RA2013-1-I

Railway Accident Investigation Report

Train Derailment Accident in the premises of Sendai station of the Tohoku Shinkansen of the East Japan Railway Company

February 22, 2013

Japan Transport Safety Board

The objective of the investigation conducted by the Japan Transport Safety Board in accordance with the Act for Establishment of the Japan Transport Safety Board is to determine the causes of an accident and damage incidental to such an accident, thereby preventing future accidents and reducing damage. It is not the purpose of the investigation to apportion blame or liability.

Norihiro Goto
Chairman
Japan Transport Safety Board

Note:

This report is a translation of the Japanese original investigation report. The text in Japanese shall prevail in the interpretation of the report.

Railway Accident Investigation Report

Railway operator :	East Japan Railway Company
Accident type :	Train derailment
Date and time :	About 14:47, March 11, 2011
Location :	Around 326,285m from the origin in Tokyo Station, in the premises of Sendai station, Tohoku Shinkansen, Sendai City, Miyagi Prefecture

February 4, 2013

Adopted by the Japan Transport Safety Board

Chairman	Norihiro Goto
Member, Chair	Akira Matsumoto
Member	Teruo Azukizawa
Member	Toshiyuki Ishikawa
Member	Norio Tomii
Member	Miyoshi Okamura

SYNOPSIS

SUMMARY

On March 11, 2011, the Test 7932B train, composed of 10 vehicles, started from Sendai General Train Depot bound for Shiroishizao station, Tohoku Shinkansen of the East Japan Railway Company, departed from Sendai General Train Depot on schedule.

While the train was entering to the premises of Sendai station at a velocity of about 72 km/h, the train driver felt the strong shake and simultaneously noticed the stop signal indicated in the cab signal device, and then he applied an emergency brake immediately. After the train had stopped, the train driver checked the situation of the train from inside and outside of the train and found that all two axles in the front bogie of the 4th vehicle had derailed to left.

The train was operating as the test run, and 12 rolling stock inspectors and a driver were onboard, but no one was injured.

Here, the "Heisei 23th year, 2011, Off the Pacific Coast of Tohoku Earthquake" had occurred at about 14:46 of the same day. The moment magnitude was 9 and the hypocenter was in offshore of Miyagi Prefecture. The maximum seismic intensity 7 was observed in northern Miyagi Prefecture.

PROBABLE CAUSES

It is highly probable that the accident train derailed due to receiving the seismic ground motion of the main shock of the Pacific Coast of Tohoku Earthquake, because it is highly probable that there was no problem in the railway facilities including tracks, the accident train and the train operation before the occurrence of the earthquake, furthermore, it is highly probable that the accident train derailed just after the main shock of the Pacific Coast of Tohoku Earthquake had arrived at Sendai City. Here, it could not be determined the reason why only two axles in the front bogie of the 4th vehicle had derailed.

It is probable that the process to the derailment were as follows. At first, the frequency component, which corresponded nearly with the natural frequency of the viaduct in the accident site, in the frequency components of the seismic ground motion by the Pacific Coast of Tohoku Earthquake, had been amplified by the resonance phenomena of the structure and induced the large displacement at the top of the viaduct. As the frequency was in the range to induce the upper rolling motion of the vehicle easily, the vehicle was forced to roll in the upper center rolling mode and resulted to be derailed.

It is probable that the damage was not spread because the train was running in low speed just before the derailment by the operation of the system to stop trains earlier, and the derailed 4th vehicle did not deviate from the track seriously by the function of the deviation preventing guide.

Contents

Attached Materials

1. PROCESS AND PROGRESS OF THE RAILWAY ACCIDENT INVESTIGATION

1.1. Summary of the Railway Accident

On Friday, March 11, 2011, the Test 7932B train, composed of 10 vehicles, started from Sendai General Train Depot bound for Shiroishizao station, Tohoku Shinkansen of the East Japan Railway Company, departed from Sendai General Train Depot on schedule at 14:40.

While the train was entering to the premises of Sendai station at a velocity of about 72 km/h, the train driver felt the strong shake and simultaneously noticed the stop signal indicated in the cab signal device, and then he applied an emergency brake immediately. After the train had stopped, the train driver checked the situation of the train from inside and outside of the train and found that all two axles in the front bogie of the 4th vehicle had derailed to left. Here, the expressions "front", "rear", "left" and "right" were based on the direction of the train destination and the vehicle number was counted from the front.

The train was operating as the test run, and 12 rolling stock inspectors and a driver were onboard, but no one was injured.

Here, the "Heisei 23th year, 2011, Off the Pacific Coast of Tohoku Earthquake" had occurred at about 14:46 of the same day. The moment magnitude was 9 and the hypocenter was in offshore of Miyagi Prefecture. The maximum seismic intensity 7 was observed in northern Miyagi Prefecture.

1.2. Outline of the Railway Accident Investigation

1.2.1. Organization of the Investigation

The Japan Transport Safety Board, JTSB, designated the chief investigator and a railway accident investigator to investigate the accident on March 30, 2011, and designated one more railway accident investigator on April 15, 2011.

The Tohoku District Transport Bureau dispatched its staffs to support investigation of the accident.

As it was probable that the seismic ground motion by the "Heisei 23th year, 2011. Off the Pacific Coast of Tohoku Earthquake", *hereinafter referred to as the "Pacific Coast of Tohoku Earthquake"*, had occurred on March 11, 2011, was related with the train derailment accident, the JTSB appointed three professional members on the seismic ground motion, structures and vehicles, shown in Table 1, and discussed on the analysis of vehicle dynamics during earthquake. Here, the JTSB entrusted the analysis based on vehicle dynamics simulation during earthquake to the Railway Technology Research Institute, RTRI. The JTSB also obtained the cooperation of the RTRI to implement the analysis of the process to the derailment.

Table 1. Professional members and their technical fields

Organization*	Title*	Name	Fields
Center for Integrated Disaster Information Research, Inter faculty initiative in information Studies, The University of Tokyo.	Professor	T. Furumura	Earthquake
Sustainable Design and Engineering Course, Graduate School of Engineering, Utsunomiya University.	Professor	A. Nakajima	Structures
Institute of Industrial Science, The University of Tokyo	Professor	Y. Suda	Vehicles

* *Organizations and Titles were as of July 2011.*

1.2.2. Implementation of the Investigation

- April 1, 2011 — Investigations of the accident site and vehicles, and interviews.
- November 22, 2011 — Investigations of the accident site and vehicles, and interviews.
- September 30, 2011 to March 16, 2012 — Simulation analysis on the vehicle dynamics during earthquake.

Here, the initial investigation could be started 21 days after the accident day, due to effects of the Pacific Coast of Tohoku Earthquake. The JTSB had approved that the East Japan Railway Company, *hereinafter referred to as "the Company"*, to implement restoring works of the Test 7932B train, *hereinafter referred to as "the accident train"*, prior to start investigation, in the condition that the Company recorded the situation of the accident accurately, considering the necessity of the prompt recovery of the accident site.

1.2.3. Comments from Parties Relevant to the Cause

Comments from parties relevant to the cause were invited.

2. FACTUAL INFORMATION

2.1. Process of the Train Operation

2.1.1. Statements of the Train Crews et al.

[Refer to Figure 1, 2, Photograph 1]

According to the statements of the driver of the accident train, *hereinafter referred to as "the driver"*, and the staff A in charge of rolling stock inspection and repair who had boarded on the accident train, the outline of the process to the accident were as follows.

(1) The driver

I was engaged in the test run operation of the accident train just finished the bogie inspection. After the accident train had started from No.10 track of Sendai General Train Depot on schedule at 14:40, the accident train received the "110" signal, then the driver operated the accident train to keep the velocity between 107 km/h and 108 km/h. After a while, the ATC brake acted as received the "75" signal, and the velocity of the accident train bacame to about 70 km/h. While the accident train was running in cruising operation at about 65 km/h in around 326.4 km from the origin in Tokyo station, *hereinafter "from the origin in Tokyo station" was* *omitted*, I felt the shake obviously different from usual motion suddenly, and at the same time, the accident train received the stop signal, and then I took procedures to the emergency stop immediately.

After the train had stopped, I felt severe jolts as violent as I had never experienced before and considered as to cause derailment easily. I felt that the rolling motion was so severe. As I had notified from the staff of rolling stock inspection and repair boarded on the intermediate vehicle that there was a difference in the floor height between the 3rd and the 4th vehicles, I walked to around the coupling device and checked from inside of the vehicle, and then I found that the 4th vehicle, *hereinafter referred to as "the derailed vehicle"*, sank around 30 to 40 cm downward. In addition, I found that the pantograph of the 6th vehicle had lowered and the MR pressure[*1] was decreasing in the monitor display on the operation desk, and then I reported these situations to the train dispatcher and took procedures against power failure. When I got off the train to set scotch blocks and checked under floor of vehicles, I found that all two axles in the front bogie of the 4th vehicle had derailed to left by about 10 cm, and then I reported it to the train dispatcher. After that, I communicated with the train dispatcher, etc., and received the instruction to get off the train on 20:59. Then I left the train with staffs of rolling stock inspection and repair at about 21:05, after reconfirmed the procedures to prevent rolling of wheels.

*1 *"MR pressure" is the pressure of the main air reservoir for reserving compressed air to operate brake etc.*

(2) Staff A in charge of rolling stock inspection and repair

I had implemented the inspection for around the bogies in the accident train, before the test run in the main line after bogie inspection, but there was no abnormal situation in the results of the inspection. I was boarded on the accident train being engaged in the measurement of vibrations of the 3rd and the derailed 4th vehicles. While the accident train was running, I had been seated in the rearmost seat located at around just above the rear bogie of the 3rd vehicle.

The accident train started on schedule. After the accident train had passed each other with two outbound Shinkansen trains running in the down track, my private cellular phone received the earthquake early warning information. As I found in the display of the cellular phone that earthquake had occurred at offshore of Miyagi Prefecture, I took defensive posture. After that, I felt as if the earth were heaving upward as being banged away, and violent rolling motion, so severe as I could not be standing unless holding seat just as if I was in hammock or boarded on ships, followed three times. The accident train stopped just after I felt the first rolling motion. When the accident train had stopped, I felt the shock as if the accident train bumped with something. As I was seated facing front direction of the train, I did not see the status of the derailed vehicle.

After the rolling motion had calmed down, I checked the coupling part between the 3rd vehicle and the derailed 4th vehicle from inside vehicle, and then I found that the derailed vehicle had slightly leaned to left.

2.1.2. Recorded Data on Operating Status of the Train

The inspection and record device in the DS-ATC*2 onboard device, *hereinafter referred to as "ATC recording device"*, to record operating status of the accident train, had been recorded operating status of the receiver control block and ATC related apparatus, etc., every 0.3 sec. Information related with stopping of the accident train obtained from the ATC recording device of the accident train were shown in Table 2.

Here, the velocity data had a possibility to include some errors because the data were not revised based on the result of measuring tests, etc.

Here, it is highly probable that the accident occurred at about 14:47, based on the discussions described in the following 3.2.1.

*2 : *DS-ATC is the abbreviation of the Digital communication & control for Shinkansen - Automatic Train Control", which is the automatic train control system based on digital signals for the Shinkansen trains of the Company.*

Table 2. Information on train stopping obtained from the DS-ATC recording device

Time*	Position*	Velocity	Remarks
14:47.01.21	326,400 m	72.2 km/h	Power failure detector detected power failure of overhead contact line and issued brake command by power failure.
14:47.02.11	326,384 m	71.8 km/h	The onboard ATC device detected power failure of overhead contact line and issued emergency brake command.
14:47.16.21	326,208 m	14.6 km/h	Around the point where the accident train derailed.
14:47.16.51	326,208 m	13.6 km/h	The same as the above.
14:47.16.81	326,206 m	12.8 km/h	The same as the above.
14:47.18.91	326,204 m	0 km/h	Velocity 0 km/h was detected.

* *Positions in the above table indicated the kilometerage, from the origin in Tokyo station, of the onboard device of the transponder installed about 7.2 m backward from front head of the train.*

* *The time data recorded in the DS-ATC recording device were based on the clock in the onboard device. To correct the time data to the actual time, about 2.3 sec should be added to the recorded time in the onboard device, in case of the accident train. In addition, the recorded time data include errors about ±0.15 sec in the process of the ATC data recording procedure.*

2.2. Injuries to Persons

None

2.3. Information on the Railway Facilities and the Vehicles

2.3.1. Information on the Accident Site *[Refer to Figures 1 to 4, Photographs 1 to 3]*

(1) Track layout

The accident occurred in around the pier 2P, located in around 326,285 m, of No.3 Odawara viaduct, located from 326,212 m to 326,331 m. There were viaducts and bridges continuously in the section around the accident site. The track around the accident site was roughly in ENE and WSW direction.

The section from around 326,060 m to 326,222 m was the straight track, the next section until 326,361 m was the 4,000 m radius left curved track with 10 mm cant and 4 ‰ upgrade section, connected to the straight section from around 326,361 m to 326,705 m. The No.18 simple turnouts were installed between 326,118 m to 326,182 m and between 326,392 m to 326,456 m, respectively.

(2) Track structures

Track in around the accident site was the slab track with the 60 kg rails.

The directly connected 8 type fasteners or the fasteners for expansion joint were used as the rail fasteners, and these fasteners were located every 625 mm or 500 mm for the directly connected 8 type fasteners, and every 550 mm for the fasters for expansion joint.

Dimensions of the slab tracks were, 4,900 mm long, 2,340 mm wide and 190 mm thick for the slab where the 1st axle in the front bogie of the derailed vehicle had stopped, 5,030 mm long, 2,340 mm wide and 190 mm thick for the slab where the 2nd axle in the front bogie of the derailed vehicle had stopped, and 4,930 mm long, 2,340 mm wide and 190 mm thick for the slab tracks installed in the direction to Shin-Aomori station. Here, the shapes of the protuberances of the slab tracks were full circle or half circle of 200 mm radius and 250 mm high.

(3) Status of the derailment

The front head of the accident train had stopped at around 326,202 m.

The 1st and the 2nd axles in the front bogie of the derailed vehicle had stopped at around 326,280 m and 326,282 m, respectively. The right and left wheels of the 1st axle and right and left wheels in the 2nd axle in the front bogie had derailed to left about 210 mm, about 95 mm, about 260 mm, and about 155 mm, respectively.

There were linear traces considered as caused by wheels on the top surface of right and left rails at around 326,283 m and around 326,286 m. Beyond there until to the stopped points of the axles in the front bogie of the derailed vehicle, there were damages considered as caused by wheels on the rail fasteners and surface of the slab tracks. The driving device of the 1st axle, the motor of the 2nd axle and the cross beam fitting the bottom plate in the rear part of the front bogie etc., had been stopped in the situation as being in contact with rails.

2.3.2. Information on the Railway Facilities

(1) Outline of Tohoku Shinkansen

The Tohoku Shinkansen of the Company originated from Tokyo station and terminated Shin-Aomori station. Its railway business mile was 713.7 km with AC 25,000 V electrified double track, and the gauge was 1,435 mm.

(2) Information on viaducts and bridges in around the accident site

[Refer to Figure 5 and Photograph 3]

The structure types of the No.3 Odawara viaduct, where was the accident site, and the Kongoincho bridge, located at 326,331 m to 326,364 m and neighboring in the direction to Shin-Aomori station, were the composite girders for the upper structures and the steel piers for the lower structures. The foundation was caisson type piles with underground beams.

According to the drawing of the whole No.3 Odawara viaduct provided from the Company, the height from the ground surface of the No.3 Odawara viaduct, *i.e.*, girder height, was about 10 to 12 m, as it varied in each girder. According to the drawing, the lengths of the girders located in forward and backward of the pier 2P, where the accident train had derailed, varied for each girder, *i.e.*, 24.60 m and 44.25 m, respectively.

There were movable and fixed types for the support connecting girder and pier and for the anti-bridge-collapse device connecting the neighboring girders each other, respectively, in the No.3 Odawara viaduct and the Kongoincho bridge. The movable type supports were used for the girders in both sides of the pier 2P, and the fixed type were used for the anti-bridge-collapse devices for the pier 2P, in the No.3 Odawara viaduct located in around the derailed site.

(3) Information on periodic inspection of the railway facilities and the tracks

Table 3 showed the dates of the latest inspections implemented obeying the "Implementing Standards on the Shinkansen Track Facilities" and the "Implementing Standards on the Shinkansen Railway Facilities" of the Company. According to the records of these inspections, there was no abnormal situation in the railway structures such as the viaduct, etc., and the track.

Table. 3 Dates of implementation of the latest inspections for the railway facilities

Category of the inspections	Inspection period	Date of implementation
Inspection of railway facilities	2 years	February 7, 2011
Inspection of slab	1 year	May 26, 2010
Inspection of rail, etc.	1 year	October 6, 2010
Inspection of long rail	1 year	February 24, 2011
Inspection of train vibration	1 year	March 10, 2011
Inspection of track irregularities, etc., in the main line	2 months	March 10, 2011, onboard.
Track general patrol	2 weeks	March 9, 2011, on foot. March 10, 2011, onboard.

2.3.3. Status of the Topography, Geology, etc. *[Refer to Figures 5 and 8]*

The accident site was in the Sendai Plain[*3] formed in geological age of Pleistocene to Holocene. The geological features in around the accident site were composed from lower layer, Kameoka layer piled up in Pliocene of Neogene period, Tatsunokuchi layer, and Sendai Kamimachi terrace sediment and similar layer piled up in latter period of Pleistocene. Here, Kameoka layer was composed of sandstone, tuff and siltstone, etc., and Sendai Kamimachi terrace sediment and similar layer were composed of rubble layer, sand layer and clay layer[*4].

According to the geological maps in the history of constructing Tohoku Shinkansen edited by the Company[*5], the geology around the accident site was composed of topsoil from surface of the ground to about 1 m depth, the gravel and gravel with sand considered as equivalent to Sendai Kamimachi terrace sediment and similar layer, in the above paragraph, in the depth between about 1 m and about 6.5 m, and tuff, mudstone, and sandstone considered as equivalent to Kameoka layer in the depth of about 6.5 m and deeper. As the properties in the soil engineering, the solid ground with N-value[*6] of over 50 were distributed continuously in the depth of 2m and deeper.

*3 *K. Koike, et al., "Topography of Japan, 3, Tohoku", The university of Tokyo Press, 2005, in Japanese.*

*4 *Geological Survey of Japan, "Geographical Map, Sendai, 1:50,000" 2002.*

*5 *Sendai Shinkansen Construction Bureau, Japan National Railway, "Tohoku Shinkansen Geographical Map, Between Kuwaori and Arikabe", 1981.*

*6 *"N-value" is the number of hitting the sampler, in the standard penetration test, required to penetrate it into the ground by the predetermined depth, i.e., 30 cm, by free falling hammer of the predetermined weight, i.e., 63.5 kg, from the height of 76 cm. The N-value was the relative number to estimate rigidity or firmness of soil. In the seismic design of railway facilities, it can be established as the ground surface for seismic design when N-value of the continuous stratum was 50 or above for the sand soil, and 30 or above for the clay soil.*

2.3.4. Information on the Vehicles

(1) Outline of the vehicles

Classification of the vehicle : AC electric railcar, 25,000 V, 50 Hz

No. of vehicles in the train set : 10 vehicles

Type and the major specifications : As shown in Table 4

Table 4 Types and major specifications of the vehicles, as of newly manufactured

<table>
<tr><td>Vehicle position</td><td>1st vehicle</td><td>2nd vehicle</td><td>3rd vehicle</td><td>4th vehicle</td><td>5th vehicle</td></tr>
<tr><td>Type</td><td>E223-1019</td><td>E226-1119</td><td>E225-1019</td><td>E226-1219</td><td>E225-1419</td></tr>
<tr><td>Manufactured date</td><td colspan="5">December 5, 2005</td></tr>
<tr><td>Mass in empty condition [t]</td><td>41.1</td><td>45.3</td><td>44.8</td><td>46.1</td><td>45.3</td></tr>
<tr><td>Passenger capacity [persons]</td><td>54</td><td>100</td><td>85</td><td>100</td><td>75</td></tr>
<tr><td>Length of vehicle [m]</td><td>25.700</td><td colspan="4">25.000</td></tr>
<tr><td>Height of vehicle [m]</td><td>3.764</td><td colspan="2">3.960</td><td>4.490</td><td>3.915</td></tr>
<tr><td>Width of vehicle [m]</td><td colspan="5">3.380</td></tr>
<tr><td>Wheelbase [mm]</td><td colspan="5">2,500</td></tr>
<tr><td>Wheel diameter [mm]</td><td colspan="5">860</td></tr>
</table>

<table>
<tr><td>Vehicle position</td><td>6th vehicle</td><td>7th vehicle</td><td>8th vehicle</td><td>9th vehicle</td><td>10th vehicle</td></tr>
<tr><td>Type</td><td>E226-1319</td><td>E225-1119</td><td>E226-1419</td><td>E215-1019</td><td>E224-1119</td></tr>
<tr><td>Manufactured date</td><td colspan="5">December 5, 2005</td></tr>
<tr><td>Mass in empty condition [t]</td><td>46.1</td><td>45.4</td><td>45.4</td><td>45.4</td><td>39.6</td></tr>
<tr><td>Passenger capacity [persons]</td><td>100</td><td>85</td><td>100</td><td>51</td><td>64</td></tr>
<tr><td>Length of vehicle [m]</td><td colspan="4">25.000</td><td>25.700</td></tr>
<tr><td>Height of vehicle [m]</td><td>4.490</td><td colspan="2">3.960</td><td>3.700</td><td>3.764</td></tr>
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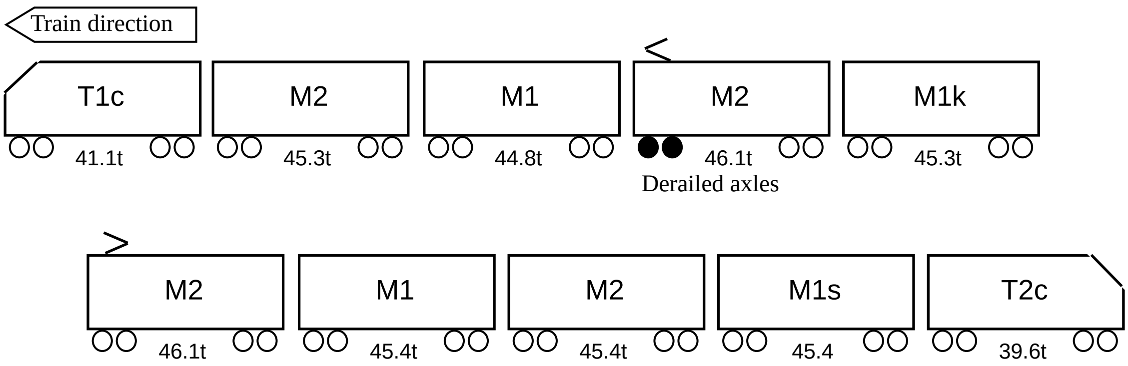
</table>



(2) Inspection of the vehicles

The dates, etc., of the latest inspections for the derailed vehicles implemented obeying the "Implementing Standards on Maintenance of Shinkansen Vehicles" of the Company, were shown in Table 5. There was no abnormal situation in the running device in the records of these inspections. Here, main parts consisting each bogie such as traction motors, power transmission devices, running gears, brake equipments, etc., were inspected in the bogie inspection.

Table 5 Dates of implementation of the latest inspection of the accident train

Category of inspection	Inspection period*7	Implemented date
General inspection	36 months or 1,200,000 km running distance	February 3, 2010
Bogie inspection	18 months or 600,000 km running distance	March 11, 2011
Regular inspection	30 days or 30,000 km running distance	March 1, 2011
Characteristic inspection of ATC device	90 days	December 25, 2010
Inspection of train radio device	6 months	January 12, 2011

*7 *Inspection period means the period not exceed the designated period or running distance.*

(3) Measures against earthquake for the vehicles *[Refer to Figure 6]*

The company attached the deviation preventing guide*8 to all the Shinkansen vehicles of the Company for the purpose of reducing damages when Shinkansen vehicles derailed.

The deviation preventing guide of the accident train was attached to the bottom surface of the axle box, so that the portion of the deviation preventing guide being contacted with the side surface of rail, *hereinafter referred as the "guided portion"*, was in about 242 mm distant from the outer surface of wheel rim.

*8 *The name "deviation preventing guide" was used in this report, however it is also called as "L-shaped vehicle guide" or "L-shaped guide to prevent derailment", etc.*

2.4. Information on the Operating Status of the Trains

The accident train, the test train started from Sendai General Train Depot of Tohoku Shinkansen and bound for Shiroishizao station, departed from Sendai General Train Depot of Tohoku Shinkansen on schedule at 14:40. Here, the inbound trains had been running without abnormal situation in around the accident site, between 14:20 to 14:24, before the occurrence of the accident.

2.5. Information on the Damages, Traces, etc., in the Railway Facilities and the Vehicles

2.5.1. Status of the Major Damages in the Railway Facilities

(1) Track *[Refer to Figure 4(1), (2)]*

(a) Damages, etc., found in rails

There were linear flaws considered as caused by wheels, from right to left on the top surface of right rail between 326,286.10 m to 326,285.70 m, and left rail between 326,285.89 m to 326,285.66 m, in around the rail fastener No.1. Here, the rail fasteners were numbered toward the train direction from the rail fastener No.1 where the first flaw was found on the top surface of rail. These traces started from top surface of rail and continued to left edges of top surface of rail.

There were linear flaws considered as caused by wheels, from right to left on the top surface of rail between 326,283.55 m to 326,283.10 m of right rail, and between 326,283.32 m to 326,283.07 m of left rail, in around the rail fastener No.5. The flaws in right rail started from top surface of rail, but the flaws in left rail continued from inside to outside of top surface of rail.

There were about 0.2 m long fretting traces on the outer side surface of right rail around the rail fastener No.4, located in around 326,283.9 m.

Furthermore, there were flaws considered as caused by the derailment of the accident train, as described in the following.

There was fretting trace being adhered with gray paint, on the top surface of left rail between the rail fastener No.4 and No.5, from 326,283.84 m to 326,283.32 m. There was fretting trace from rail surface to side of top surface of rail in the inner side of left rail in around the rail fastener No.6, and fretting traces caused by the contact between the motor of the 2nd axle and rail, on the inner side of top surface of left rail in around the rail fastener No.6.

There were the other fretting traces in places on top surface of right and left rails.

(b) Damages found on slab surface and rail fasteners

There were hit traces and continuous linear flaws considered as caused by the derailed wheels on the slab surface inside of right rail, from around the rail fastener No.2 in around 326,285.1 m, to the stopped position of the 2nd axle in the front bogie in around 326,282.33 m.

There were the hit traces considered as caused by the derailed wheels between the rail fasteners No 2 and No.3, and between the rail fasteners No.3 and No.4. Among these, the linear flaw started from the hit trace between the rail fasteners No. 3 and No. 4, continued to the position where right wheel of the 2nd axle had stopped. The linear flaws gradually left from rail between around the rail fasteners No.3 to No.4, around 326,283.9 m, to about 260 mm apart from bottom of rail at around the rail fastener No.4, and about 200 to 210 mm apart from bottom of rail beyond around the rail fastener No.4 toward direction to Sendai station.

There was the hit trace considered as caused by the derailed wheels on the outside of left rail between the rail fasteners No.2 and No.3, beyond there in the direction to Sendai station, the damages of the rail fasteners considered as caused by the derailed wheels continued to the stopped position of the left wheel of the 2nd axle.

There were the hit traces considered as caused by the derailed wheels on the slab surface in the inside of right rail and outside of left rail at around the rail fastener No.7, beyond there to the position where right and left wheels of the 1st axle in the front bogie had stopped, the linear flaws on the slab surface and broken rail fasteners, both considered as caused by the derailed wheels, were existed discretely.

(2) Viaducts and Bridges

In the section from No.3 Odawara viaduct, the accident site, to Kongoincho bridge, there was no damage in girders and bridges, and no deformation, etc., in troughs containing electric cables, etc., was found. Furthermore, deformation and remarkable displacement due to angular rotation, etc., was not found in the supports or the anti-bridge-collapse devices.

(3) Electric circuit facilities

No abnormal situation was found in electric circuit facilities such as overhead contact line etc., in the up and down tracks in around the accident site.

2.5.2. Status of the Major Damages in the Vehicles *[Refer to Figure 7]*

Major damages in each vehicle were as follows.

(1) The 3rd vehicle

(a) Three height controlling rods of the automatic level controlling devices, hereinafter named as the "leveling valve", had been bent and broken.

(2) The 4th vehicle, *i.e.*, the derailed vehicle.

(a) There were plural hit traces in all wheels of the front bogie.

(b) There were traces due to coming into contact with rail, in the bottom of driving device of the 1st axle in the front bogie.

(c) There were traces due to coming into contact with rail in the bottom of the motor of the 2nd axle in the front bogie.

(d) There were traces due to coming into contact with rail in the cover of pressure intensifier in left side of the front bogie.

(e) All four height controlling rods of the leveling valve had been bent or broken.

(f) There were traces due to coming into contact with each other, in the bogie frame and the metal fittings of the stopper.

(g) There were fretting traces in Shin-Aomori station side of the deviation preventing guide in right side of the 2nd axle in the front bogie.

(h) There was the deformation in the corner edge of the window in left side of rear part of the body structure.

(i) The worn particles of rubber considered as caused by large displacement, had been mixed to inside the air spring of the front bogie.

(j) Pistons of the semi-active lateral dampers in the front and the rear bogies were damaged.

(k) There were traces considered as the single link had contacted with the cradle against abnormal rise stopper.

(l) The cradle of the lateral motion stopper was deformed.

(m) There were deformations considered as caused by being contacted with rail, in the bottom plate of front part of the front bogie.

(3) The other vehicles

The height controlling rods of the leveling valves, *i.e.*, one rod in the 1st vehicle, four rods in the 5th vehicle, two rods in the 7th vehicle, all rods in the 8th vehicle to the 10th vehicles, had been bent and damaged or broken. Furthermore, there were deformations of cradles against lateral motion stopper in many vehicles. In addition, pantograph in the 6th vehicle had been dropped.

2.6. Information on the Train Crews

The driver of the accident train was 52 years old male. He received the driver's license for Shinkansen electric motor car on November 13, 1996.

2.7. Information on the System to Stop Trains Urgently when Earthquake had Occurred

The Company had been adopted the urgent earthquake detection system for Shinkansen to detect seismic ground motion earlier and stop power feeding system, and the onboard system to detect power failure information immediately and operate an emergency brake, as the system to stop Shinkansen train urgently when earthquake had occurred.

The urgent earthquake detection system for Shinkansen estimate the position of the epicenter and the scale of the earthquake, when one of the seismographs located on 97 measuring points, as of March 2011, along tracks and coastlines, detects the initial tremor, "P wave", arrived prior to the secondary wave, "S wave", of earthquake. When the estimated shaking level is supposed to damage railway structures, or detected the violent shake, *i.e.*, S wave, of above the predetermined level, the system communicates the information to let the substations stop power feeding. The system that the ATC onboard device activates the emergency brake automatically according to the detection of the power failure due to the instruction to stop power feeding, has been equipped onboard, in addition, the system to detect power failure about 1 sec earlier and operate the emergency brake, has been introduced as the onboard device.

2.7.1. Operation Records of the Urgent Earthquake Detection System for Shinkansen

Operating status of the urgent earthquake detection system for Shinkansen were recorded in the information process device of the system.

When the Pacific Coast of Tohoku Earthquake had occurred, the Kinkazan seismograph, one of the coastline seismographs of the Company, detected jolts over 120 Gal, *i.e.*, 120 cm/s^2, at about 14:47:03, and transmitted the exceeding standard value telegram[*9] to Shin-Sendai substation and the other facilities of the Company. Based on this information the circuit breaker for power feeding system operated and stopped power feeding at about 14:47:03, in Shin-Sendai substation. Here, the Kinkazan seismograph detected the P wave and estimated position of the epicenter and scale of the earthquake before transmitted the exceeding standard value telegram for display based on the detection of the S wave, but the estimated value was lower than the level to stop power feeding system.

There was no abnormal situation in the Kinkazan seismograph of the Company in the latest inspection. Also, there was no abnormal status in the urgent earthquake detection system for Shinkansen in the latest inspection.

*9 *"Exceeding standard value telegram" in this context means the electronic information in accordance with the certain rule in the system.*

2.7.2. Status of Stopping Operation of the Running Trains except for the Accident Train

When the Pacific Coast of Tohoku Earthquake had occurred, 33 trains were operating in up and down tracks between Tokyo station and Shin-Aomori station of Tohoku Shinkansen, and 10 trains among them had been stopped at stations. As for the section between Utsunomiya station and Morioka station, where the ground motions of huge acceleration were observed, the accident train and the other 16 trains were operating. Among them, 10 trains listed in Table 6 were running between stations.

All these trains were decelerated by emergency brake automatically and stopped without derailment.

Here, when the Pacific Coast of Tohoku Earthquake had occurred, the feeding system of all the Shinkansen sections of the Company was stopped by the urgent earthquake detection system.

Table 6. Information on the running trains except for the accident train
(Between Utsunomiya station and Morioka station)

Train No., Train name	Section	Direction	Estimated velocity#1	Stopped posistion#2
3029B, Hayate & Komachi 29	Utsunomiya - Nasushiobara	Outbound	No record#3	No record#3
259B, Nasuno 259	Nasushiobara - Shin-Shirakawa	Outbound	No record#3	No record#3
142B, Max Yamabiko & Tsubasa 142	Nasushiobara - Shin-Shirakawa	Inbound	238 km/h	Around 163,342m
63B, Yamabiko 63	Shin-Shirakawa - Koriyama	Outbound	272 km/h	Around 181,414m
3026B, Hayate & Komachi 26	Koriyama - Fukushima	Inbound	271 km/h	Around 246,497m
144B, Max Yamabiko 144	Shiroishizao - Sendai	Inbound	95 km/h	Around 321,771m
61B, Yamabiko 61	Sendai - Furukawa	Outbound	271 km/h	Around 340,532m
3027B, Hayate & Komachi 27	Sendai - Furukawa	Outbound	271 km/h	Around 356,980m
3028B, Hayate & Komachi 28	Shin Hanamaki - Morioka	Inbound	267 km/h	Around 474,738m
59B, Yamabiko 59	Shin Hanamaki - Morioka	Outbound	270 km/h	Around 488,568m

#1 : *Estimated velocity when the train detected power failure.*
#2 : *Kilometerage recorded in the onboard recording device.*
#3 : *The required data could not be obtained because the data, recorded when trains had stopped by the earthquake, were overwritten as the electricity had recovered in early stage after trains were stopped.*

2.8. Information on the Weather Condition

It was snow in around the accident site, at the time of the accident.

According to the observation records by Sendai District Meteorological Observatory, located in Miyagino-ku, Sendai City, temperature was 5.0 °C, average wind speed was 6.0 m/s SSW, snowfall amount was less than 0.5 mm, at 14:40, March 11.

2.9. Information on the Pacific Coast of Tohoku Earthquake

2.9.1. Outline of the Earthquake

According to Japan Meteorological Agency, JMA, the Pacific Coast of Tohoku Earthquake had occurred at 14:46:18.1, March 11, 2011. Its hypocenter was in 38°06.2' N, 142°51.6' E, 24 km in depth, and hypo-central region had spread from off Iwate Prefecture to off Ibaraki Prefecture. Its moment magnitude was 9.0, and the maximum seismic intensity 7 was observed in northern Miyagi Prefecture.

The earthquake was the trench type earthquake, and so many earthquakes occurred continuously with a few time differences in the vast hypo-central region, analyzed as about 400 km long in north and south direction, and about 200 km width in east and west direction. The K-NET Sendai, National Research Institute for Earth Science and Disaster Resilience, Independent Administrative Corporation, observed about 1,808 Gal as the maximum acceleration synthesized components in three directions.

Here, the epicenter was in about 172 km distant in almost east direction from the accident site.

According to the seismic intensity distribution issued from the JMA, seismic intensity of over 6 were observed in wide region along the trackside of the Tohoku shinkansen, especially, seismic intensity 6 plus to 7 were observed in the track side in around Utsunomiya station, Koriyama station, and between Sendai station and Kurikoma-Kogen station.

According to the existing references[*10, *11] etc., the features of the seismic ground motion in the Pacific Coast of Tohoku Earthquake, in comparison with the earthquakes that brought considerable damages in railway structures etc., such as the 2004 Chuetsu in Niigata Prefecture earthquake, occurred on October 23, 2004, *hereinafter referred to as the "Niigata Prefecture Chuetsu Earthquake"*, etc., were as follows.

(a) Extremely strong jolts were observed in the vast area of Pacific coast from Hokkaido to Kanto district.

(b) The jolts had been continued for a long time because destructions of the vast hypo-central region had occurred one after another.

(c) In the many regions, where the strong jolts were observed in the Pacific Coast of Tohoku Earthquake, the seismic ground motion of relatively higher frequency, about 3 to 5 Hz, were dominant, compared with that the seismic ground motion of relatively lower frequency, 1 to 2 Hz, that would influence to the structures, etc., was dominant in the vicinity of the hypocenter of the 1995 Southern Hyogo Prefecture Earthquake, occurred on January 17, 1995, *hereinafter referred to as the "Southern Hyogo Earthquake"*, and the Niigata Prefecture Chuetsu Earthquake.

*10 *H.Takai, "Measures against earthquake for Shinkansen : Progress and future problems of research and development", JRgazette, Vol.69, No.9, pp.26-30, 2011, in Japanese.*

*11 *T. Murono, "How moved the ground by the Pacific Coast of Tohoku Earthquake", RRR, Vol.69, No.3, pp.2-5, 2012, in Japanese.*

2.9.2. Recorded Data in the Seismographs Located in around the Accident Site *[Refer to Figure 8]*

The maximum acceleration, etc., by the Pacific Coast of Tohoku Earthquake, observed by the seismographs located in around the accident site, at about the same time as the supposed time of derailment of the accident train, were shown in Figure 8.

Here, among these measuring points, the nearest to the accident site and in almost the same ground condition as in the accident site was the seismograph of the Company located in Sendai station of the Company, located in around 325,120 m, about 50 m apart toward the up track, hereinafter named as the "Sendai station seismograph".

According to the records of the seismic ground motion of the main shock observed by the Sendai station seismograph, the maximum accelerations were about 712 Gal in N-S direction, about 566 gal in E-W direction and about 367 Gal in vertical direction.

Here, according to the data[*12] issued by the JMA, the main shock, *i.e.*, S wave, of the Pacific Coast of Tohoku Earthquake arrived at Sendai City 16 sec after the earthquake early warning information was announced at 14:46:48.8. Therefore, it is probable that the main shock of the Pacific Coast of Tohoku Earthquake arrived at around the accident site on about 14:47:05.

*12 *Japan Meteorological Agency, "Monthly report on earthquakes and volcanic eruptions, Protection against disasters", March 2011.*

2.10. Analysis by the Simulation on the Vehicle Dynamics during Earthquake

As describe in the following paragraph 3.1, it was somewhat likely that the Pacific Coast of Tohoku Earthquake had related to the probable causes of the accident, because there was no abnormal situation in the railway facilities and the vehicles, etc., before the occurrence of the earthquake, and the earthquake had occurred just before the occurrence of the accident. Then, the simulation analysis on the vehicle dynamics during earthquake, to analyze the provable causes of the derailment of the accident train based on the observed results about the aftershocks, *hereinafter referred to as the "vehicle dynamics simulation"*, were implemented.

2.10.1. Observation of the Aftershocks *[Refer to Figure 9]*

The observation of the aftershocks was implemented from March 31 to April 2, 2011, in around 326,282 m on the No.3 Odawara viaduct, the accident site, and on the ground surface near the pier 2P of the viaduct.

Among the observed records of aftershocks, the observed data of the aftershock occurred on 7:17, April 1, that the Sendai station seismograph also recorded the observed data, were used for the recreation of waveforms of seismic ground motion by the main shock in the accident site in the vehicle dynamics simulation described in the following paragraph 2.10.2. The aftershock occurred on 7:16:57.0, April 1 in off the Miyagi Prefecture. The epicenter was in about 74 km east from the accident site, the depth of hypocenter was 54 km, the magnitude signifying scale of the earthquake was M 4.3, and the seismic intensity 2 was observed in the Sendai District Meteorological Observatory.

The maximum accelerations in the orthogonal direction to tracks, *i.e.*, direction of sleepers, and the most dominant frequency components of the seismic ground motion observed for the aftershock were, 16.4 Gal and around 9 Hz in the ground surface around the accident site, -7.0 Gal and around 1.8 Hz at the top of No.3 Odawara viaduct. Here, the acceleration to left direction was indicated as plus, refer to Figure 14. The damping factor[*13] of No.3 Odawara viaduct, 2P, estimated from the observed data in the both measuring points, was 1.5 %. The displacement in the orthogonal direction to rail at the top of the viaduct was about 0.4 mm in maximum. The Fourier spectrums of acceleration waveforms calculated based on the observed data for the bedrock for seismic design[*14] and for the top of the viaduct were shown in Figure 9, showing that the Fourier amplitude of frequency components around 1.8 Hz was remarkably large at the top of the viaduct compared with the frequency components in the bedrock for seismic design, and the amplification factor was about 50 based on the measurements and the analyses.

Furthermore, the results of Fourier analysis for acceleration waveforms of the other aftershocks obtained in the period of observation of aftershocks, showed that the dominant frequency were in around 1.7 to 1.8 Hz, in both directions of rail and orthogonal to rail at the top of the viaduct in around the accident site, for all observed aftershocks.

*13 *"Damping factor" is an index expressed damping effect by consuming vibration energy as heat, etc., in the inside of the structure or scattering vibration energy out of the structure system. Refer to RTRI, "Design standards and comments of railway structures etc., Seismic design", Maruzen, 1999, in Japanese.*

*14 *"Bedrock for seismic design" is the upper surface of the ground, existing under the surface layer ground, considered as the base against behaviors of surface layer of ground when earthquake occurred. Refer to RTRI, "Design standards and comments of railway structures etc., Seismic design", Maruzen, 1999, in Japanese.*

2.10.2. Vehicle Dynamics Simulation

Here, the vehicle dynamics simulation was implemented using almost the same method used in the investigation of the probable causes of the train derailment accident of Joetsu Shinkansen induced by the Niigata Prefecture Chuetsu Earthquake, as described in the railway accident investigation report RA2007-8-I.

The vehicle dynamics simulation was consisted of 3 stages. In the first stage, waveforms of seismic ground motion by the main shock on the bedrock for seismic design at the accident site, were recreated based on the observed records of seismographs located in around the accident site, "recreation of waveforms of seismic ground motion". Next, the estimated waveforms of seismic ground motion on the top of the viaduct was obtained through the analyses of dynamic behavior of the structures to input the recreated waveforms of seismic ground motion to the structure model, "response analysis of structures". The simulation of the behavior of running vehicles was performed, to input the estimated waveforms of seismic ground motion on the top of the viaduct to the vehicle model, "analysis of vehicle behaviors".

The contents of each stage and the results obtained by the simulation were as follows.

(1) Recreation of waveforms of seismic ground motion *[Refer to Figure 10]*

At first, the seismic wave to be the standard, *hereinafter referred to as the "standard seismic wave"*, was selected to recreate waveforms of seismic ground motion on the bedrock in around the accident site, under the supposition that the same seismic ground motion as that on the bedrock just under the observing point around the accident site, was transmitted to the bedrock just under the accident site.

The standard seismic wave should be selected from the data obtained in the same ground conditions and in the place near to the accident site. Then, the recorded data in the Sendai station seismograph, described in 2.9.2, was selected as the standard seismic wave in the simulation.

Summary of the method to recreate seismic ground motion of the main shock on the ground surface around the accident site in the simulation, was as follows. At first, the seismic ground motion at the bedrock for seismic design, which was assumed as around the upper surface of the Neogene period layer in the simulation, was estimated for the seismic ground motion of the main shock observed by the Sendai station seismograph. Here, as the running direction of the train in around the accident site was almost ENE to WSW, the N-S and E-W components of the seismic ground motion were transformed to the components in the direction of track and orthogonal direction to track, *i.e.*, forward and backward direction and left and right direction of the train.

Next, to remove the difference of ground motions due to different surface grounds at Sendai station of the Company and the accident site, the data of the aftershock observed at 7:17, April 1, at Sendai station of the Company and the data observed at the ground surface around the accident site described in 2.10.1, were converted to the seismic waves at each depth of the bedrock, and calculated the ratio of amplitudes of Fourier spectrum of each waveform, *i.e.*, the amplification factor. Then, the seismic wave on the bedrock for seismic design at the accident site, *hereinafter referred to as the "estimated bedrock seismic wave"*, was estimated to multiply the seismic wave of the main shock on the bedrock for seismic design at Sendai station of the Company by the amplification factor. The maximum acceleration of the estimated bedrock seismic wave was about -579 Gal in the orthogonal direction to rail.

(2) Response Analysis of the structures *[Refer to Figures 11 to 13]*

The area of the analysis was set for the total length of about 114 m from No.3 Odawara viaduct to Kongoincho bridge, and the structures were expressed by the three dimensional frame model based on the drawings of the structures showing how the structures would look when completed, etc., provided from the Company.

The structures of No.3 Odawara viaduct and Kongoincho bridge were modeled as the rigid beams, considering that the rigidity in the orthogonal direction to track was extremely large and deflection in the same direction could be neglected, because the girders of No.3 Odawara viaduct and Kongoincho bridge were the composite girders.

The difference of fixed or movable supports was considered in the behavior of the structure in the direction of the track. Here, the support was treated rigid in the orthogonal direction to track, considering that there was no damaged trace in the orthogonal direction to track and the shift limiter device was equipped.

The anti-bridge-collapse device was modeled as the spring element. Here, rigidity of the spring was set as large as the girders could move with each other, because there was no damage considered as caused by the earthquake.

In the model, girders were divided every 1 m span in the direction of the track, added the components to keep rail level for each node, and also added the nodes at the supports and the anti-bridge-collapse devices, following the standard dividing methods shown in "Design Standards and Comments of Railway Structures etc., Seismic Design", edited by the RTRI, 1999.

The boundary conditions between analytical area and the neighboring sections were set as no constraint. The damping characteristics of the whole structure was set using the Rayleigh damping[*15], based on the damping factor, etc., obtained from the observed data for the aftershocks.

As for the piers, rigidities of the composed parts, etc., were set based on their characteristics of cross section and materials, and nonlinear characteristics were set based on the "Design Standards and Comments of Railway Structures etc., Steel and Composite Structures", edited by RTRI, 2000.

The caisson type piles and underground beams were modeled as the elastic beams, as it was supposed that there was no damage by the earthquake. Their spring characteristics were considered as bi-linear type nonlinear characteristics, based on the "Design Standards and Comments of Railway Structures etc., Foundation", edited by RTRI, 2012.

The area of about 100 times of the area of the foundation was modeled as the free ground, considering the effects of the vibration of the structure models to the peripheral ground model. The response values were estimated by the nonlinear transient analysis, to input the estimated bedrock seismic wave obtained in 2.10.2(1), to the bottom edge of the foundation in the free ground model.

The estimated response values on the top of the viaduct in around the pier 2P near the derailed point were, the maximum horizontal acceleration of about 1,067 Gal, the dominant frequency of 1.5 to 1.7 Hz, and the maximum deflection of 167 mm.

*15 *"Rayleigh damping" is the damping considered the damping related with both the mass and the rigidity in the vibration analysis of structures etc.*

(3) Analysis of the vehicle behaviors *[Refer to Figures 13 and 14]*

The degrees of freedom, DoF, of the vehicle model were set as, 6 DoFs each for the vehicle body, the bogie frame and the wheel axle, and 2 DoFs each for 8 points on rails just under the wheels.

The simulation was performed using one vehicle model in which the connecting elements between vehicle body and bogie frame, and between bogie frame and wheel axle, were set as spring and damper elements. Here, the gap in the lateral displacement stopper was modeled as 30 mm, considering the deformation found in the 4th vehicle. Here, the damping characteristics of the wheel axle damper was set as 0.8 times the designed value.

The vehicle dynamics simulation program "Vehicle Dynamics Simulator"[*16] of the RTRI was used in the analysis.

Velocity was set as 14 km/h, based on the results of analysis on the velocity at the derailment, described in the following 3.2.1. The analysis was performed to set the coefficient of friction between wheel and rail as 0.2, considering weather condition when the accident had occurred.

The response wave at the top of pier 2P of No.3 Odawara viaduct obtained in 2.10.2(2), were used as the input waveform for the lateral vibration of the vehicle, *i.e.*, vibration in orthogonal direction to the track, and the estimated seismic ground motion at the ground surface in the derailed point were used as the input waveform for the vertical vibration of the vehicle. Both input waveforms had applied at beneath of the four axles in the vehicle model, simultaneously.

Here, the simulation was stopped when one of the relative displacements between wheels and rails had reached to ±70 mm, as the vehicle was judged as derailed.

*16 *T. Miyamoto, H. Ishida and M. Matsuo, "The behavior analysis of railway vehicle during earthquake", Transactions of the Japan Society of Mechanical Engineers, Ser.C, Vol.64, No.626, pp.236-243, 1998, in Japanese.*

(4) Results of vehicle dynamics simulation *(Refer to Figures 15 to 18 and Reference Figure 1)*

(a) The derailed vehicle

According to the results of vehicle dynamics simulation shown in Figure 15, the flange of the left wheels of the 1st to the 4th axles stepped on top surface of the left rail at about 61 sec, then the left wheels moved to left and derailed.

As the 2nd axle had derailed at first, differences of lateral displacement between the 2nd axle and the other axles were very small, then flanges of all left wheels of four axles were on the top surface of rail when the 2nd axle had derailed.

The behaviors of the vehicle just before the derailment were as follows.

a. At about 60.5 sec, the vehicle body leaned to left while the bogie leaned to right, then the large lateral force had acted to the right wheel of the 2nd axle. Immediately after that, at about 60.6 sec, the left wheel of the 2nd axle rised up 63 mm above the top surface of rail. At this moment, the track had deflected to left, as shown in Figure 18(a).

b. At just before about 60.8 sec, the vehicle body leaned to right and the large lateral force had acted to the left wheel of the 2nd axle. Just after that, flange of the left wheel of the 2nd axle stepped onto the rail surface. The track had deflected to right at this moment, as shown in Figure 18(b).

The results of frequency analysis of the vehicle behaviors from 40 sec to 60.9 sec, *i.e.*, just before the derailment, showed that the dominant frequency of the lateral displacement was in around 1.7 Hz.

Here, the derailed vehicle was equipped with the semi-active vibration suppression control device, composed of semi-active lateral damper, acceleration sensor and damper control device. The device had the function to record information about acceleration sensors etc., when abnormal status had occurred in the device. According to the recorded data of the acceleration sensor when the accident had occurred, the maximum acceleration exceeding 1 G, the limit of measuring devices, were measured with the period of about 0.6 to 0.7 sec, *i.e.*, about 1.4 to 1.7 Hz.

(b) Front and rear vehicles of the derailed vehicle.

The simulation, same as for the derailed vehicle, was implemented for the 3rd and the 5th vehicles. Based on the results of analysis described in 2.10.2(3), the waveform of displacement at each vehicle position was input to the vehicle model. The results of the simulation showed that the 3rd and the 5th vehicles did not derail before the derailment of the derailed 4th vehicle.

(5) Effects of front and rear vehicles of the derailed vehicle

The couplers and dampers between vehicle bodies were the major component between vehicle bodies in the accident train. Then the rough values for the forces etc., acing on the couplers and dampers between vehicle bodies, were estimated based on the analytical results for each vehicle.

(a) Couplers

The relative roll angle between vehicle bodies calculated from the roll angle of each vehicle was about 2 deg in maximum. The coupler forces acting to vehicles as the axial force were less than 1 kN for the lateral component, *i.e.*, component in orthogonal direction to the track, and less than 0.5 kN for the vertical component.

(b) Dampers between vehicle bodies

The estimated maximum yawing moment acting on the derailed vehicle from adjoining vehicles was about 40 kNm, and the associated acceleration of lateral vibration at just above the bogie was about 0.28 m/s^2. The axle force had acted to the damper between vehicle bodies as well as to the couplers, caused displacements in lateral and vertical directions between vehicles. The axle forces estimated considering the attached length of the damper between vehicles, were about 0.8 kN for both lateral and vertical components.

2.11. Information on the Measures against Earthquakes for Shinkansen in the Company

When the Niigata Prefecture Chuetsu Earthquake occurred on October 23, 2004, the train derailment accident due to the seismic ground motion occurred between Urasa station and Nagaoka station, Joetsu Shinkansen of the Company. Taking the accident as an opportunity, the various measures to prevent derailment and to reduce damages in case of derailment for the Shinkansen train, had been implemented.

In the remarks of the railway accident investigation report on the train derailment of Joetsu

Shinkansen described in the above, *i.e.*, "Investigation Report of Railway Accident RA2007-8-I", measures to prevent recurrence of the accident were described as follows.

When the train encounters the huge earthquake at around its epicenter as in this accident, it is considered that the train derailment accident may occur, and it is difficult to prevent train derailment completely, in the present railway system.

To prevent the train derailment such as this accident, it should be considered to install the equipments or facilities in the vehicles or the railway facilities to prevent train derailment against large seismic ground motion as far as possible, comprehending as the problems for the whole railway system.

In addition, the measures form the view point of both the railway facilities and the vehicles should be promoted to prevent enlargement of damages by the large deviation of vehicles from the track, even if the train derailment could not be prevented.

Here, it is necessary to promote continuously the measures such as the earthquake resistant reinforcement, to prevent enlargement of damage for the train running in bridges, etc., when these structures are remarkably damaged by the earthquake.

The "Meeting on Measures against Derailment of Shinkansen", organized by the Ministry of Land, Infrastructure, Transport and Tourism, MLIT, after the accident, composed of the members engaged in practical business, had investigated measures against earthquake and related technology development, etc., for the Shinkansen. In the "Interim Report on Measures against Derailment of Shinkansen", issued by the Meeting on March 30, 2005, the following items were presented as the measures against derailment etc.

(a) Reinforcement of tolerance against seismic ground motion in the railway structures, *i.e.*, mountain tunnels and viaducts.

(b) Measures to prevent derailment, such as increase of detecting points and renewal to new type devices, related with detection of earthquake and warning device.

(c) Measures to prevent deviation.

(d) Items to be investigated and researched continuously.

- Measures to prevent damages in the rail fasteners and the rail joints.
- Structures and installation method of the guard angles.
- Shortening distance to stop train by the emergency brake.
- Enrichment of the urgent earthquake detection system

In cooperation with the report, the Company improved the system enable to stop power feeding earlier by increasing track side seismographs, etc., and to activate emergency brake by earlier detection of power failure in the onboard device.

Furthermore, the Company have been promoting measures to reduce damages if the train derailment occurs, such as the installation of the deviation preventing guide as the vehicle side measures, and improvement of the glued insulation joints and installation of the rail overturn preventing devices as the track side measures.

In addition, considering damages in the past earthquakes such as Southern Hyogo Earthquake, the Company have been implementing reinforcement of tolerance against seismic ground motion of columns of viaducts and piers as the measures in the railway structures against seismic ground motion. In these measures, reinforcements for the shear failure preceding type columns and piers had been completed by the end of 2008 fiscal year.

3. ANALYSIS

3.1. Analysis on Railway Facilities, Vehicles, etc., before the earthquake

3.1.1. Railway Facilities

It is highly probable that there was no abnormal situation related to the derailment in the railway facilities before the accident, because there was no abnormal description in the latest inspection records about railway facilities such as viaduct and track, etc., before the accident, as described in 2.3.2 (3), and the inbound train was running normally just before the accident as described in 2.4.

3.1.2. Vehicles

It is highly probable that there was no abnormal situation in the vehicles before the accident, according to the statements of the driver and the staff A in charge of rolling stock inspection and repair, described in 2.1.1, and the records of the inspection of the vehicle, described in 2.3.4(2).

3.1.3. Analysis on the Handling of the Train Operation

It is highly probable that there was no mistake in the handling of train operation before the accident, according to the statements of the driver described in 2.1.1(1), and the recorded data, etc., in the ATC recording device described in 2.1.2.

3.2. Analysis on the Derailment

3.2.1. Analysis on the Operation of Emergency Brake, and Time and Velocity at the Derailment

It is highly probable that the train started its deceleration from the velocity of about 72 km/h at about 14:47.02, here, the revised time based on the data recorded in the ATC recording device was about 14:47.04, due to an emergency brake operated automatically according to detection of power failure set by the urgent earthquake detection system for Shinkansen, as described in 2.1.2. Just after that, it is probable that the driver took the emergency stop procedures obeying to the stop signal received from the ATC system. It is probable that the time when velocity of the train became to 0 km/h was 14:47.21 as the revised time based on the data recorded in the ATC recording device. Furthermore, it is probable that the vehicle derailed at about 14:47:18 as the revised time based on the data recorded in the ATC recording device, and the velocity at that time was around 14 km/h, because the trace of the derailment had existed from about 3.5 m before the position where the front bogie of the derailed vehicle had stopped.

Thus, it is probable that the accident train, running at about 72 km/h, had been decelerated to about 14 km/h when derailed, as the result of a series of the systematic procedures to stop trains earlier when earthquake had occurred.

3.2.2. Analysis on the Probable Causes of the Derailment

It is highly probable that the accident train derailed by receiving the seismic ground motion of the main shock of the Pacific Coast of Tohoku Earthquake, considering the following information and analysis.

- It is highly probable that there was no problem in the railway facilities including tracks, vehicles and handling of train operation, as analyzed in 3.1.
- The time of the train derailment, analyzed in 3.2.1, was about 13 sec after the time when the main shock of the earthquake reached at around the accident site as described in 2.9.2.
- The acceleration of over 100 Gal reached to the accident site at about 10 sec after the arrival time of the main shock.
- The accident train stopped just after the huge rolling force had acted to the vehicle body, and the derailment was confirmed after that, according to the statements described in 2.1.1(2).

3.2.3. Analysis on the Seismic Ground Motion at the Accident Site

There was no deformation or damage considered as to disturb train operation in the viaducts around the accident site due to the Pacific Coast of Tohoku Earthquake, as described in 2.5.1(2).

It is highly probable that the natural frequency of No.3 Odawara viaduct, the accident site, was around 1.8 Hz, which was the most dominant frequency of vibration in orthogonal direction to track observed on top of the viaduct in the accident site for the aftershocks of the Pacific Coast of Tohoku Earthquake, as described in 2.10.1. It is probable that the top of the No.3 Odawara viaduct, the accident site, deflected nearly 140 mm in orthogonal direction to track at around the supposed time of the derailment, as the component of seismic ground motion in the frequency range around the supposed natural frequency were amplified by resonance, because the Fourier amplitude of the frequency range around 1.8 Hz was remarkably large compared to the other frequency range on the top of the viaduct.

3.2.4. Analysis on the Process to the Derailment *[Refer to Figure 18 and Reference Figure 2]*

The dominant frequency of lateral motion of the derailed vehicle just before the derailment, obtained from results of the vehicle dynamic simulation, was about the same frequency as the operation record measured by the acceleration sensors attached to the semi-active vibration suppression control system of the accident vehicle, as described in 2.10.2 (4). Then, it is probable that the results of the simulation implemented in the investigation were considered as valid substantially. According to the results of vehicle dynamics simulation, wheels had moved to right and left and hit rails, accompanied with the rolling motion of the vehicle body, as described in 2.10.2 (4). Then, it is somewhat likely that the behavior of the derailed vehicle was in the upper center rolling[*17], that will occur for the vehicle in the situation that the center of rolling motion is in higher position with respect to the gravity center of the vehicle, as one of the "vehicle behaviors responding to the vibrating frequency of sinusoidal lateral vibrations", when the seismic ground motion by the Pacific Coast of Tohoku Earthquake had acted to the derailed vehicle as the external force.

According to the traces considered as caused by wheels found on top surface of rail, described in 2.5.1(1), and the results of vehicle dynamics simulation described in 2.10.2(4), it is somewhat likely that the process to the derailment of the accident train was as follows.

(1) The accident train received the seismic ground motion having the main frequency component of around 1.5 to 1.7 Hz in the orthogonal direction to track at the top of the No.3 Odawara viaduct. *[Refer to 2.10.2(2)]*

(2) The flanges of the right and left wheels of the derailed vehicle hit rails alternately, due to the lateral motion of the axles corresponding to the rolling motion of the vehicle body, *i.e.*, the upper center rolling, as the center of rolling motion of the vehicle body had existed in higher position with respect to the gravity center of the vehicle. *[Refer to 2.10.2(4)]*

(3) At the time of the derailment, in the situation that the wheel flange had been in contact with the shoulder of rail, the lateral force was induced and the wheel load reduced at the same time, then wheel flange of the left wheel of the 2nd axle climbed onto the rail surface at first. *[Refer to 2.10.2(4)]*

(4) When the flange of left wheel of the 2nd axle climbed up to rail, the rail deflected to right due to the seismic ground motion, then, the wheel flange climbed up to top surface of rail as jumping, so that the corner in the outer edge of tread of right wheel of the 2nd axle came into contact with top surface of right rail, and immediately after that, the 1st axle climbed up to top surface of rail as sliding and derailed. *[Refer to 2.5.1(1)]*

According to the results of the vehicle dynamics simulation, it is probable that the vehicle rolled in the upper center rolling mode because there was a big shake having the dominant frequency components of around 1.5 to 1.7 Hz, which are consistent with the frequency to induce the upper center rolling easily[*18, *19] in the orthogonal direction to track, on the viaduct in the accident site, in the Pacific Coast of Tohoku Earthquake. It is probable that such big shake occurred on the top of viaduct because the vibration with frequency of around 1.8 Hz, that is considered as the natural frequency of the viaduct in the accident site, became remarkably large by resonance phenomena, compared with the other frequency components of the seismic ground motion due to the Pacific Coast of Tohoku Earthquake, as described in 3.2.3.

Here, according to the results of the vehicle dynamics simulation described in 2.10.2 (4), all the axles of the derailed vehicle derailed. But, actually, only all 2 axles in the front bogie of the derailed vehicle derailed in the accident. The dominant frequency of 1.5 to 1.7 Hz for the waveform of the seismic ground motion on the rail surface, *i.e.*, top of the viaduct inputted to the model of the derailed vehicle, and the maximum displacement of 137 mm until the derailment, were plotted in the vicinity of the limit line of running safety, as referred to diagrams of the limit line for running safety for Shinkansen train[*20] shown in the existing references[*21]. Therefore, it is highly probable that the occurrence of derailment depends on a little difference in the condition of the vehicles or the railway facilities that could not be considered in the simulation. It could not be determined the reasons why only two axles in the front bogie were derailed, because the little differences in the condition could not be estimated.

*17 *The vehicle motion rotating around the front and rear axis is called as rolling. The upper center rolling is the rolling when the center of rolling motion existed in higher position than the gravity center of the vehicle. On the other hand, the lower center rolling is the rolling when the center of rolling motion existed in lower position than the gravity center of the vehicle. The frequency of rolling motion mainly decides that the rolling motion is the upper center rolling or the lower center rolling or the combined upper and lower center rolling. Refer to Reference Figure 4.*

*18 *N. Matsumoto, "Dynamic behaviors of vehicles and structures in earthquake", Proceedings of railway dynamics presented in the symposium, No.9, pp.77-82, 2005, in Japanese.*

*19 *Y. Suda, M. Miyamoto, "Introduction to Vehicle dynamics No.8, Natural frequency", Rolling Stock & Machinery, Vol.2, No.3, pp.34-57, 1996, in Japanese.*

*20 *Here, figure of the limit for running safety against sinusoidal vibration is considered. Vertical axis shows amplitude, i.e., limit for safety, and horizontal axis shows frequency of vibration. Limits of running safety varies by condition of vehicles and running velocity, etc..*

*21 *For instance, (1) RTRI, "Design standards and comments of railway structures etc., Deviation limit", Maruzen, 2006, (2) K. Nishimura, et al., "Analytical study on running safety of high speed railway vehicle on the vibrating track, study on the model considering yawing of axle", Transactions of the Japan Society of Mechanical Engineers, Ser.C, Vol.75, No.735, pp.90-96, etc., in Japanese*

3.2.5. Analysis on the Effects of Front and Rear Vehicles

The coupler and the damper between vehicles are the principal elements between vehicle bodies in the accident train. Here, the effects of front and rear vehicles to the behavior of the derailed vehicle were analyzed based on the results of simulation described in 2.10.2 (5).

(1) Couplers

It is probable that the effect of the twisted couplers to the derailment of the derailed vehicle was small because the maximum relative roll angle between vehicle bodies were about 2 deg in maximum that was the same level as the relative roll angle in the normal train running, as described in 2.10.2(5)(a). It is probable that the coupler force hardly affected to the vehicle behaviors during earthquake, because the coupler forces were small as less than 1 kN in the lateral components and less than 0.5 kN in the vertical components, as described in 2.10.2(5)(a).

(2) Damper between vehicles

The acceleration of vibration in lateral direction acted to the vehicle body just above the bogie, estimated from the supposed maximum yawing moment being acted from the adjoining vehicles was about 0.28 m/s^2, as described in 2.10.2(5)(b). Then it is probable that the yawing motion of the vehicle body hardly affected the derailment of the derailed vehicle, because it is probable that the acceleration of vibration in lateral direction, as large as about 15 m/s^2, had been acted to the vehicle during the earthquake. In addition, it is probable that the effects of the axial forces induced in the damper between vehicle bodies hardly affected the behavior of the derailed vehicle during the earthquake, because the axial force induced in the damper between vehicle bodies were small as about 0.8 kN for both lateral and vertical components, as described in 2.10.2(5)(b).

Furthermore, the noticeable damage was not found in the couplers and the dampers between vehicle bodies, as described in 2.5.2.

Based on the above discussions, it is probable that the behaviors of front and rear vehicles of the derailed vehicle hardly affected the derailment of the derailed vehicle.

3.3. Analysis on the Damages in the Railway Facilities and the Vehicles

It is certain that the damages on the track described in 2.5.1(1) were caused by the derailment of the derailed vehicle, because there was no damage in the viaducts, bridges and the electric circuit facilities, as described in 2.5.1(2) and (3).

It is highly probable that the linear traces on the damaged rail fasteners and slab surfaces in the area from rail fasteners No.2 to No.6, were caused by the 2nd axle in the front bogie of the derailed vehicle, and the linear traces on the damaged rail fasteners and slab surfaces in the area from rail fasteners No.6 to No.11, were caused by the 1st axle in the front bogie, based on the derailed status and damages on the track described in 2.3.1(3) and 2.5.1(1).

The deviation from the bottom of rail of the linear traces on the slab surface, estimated as caused by the flange of right wheel of the 2nd axle in the front bogie, was about 260 mm in around the rail fastener No.4 as described in 2.5.1(1)(b), and became smaller toward Sendai station to about 200 mm. Then, it is probable that the derailed 2nd axle in front bogie was brought back to right sharply based on shapes of the linear traces. There were the fretting traces on the outside surface of the head of right rail, in around the place where the deviation of the traces from the bottom of rail became smaller quickly. The distance between the linear trace on the slab surface and the side surface of the head of right rail with the fretting traces was about 365 mm, which was the distance roughly corresponded to the position of the guide part of the deviation preventing guide attached to bottom surface of the axle box, considering width of the wheel. Furthermore, the fretting trace was found in the guide part of the deviation preventing guide in right side of the 2nd axle of the front bogie. Then, it is probable that the derailed 2nd axle was brought back to right quickly, as the guide part of the deviation preventing guide in right side of the 2nd axle in the front bogie had been contacted with rail.

It is probable that the fretting traces with adhered gray paint, on top surface of left rail between rail fastener No.4 and No. 5, were considered as caused by the cover of the pressure intensifier in the front bogie, and the fretting traces from inside top surface to side surface of the head of left rail in around fastener No.6, were considered as caused by the driving device of the 1st axle of the front bogie, considering layouts of the underfloor equipments and the stopped position. Furthermore, it is probable that the other discrete fretting traces on top surfaces of right and left rails, were considered as caused by the bottom plates or the cross beams for fitting bottom plates, etc.

It is highly probable that damages and deformations of the height controlling rods of the leveling valve and the cradle of the lateral motion stopper in the bogies in the accident train, except for the derailed front bogie of the derailed vehicle, were considered as caused by large jolts acted to the vehicles by the seismic ground motion of the main shock or the aftershocks of the

Pacific Coast of Tohoku Earthquake, because there was no trace showing derailment of the other bogies in the accident train. It is somewhat likely that the distortion in the corners of the rear left windows of the body structure of the derailed vehicle was also caused by the similar causes. Here, it could not be determined why the pantograph in the 6th vehicle was dropped.

3.4. Analysis on the Other Running Trains, etc.

When the Pacific Coast of Tohoku Earthquake had occurred, the Shinkansen trains, except for the accident train, running in the sections where remarkably large ground motions were observed, stopped safely, although it is probable that these trains also received the seismic ground motion by the Pacific Coast of Tohoku Earthquake while decelerating by the emergency brake operated automatically by the system to stop Shinkansen earlier such as the urgent earthquake detection system for Shinkansen, etc., as described in 2.7.2. There was no casualty in passengers and train crews. Furthermore, there was no damage etc., to disturb train operation, in the railway structures of the sections where these trains were running.

Based on these facts, it is probable that the measures in software such as improvement of performances of the system to stop train earlier as the urgent earthquake detection system for Shinkansen, and measures in hardware such as reinforcement of tolerance against seismic ground motion for the viaducts, implemented by the Company after the Niigata Prefecture Chuetsu Earthquake, showed the definite effectiveness.

3.5. Analysis on the Measures against Earthquake Implemented after the Niigata Prefecture Chuetsu Earthquake

3.5.1. Comparison of the Shinkansen Derailment Accidents in the Niigata Prefecture Chuetsu Earthquake and the Pacific Coast of Tohoku Earthquake *[Refer to Reference Figures 3 and 4]*

Here, the probable causes of the derailments, especially vehicle behaviors due to the seismic ground motion, in the train derailment accidents in the Niigata Prefecture Chuetsu Earthquake and the Pacific Coast of Tohoku Earthquake, were compared and analyzed the different points, etc., based on the railway accident investigation report for the train derailment accident occurred in the section between Urasa station and Nagaoka station of the Company, RA2007-8-I, etc. Outlines of the Niigata Prefecture Chuetsu Earthquake and the Pacific Coast of Tohoku Earthquake were listed in Table 7. Outlines of the derailment sites of the Shinkansen in both earthquakes were listed in Table 8.

Table 7. Outlines of the Niigata Prefecture Chuetsu Earthquake and the Pacific Coast of Tohoku Earthquake

	Niigata Prefecture Chuetsu Earthquake	Pacific Coast of Tohoku Earthquake
Date and time of occurrence	About 17:56, October 23, 2004	About 14:46, March 11, 2011
Depth of hypocenter	About 13 km	About 24 km
Scale of earthquake	M 6.8	Mw 9.0
Maximum seismic intensity	7	7
Classification of earthquake	Inland type earthquake, directly above its epicenter	Trench type earthquake
Major damages in trains	- Train derailed between Urasa station and Nagaoka station of Joetsu Shinkansen.	- Train derailed in the premises of Sendai station of Tohoku Shinkansen - Freight train derailed in Joban Line, Tohoku Line.

Table 8. Outlines of derailment sites of the Shinkansen

	Train derailment accident of Joetsu Shinkansen, 325C Train	Train derailment accident of Tohoku Shinkansen, Test 7932B Train
Type of vehicle, train set	Series 200, 10 vehicle train set	Series E2, 10 vehicle train set
Estimated velocity when earthquake occurred	About 204 km/h	About 72 km/h
Estimated velocity when derailed	About 200 km/h	About 14 km/h
Distance from the epicenter	About 9.6 km	About 172 km
Type of railway structures	Concrete rigid frame viaduct, etc. Height : About 9 m Pile length : About 10 m	Steel composite simple girder viaduct. Height : About 12 m Pile length : About 12 m
Topography	Region from mountainous region to alluvial low land, via river terrace.	Plain
Geological features of surface stratum	Terrace sediment in quaternary period of Pleistocene	Terrace sediment in quaternary period of Pleistocene

According to the existing references[*22, *23, *24], the frequency components of seismic ground motion affected behaviors of vehicles in the main shock of the Niigata Prefecture Chuetsu Earthquake, estimated at top of the viaduct near the derailed site, *i.e.*, Tokamachi R3 viaduct, were around 0.7 Hz and around 1.7 Hz, and the remarkably dominant component was around 0.7 Hz.

Based on the status of the derailment and the results of vehicle dynamics simulation, process to the derailment of the 325C train in the Niigata Prefecture Chuetsu Earthquake was analyzed as follows.

When the north bound train, just as the accident train, received huge seismic ground motion as in the Niigata Prefecture Chuetsu Earthquake having large shaking component in east and west direction, it is somewhat likely that a vehicle derailed by the rocking derailment, i.e., axles jolted violently in vertical and lateral direction, then the wheels in one side were raised up from rail surface while the other side wheels had been in contact with rail, and the wheels being in *contact with rail slipped on the rail surface and the axle moved to lateral direction keeping its posture, then the falling wheel flange of the other side of the axle fell on the rail surface and went out of rail.* (Quoted from the railway accident investigation report RA2007-8-I[*22])

In addition, it was shown that the probable causes of the train derailment accident of Joetsu Shinkansen at the Niigata Prefecture Chuetsu Earthquake, was the results of the dominant vehicle behavior of the lower center rolling, that occurrs when the height of the center of rolling motion of the vehicle is in lower position than the gravity center of the vehicle, because the major frequency component of seismic ground motion acted in orthogonal direction to rail was around 0.7 Hz[*23, *24].

It is somewhat likely that the Test 7932B train, at the Pacific Coast of Tohoku Earthquake, derailed by the upper center rolling that occurred when the height of the center of rolling motion of the vehicle was in upper position than the gravity center of the vehicle, because the major frequency of the seismic ground motion acted in the orthogonal direction to rail, was about 1.5 to 1.7 Hz as described in 3.2.4, in contrast to the derailment of the 325C train at the Niigata Prefecture Chuetsu Earthquake.

It is probable that the two derailment accidents were caused by the different behaviors of the vehicles as the results of differences in the magnitudes and characteristics of the seismic ground motions acted on the vehicles in the orthogonal direction to rail, on the top of the viaduct near the derailed point, between in the Niigata Prefecture Chuetsu Earthquake and in the Pacific Coast of Tohoku Earthquake.

*22 *Aircraft and Railway Accident Investigation Commission, "Railway Accident Investigation Report RA2007-8-I : Train derailment accident between Urasa station and Nagaoka station of Joetsu Shinkansen, East Japan Railway Company", published in 2007.*

*23 *Group of simulation analysis for derailment of Shinkansen by the earthquake, "Simulation analysis of derailment of Shinkansen in the Niigata Prefecture Chuetsu Earthquake", RTRI special report No.52, RTRI, Railway Technology Research Institute, 2008, in Japanese.*

*24 *East Japan Railway Company, "Investigation Report of Joetsu Shinkansen Derailment Accident", 2008, in Japanese.*

3.5.2. Analysis on the Measures against Earthquake in the Company Implemented after the Niigata Prefecture Chuetsu Earthquake

The measures considered as related directly to the reduction of damages by the accident, implemented by the Company after the Niigata Prefecture Chuetsu Earthquake, described in 2.11, were analyzed in the followings.

(1) The system to stop train earlier when earthquake occurred

It is probable that the system, to stop trains earlier when earthquake occurred, functioned well, because the accident train, running at about 72 km/h, had decelerated to about 14 km/h by the system as described in 3.2.1, and all the Shinkansen trains except for the accident train, running in the sections where the remarkable ground motions were observed after the Pacific Coast of Tohoku Earthquake had occurred, including trains operated in the maximum velocity in the commercial operation, considered as received seismic ground motion while decelerating, stopped without derailment as described in 3.4.

Here, some references have reported that there was an ability that the scale[*25] of the main shock of the Pacific Coast of Tohoku Earthquake, estimated based on the start up of the P wave, was smaller than the actual seismic ground wave[*26, *27]. Therefore, as a result, it is highly probable that the urgent earthquake detection system for Shinkansen issued the exceeding standard value telegram, when the ground motion of over 120 Gal, considered as caused by the S wave of the earthquake, was detected, and then the power feeding circuit disconnected in Shin-Sendai substation.

(2) The deviation preventing guide

It is probable that the guide part of the deviation preventing guide, in right side of the 2nd axle in the front bogie of the derailed vehicle, came into contact with rail after derailed, as a result, the axle was brought back to right. Then, it is highly probable that the deviation preventing guide functioned well, although the train velocity was relatively slow in the accident.

*25 *For example, S. Tsukada, et al., "New methods to estimate parameters of earthquake in the urgent earthquake detection", RTRI Report, Vol.16, No.8, pp.1-6, 2002, in Japanese.*

*26 *Meeting to evaluate and improve the earthquake early warning information of JMA, "Materials of the 4th meeting of technical section", Oct.1, 2012, in Japanese.*

*27 *K. Ashitani, "The features of the Pacific Coast of Tohoku Earthquake and urgent detection", 24th Lecture of RTRI titled "Prepare the huge natural disasters, Further improvement of railway safety", pp.13-20, 2012, RTRI, in Japanese.*

3.6. Analysis on the Measures to Prevent Recurrence

It is probable that severe damages, such as human damage etc., were not induced as described in 2.2, although the vehicle was derailed, because there was no damage of the railway structures by the Pacific Coast of Tohoku Earthquake in the viaduct in the accident site, and the measures to reduce damages were considered as effective at a certain level as described in the following paragraph 3.7.

However, it is probable that the accident was caused by the occurrence of displacement to induce derailment of the accident train on the top of viaduct, as the results of amplification of the frequency component of the seismic ground motion, estimated as the natural frequency of the structures, on the viaduct suffered the seismic ground motion by the Pacific Coast of Tohoku Earthquake, as described in 3.2.3 and 3.2.4. Therefore, it is expected to investigate thoroughly the vibration characteristics of the viaduct in the accident site, and study the measures to suppress enlargement of vibration due to resonance of the viaduct, if necessary, then implement measures after verification of these effects, to obtain more high level running safety of trains against seismic ground motion in the accident site.

It is probable that the accident was caused by the combination of conditions of seismic ground motion, vibration characteristics of the structures and the vehicles, etc. Then, it is expected, especially in the structures for high speed railway such as Shinkansen, to promote research on definition of the place where the resonance phenomena would become problems for the running safety of vehicles as in the accident, and to promote research and technology development to implement proper countermeasures.

3.7. Analysis on the Reduction of Damages

It is important to implement measures to reduce damages preparing to the sudden derailment, together with the measures to prevent derailment when the seismic ground motion acts as the external force such as in the accident.

It is probable that slower the train velocity, slighter the damages by derailment, although there was the case that the stopped train had derailed by earthquake[*28].

It is probable that in the Pacific Coast of Tohoku Earthquake, the emergency brake in all the Shinkansen trains in running operation operated automatically by the system to stop trains earlier, and the trains received seismic ground motion while decelerating, as described in 3.5.2. However, the trains stopped without derailment except for the accident train. It is probable that the slow velocity of the accident train showed the effectiveness of a certain level to reduce damages, because the accident train had been decelerated to about 14 km/h when derailed.

Furthermore, it is probable that the deviation preventing guide prevented further deviation of the derailed vehicle by coming into contact with rail in the accident, as described in 3.5.2(2).

Based on the above discussions, it is probable that the measures to reduce damages that were arranged in the "Interim Report about Measures against Derailment of Shinkansen" by the Meeting for Measures against Derailment of Shinkansen, and implemented by the Company, after the Niigata Prefecture Chuetsu Earthquake, were effective, although the types of the earthquakes, distances from hypocenters and behaviors of the vehicles at the derailments, were different, as described in 3.5.1. The Company and related organizations are required to implement the measures to reduce damages such as research and development to shorten the time required to decision and communication in the system to stop trains earlier when earthquake occurrs, successively from now, based on the results of the analyses of the accident.

*28 *For instance, (1) "Train derailment accident in the premises of Kashiwazaki station, Echigo Line, East Japan Railway Company, occurred on July 16, 2007", Railway accident report RA2008-6, Aircraft and Railway Accident Investigation Commission, published in 2008, written in Japanese, (2) "Train derailment accident, in the premises of Nagamachi station, Tohoku Line, Japan Freight Railway Company, occurred on March 11, 2011", Railway accident report RA2012-5, Japan Transport Safety Board, published in 2012, written in Japanese.*

4. CONCLUSIONS

4.1. Findings

The results of analyses for the accident are summarized as follows.

(1) Railway facilities and vehicles before the derailment

It is highly probable that there was no abnormal situation in the railway facilities, the vehicles, and there was no mistake in the train operation, related to the accident.

(2) Derailment

(a) Operation of emergency brake and time and velocity at the derailment

It is highly probable that the accident train started deceleration from about 72 km/h at about 14:47:04 in the revised time from the data in the ATC recording device, as the emergency brake had acted automatically following the detection of power failure implemented by the operation of urgent earthquake detection system. It is probable that the time of the derailment was about 14:47:18, and the train was decelerated to about 14 km/h at that time.

(b) Probable causes of the derailment

It is highly probable that the accident train derailed due to receiving the seismic ground motion of the Pacific Coast of Tohoku Earthquake.

(c) The seismic ground motion in the accident site

It is probable that the displacement in the orthogonal direction to track was nearly 140 mm at around the time of the derailment, as the results of amplification of the frequency component of around 1.8 Hz, that was estimated as the natural frequency of the No.3 Odawara viaduct, the accident site, due to resonance phenomena in the viaduct.

(d) Process to the derailment

It is somewhat likely that the derailed vehicle derailed by the upper center rolling, that was induced as the right and left wheels moved in lateral direction and bumped violently against rails accompanied to the rolling motion of the vehicle body, due to the strong lateral vibration by the Pacific Coast of Tohoku Earthquake when derailed, based on the vehicle dynamics simulation and the traces of the derailment.

It is probable that the vehicle behavior became to the upper center rolling motion, because there was the large vibration having the dominant frequency component of about 1.5 to 1.7 Hz, that would cause the upper center rolling easily, at the top of the viaduct where was the accident site, based on the vehicle dynamics simulation.

Here, it could not be determined the reason why only two axles in the front bogie of the derailed vehicle were derailed.

(e) Effects of the adjoining vehicles

It is probable that the front and rear vehicles of the derailed vehicle hardly affected the derailment of the derailed vehicle, based on the vehicle dynamics simulation.

(3) The other running train etc.

The Shinkansen trains, except for the accident train, running in the section where remarkably large vibration by the Pacific Coast of Tohoku Earthquake were observed, stopped safely with no casualty in passengers and train crews, as it is probable that trains received the seismic ground motion during decelerating operation by the automatically operated emergency brake. In addition, there was no damage to disturb the train operation, in the railway structures in the sections where trains were running.

It is probable that the various measures against earthquake, implemented by the Company after the Niigata Prefecture Chuetsu Earthquake, showed their effectiveness at a certain level.

(4) Comparison of the derailment accidents of Shinkansen in the Niigata Prefecture Chuetsu Earthquake and the Pacific Coast of Tohoku Earthquake

It is probable that the accident vehicle derailed by the upper center rolling motion, in which the center of rolling motion was in higher position than the gravity center of the vehicle, in contrast to the vehicle derailed by the lower center rolling, in which the center of rolling was in lower position than the gravity center of the vehicle, in the Niigata Prefecture Chuetsu Earthquake.

(5) Measures against earthquake implemented after the Niigata Prefecture Chuetsu Earthquake.

Among the measures against earthquake implemented after the Niigata Prefecture Chuetsu Earthquake, the measures, considered as related to prevent enlargement of damages directly in the accident, were analyzed in the followings.

(a) The system to stop trains earlier when earthquake occurs

It is probable that the system showed its effectiveness at a certain level considering that the accident train was decelerated by the system to stop trains earlier, when the earthquake had occurred, and the other Shinkansen trains except for the accident train, running in the sections where remarkably strong ground motion were observed, stopped without derailment by automatically acted emergency brake.

(b) The deviation preventing guide

It is probable that the deviation preventing guide in right side of the 2nd axle in the front bogie of the derailed vehicle had been in contact with rail after derailed, and the axle was brought back to right as the result. It is probable that the deviation preventing guide functioned well in the accident, although the velocity of the accident train was relatively slow.

(6) Prevention of recurrence

It is probable that there was no severe damage such as human damage even though the train was derailed, because there was no damage by the seismic ground motion in the structures of the viaduct in the accident site, and the measures to reduce damages were considered as effective at a certain level.

However, it is probable that the accident occurred by the displacement to induce derailment of the accident train by the resonance phenomena of the viaduct received the seismic ground motion by the Pacific Coast of Tohoku Earthquake. Therefore, it is expected to investigate thoroughly the vibration characteristics of the viaduct in the accident site, and implement, according to the necessity, measures against resonance phenomena of the viaduct after verified the effectiveness, to obtain higher level running safety of trains against seismic ground motion in the accident site.

It is probable that the accident was caused by the combination of conditions of seismic ground motion and vibration characteristics of the structures and the vehicles, etc. Then, it is expected, especially in the structures designed for high speed railway such as Shinkansen, to promote research on determination of the place where the resonance phenomena would become problems for the running safety of vehicles as same as in the accident, and to promote research and technology development to implement proper measures in future.

(7) Reduction of damages

It is important to implement the measures to reduce damages when the derailment occurrs, together with the measures to prevent derailment by large seismic ground motion acted in the accident.

In the Pacific Coast of Tohoku Earthquake, it is probable that the measures to reduce damages being implemented by the Company, that were arranged in the "Interim Report about Measures against Derailment of Shinkansen" by the meeting for measures against derailment of Shinkansen, after the Niigata Prefecture Chuetsu Earthquake, were effective. Therefore, these measures should be implemented successively in future.

4.2. Probable Causes

It is highly probable that the accident train derailed due to receiving the seismic ground motion of the main shock of the Pacific Coast of Tohoku Earthquake, because it is highly probable that there was no problem in the railway facilities including tracks, the accident train and the train operation before the occurrence of the earthquake, furthermore, it is highly probable that the accident train derailed just after the main shock of the Pacific Coast of Tohoku Earthquake had arrived at Sendai City. Here, it could not be determined the reason why only two axles in the front bogie of the 4th vehicle had derailed.

It is probable that the process to the derailment were as follows. At first, the frequency component, which corresponded nearly with the natural frequency of the viaduct in the accident site, in the frequency components of the seismic ground motion by the Pacific Coast of Tohoku Earthquake, had been amplified by the resonance phenomena of the structure and induced the large displacement at the top of the viaduct. As the frequency was in the range to induce the upper rolling motion of the vehicle easily, the vehicle was forced to roll in the upper center rolling mode and resulted to be derailed.

It is probable that the damage was not spread because the train was running in low speed just before the derailment by the operation of the system to stop trains earlier, and the derailed 4th vehicle did not deviate from the track seriously by the function of the deviation preventing guide.

5. SAFETY ACTIONS

5.1. Actions taken by the Company after the Accident

The Company implemented the following measures against earthquake for Shinkansen, after the accident.

(1) Measures to stop trains urgently

To reinforce the system to observe and detect earthquake, additional seismographs were installed in 30 observing points, and introduced in the urgent earthquake detection system for Shinkansen on August 3, 2012. In addition, the earthquake early warning information from Japan Meteorological Agency was introduced in the urgent earthquake detection system for Shinkansen on October 28, 2012.

(2) Measures to reinforce tolerance against earthquake

The Company has been promoting measures to accelerate and expand target areas of reinforcement of viaducts and bridges considered as feared to be damaged by the strong seismic ground motion, in the bending failure preceding type viaduct columns and piers. In addition, the Company determined to implement earthquake resistant reinforcement of the electrification poles, the ceilings of stations and platforms, and it has been promoting it.

(3) Measures to prevent deviation

The measures to prevent break of the glued insulated rail joints, being promoted from the days before the accident, had completed in the whole section of Shinkansen, by the end of 2011 fiscal year. The installation of the device to prevent overturn of rail have been implemented successively in some areas.

(4) Measures against resonance

The Company has been promoting researches from the view points of both vehicle and railway structures on the measures against resonance phenomena that would become problems for the running safety of vehicles.

5.2. Actions taken by the Ministry of Land, Infrastructure, Transport and Tourism after the Accident

The Railway Bureau, MLIT, held the Meeting for Measures against Derailment of Shinkansen, that was established taking an occasion of the occurrence of the derailment accident of Joetsu Shinkansen, after the accident in question. In the Meeting held on May 13, 2011, the previous measures against earthquake for Shinkansen, damages and restoring status in Tohoku Shikansen were checked, and it was decided to study about the damaged columns of viaducts and electrification poles, in the working groups.

5.3. Measures Expected to be Implemented in the Future

It is probable that there was no severe damage such as occurrence of human damage although the vehicle had derailed, because there was no damage in the railway structures by the seismic ground motion in the viaduct of the accident site, and it is probable that the measures to reduce damages were effective at a certain level.

It is expected to investigate the vibration characteristics of the viaduct at the accident site thoroughly, and study measures etc., to suppress enlargement of vibration due to resonance of the viaduct, according to the necessity, then implement measures after verification of these effects, to realize higher level running safety for the trains running in the accident site.

It is probable that the accident was caused by the combination of conditions of seismic ground motion, and the vibration characteristics of the structures and the vehicles. Then, it is expected to promote research to define the place where the resonance phenomena would become problems for the running safety of vehicles as in the accident, and to promote research and technology development to implement proper measures, especially in the railway structures for Shinkansen where trains are running in high speed.

As for the measures to reduce damages, the various measures arranged in the "Interim Report about Measures against Derailment of Shinkansen" by the Meeting for Measures against Derailment of Shinkansen, established by MLIT after the Niigata Prefecture Chuetsu Earthquake, and having been implemented, should be implemented successively in future.

Figure 1. Location of the Accident Site

Tohoku Shinkansen : Between Tokyo station and Shin-Aomori station, 713.7 km, double track.

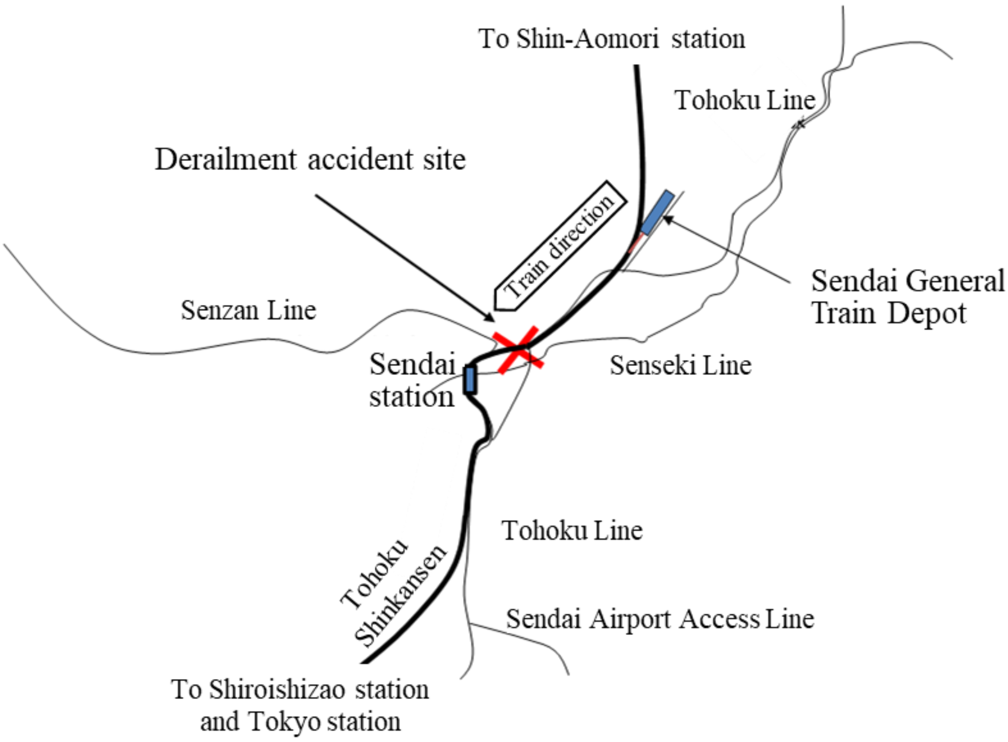


Figure 2. Topographical Map around the Accident Site

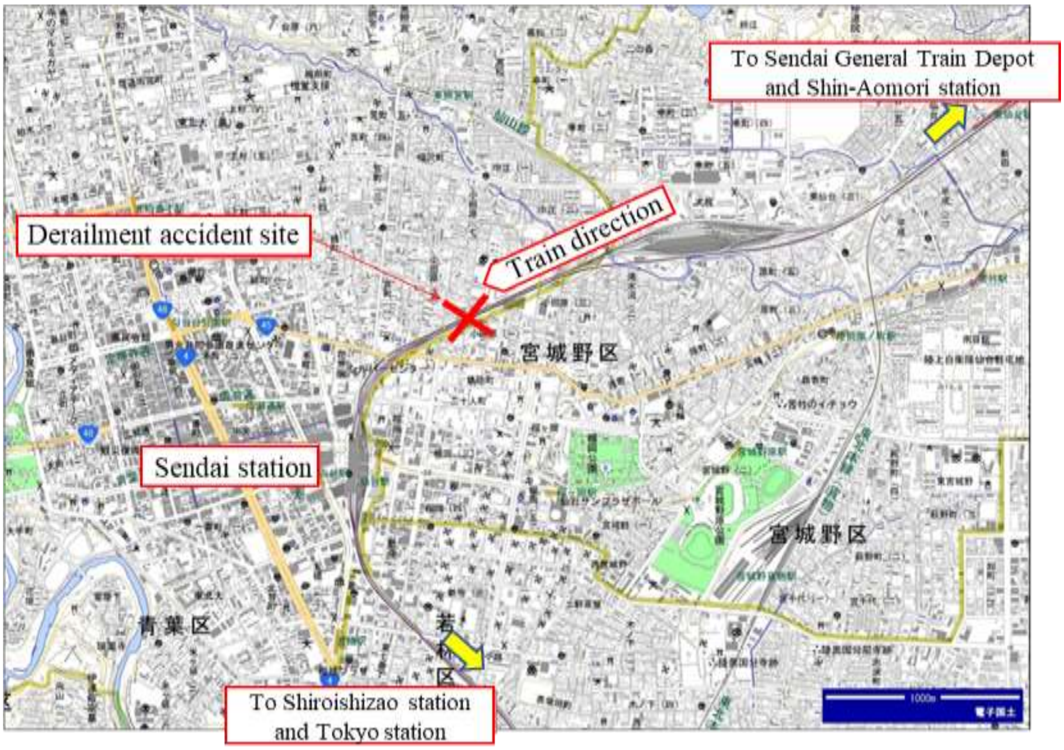


Figure 3. Schematic Diagram of the Accident Site

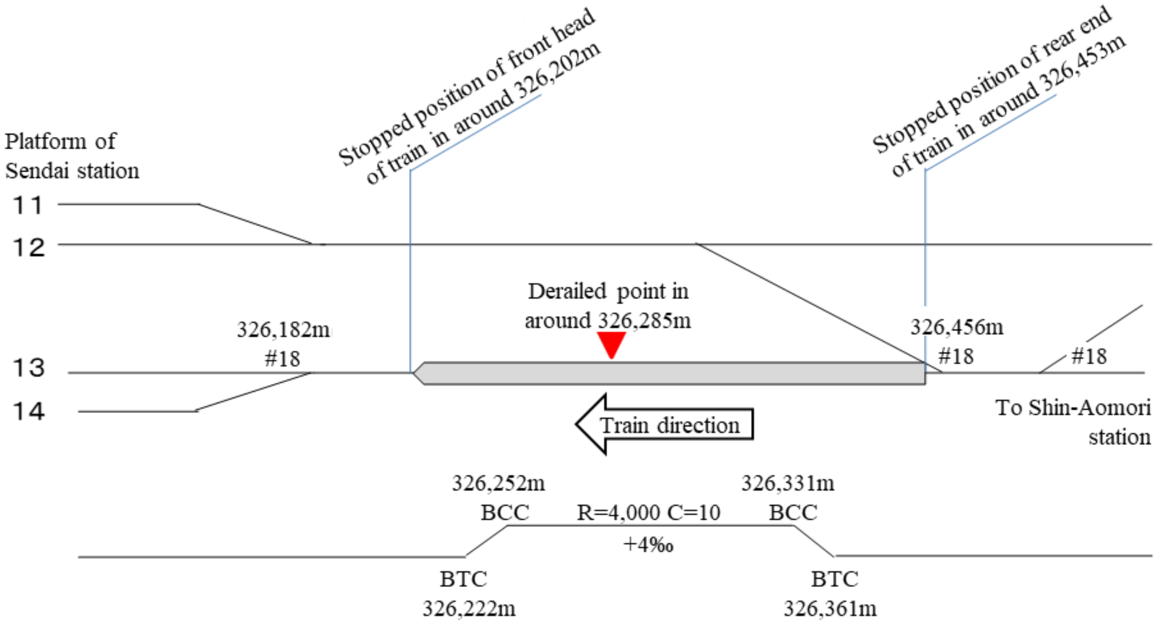


Figure 4. Status of the Major Damages in the Track (1)

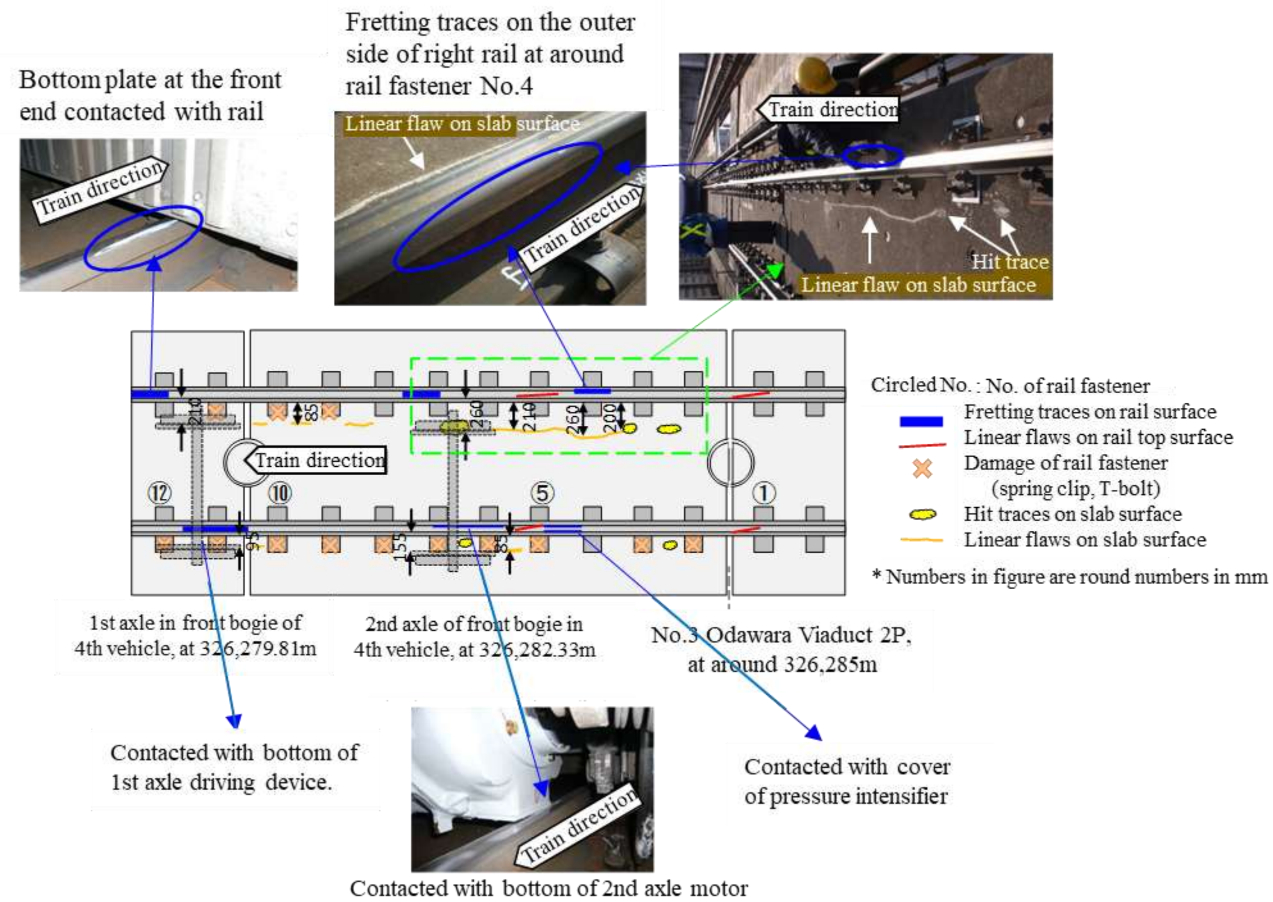


Figure 4. Status of the Major Damages in the Track (2)

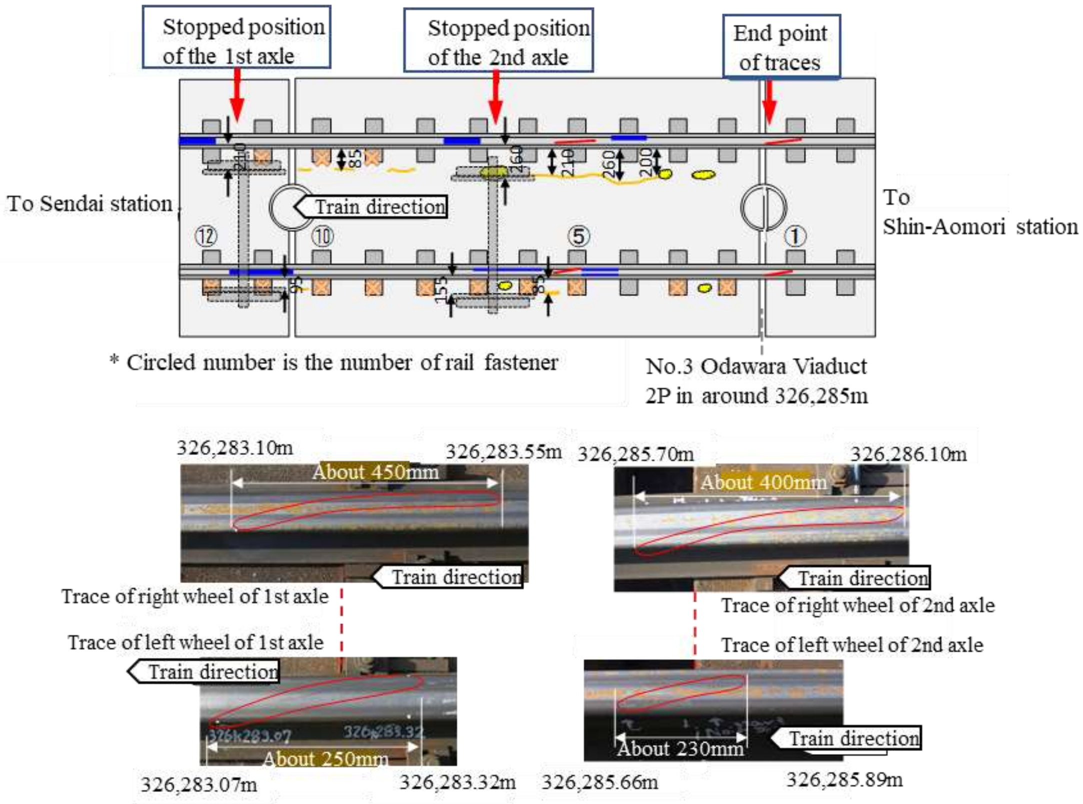


Figure 5. Outline of the Railway Structures

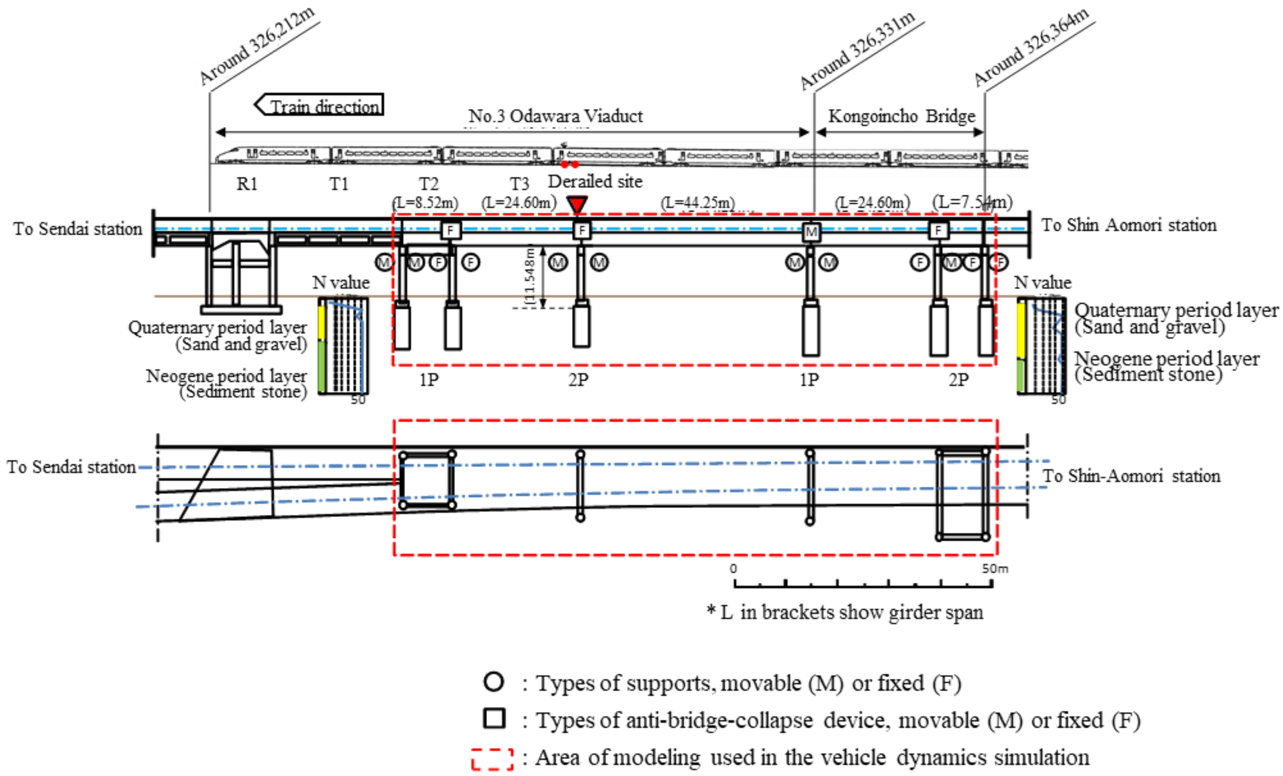


Figure 6. Status of the Deviation Preventing Guide

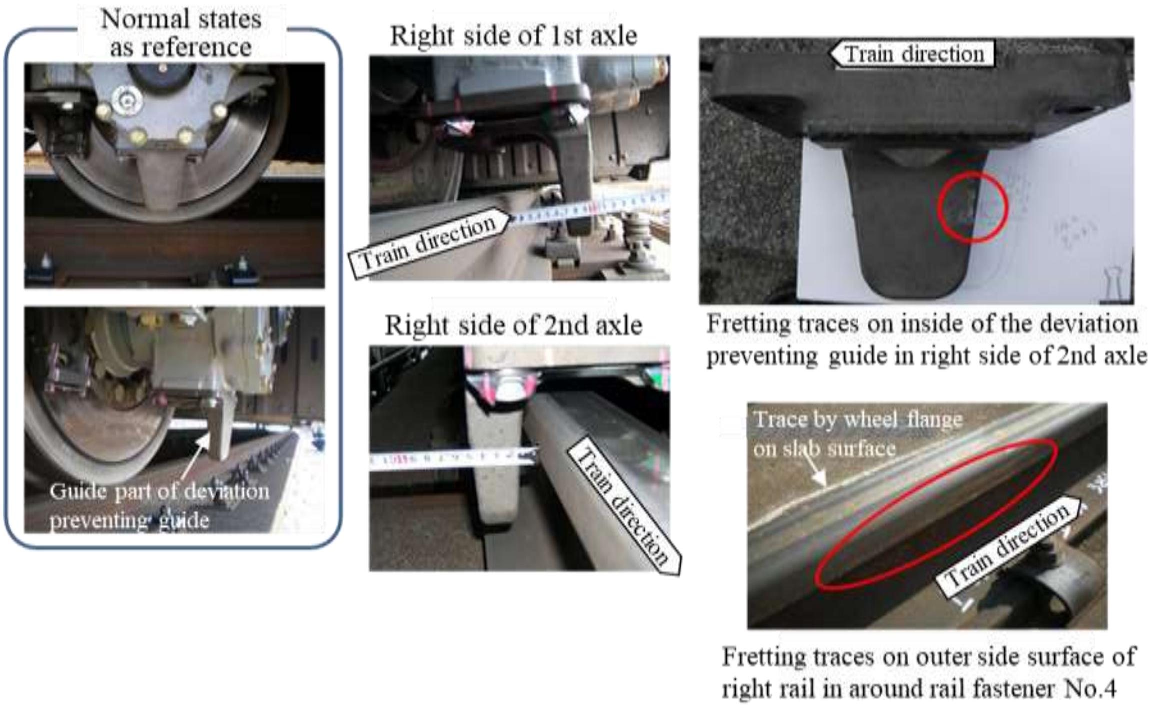


Figure 7. Status of the Major Damages in the Vehicles

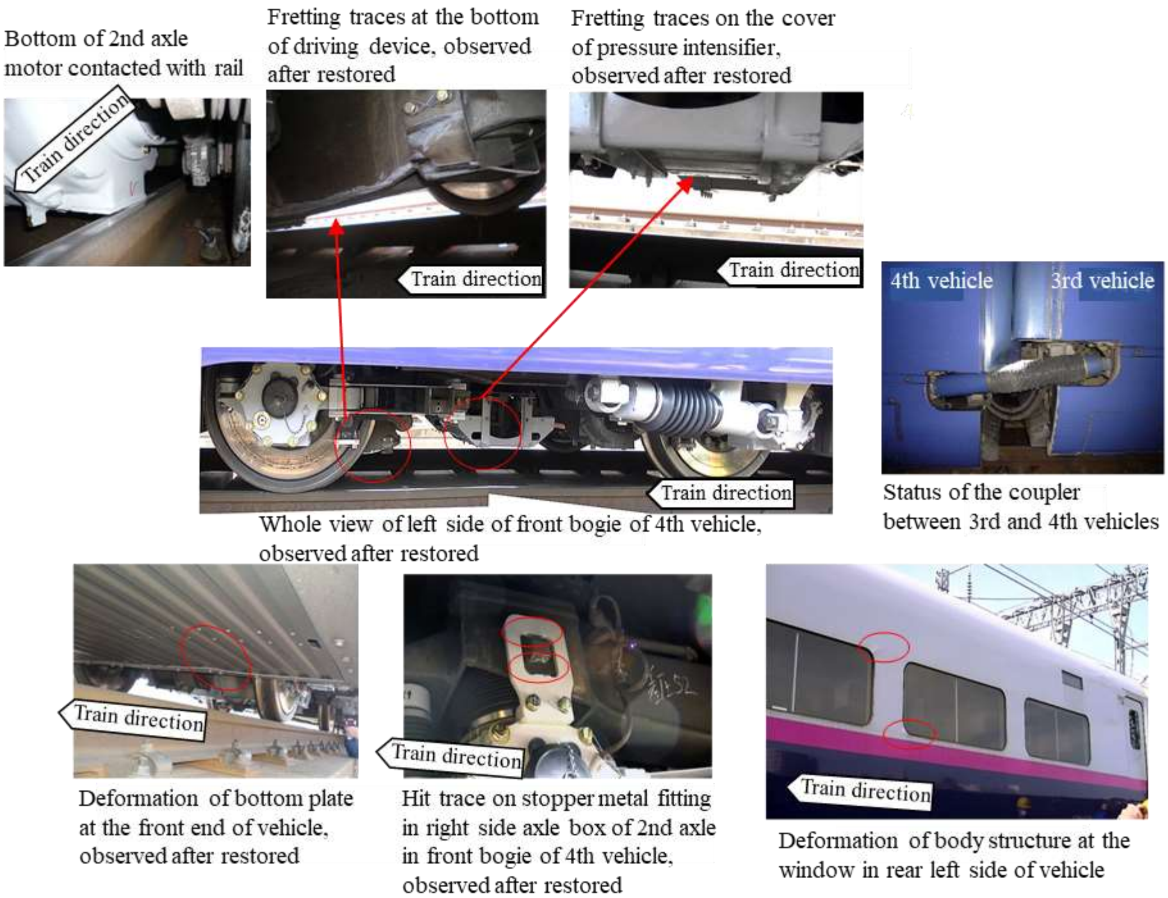


Figure 8. Seismic Ground Motion by the Pacific Coast of Tohoku Earthquake observed by the Seismographs Located in around the Accident Site

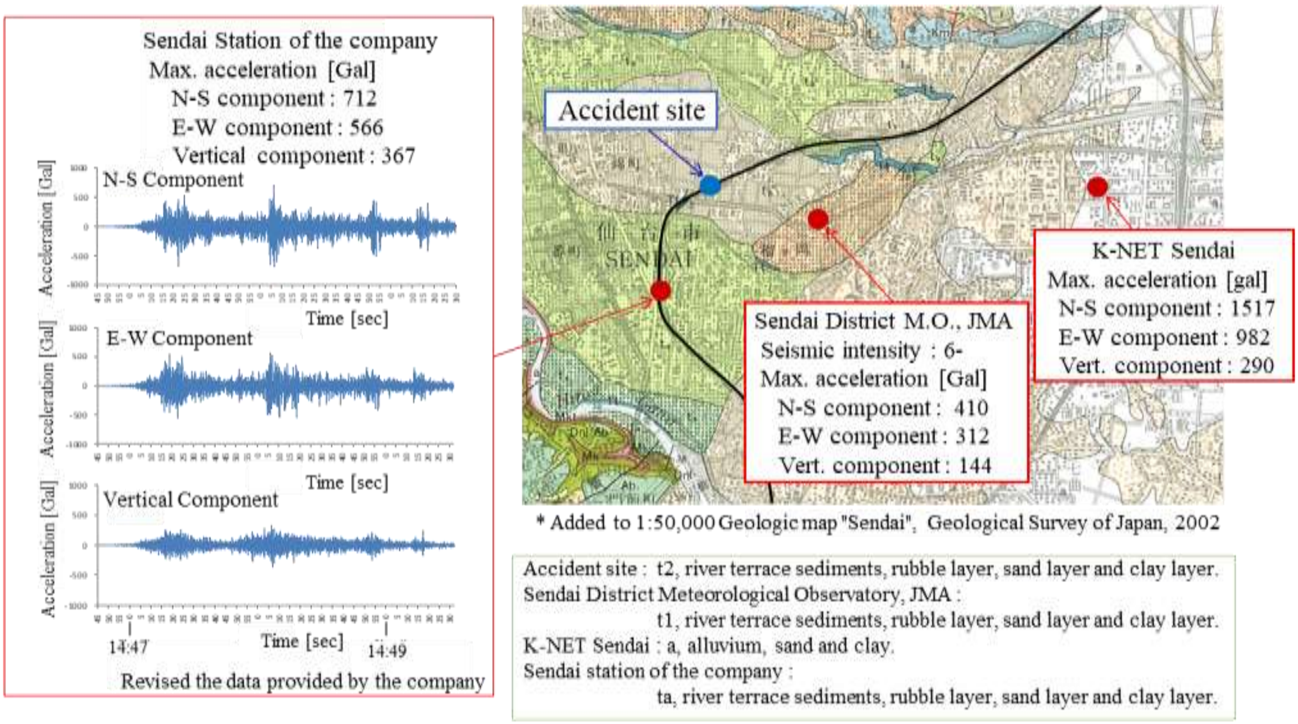
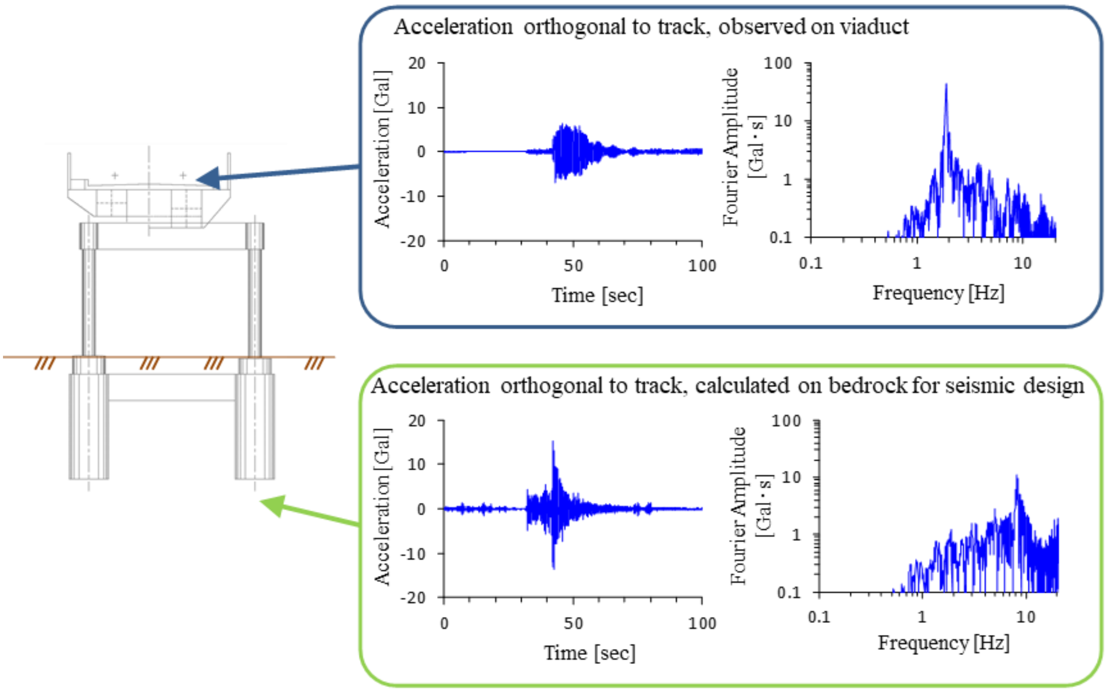


Figure 9. Acceleration Waveforms observed in the Aftershock Observation at the top of the Viaduct, and Acceleration Waveforms calculated on Surface of the Ground for Seismic Design



* Time and magnitude of the after shock of the earthquake :
7:17am, April 1, 2011, Magnitude 4.3

Figure 10. Recreated Seismic Ground Motion by the Main Shock of the Earthquake at the Derailment Site

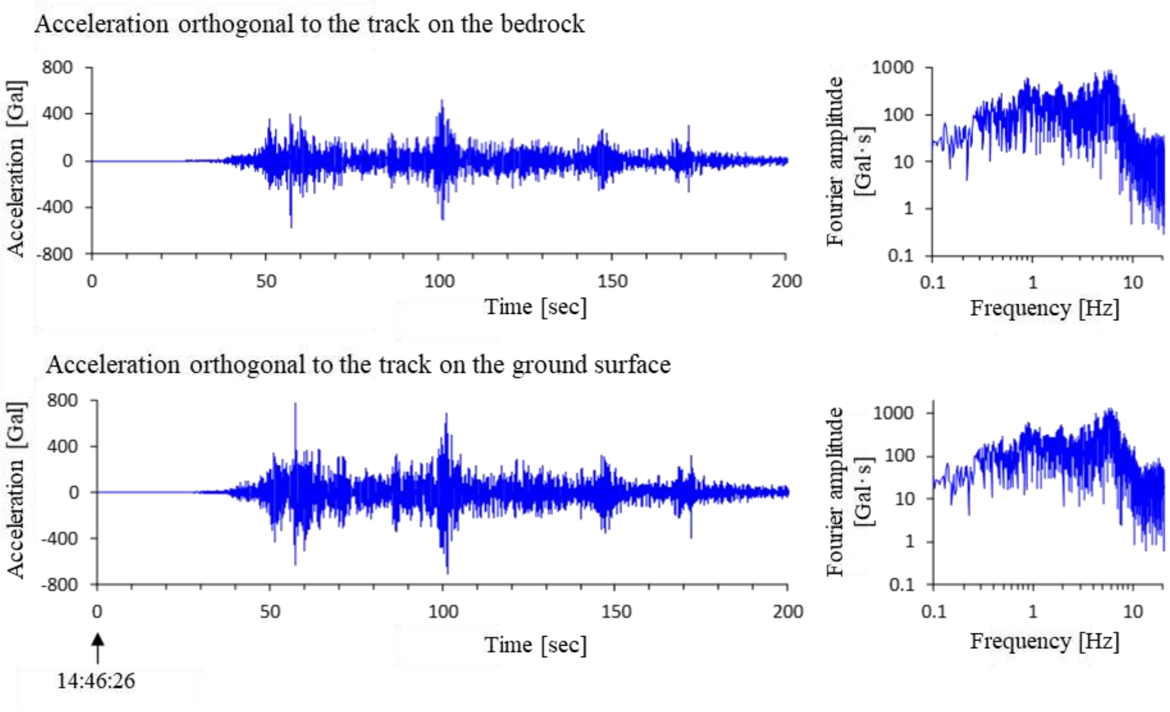


Figure 11. Outline of the Simulation Model for the Structures

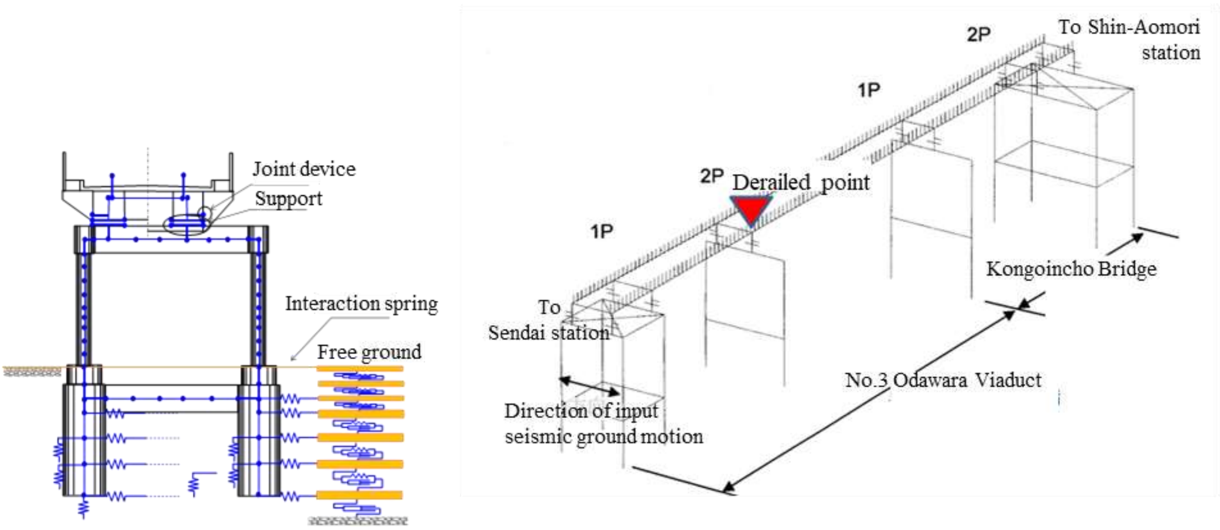


Figure 12. Supposed Seismic Ground Motion at the Derailment Site

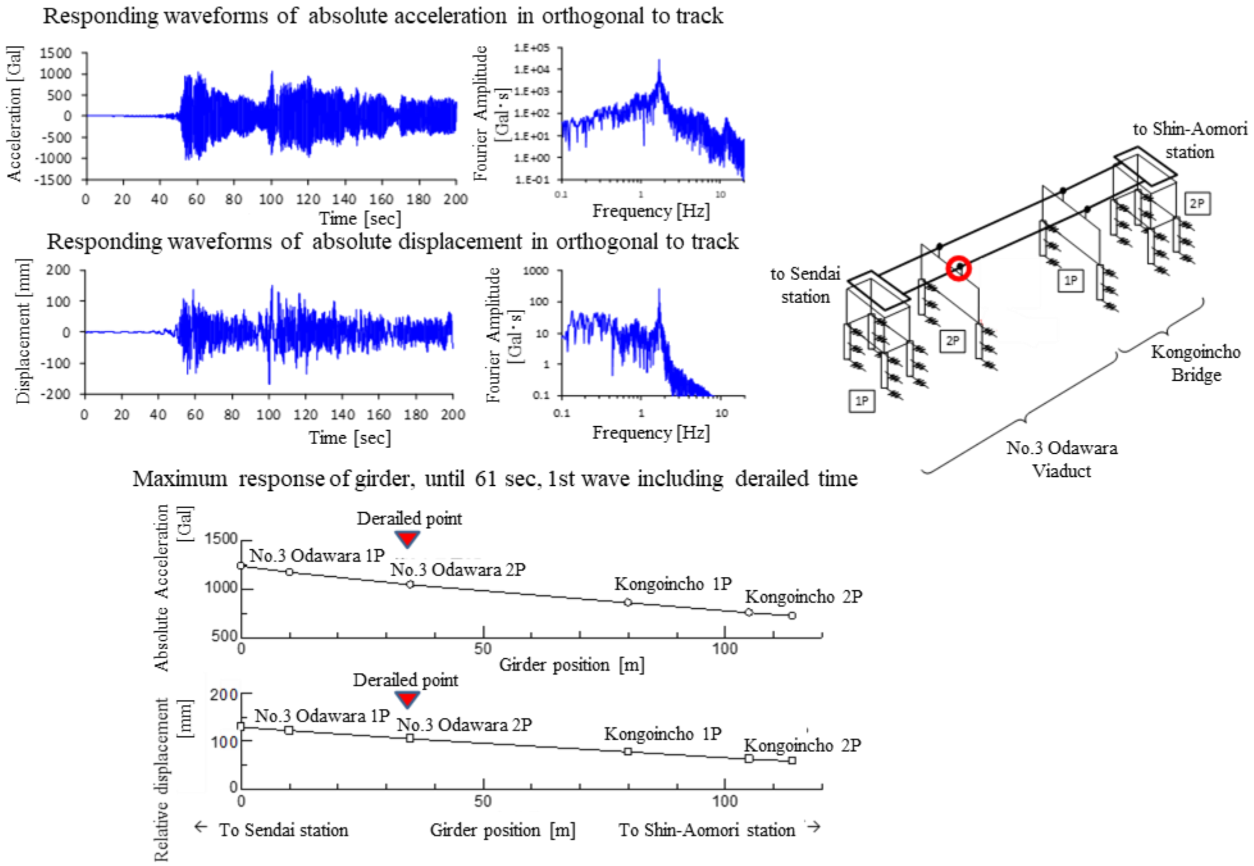


Figure 13. Input Waveform to the Vehicle Model

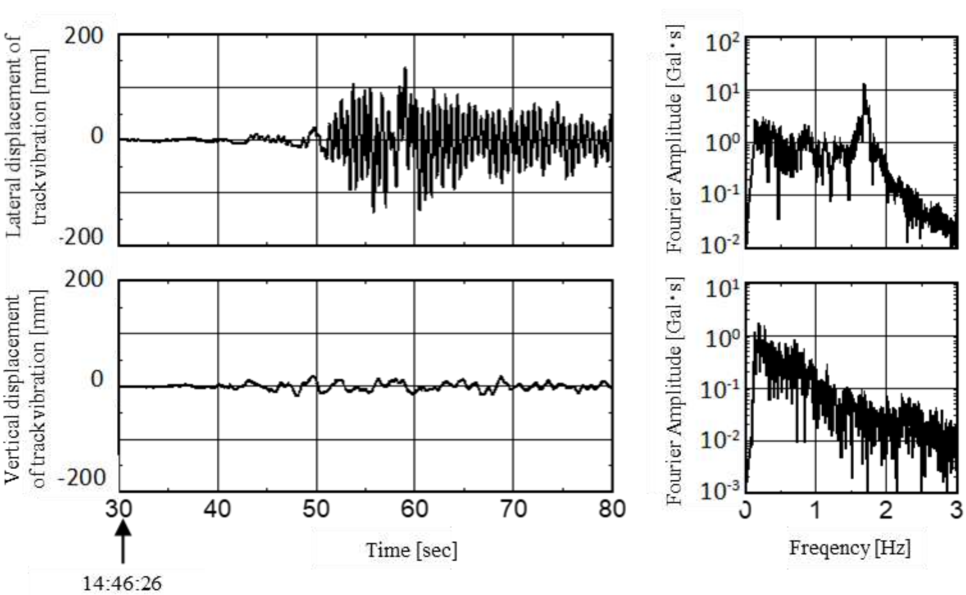


Figure 14. Outline of the Vehicle Model

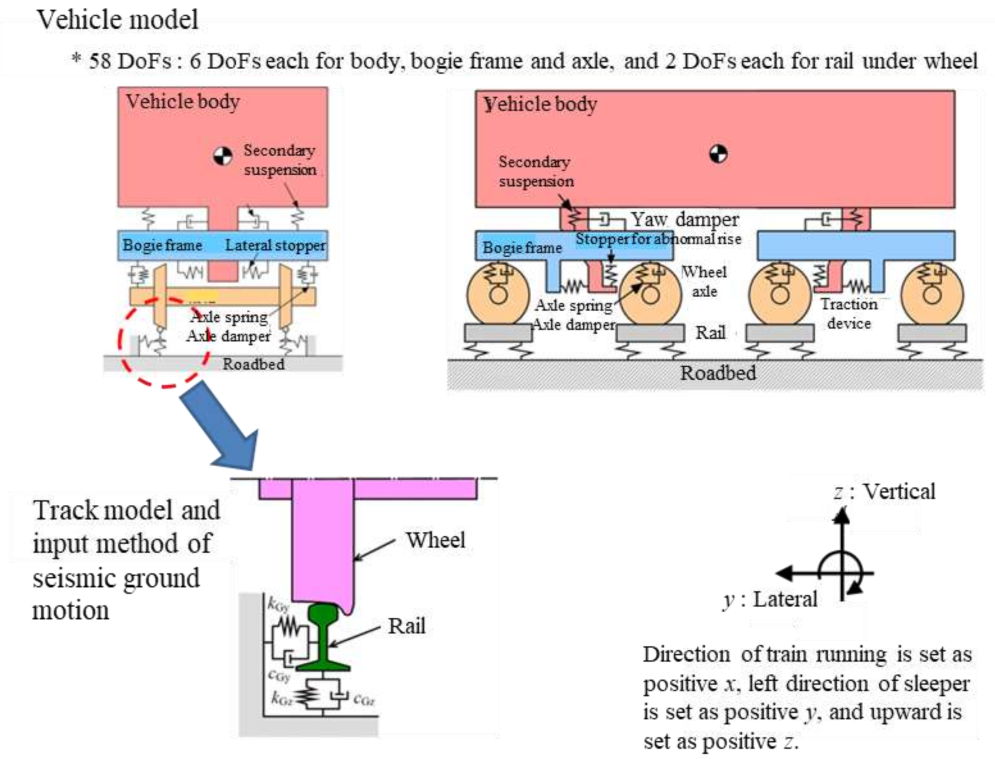


Figure 15. Results of the Simulation I (Behaviors of the 1st Axle)

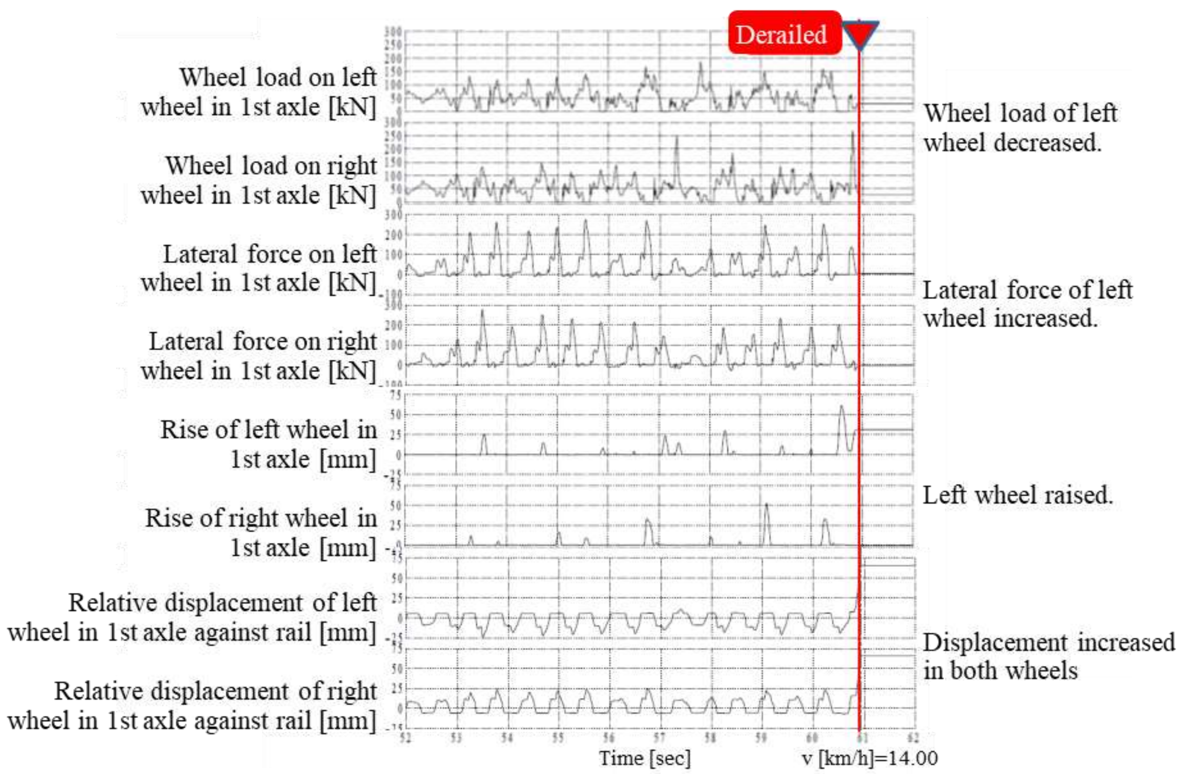


Figure 15. Results of the Simulation II (Behaviors of the 2nd Axle)

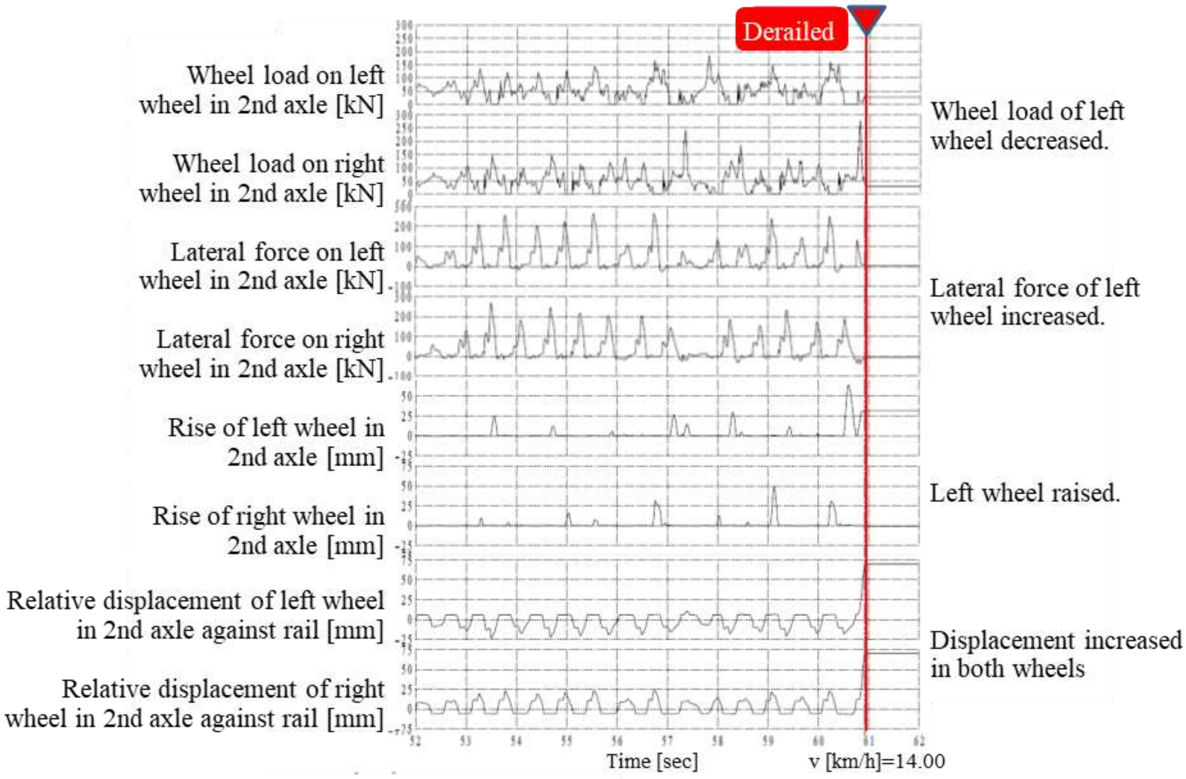


Figure 15. Results of the Simulation III (Behaviors of the 3rd Axle)

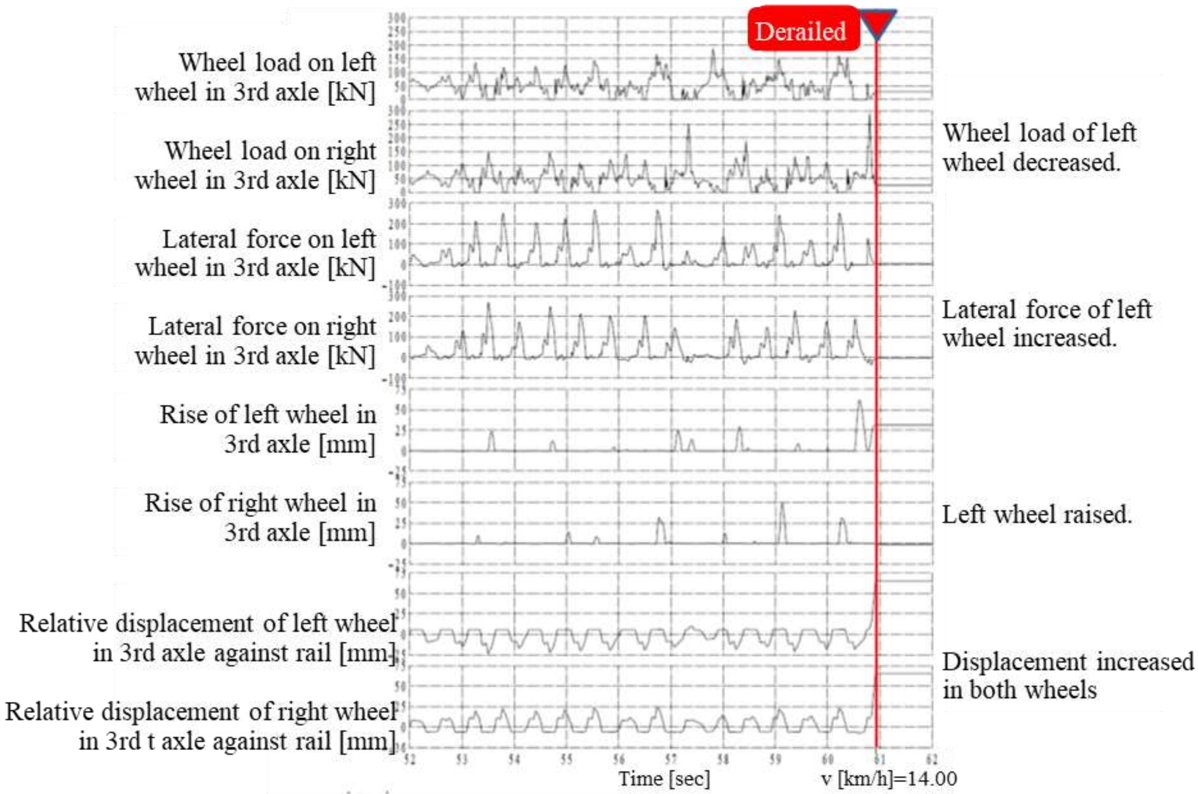


Figure 15. Results of the Simulation IV (Behaviors of the 4th Axle)

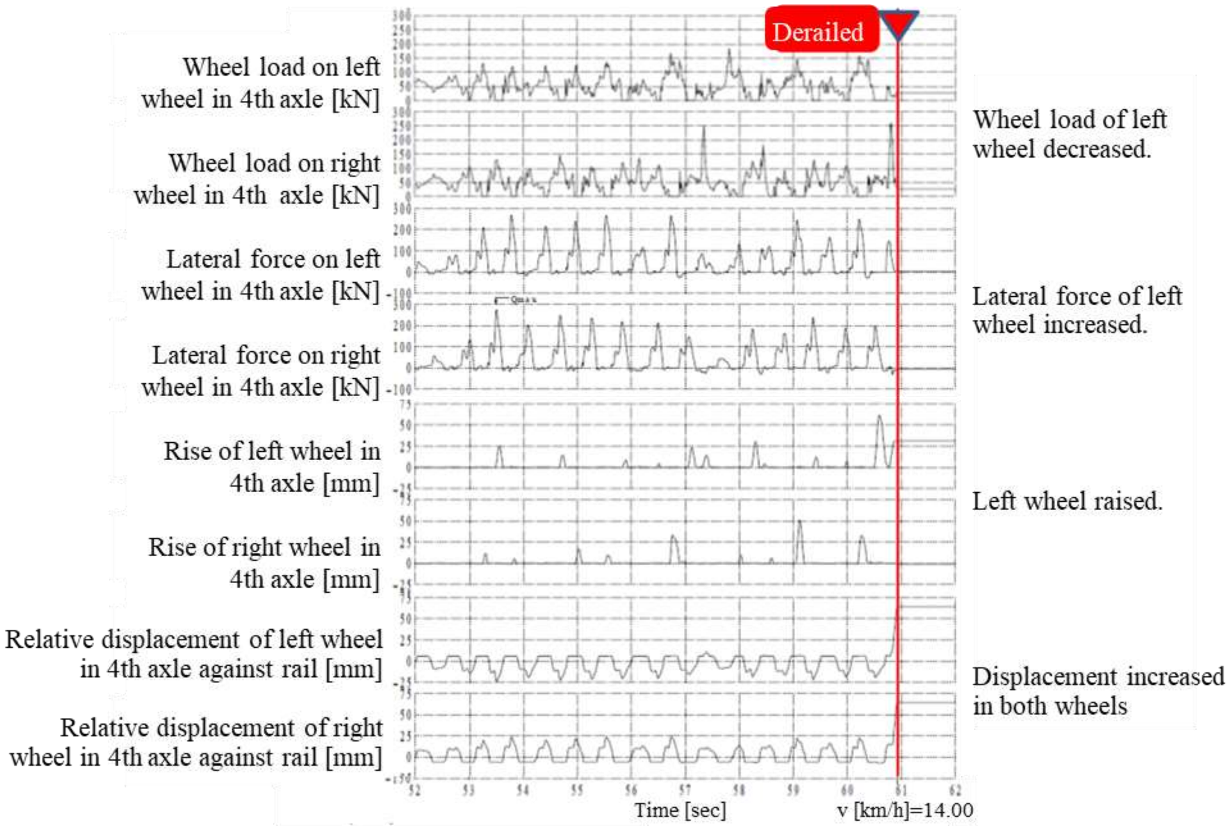


Figure 16. Behavior of the Vehicle just before the Derailment (Motion of the 1st Axle)

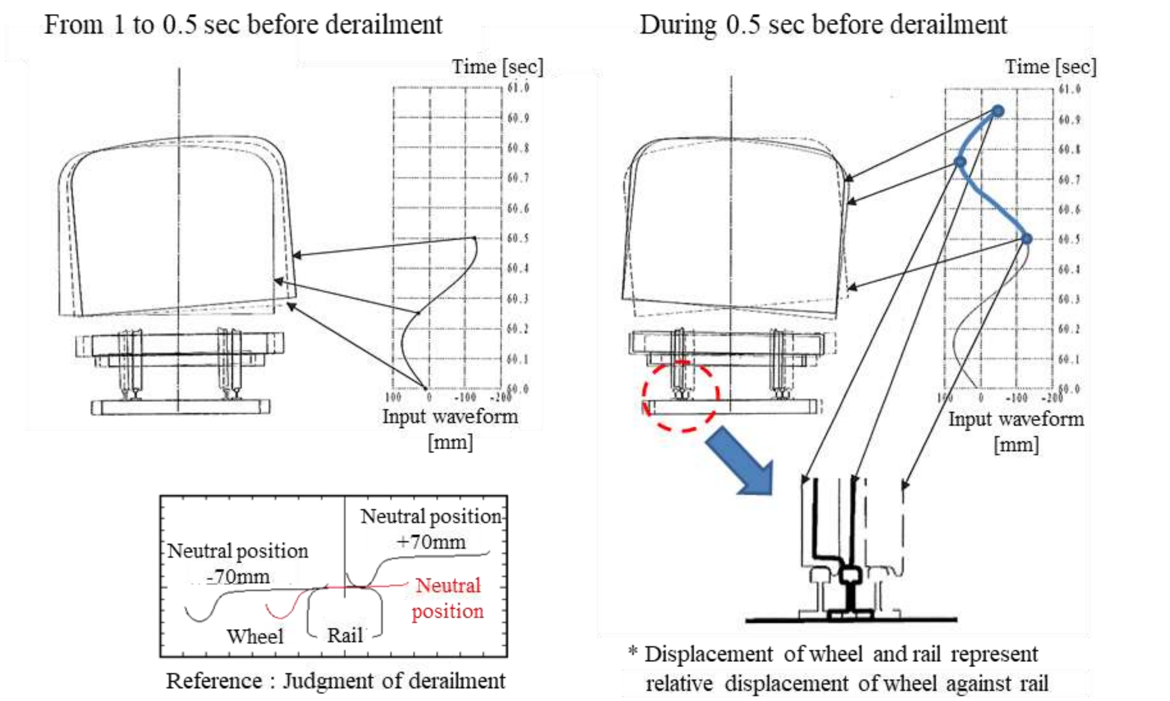
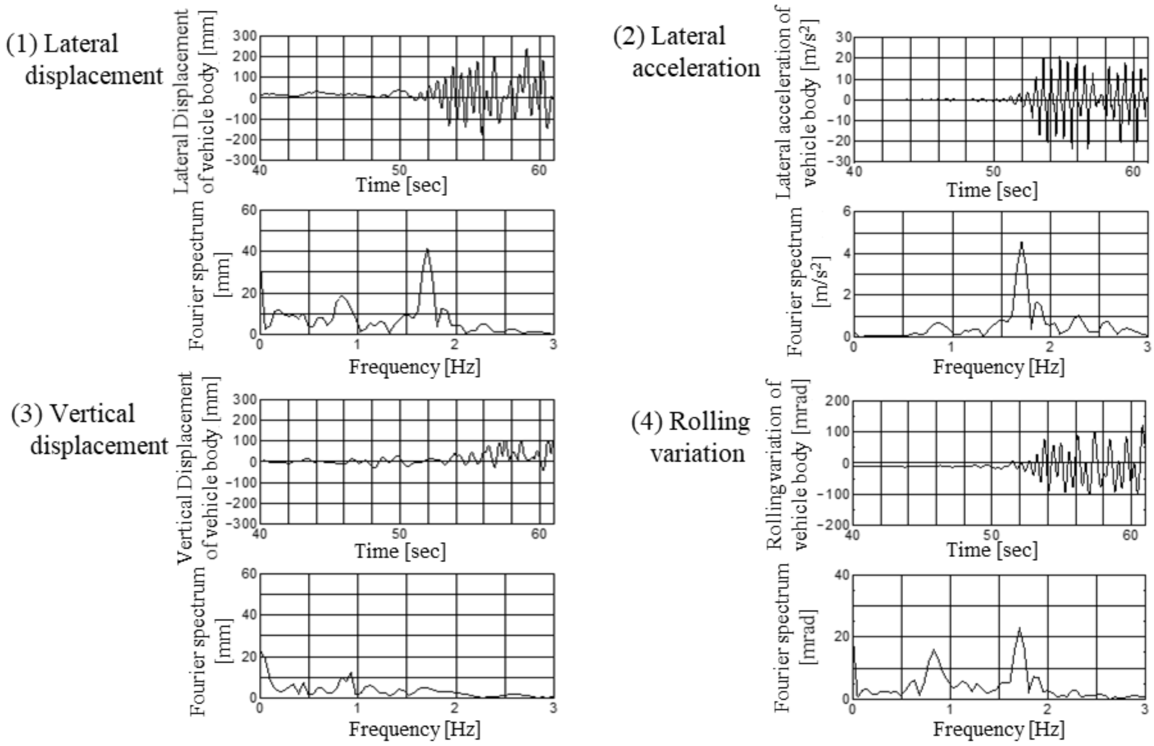
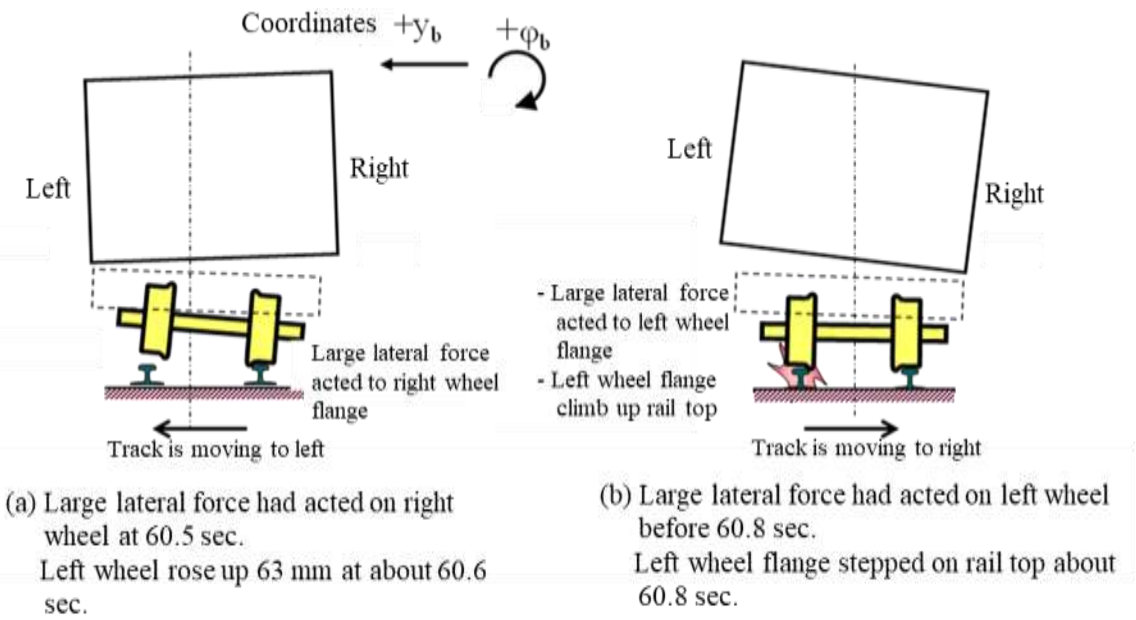


Figure 17. Behavior of the Vehicle until the Derailment (Frequency)



Remarks : Frequency analysis was performed from 40 second when the estimated shocks of the earthquake at the derailed point began to increase, to 60.9 second *i.e.*, just before the derailment.

Figure 18. Conceptual Diagram of the Vehicle Behaviors just before the Derailment

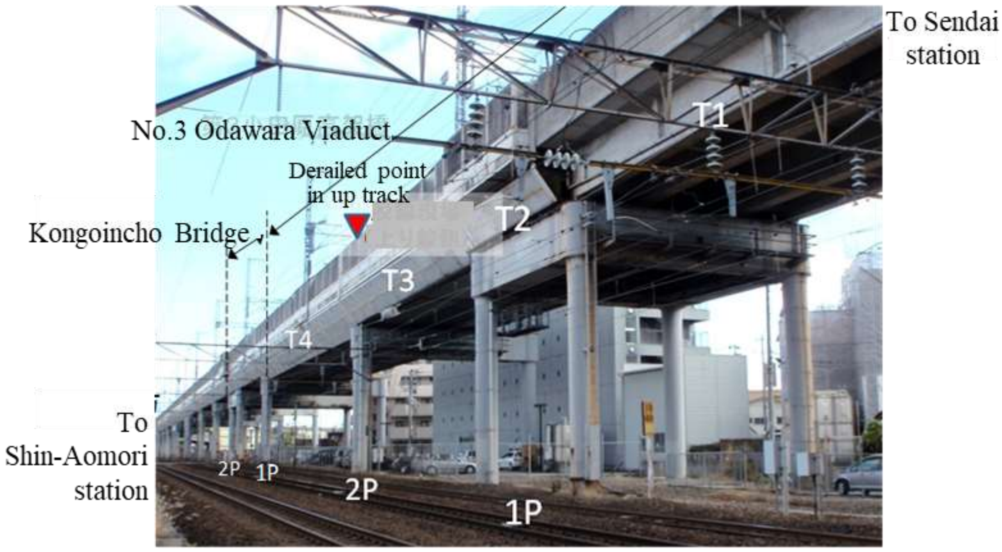


Photograph 1. Status of the Accident Train

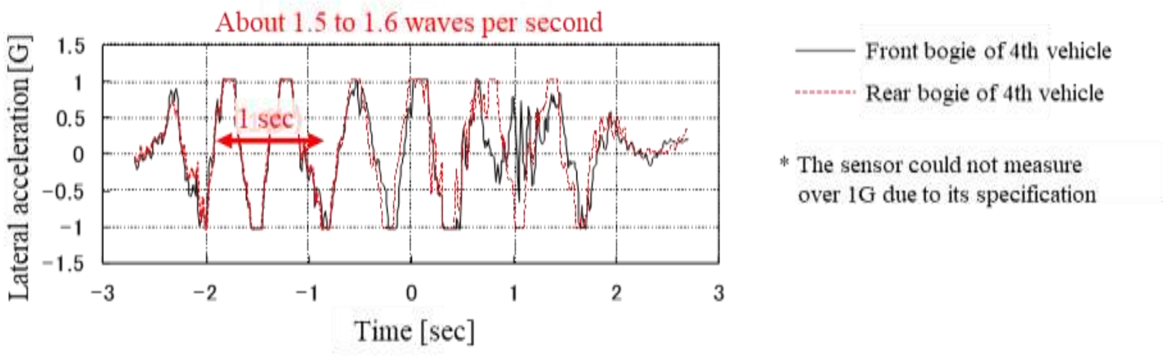
Photograph 2. Status of the Accident Site I

* Photo was taken after the accident train had moved in the direction to Sendai station.

Photograph 3. Status of the Accident Site II

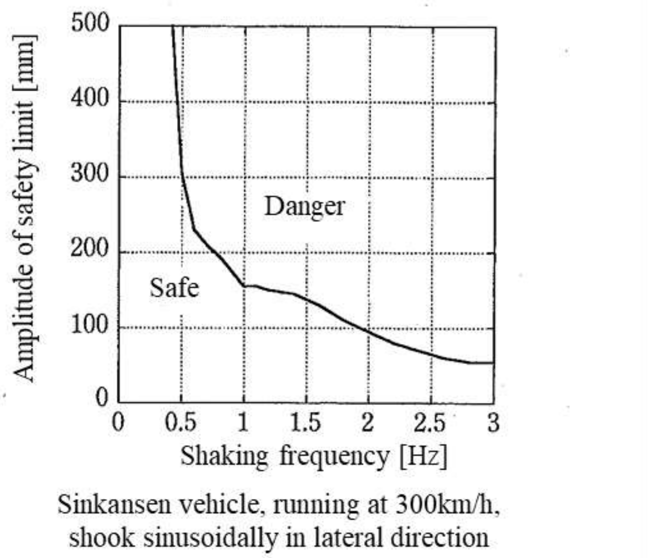


Reference Figure 1. Operation Records of the Acceleration Sensors in the Semi-Active Vibration Suppression Control Device in the 4th Vehicle



Remarks : The operation records of acceleration sensors in the semi-active vibration suppression control device were accumulated for the purpose of grasping status of the device and investigating causes of the failure when it is failed. Then, this information was used as the reference to verify the validity of the results for the vehicle dynamics simulation in this report.

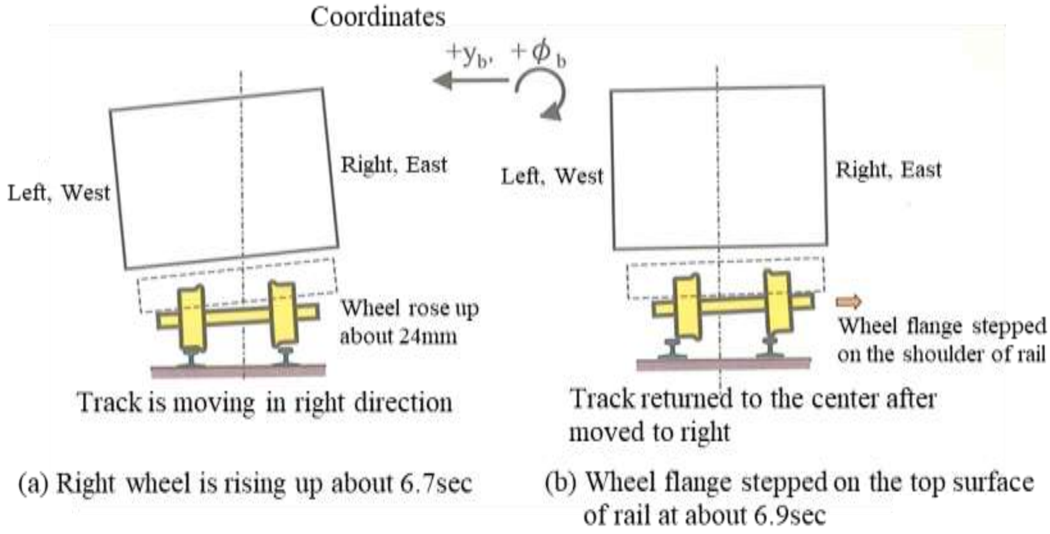
Reference Figure 2. Sample of the Running Safety Limit Curve



Attached figure 8.2. Running safety limit curve based on simulation

** Quated from "Design standards and comments of railway structures etc., Displacement Limit", p.130, Maruzen, 2006, edited by the RTRI, in Japanese.*

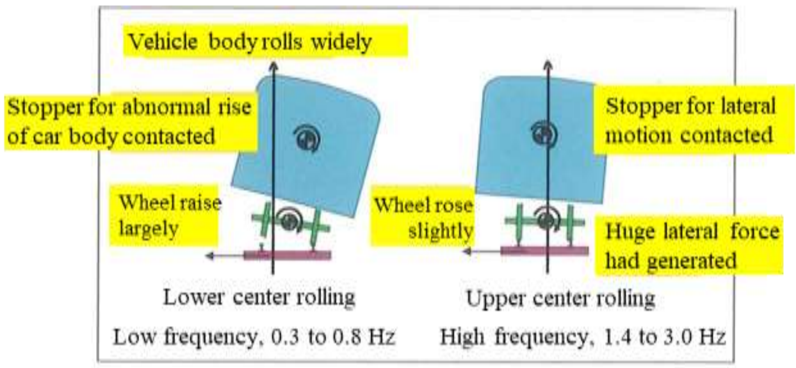
Reference Figure 3. Vehicle Attitude in the Train Derailment Accident of the Joetsu Shinkansen



Simulated behavior of the vehicle at Tokamachi viaduct R3.

** Quoted from a part of "Figure 7.15 Simulated results for vehicle attitude against the supposed seismic ground motion at Tokamachi BL R3" in "Simulated analysis of derailment of Shinkansen vehicle caused by the Niigata prefecture Chu-Etsu earthquake" edited by the group of analytical simulation for the derailment of Shinkansen due to earthquake, RTRI Report Special edition, No.52, p.59, RTRI, 2008, in Japanese.*

Reference Figure 4. Summary of the Upper Center Rolling and the Lower Center Rolling



Vehicle behavior corresponding to the frequency of the sinusoidal lateral vibration.

** Quoted from T. Miyamoto, "Measures to prevent vehicle derailment in earthquake", RRR, Vol.69, No.3, p.15, 2012, in Japanese.*