Introduction with New Methods for Train Operation Control in Strong Winds at East Japan Railway Company

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Abstract
This paper introduces the new methods for train operation control in strong winds at East Japan Railway Company (JR East) based on previous papers. In order to secure running safety of trains in strong winds, JR East implements operation control such as speed control and operation suspension at prescribed wind speeds. In the new method of wind observation, the spatial average of instantaneous wind speeds observed at the same time by three anemometers is applied. Furthermore, the 3-second time average wind speed by an anemometer has almost equal performance to the spatial average wind speed observed by three anemometers. In the new method of calculation of critical wind speed of overturning, the Railway Technology Research Institute (RTRI) Detailed Equation is employed. The methods have already been introduced on seven sections on the advance of other lines.
1. INTRODUCTION

The fundamental concept behind train operation control in strong winds is to compare aerodynamic force acting on the train body due to wind and overturn resistance—ability of rolling stock to resist overturning—and secure train operation in conditions where overturn resistance exceeds aerodynamic force. In order to appropriately issue operation control commands, it is important to appropriately recognize the peak value of the aerodynamic force acting on the train body. It is, however, technically difficult to measure the aerodynamic force on the trains in service. Thus, railway operators actually use a method of estimating aerodynamic force from wind speed values, issuing train operation control commands in strong winds based on those wind speeds. After the overturning of a train on the Uetsu Line on December 25, 2005, JR East provisionally reduced the standard wind speeds for issuing control commands as one measure against strong winds. However, this was not based on technical evidence. We thus developed and put into practical use a new method for train operation control in strong winds whereby both aerodynamic force and overturn resistance of rolling stock are precisely assessed.

In this method, we estimate the aerodynamic force acting on the train body from the spatial average of instantaneous wind speeds observed at the same time by three anemometers equally spaced in a 20 m space equivalent to the total length of a car (hereinafter, “three-anemometer spatial average wind speed”) and calculate the overturn resistance by the Railway Technology Research Institute (RTRI) Detailed Equation. The methods have already been introduced on seven sections on the Uetsu, Keiyo, and Echigo lines in advance of other lines. Furthermore, for the method of wind observation, we analyzed the time average wind speed observed by an anemometer with performance almost equal to the spatial average wind speed observed by three anemometers, and our results show that such time average wind speed is the average of wind speed observed for three seconds.

This paper introduces the new methods for train operation control in strong winds at JR East based on previous papers.

2. CURRENT METHODS FOR TRAIN OPERATION CONTROL

(1) Current Operation Control

Current requirements of operation control in strong winds for conventional lines of JR East are as follows.

(a) Method of Wind Observation

*Using instantaneous wind speed measured with a single anemometer

(b) Critical Wind Speed of Overturning

*Calculating by the Kunieda formula

*Confirming that the critical wind speed of overturning is greater than 30 m/s

(c) Operation Control Rules

*Applying general control and early control (TABLE 1)

(2) Current Wind Observation System

On individual lines of JR East, anemometers are installed along the track at one or more locations within specified individual operation control sections. When the forecast wind speed or instantaneous wind speed observed by one of those anemometers exceeds the prescribed standard values, we implement operation control such as operation suspension (TABLE 1). The length of the operation control section allocated to each anemometer is about 2 to 10 km (FIGURE 1).
Anemometers are installed at locations where strong winds are assumed to often occur in the operation control sections. They are also installed where large aerodynamic force is assumed to act on trains due to strong winds, such as on embankments and bridges with large girder height. Anemometers are usually set up at 5 m above the rail surface. Wind speeds are output every 0.5 seconds based on the rotation speeds of cups of cuptype anemometers.

### 3. NEW METHODS FOR TRAIN OPERATION CONTROL

#### (1) New Method of Wind Observation (First step: Three-anemometer)

As the instantaneous wind speed of a single anemometer is used as the index in the current method, there is a possibility that the value does not represent wind that acts on the entire vehicle of around 20 m in length. Natural wind is not a uniform flow; instantaneous wind speed varies both in terms of time and space. For example, observations of natural wind with nine anemometers at 2.5 m intervals and time series data of the instantaneous wind speed of those observations are shown in FIGURE 2 and FIGURE 3 respectively.

**FIGURE 2 Observation of Natural Wind with Nine Anemometers**

- **Observation location:**
  - The Joban line: Between Mito and Katsuta Stations
  - (near Nakagawa depot)
- **Anemometers:**
  - Approx. 2.5–3 m above ground
  - Nine anemometers placed at 2.5 m horizontal intervals (total length 20 m)
- **Surrounding geography:**
  - Level ground (rice fields)
Looking at the large—several seconds—variation of the frequency of wind speed, FIGURE 3 indicates fluctuation of 2–5 m/s when comparing instantaneous values at the same time, even though observation values of each anemometer similarly vary at first glance. That means, accordingly, instantaneous wind speed measured with only one anemometer include noise-like micro-variation, so the values do not necessarily represent the speed of the wind that acts on the entire car body.

In light of that, we cover here an observation method for wind speed representing the size of the car body. The most basic method would be placing numerous anemometers in a space equal to that of the car body and using the integral value (spatial average) of the values measured with those anemometers, but that is not realistic. So, as a method approximating that, we consider the number and interval of anemometers that can measure wind speed equivalent to the assumed wind speed and that would also be practical, assuming that the spatial average of instantaneous wind speed measured with the aforementioned nine anemometers would be the wind speed representing the car body size. TABLE 2 shows the patterns examined for how to figure out the spatial average (the number and interval of anemometers).

**TABLE 2 Number and Interval of Anemometers**

<table>
<thead>
<tr>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image-url" alt="Pattern Image" /></td>
<td>Nine (at 2.5 m intervals)</td>
<td>Five (at 5 m intervals)</td>
<td>Four (at random intervals)</td>
<td>Three (at 10 m intervals)</td>
<td>Three (at 7.5 m intervals)</td>
<td>Three (at 5 m intervals)</td>
<td>Three (at 2.5 m intervals)</td>
<td>Two (at 20 m interval)</td>
</tr>
</tbody>
</table>
FIGURE 4 indicates the maximum values and standard deviations of the wind speed data for 10 minutes in a different method of calculating spatial average (average values of the analysis results of 10 minutes data for total three hours; the same applies for FIGURE 4 too).

FIGURE 4 shows the correlation between the time series data of the spatial average of nine anemometers and the time series data of the spatial averages. The figure indicates that the special average when using five and three anemometers at a 5-10 m interval shows high correlation with the special average of nine anemometers, and it indicates that the correlation is smallest when measuring with only one anemometer. Consequently, it would be practical to calculate the spatial average of three anemometers at 5–10 m-intervals as a method with high correlation of special average of nine anemometers with its special average, maximum value and standard deviation. That would also be a more appropriate evaluation method than the current observation using only one anemometer. Thus, in the new methods for operation control, we will test operation control using the spatial average of the instantaneous wind speed of three anemometers placed at 5–10 m-interval.

There are two methods of calculating spatial average, namely vector averaging and scalar averaging. Since current three-cup anemometers cannot obtain wind direction information, we will use scalar averaging. Furthermore, scalar averaging is classified as arithmetic averaging where the sum of the wind speed is divided by the number of anemometers and root mean square (RMS) where the sum of the squares of the wind speed is divided by the number of anemometers and then the square root is extracted. We will use RMS for the new methods for operation control because the average value of RMS is slightly larger compared to that of arithmetic averaging, enabling us to operate on the safe side.

(2) New Method of Wind Observation (Second Step: One-anemometer)

While the three-anemometer spatial average wind speed is an appropriate index of wind speed assessment, it differs from methods using one-anemometer time average wind speed that are common in the fields of meteorology and wind engineering. The World Meteorological Organization (WMO) sees average wind speed for a few seconds as the best index to estimate the effect of wind speeds on structures and transport. It is thus internationally common to use the time average of instantaneous wind speed observed by an anemometer for a few seconds as the wind speed for assessment. If we can apply our new method to operation control, it could be significant in terms of conforming to international standards and effective on reduction of installation and maintenance costs of anemometers.

For analysis, RTRI provided us with data of aerodynamic force and wind direction/speed measurement tests using a full-scale vehicle model carried out in Shimamaki Village,
Hokkaido Prefecture from December 2001 to March 2004. As aerodynamic force acting on a vehicle model could be measured in experiments, we compared actual aerodynamic force using aerodynamic force estimated from the three-anemometer spatial average wind speed and the one-anemometer n-second average wind speed (several examples of average time of n seconds were set) to find out the time average wind speed that could match the measured data well.

Measurement items used in analysis were wind direction, wind speed, atmospheric pressure, temperature, and aerodynamic force (lateral force), and the sampling frequency was 10 Hz.

FIGURE 5 and 6 show the measurement environment.

A model of a single-line viaduct and a full-scale vehicle model were situated at a right angle to the main wind direction on level ground facing the Sea of Japan (FIGURE 5 (a)). RTRI measured wind direction and speed using vane anemometers and aerodynamic force using load cells (FIGURE 5 (b)). Three vane anemometers were placed 20 m from the lead car at a right angle to the track at a height of 10 m and an interval of 10 m (FIGURE 6 (a)). Four load cells were placed between the viaduct and the vehicle (FIGURE 6 (b)). We considered the horizontal element at a right angle to the track of the values measured by the load cells to be the aerodynamic force.

Measured aerodynamic force $F_M$ is obtained as the sum of the values $F_{L1}$ to $F_{L4}$ measured by the load cells $L1$ to $L4$ at the same time:

$$F_M = F_{L1} + F_{L2} + F_{L3} + F_{L4} \quad [1]$$

The estimated aerodynamic force $F_E$ is found by the following formula.
Here, $\rho$ is air density, $u$ is assessment wind speed, $A$ is area of the side surface of the car body, and $C_S$ is aerodynamic force coefficient. Air density $\rho$ is calculated as follows.

$$\rho = \frac{1}{2} \frac{273.15}{273.15 + t} \frac{P}{1013.25}$$  \[3\]

Here, $t$ is air temperature [$^\circ$C], and $P$ is atmospheric pressure [hPa].

Assessment wind speed $u$ is defined as follows.

*One-anemometer instantaneous wind speed:

Arithmetic average of instantaneous value (10 Hz) for the latest 0.5 seconds until the current time observed by anemometer No.2 (FIGURE 6 (a)), taking into account the response performance of the anemometers

*One-anemometer n-second time average wind speed:

Arithmetic average of instantaneous wind speed for the latest n seconds until the current time observed by anemometer No.2

*Three-anemometer spatial average wind speed:

Root mean square (RMS) of instantaneous wind speed (0.5-second average wind speed) observed at the same time by anemometers No.1, No.2 and No.3

The area of side surface of the vehicle $A$ was 51.3$\text{m}^2$, and the aerodynamic force coefficient $C_S$ used was the value obtained per wind direction angle in the wind tunnel tests by RTRI$^7)$. FIGURE 7 shows an example of the waveform of aerodynamic force.
(d) Aerodynamic force estimated from one-anemometer 3-second average wind speed

(e) Aerodynamic force estimated from three-anemometer spatial average wind speed

FIGURE 7 Examples of Waveforms of Aerodynamic Force

FIGURE 7 (a) is the value measured with the load cell, and FIGURE 7 (b), (c), (d), and (e) are the estimated values from one-anemometer instantaneous wind speed, one-anemometer 1-second average wind speed, one-anemometer 3-second average wind speed, and three-anemometer spatial average wind speed respectively. As average time becomes longer, the waveform tends to become slack.

Comparing estimated aerodynamic forces with measured aerodynamic force moment-by-moment, none of the estimated ones match the measured one. However, considering that there is time lag between issuance of a control command and its implementation in actual train operation, the issue is whether or not the maximum value within the assessment time is appropriately reproduced, instead of moment values. We therefore set the assessment time at 60 seconds taking into account past findings on assessment time for railways, and compared the maximum values with the actual value within the assessment time. In FIGURE 7, the horizontal straight lines are the maximum values for 60 seconds.

FIGURE 8 shows a comparison of the maximum aerodynamic forces within the assessment time.
Defining maximum aerodynamic force actually measured with a load cell as the denominator and maximum aerodynamic force estimated from each wind speed as the numerator, frequency distributions of the ratios between the denominator and the numerator are shown on the diagram. After confirming that the line plot of the actual value largely follows normal distribution, we approximated estimated values by the normal distribution curve. The one-anemometer n-second average wind speed of which the mean value is closest to 1 is the one-anemometer 3-second average wind speed. Closeness to 1 and deviation from the mean value of the one-anemometer 3-second average wind speed and those of the three-anemometer spatial average wind speed are nearly equal. The mean values of one-anemometer instantaneous wind speed, one-anemometer 1-second average wind speed, and one-anemometer 2-second average wind speed are larger than 1, and that of one-anemometer 4-second average wind speed is smaller than 1.

Those findings revealed that one-anemometer 3-second average wind speed is appropriate for estimating the maximum value of measured aerodynamic force and it has almost equal performance to that of three-anemometer spatial average wind speed.

4. CALCULATION OF CRITICAL WIND SPEED OF OVERTURNING OF VEHICLES

The findings of recent research are not reflected in the current method (the Kunieda formula). For the aerodynamic force that greatly affects overturn in particular, the current method cannot take into account factors such as the effects of shape of car body and wayside structures, wind angle and differences between leading cars and middle cars. We thus consider those effects on aerodynamic force and evaluate the critical wind speed of overturning using the RTRI Detailed Equation that can take account of factors such as the effect of suspension of the vehicle in detail. FIGURE 9 shows the calculation model of the RTRI Detailed Equation.
The principle of the equation is the same as that of the Kunieda formula in that it finds the relation between the wind speed and the wheel unloading ratio based on the formula of static equilibrium of moments by external forces acting on the vehicle. The RTRI Detailed Equation is, however, different from the Kunieda formula in the following points.

(a) Aerodynamic force coefficients are found in wind tunnel tests. In wind tunnel tests, measurement is done at different wind angles to the vehicle to clarify the dependence of the aerodynamic force coefficient on the wind angle.

(b) Lift and rolling moment as well as side force as the aerodynamic force of crosswinds are taken into account, and height of the center of the wind pressure is found based on wind tunnel test results.

(c) Aerodynamic force is evaluated using aerodynamic force coefficients according to the relative wind angle to the vehicle, assuming that the resultant vector of the running speed vector of the vehicle and the wind speed vector of the natural wind acts on the vehicle (FIGURE 10).

\[ \begin{align*}
F_s & : \text{Side force due to crosswind [N]} \\
F_L & : \text{Lift due to crosswind [N]} \\
m_s & : \text{Half mass of car body [kg]} \\
m_b & : \text{Mass of bogie} \\
\omega & : \text{Car body lateral acceleration [m/s²]} \\
g & : \text{Gravitational acceleration [m/s²]} \\
C_s & : \text{Center of wind pressure} \\
G_s & : \text{Center of gravity of car body} \\
G_b & : \text{Center of gravity of bogie} \\
\gamma & : \text{Squat angle [rad]} \\
e & : \text{Distance between center of wind pressure and center of gravity of car body [m]} \\
\gamma & : \text{Height of center of wind pressure [m]} \\
h_G & : \text{Height of center of gravity of car body [m]} \\
h_B & : \text{Height of center of gravity of bogie [m]} \\
P_L & : \text{Wheel load of right wheels [N]} \\
P_L & : \text{Wheel load of left wheels [N]} \\
2b & : \text{Distance between wheel/axle contact points [m]} \\
R & : \text{Curve radius [m]} \\
\phi & : \text{Roll angle displacement of car body [rad]} \\
y & : \text{Lateral displacement of center of gravity of car body [m]}
\end{align*} \]
(d) Displacement of the center of gravity of the car body by external forces is found using the balance of potential energies of the suspension of the vehicle. Lateral displacement and roll angle displacement of the center of gravity of the car body are considered in that.

(e) Lateral displacement stoppers and vertical displacement stoppers are taken into consideration in addition to primary suspension and secondary suspension. Calculation is done while judging whether the car body hits the stoppers.

(f) Values appropriate to recent vehicle and track conditions are used for lateral acceleration of the car body.

Consideration of (a)–(c) above in particular enables quantitative evaluation of the effects of shape of car body and wayside structures, angle of natural wind and train running speed (relative wind angle to the vehicle), which the Kunieda formula cannot take into account. Results of past general studies proved that the difference between the calculation results of the RTRI Detailed Equation and the Kunieda formula is often large on running trains, particularly on the leading car, while the Kunieda formula delivers results equivalent to those of the RTRI Detailed Equation on standing middle cars on level ground.

5. METHODS OF ESTABLISHING OPERATION CONTROL RULES

Since current methods for operation control basically stipulate uniform control rules, too much or too little control might be placed on some vehicles or locations. Thus, it would be more reasonable to develop operation control rules according to individual evaluation of critical wind speed of overturning based on vehicle conditions (car body shape, specifications and running speed) and ground conditions (wayside structures, geographic condition). In the new method, therefore, we divide sections subject to operation control under wind by individual condition. We then calculate critical wind speeds of overturning for each subsection according to wayside structure, track configuration, running speed and vehicles that run there, and we specify the minimum calculated value of them as the critical wind speeds of overturning to be referred to in establishing operation control rules for the sections (FIGURE 11).
In the calculation, we include safety margins, then we stipulate the wind speed at which to issue operation control commands and the running speed so the critical wind speed of overturning will exceed the wind speed for issuing operation control commands in the section. An image of the setting operation control for the critical wind speed of overturning is shown in FIGURE 12.

Operation control rules can be established by the following two methods; wind speed at which to issue operation control commands is set, and then running speed is set according to the wind speed. And, running speed in operation control is set, and then wind speed at which to issue operation control commands is set according to running speed. In each case, running speed in operation control can be set in a single step as is presently done, or it can be set in multiple steps to alleviate operation disruption due to slowing down. In both cases, wind speed at which to issue operation control commands and running speed in operation control are set within the shaded area of FIGURE 12. This figure shows an example of setting running speed in operation control in two steps and setting the wind speed at which to issue operation control commands according to the running speed steps.

Since new operation control rules allow detailed application according to sections and vehicles subject to control, they could be safer and more reasonable than the current rules. On the other hand, as the rules become more detailed, operation instructions would be so
cumbersome that there is concern of an increase in errors in communication and actual driving. So, operation control rules should be developed based on sufficient consideration of such tradeoffs. Moreover, running safety in strong winds should be considered in a comprehensive manner from a perspective of physical methods such as providing windbreak fences as well as applicational measures including operation control.

5. CONCLUSION
In this paper, we introduced the new methods of train operation control in strong winds at JR East. The points of the methods are as follows.

1) Method of wind observation
* Spatial average of instantaneous wind speed measured with multiple anemometers is applied.
* 3-second time average wind speed by an anemometer has almost equal performance to the spatial average wind speed observed by three anemometers.

2) Calculation of Critical Wind Speed of Overturning
* The RTRI Detailed Equation is employed
* Safety margin is included in calculation

3) Operation Control Rules
* Critical wind speeds of overturning for individual sections subject to control including a safety margin are found according to wayside structures, track configuration, running speed and vehicle specifications. Wind speed at which operation control commands are issued and running speed are set so the calculated critical wind speed of overturning exceeds the wind speed at which operation control commands are issued.

REFERENCES