Analysis on Steering Performance of Active Steering Bogie according to Steering Angle Control in Curve section

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Abstract

The steering performance according to the steering angle control was tested by using the active steering bogie developed to reduce excessive wheels and rail wear and noise generated when the railway vehicle run in a curved section. As a result of the test of increasing the steering angle in accordance with the target steering angle in the 300m radius of curvature, the bogie is gradually aligned in the radial steering position, and when the control is carried out to 100% of the target steering angle, the bogie angles of the front and rear bogies appeared almost the same. As the steering angle increased, wheel lateral force and derailment coefficient also decreased. Therefore, the validity of the radial steering position control method applied in this paper was confirmed experimentally. This test results will be used for future research on active steering bogie commercialization.

Keywords: Active Steering bogie, Steering angle, Steering Performance, Bogie angle, Lateral force, Derailment coefficient

1. Introduction

When a railway vehicle run in curve sections, severe wheel wear and noise occur between the wheel and the rail. This is because the railway vehicle is not equipped with a steering device, so it is difficult to smoothly run in the curve section. That is, attack angle is generated between the wheel and the rail, which causes unnecessary force in the running and lateral direction of the wheel, which causes wheel wear and noise.

Active steering bogie technology has been actively studied to improve the poor steering performance of conventional railway vehicles.[1-5] Recently, a railway vehicle with active steering technology have been commercialized.[6]

The direct effect of applying active steering technology is to reduce wheel wear However, to verify this, it is necessary to measure the wear shape of the wheel of the test train through a long term test run. Therefore, in the stage of development, it is efficient to measure the lateral force of wheel which directly affects the wheel wear and analyze the lateral force reduction according to the active steering control.

Umehara has performed active steering control tests in the curve section of the factory test line using active steering bogie prototypes equipped with an electro-hydraulic actuators, and analyzed the reduction of wheel lateral force.[7] Suzuki tested the wheel lateral force reduction according to active steering control in the steep curve of the factory test line for a prototype steering bogie with a pneumatic active steering system.[8] Hur developed an active steering bogie prototype for EMU (electric multiple unit) train installed an electro-mechanical actuator and conducted steering performance test according to active steering control on an commercial line rather than the factory line.[9-12]

All these papers apply radial steering position steering control to reduce attack angle between wheel and rail. In other words, if the steering angle formed between the front and rear wheelsets in the bogie is implemented as the target steering angle, the bogie is geometrically aligned with the center of curvature of the curve section and the attack angle is zero. The wheel lateral force is then minimized as the attack angle disappears. Therefore, running performance such as wheel lateral force and derailment safety may vary depending on the degree of steering angle implementation.

Therefore, in this paper, we analyze steering performance according to steering angle implementation level that affect steering performance of active steering bogie. Steering control tests were performed in the steep curve section with curvature radius of 300m for the active steering bogie prototype for the EMU. This study analyzes the bogie angle, wheel lateral force reduction and derailment safety under the steering angle control of the active steering bogie and describes the results.

2. Active Steering Control Strategy

When the railway vehicle run in the curve section, attack angle between the wheel and the rail are generated as shown in Fig. 1 due to the lack of steering function of the wheel.[13] This causes unnecessary force in the driving direction and the lateral direction of the wheel, which is a major factor causing the wear of the wheels and rails and the generation of noise.

Therefore, in order for the railway vehicle smoothly run the curve section, the angle of attack becomes "0" if the wheelset is aligned with the center of curvature as shown in Fig. 2 using active steering control technology. At this time, this geometric position is called the radial steering position.
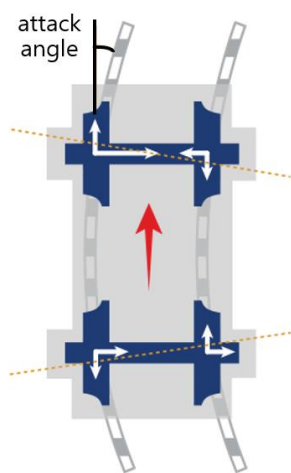

Fig. 1 Wheelset alignment of a conventional
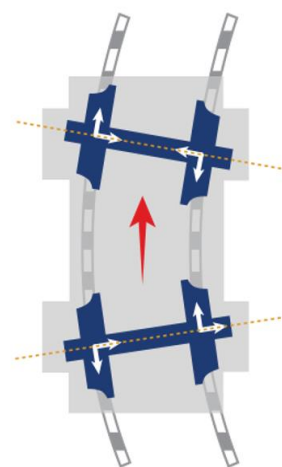railway vehicle when running in curve
section

Fig. 2 Wheelset alignment of a railway vehicle
with active steering technology
when running in curve section

Fig. 3 shows the geometrical relationship between the body and the bogies, assuming the vehicle is in the radial steering position in the curve section. In Fig. 3, the angle (2δ) formed between two wheelsets is called the steering angle, and the angle (θ) at which the bogie is rotated with respect to the vehicle body is called the bogie angle.

When the bogie and wheelset are aligned with the radial steering position, the bogie angles of the front and rear bogies are the same. At this time, from the geometric relationship of Fig. 3, the target values for wheelset steering angle and bogie angle for the ideal wheelset steering in the curve section of radius R are derived as shown in Equations (1) and (2).[12]

$$2\delta = 2d/R \tag{1}$$

$$\theta = L/R \tag{2}$$

where, 2δ : steering angle(rad)

　　R : radius of curve(m)

　　2d : wheel base(m)

L : semi-spacing of distance between bogie centers(m)
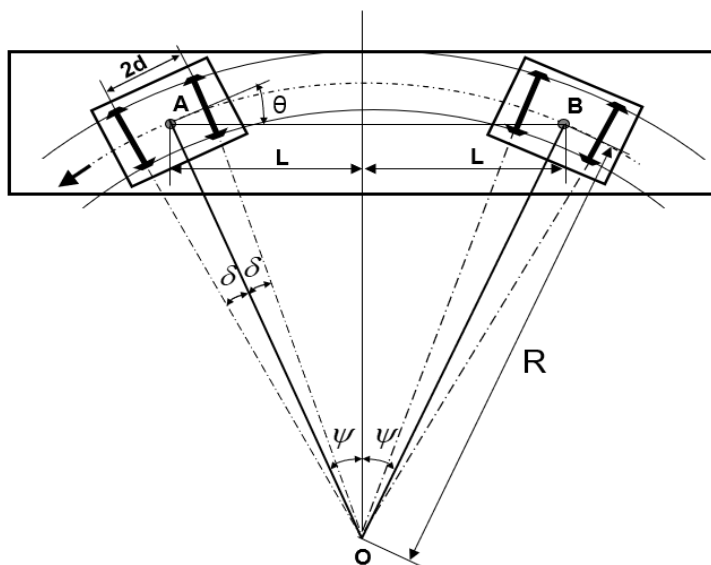
θ : bogie angle between body and bogie(rad)

Fig. 3 Radial steering position

3. Steering Control Test in the curve section

3.1 Active Steering Bogie

To analyze the steering performance according to the steering angle in the curve section, the test run was carried out using the active steering bogie prototype. Active steering bogie prototype was developed for EMU trains running on urban railway areas.[12, 13] Fig. 4 shows the configuration of the active steering bogie and Fig. 5 shows the active steering bogie prototype installed on the test train.

Active steering bogie adopts radial steering position control strategy based on real-time curvature radius estimation. The active steering bogie consists of a sensor unit, a control unit and a driving unit.

The sensor unit estimates the radius of curvature of the curve in real time, the controller calculates the target steering angle for active steering, and the steering driving unit conducts steering the wheelset according to the controller command.

The minimum radius of the curve section that can be detected by the active steering bogie is R80 with a radius of curvature of 80m and the maximum controllable steering angle is 0.5deg. In other words, steering control is possible up to R250, a radius of curve of 250 m, the smallest curve in commercial lines. The steering driving unit is adopting an electro-mechanical actuator type actuator, with a maximum steering thrust force of more than 50,000 N. Table 1 shows the specifications of the active steering system of the active steering bogie
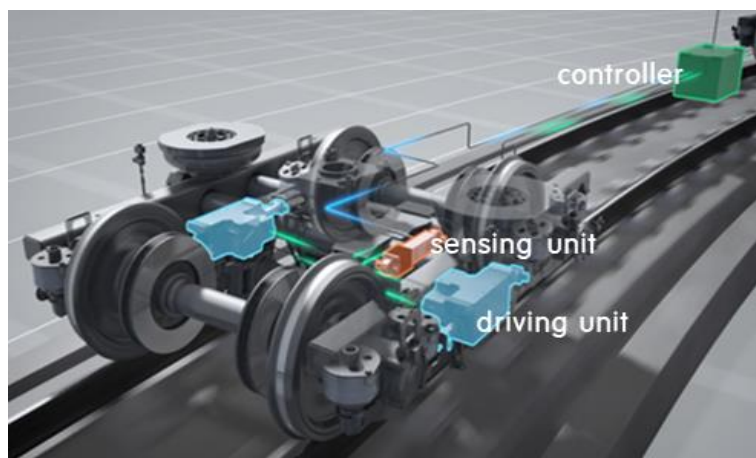
Fig. 4 Configuration of the active steering bogie

Fig. 5 Prototype of the active steering bogie

Table 1 Specifications of the active steering system

Category	Specification
Detectable curve radius	min. 80 m
Steering angle	0.5 deg.
Supply voltage	three phase 380 VAC
Maximum current (per vehicle)	16 A
Thrust force(per driving unit)	above 50,000 N

3.2 Test curve section

The steering control test to analyze the steering performance according to the steering angle in the curve section was performed on the R300 curve with a radius of 300 m of the commercial line. Fig. 6 shows the curvature of the test section measured by the curvature sensor unit mounted on the active steering bogie for real-time curve detection. The total length of the test curve section is 450 m and the length of circular curve is 250 m.
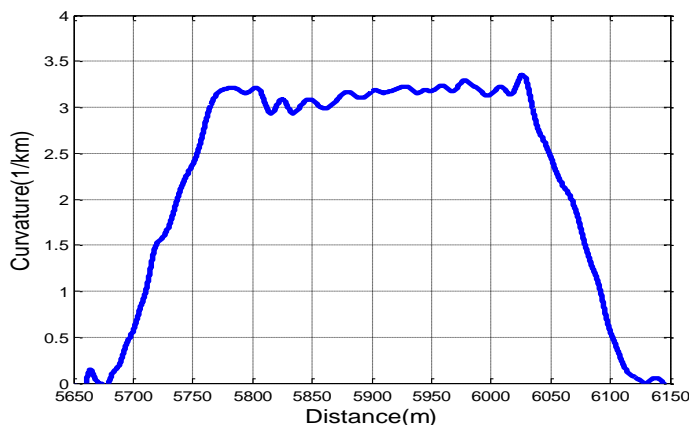

Fig. 6 Curvature of the test curve section

3.3 Test condition for active steering condition

Table. 2 shows the test conditions for analyzing the steering performance according to the steering angle in the curve section. Passive is the running condition of the curve section of the existing bogie not equipped with the active steering system. Active (25%) refers to the case when the active steering bogie run the test section while controlling to 25% of the target steering angle.

Active (50%) and Active (75%) represent when steering control is conducted at the 50% and 75% levels of the target steering angle, respectively. Active (100%) means that steering control is conducted completely to 100% level of the target steering angle.

Table 2 Test condition for active steering control

Case	Test condition
Passive	No active steering
Active(25%)	Control to 25% of the target steering angle
Active(50%)	Control to 50% of the target steering angle
Active(75%)	Control to 75% of the target steering angle
Active(100%)	Control to 100% of the target steering angle

4.   Test results of the active steering control

4.1 Analysis method

In order to analyze the steering performance according to the steering angle in the curve section, the bogie angle of the front and rear bogies, which are related to the radial steering position of the bogie, and the lateral force and the derailment coefficient of the wheel, which are dynamic factors, were measured.

To confirm the test conditions for steering angle implementation, steering angle was measured using a steering angle sensor as shown in Fig. 7. To measure the bogie angle, which is the rotating angle between the body and the bogie, the geometric displacement between the body and the bogie was measured and converted into the bogie angle.

And, to measure the lateral force and the derailment coefficient of the wheel, a measuring wheelset was manufactured to measure the lateral and vertical force applied to the wheel and it was installed on the active steering bogie.[12] Fig. 8 shows the measuring wheelset to measure wheel forces such as wheel lateral force and derailment coefficient.
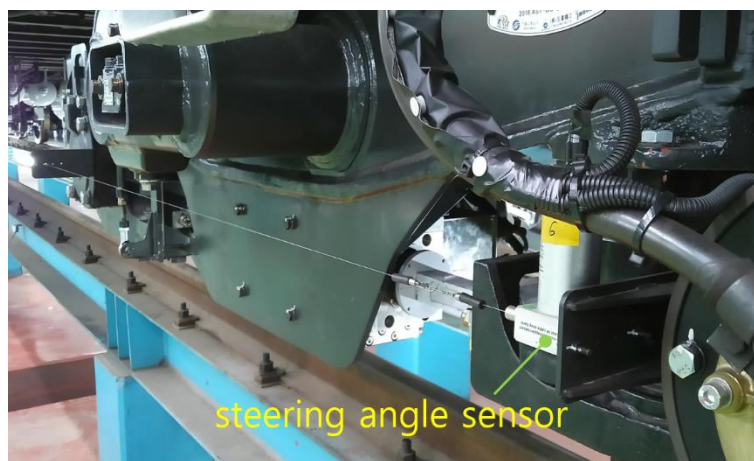

Fig. 7 Steering angle sensor

Fig. 8 Wheel force measuring wheelset

4.2 Steering angle

The steering control test was performed according to the test conditions in Section 3.3 to analyze the steering performance according to the steering angle in the curve section. Fig. 9 shows the steering angle test results measured by the steering angle sensor to verify that the active steering control test conditions are properly implemented. And Table. 3 shows the mean values for the steering angles when the steering bogie run in the circular section of the test section.

The steering angle of passive condition with insufficient steering function is 0.029 deg. This indicates that the measured value is very low at 7.3% of the target value, considering that the target steering angle required to pass the R300 curve is 0.4 degrees according to equation (1). As the steering angle implementation level increases with active steering control, the steering angle is approximated to the test conditions. That is, in case of Active (50), it is 0.208 deg, which is 52% of the target steering angle. In case of Active (100) which performs 100% steering control, the measured value is 0.393deg, which is well controlled as 98.3% of the target steering angle.
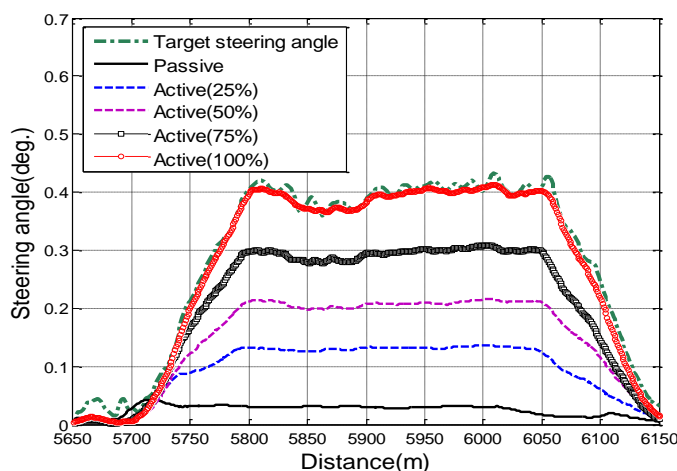

Fig. 9 Measured steering angle according to steering control condition

Table 3 Mean steering angle for the circular section of the test section

Case	Steering angle(deg)	Ratio to target steering angle(%)
Passive	0.029	7.3
Active(25%)	0.131	32.8
Active(50%)	0.208	52.0
Active(75%)	0.295	73.8
Active(100%)	0.393	98.3

4.3 Bogie angle

Fig. 10 and Fig. 11 show the measured bogie angles generated in the front and rear bogie according to the steering angle test conditions. Fig. 12 shows the bogie angle difference between the front and rear bogie. Table. 4 shows the mean values for the bogie angles when the steering bogie run the circular section of the test section.

In case of passive state with insufficient steering function, the bogie angle for the front bogie is 1.404deg and that for the rear bogie is 1.055deg and the difference is 0.349deg, which is very large. This result is due to the lack of steering function and the bogie is not aligned in the radial steering position when running in the curve section.

On the other hand, as the steering angle level increases with active steering control, it is shown that the bogie angle for the front bogie decreases and that for the rear bogie tends to increase. In addition, the bogie angle difference is also gradually decreasing. That is, in the case of Active (100) which performs 100% steering control, the bogie angle for the front bogie is 1.242deg, that for the rear bogie is 1.228deg, and the difference is only 0.014deg. This shows that the bogie is aligned in the radial position when running the curve section with active steering control.
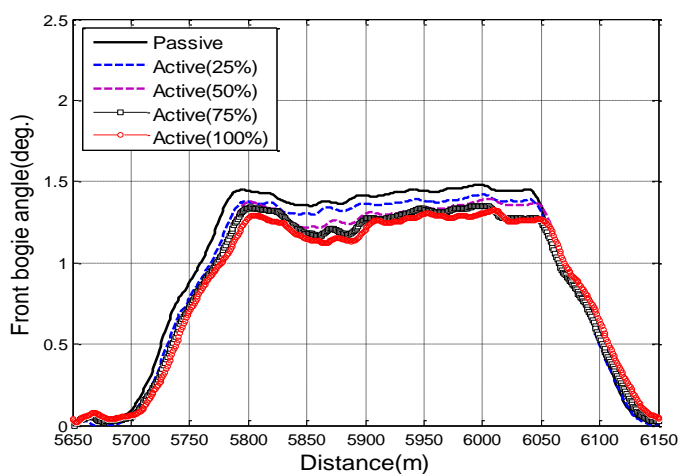

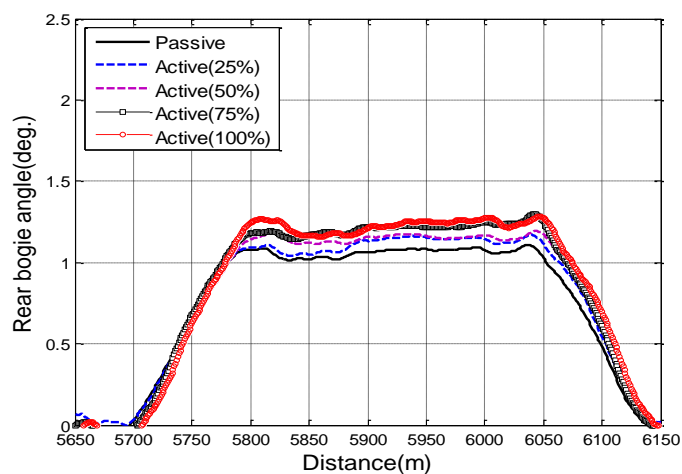Fig. 10 Measured bogie angle of the front bogie
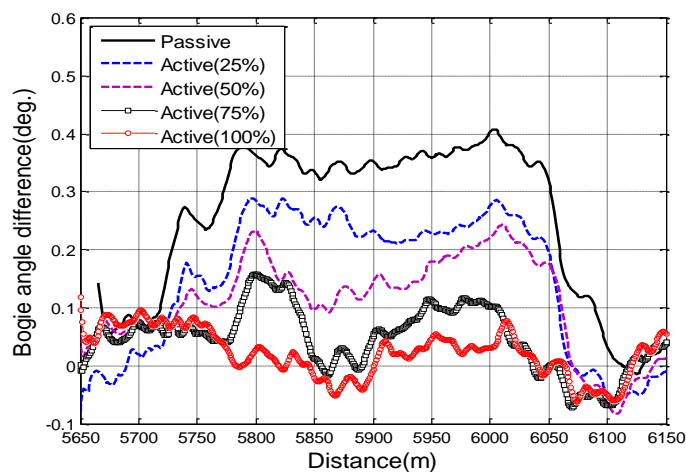
Fig. 11 Measured bogie angle of the rear bogie

Fig. 12 Bogie angle difference between front and rear bogies
according to steering control conditions

Table 4 Mean bogie angle for the circular section of the test section

Case	Bogie angle(deg.)		
	front	rear	difference
Passive	1.404	1.055	0.349
Active(25%)	1.363	1.118	0.244
Active(50%)	1.317	1.151	0.165
Active(75%)	1.278	1.211	0.067
Active(100%)	1.242	1.228	0.014

4.4 Lateral force of the wheel

Fig. 13 is test data obtained by measuring the lateral force generated on front outer wheel of the test vehicle according to the steering angle test conditions. For lateral force analysis, UIC 518 OR "Testing and approval of railway vehicles from the point of view of their dynamic behaviour - Safety - Track fatigue - Running behaviour", the world's railway standard, is applied.[14]

Fig. 14 is the result of analyzing the lateral force test data by subdividing 70m into small sections and arranging them in the cumulative distribution order to extract 99.85% of the values as the representative sections of the small sections. Table 5 shows the mean values of the small section representative values for the analysis results in Fig. 14 and the reduction rate for the lateral force of each test case for the passive case.

The mean lateral force of the wheel in passive case with insufficient steering is 14.99 kN. On the other hand, in the active steering control test condition, the wheel lateral force decreases as the steering angle implementation level increases. In the case of Active (25), it is 7.53 kN, which is 49.8% lower than Passive case. In the case of Active (50) and Active (75), the mean lateral forces were 4.68 kN and 3.20 kN, respectively, decreasing by 68.8% and 78.6%, respectively. In the case of Active (100) with 100% steering control, the mean lateral force is 2.46 kN, which is 83.6% lower than the passive case.

Therefore, it was confirmed that the bogie was aligned with the radial position as the steering angle increased to meet the target steering angle as the test train passed through the curve section, and the wheel lateral force was also significantly reduced.
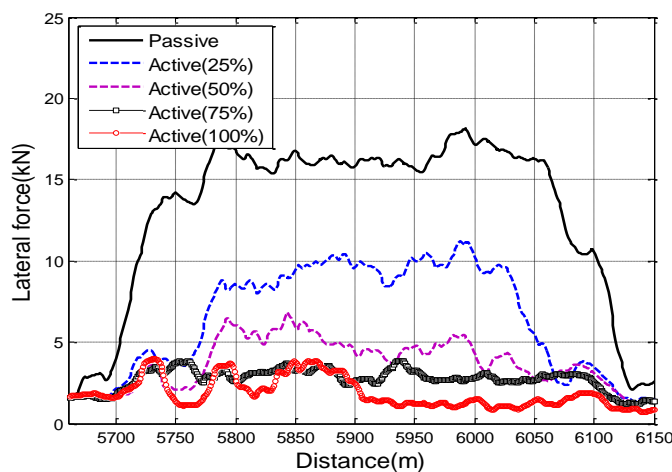

Fig. 13 Wheel lateral force test data according to steering control test conditions

(a) Passive

(b) Active(25%)
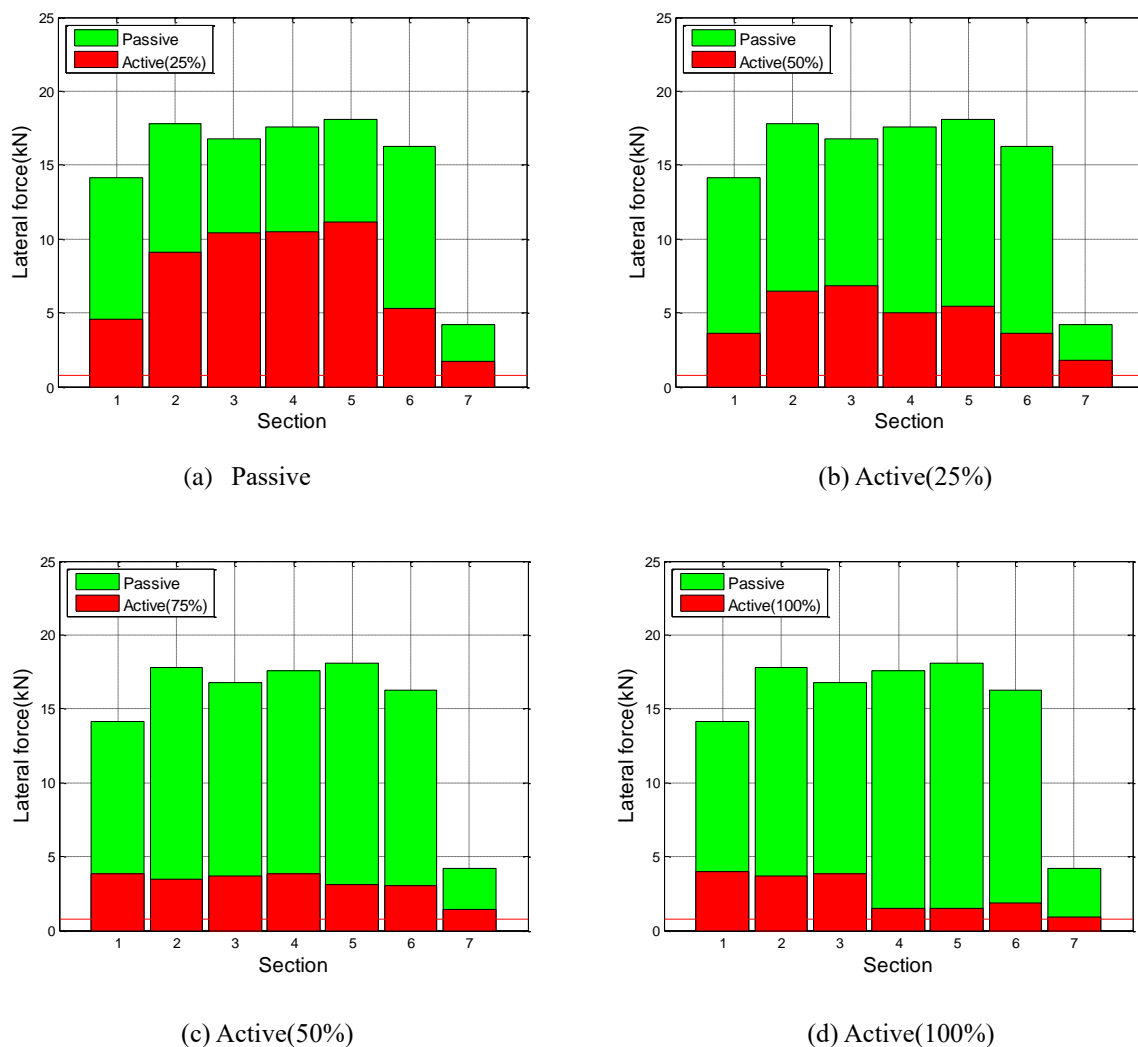

(c) Active(50%)

(d) Active(100%)

Fig. 14 Analysis results for wheel lateral force according to steering control test conditions

Table. 5 Mean lateral force for the circular section of the test section

Case	Force (kN)	Reduction (%)
Passive	14.99	-
Active(25%)	7.53	49.8
Active(50%)	4.68	68.8
Active(75%)	3.20	78.6
Active(100%)	2.46	83.6

4.5 Derailment coefficient

Derailment coefficient is a factor that indicates derailment safety when the vehicle is running and is defined as the ratio of the lateral force to the vertical force acting on the wheel. Fig. 15 shows the measured derailment coefficient test data of the front outer wheel of the test vehicle according to the steering angle test conditions using wheel force measuring wheelset.

For the analysis of the derailment coefficients, the UIC 518 OR test standard used for wheel lateral force analysis was applied.[14] Fig. 16 is the result of analyzing the derailment coefficients test data by subdividing 70m into small sections and arranging them in the cumulative distribution order to extract 99.85% of the values as the representative sections of the small sections. Table. 6 shows the mean values of the small section representative values for the analysis results in Fig. 16 and the reduction rate for the derailment coefficient of each test case for the passive case.

The mean derailment coefficient of the wheel in passive case with insufficient steering is 0.537. On the other hand, in the active steering control test condition, the derailment coefficient decreases as the steering angle implementation level increases. In the case of Active (25), the mean derailment coefficient is 0.232, which is 49.3% lower than Passive case. In the case of Active (50) and Active (75), the mean derailment coefficients were 0.148 and 0.099, respectively, with 72.5% and 81.6% reduction rates.

In the case of active (50) and active (75), the average derailment coefficients were 0.148 and 0.099, respectively, decreasing by 72.5% and 81.6%, respectively. In the case of Active (100) with 100% steering control, the mean derailment coefficient is 0.074, which is 86.3% lower than the passive case. This means that the derailment coefficient is naturally reduced if the wheel lateral force is reduced because the derailment coefficient is the ratio of the lateral force to the vertical force of the wheel. Accordingly, it can be seen that the wheel lateral force is reduced by the active steering control and the derailment coefficient, which is a vehicle running safety evaluation factor, is also significantly reduced.
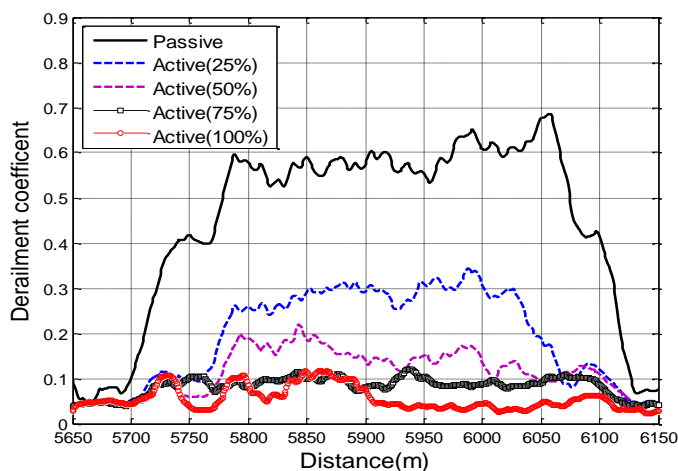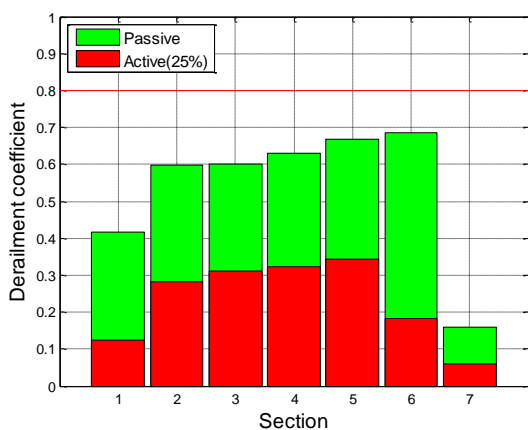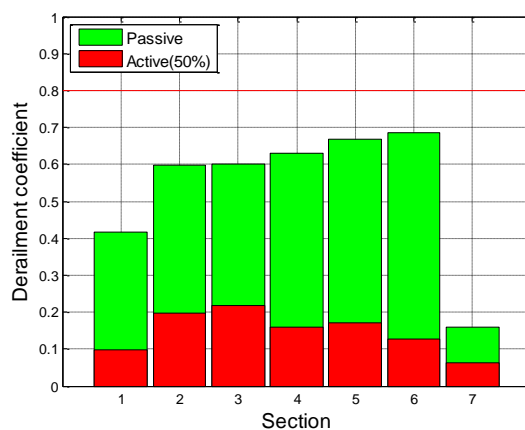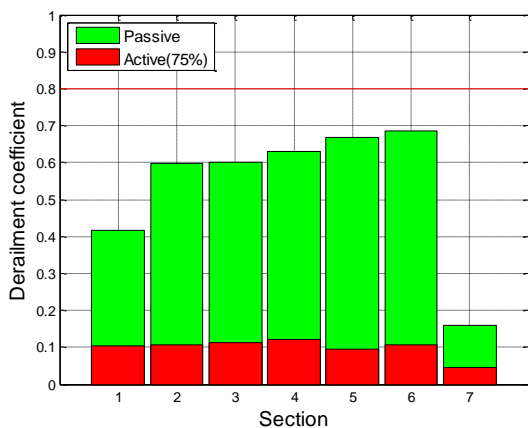

Fig. 15 Derailment coefficient test data according to steering control test conditions
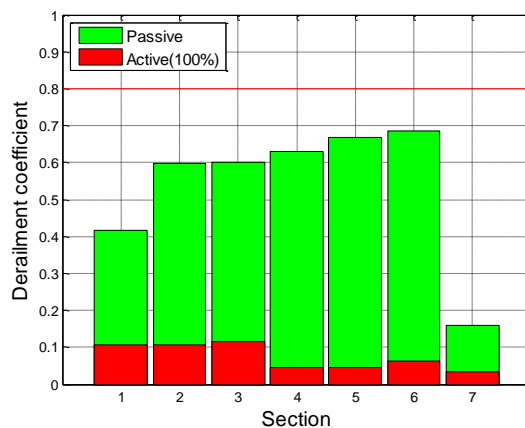
(a) Passive

(b) Active(25%)

(c) Active(50%)

(d) Active(100%)

Fig. 16 Analysis results for Derailment coefficient according to steering control test conditions

Table. 6 Mean Derailment coefficient for the circular section of the test section

Case	derailment coefficient	Reduction (%)
Passive	0.537	-
Active(25%)	0.232	56.7
Active(50%)	0.148	72.5
Active(75%)	0.099	81.6
Active(100%)	0.074	86.3

5.   Conclusions

The results of the steering test according to the steering angle implementation level of the active steering bogie developed to reduce the severe wear and noise of the wheels generated during the railway vehicle running in the curve section are as follows.

As the steering angle was increased to match the target steering angle, the bogie angle difference between the front and rear bogies was gradually decreased. When steering control was conducted at 100% level, the bogie angles of the front and rear bogie were almost the same, and the difference was only 0.014 deg. This means that the bogie is aligned in the radial steering position in the curve section. Wheel lateral force also tended to decrease significantly with increasing steering angle. When steering control was performed at 25%, 50%, 75%, and 100% of the target steering angle, respectively, 49.8%, 68.8%, 78.6%, and 83.6% decreased compared to passive conditions.

The above results indicate that the bogie is aligned in the radial steering position in the curve section as the steering angle increases according to the target steering angle by active steering control. Therefore, the validity of the radial steering position control method applied in this paper was confirmed experimentally. This test results will be used for future research on active steering bogie commercialization.

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