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Wind Tunnel Test and Lateral Acceleration Measurement for Application of RTRI's Detailed Equation to Shinkansen

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Abstract

By considering the application of RTRI's detailed equation to Shinkansen, the aerodynamic coefficients and lateral accelerations of car bodies were obtained and verified, taking into account the special geometry of Shinkansen vehicles and their high-speed running. Aerodynamic force coefficients were measured in a wind tunnel test by reproducing the geometry and the running conditions. The lateral accelerations were measured by running the actual vehicle, and it was confirmed that the assumed equation used in the RTRI's detailed equation can be applied to the Shinkansen. The obtained and verified results were used to evaluate vehicles' overturning resistance against strong crosswinds of all vehicle types in all sections of the Shinkansen.

Keywords: crosswinds, wind tunnel test, aerodynamic coefficient, lateral acceleration, critical wind speed, RTRI's detailed equation

1 Introduction

RTRI's detailed equation is an equation proposed by the Railway Technical Research Institute [1] and can calculate the critical wind speed of train overturning at each location, considering in detail the geometry, running speed, and other specifications of vehicle, as well as the conditions of track and surrounding structures. East Japan Railway Company (JR East) developed a wind regulation method for train operation control in strong winds using the RTRI's detailed equation [2] and has been introducing the method to conventional railway sections in response to the train derailment accident that occurred on December 25, 2005 between Sagoshi and Kita-Amarume Stations on the Uetu Line [3].

To apply RTRI's detailed equation to the Shinkansen, it is necessary to obtain aerodynamic force coefficients that consider the special geometry of the Shinkansen vehicles. In previous research [4], wind tunnel tests were conducted only for car types with relatively large side areas that are exposed to wind, and not for intermediate cars with noise insulation plates for pantograph. The assumed value of lateral accelerations of car body, which is 0.98 m/s^2 at maximum speed in proportion to running speed, is used in the RTRI's detailed equation, but it was verified mainly on conventional trains with the running speed up to 130 km/h [5], [6], but not on the current Shinkansen with the maximum running speed of 320 km/h. Furthermore, there was no verification under the assumption that active suspension was not available due to malfunction, which is considered to cause larger lateral accelerations.

In this study, the aerodynamic force coefficients and lateral accelerations of car body were obtained and verified, which were necessary to apply RTRI's detailed equation to the Shinkansen. Specifically, wind tunnel tests were conducted on Series E6 and E8 lead cars and Series E6 and E8 intermediate cars with noise insulation plates for pantograph, which had not been obtained for the aerodynamic force coefficients. This, together with the results of previous research [2], enabled us to utilize the aerodynamic force coefficients for all shapes of Shinkansen cars owned by JR East as of December 2023, which were considered to affect aerodynamic forces of the cars. In addition, wind tunnel tests were conducted for each intermediate car with different roof curvature radii to confirm the effect of the shoulder curvature radius on aerodynamic forces.

For the lateral accelerations of car body, sensors were attached to the actual Shinkansen lead car, and the lateral accelerations generated in the car body were measured under the condition that the active suspension was "off" when running at a maximum speed of 320 km/h. By comparing the measured results with the assumed values defined in RTRI's detailed equation, it was confirmed that the assumed values are applicable to the Shinkansen.

By using the obtained aerodynamic force coefficients and the verified assumed values of lateral accelerations, RTRI's detailed equation can be used to evaluate the overturning resistance of all models of Shinkansen trains in all sections of the Shinkansen lines.

2 Wind Tunnel Test

Table 1 shows the wind tunnel test conditions, and Figure 1 shows how the wind tunnel tests were conducted. Wind tunnel tests were conducted in a closed working section (5.0 m wide × 3.0 m high × 20.0 m long) of a large-scale low-noise wind tunnel (Göttingen type single return wind tunnel) at the Railway Technical Research Institute. The scale of the model was set to 1/40. A barrier wall, a spire with a triangular splitter and roughness elements were placed in front of the measurement section to generate a turbulent boundary layer with a power law of 0.26. The structure was a double-track viaduct, and the girder thicknesses were set to 1, 3, and 5 m in actual dimensions. Five vehicle types were selected for the verification. Test wind speeds of 20, 25, and 30 m/s were obtained, and 30 m/s was chosen after confirming that the Reynolds number effect was small.

Wind tunnel	Owned by Railway Technical Research Institute Large-scale low-noise wind tunnel (Göttingen type single return wind tunnel) Closed working section (5.0 m wide × 3.0 m high × 20.0 m long)
Scale of model	1/40
Train type	
(lead car)	Series E6, Series E8
(intermediate car)	Series E2 Series E5 (with or without noise insulation plates) Series E6 (with or without noise insulation plates) Models with variable shoulder curvature
Structure model	Double-track viaduct (girder thickness: 1m, 3m, 5m (actual size))
Air flow conditions	Turbulent boundary layer (power law of 0.26)
Wind speed [m/s]	30 (Reynolds number effects were checked at 20, 25, and 30 m/s)
Wind angle for vehicle (Yaw angle) [deg]	(basic) 10 to 90 degrees (select the required angle of ~350 degrees depending on how the noise insulation plates for pantograph are installed)

Table 1: Wind tunnel test condition

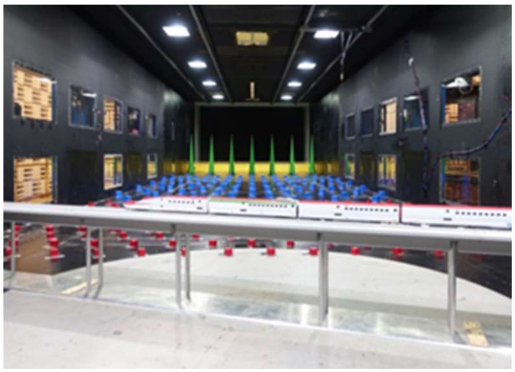

Figure 1: Wind tunnel test

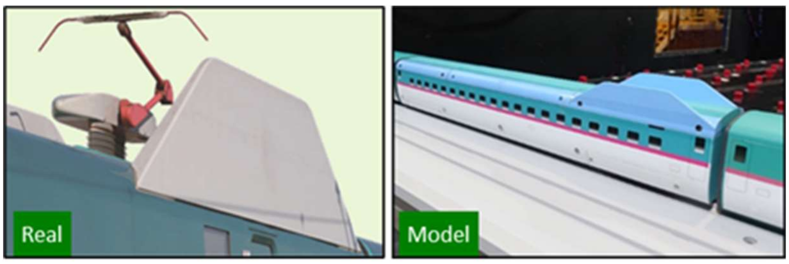

Figure 2: Noise insulation plates for pantograph (left: real, right: model)

2.1 Verification of the Effects of Lead Car Shape and Noise Insulation Plates for Pantograph

The target Shinkansen cars were those for which wind tunnel tests had not been conducted: Series E6 and E8 for the lead cars, Series E5 with and without the noise insulation plates for pantograph for the intermediate cars, and Series E6 with and without the noise insulation plates for pantograph for the intermediate cars. Figure 2 shows the actual and reproduced models of the noise insulation plates for pantograph. The wind angles were set from 10 to 170 degrees in the direction of travel as 0 degrees for intermediate cars with the noise insulation plates for the pantograph, which were installed symmetrically on the car body. The wind angles were set from 10 to 350 degrees for those installed asymmetrically. For other cars, the wind angles were set from 10 to 90 degrees.

2.2 Verification of the Effect of Shoulder Curvature Radius of Vehicle Roof

Wind tunnel tests were conducted on intermediate cars with different roof curvature radii by varying the shoulders curvature radii to contribute to the study of future train configurations. The target trains were Series E2, E5, and E6 which have different roof curvatures and have intermediate cars with or without the noise insulation plates for pantograph, and the radii of curvature of the shoulder were varied as listed in Table 2. The wind angles were set from 10 to 90 degrees with the direction of travel being 0 degrees.

	Noise insulation plates for pantograph	Radius of curvature of shoulder [mm]		
Series E2 (Roof curvature: 8000 mm)	With	400	500	600
	Without	400	500	600
Series E5 (6000 mm)	With	400	500	600
	Without	400	500	600
Series E6 (2640 mm)	With	400	500	600
	Without	400	500	600

Table 2: Intermediate Car Shape List

2.3 Wind Tunnel Test Results

(1) Wind tunnel test results on the effect of the shape of lead cars

Figure 3 shows the results of the side force coefficient ratio obtained for the lead cars as an example of the test results. The values are the ratios to the side force coefficient for Series E2 car at a wind angle of 90°.The ratios for Series E2, E3, E5, and E7 cars obtained in previous research [4] are also shown in this figure. The structure is a double-track viaduct with a girder thickness of 3m. The aerodynamic coefficient ratios of the lead cars of Series E3, E6, and E8 tend to be lower than those of other types at wind angles from 70 to 90 degrees. Those three types of Shinkansen cars have narrower car bodies than other Shinkansen cars, and it is known that the negative pressure areas on the downwind side of those cars are smaller than those of other Shinkansen cars, resulting smaller aerodynamic forces. See previous studies [4] for the CFD findings on the distribution of wind velocity around the car body.

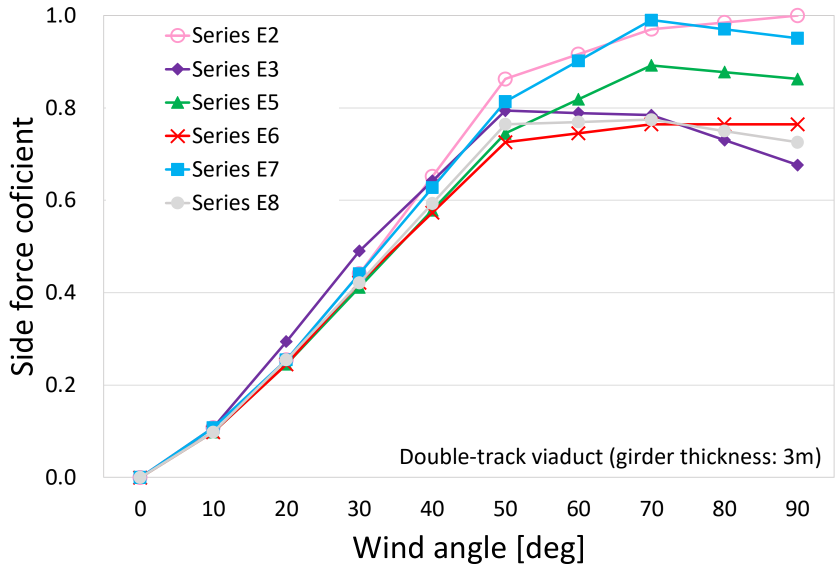

Figure 3: Side force coefficient ratios for wind angles by car types (Lead cars)

(2) Wind Tunnel Test Results with and without Noise Insulation Plates for Pantograph

Figure 4 shows the results of wind tunnel test with and without noise insulation plates for pantograph. The values are the ratios to the side force coefficient for Series E5 intermediate car with noise insulation plates for pantograph at a wind angle of 90°. The structure is a double-track viaduct with a girder thickness of 3 m. The side force coefficients with the noise insulation plates for pantograph are higher than that without the plates. The side force coefficient with noise insulation plates for pantograph compared to that without sound insulation. The increase ratio in the side force coefficient at a 90-degree wind angle due to the noise insulation plates for pantograph, which is obtained by dividing the increase in the side force coefficient due to the plates by the side force coefficient of the intermediate car without the plates, is 16% for Series E5 and 36% for Series E6. The ratio of the projected area of the noise insulation plates for pantograph to the car body side area is about 7% for Series E5 and about 3% for Series E6, indicating that the increase in the side force coefficients are greater than the increase in projected areas due to the noise insulation plates for pantograph.

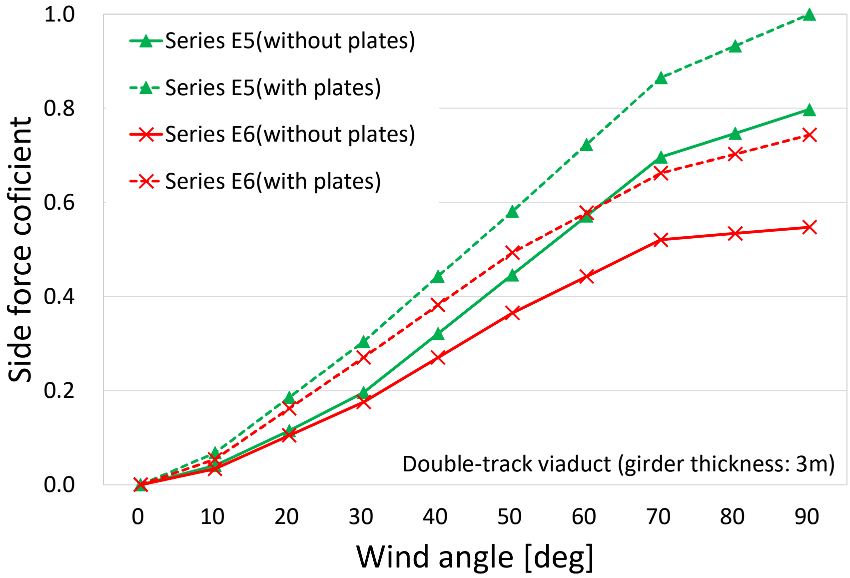

Figure 4: Side force coefficient ratios for wind angles by car types (Intermediate cars with or without noise insulation plates)

(2) Wind tunnel test results on the effect of shoulder curvature radius of intermediate cars

(3)

As an example of the test results, Figure 5 shows the side force coefficient ratios of Series E5 intermediate car with different shoulder curvature radii. The values are the ratios to the side force coefficient for Series E5 series intermediate car with a noise insulation plates for pantograph at a wind angle of 90° as described in (2) above. The figure shows that the side force coefficient ratios tend to be lower as the shoulders become more rounded (i.e., the curvature radius of the shoulder becomes larger). This is thought to be due to the suppression of flow separation at the shoulder when the shoulder curvature radius is large.

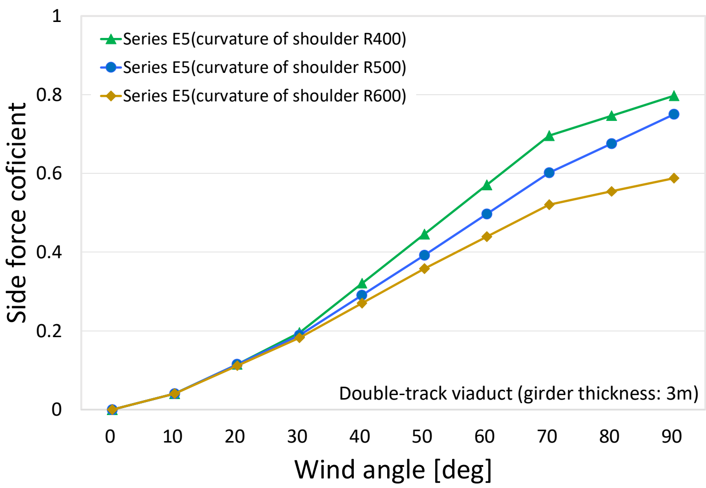

Figure 5: Side force coefficient ratios for wind angles on Series E5 intermediate cars with different shoulder curvature radii

4 Lateral Acceleration Measurement

4.1 Measurement Overview

Sensors were attached to the actual lead car of a Series E5 Shinkansen train, and the lateral accelerations generated in the car body were measured under the condition of the active suspension was "off" from Furukawa Station to Morioka Station, when the train run between Sendai Station and Morioka Station at a maximum speed of 320 km/h. Table 3 shows the measurement conditions. Motion sensor CSM-MG100CS, GPS antenna ANN-MS-0, and data logger LOGGER-CSM were used for the measurement. The motion sensor is capable of measuring 3-axis acceleration and 3-axis angular velocity, of which 1-axis acceleration in the lateral direction of the vehicle body was targeted. The measurement position was set at the center of the car body floor, which approximates the center of gravity of the car body, in accordance with previous studies [5], [6]. However, the center of the car body and the center position between bogies are different because of the long nose of the Shinkansen lead car. Therefore, measurements were taken at two points: the center of the car body and the center of the space between the bogies as shown in Figure 5.

The processing of the measured lateral accelerations for the evaluation of train overturning resistance was conducted in accordance with the methods used in previous studies [5], [6]. Specifically, a 2-Hz low-pass filter processing (hereinafter referred to as "LPF") was applied to the data to extract only the frequency components necessary for analysis. Then, to remove the inherent excess centrifugal force components at the time of curve passage, 3-second moving averages of the data after LFP processing were calculated and subtracted from the values after LPF processing.

Test car	Series E5 lead car
Measurement section	From Sendai Station to Morioka Station
Active suspension “off”	Between Furukawa and Morioka Stations
Running speed	0 ~ 320km/h
Measurement equipment	Motion sensor: CSM-MG100CS GNSS antenna: ANN-MS-0 Data logger: LOGGER-CSM
Measurement item	1-axis acceleration in lateral direction of car body Latitude, longitude
Measurement location	Center of car body on the floor Center between two bogies on the floor

Table 3: Lateral acceleration measurement test conditions

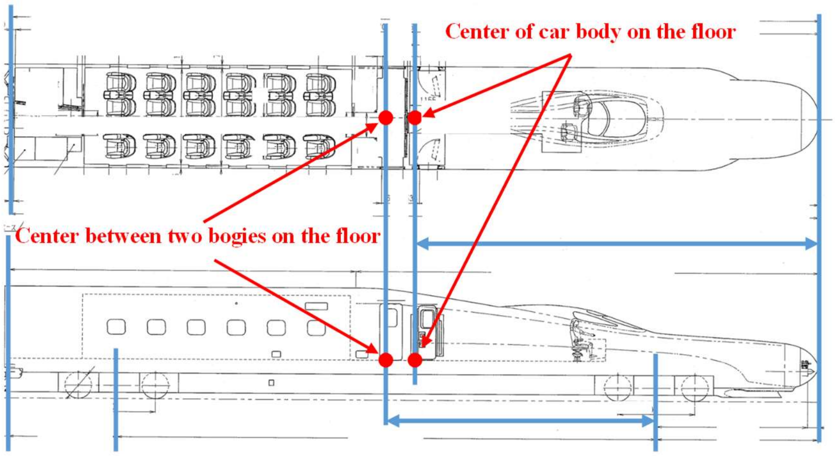

Figure 5: Locations of measurement equipment

4.2 Results of the measured lateral accelerations

The measured lateral accelerations were compared with the assumed value of lateral accelerations in RTRI's detailed equation. Figures 6 and 7 show the measured lateral accelerations at the center of the car body on the floor and at the center between two bogies on the floor. Only the maximum value of obtained acceleration every two seconds are shown in the figures. The red lines in these figures are the assumed value of the lateral accelerations in RTRI's detailed equation, which is 0.98 m/s^2 at maximum speed in proportion to running speed. From these figures, it is found that there are no significant difference in the accelerations measured at the different locations, and it is also confirmed that most of the lateral accelerations subjected to the car body during running are less than the assumed value of the lateral accelerations in RTRI's detailed equation even when the active suspension is "off". The exceedances were limited to passing through turnouts in the 0-70 km/h speed range. Considering that the occurrence of the exceedances is limited to low speeds and specific locations, the effect of the exceedances on the vehicle overturning resistance is considered small [5], [6].

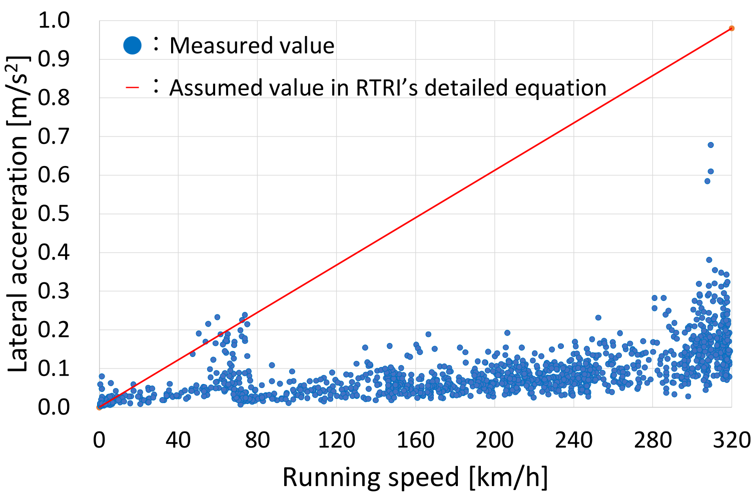

Figure 6: lateral acceleration (center of car body on the floor)

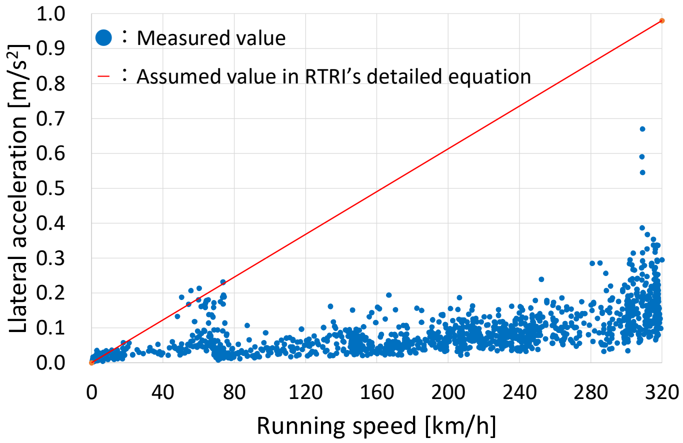

Figure 7: lateral acceleration (center between bogies on the floor)

5 Evaluation of overturning limit wind speed along the line

5.1 Evaluation Overview

By using the aerodynamic force coefficients for each car type obtained and organized through wind tunnel tests and the assumed values of lateral accelerations in RTRI's detailed equation verified through measurement tests, the critical wind speeds of train overturning (hereinafter referred to as "CWS") were obtained as the evaluations of overturning resistances for all Shinkansen car types on the entire Shinkansen lines, using RTRI's detailed equation.

5.2 Evaluation Results of Vehicle Overturning Resistance

Figure 8 shows an example of the results of the CWSs for the Tohoku Shinkansen. The CWSs were calculated at every 20 m, using the fastest available running speed at each evaluation point. By understanding the CWS at each location, appropriate train operation control methods and measures such as windbreak fences can be selected.

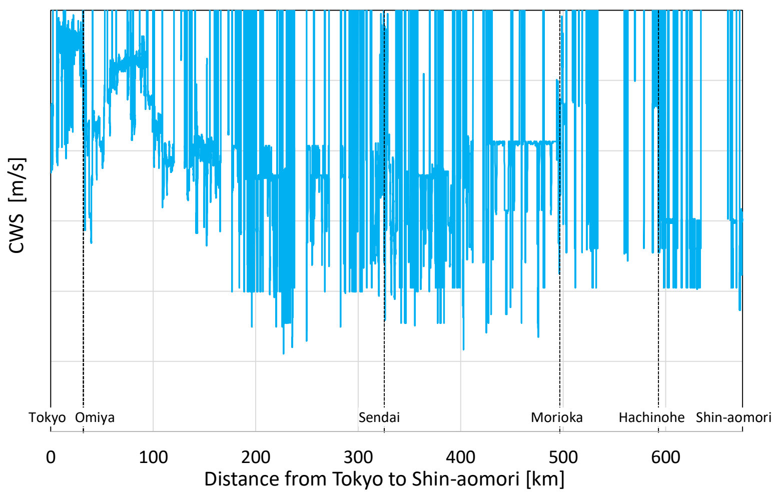

Figure 7: Example of CWS evaluation results

6 Conclusion

In this study, to apply RTRI's detailed equation to the Shinkansen, the necessary aerodynamic force coefficients were obtained through wind tunnel tests, and lateral accelerations were obtained and verified on an actual running vehicle. The conclusions obtained are as follows

(1) Aerodynamic force coefficients for the Shinkansen trains, which had not been obtained before, were obtained. This, together with the results of the previous study, enabled us to utilize the aerodynamic force coefficients for all shapes of Shinkansen cars owned by JR East as of December 2023, which were considered to affect aerodynamic forces of the cars.

(2) The aerodynamic force coefficients of lead cars of Series E3, E6, and E8 tended to be lower than those of other types at wind angles of 70 to 90 degrees. This was thought to be due to the characteristics of the narrower car bodies than other Shinkansen cars.

(3) The side force coefficients for intermediate cars with and without noise insulation plates for pantograph were compared, and the results showed that the side force coefficients with sound insulation panels were higher, with an increase of 16% for Series E5 and 36% for Series E6 at a wind angle of 90 degrees. These increases were larger than the increases in projected area due to the noise insulation plates for pantograph, which were about 7% for Series E5 and about 3% for Series E6.

(4) Wind tunnel test results on the effect of shoulder curvature radius of intermediate cars revealed that the rounded shoulders, which have larger shoulder curvature radius, tended to have lower side force coefficients.

(5) The lateral accelerations of the car body were measured and verified under the condition that the active suspension was "off" when running at a maximum speed of 320 km/h. The results showed that most of the lateral accelerations subject to the car body, except when passing through turnouts, were less than the assumed value in RTRI's detailed equation, even when the active suspension was off at 320km/h.

(6) By using the obtained aerodynamic force coefficients and the assumed values of the lateral accelerations in RTRI's detailed equation, it made us possible to evaluate the critical wind speeds of train overturning by RTRI's detailed equation for all Shinkansen types of cars on the entire Shinkansen lines.

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