rails will follow.

Nippon Steel & Sumitomo Metal will further examine the behavior of steering bogies at curves to solve various problems originating from the contact between wheels and rails.

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