

Study of New Methods for Train Operation Control in Strong Winds



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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. Current operation control rules basically follow the operation control framework of the era before Japan National Railways (JNR) was privatized. Recent technical trends such as for improvement of operation speed and more lightweight vehicles have brought about renewed awareness of the importance of the operation control rules. However, we have also come to realize the need for fundamental improvement of the rules based on scientific review on their rationality and validity as safety improvement measures instead of simply lowering the wind speed at which operation control commands are issued. Thus, based on the recent results of investigations of accidents due to strong wind and results of research, we reviewed methods for wind observation and for calculating the critical wind speed of overturning of rolling stock, and studied new methods for operation control that are safer and more reasonable. We introduced the new methods on a trial basis from the winter of 2011 after deliberation in committees that include external experts.

●Keywords: Disaster due to strong wind, Operation control, Wind observation, Critical wind speed of overturning, Measurement by multiple anemometers, Railway Technical Research Institute Detailed Equation

1 Introduction

On December 25 2005, an accident occurred where the “Inaho” limited express derailed and overturned just after passing over the Daini Mogamigawa Bridge between Sagoshi and Kita-Amarume stations on the Uetsu Line. The report of a fact-finding investigation into the accident¹⁾ by the Aircraft and Railway Accidents Investigation Commission (current Japan Transport Safety Board) of the Ministry of Land, Infrastructure, Transport and Tourism (MLIT) deduces that the cause was localized gusts. After this accident, railway operators including JR East lowered the wind speed standard at which operation suspension commands are issued in train operation control according to wind speed from 30 m/s to 25 m/s as a provisional safety improvement measure. But there has been little quantitative evaluation of that measure and review of rationality and validity of the current operation control rules up to now. In confirming the most fundamental concept of operation control, it is important to secure train running in conditions where overturn resistance of the vehicle exceeds aerodynamic force of wind on the car body. When applying the principle to actual operation control situations, the basis is to set down the wind speed at which operation control commands are issued to ensure trains run in a state where the critical wind speed of overturning constantly is greater than the expected wind speed. That is done by first comparing the wind speed that is expected to act on the car body and the critical wind speed of overturning that is the overturn resistance converted into wind speed.

We thus studied wind observation methods that allow evaluation in situations closer to reality and a calculation method for the critical wind speed of overturning. In that, we considered information from recent results of investigations of accidents due to strong wind and related research results. Furthermore, using those methods, we studied how to establish new operation control rules that are safer and more reasonable. An overview of that study and a documentation of past developments are

reported in this article.

2 Operation Control in Strong Winds

2.1 Current Operation Control

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

- (1) Wind Observation Method
 - Using instantaneous wind speed measured with a single anemometer¹⁾
- (2) Critical Wind Speed of Overturning
 - Calculating by the Kunieda formula²⁾
 - Confirming that the critical wind speed of overturning is greater than 30 m/s
- (3) Operation Control Rules
 - Applying general control and early control (Table 1)³⁾

Table 1 Current Operation Control Rules

Wind speed	Over 20 m/s	Over 25 m/s	Over 30 m/s
Early control	25 km/h	Operation suspension	
General control	—	25 km/h	Operation suspension

*1 There are sections subject to operation control under wind that have more than one anemometer to check the wind speed. However, even in such a case, control commands are issued when the instantaneous wind speed of any one of the anemometers exceeds the control value. In the strong wind warning system²⁾ also, the upper limit value of wind speed (equal to the maximum instantaneous wind speed) at a short time in the future is estimated according to the values measured with the anemometers in the system, and control commands are issued when any one of the upper limit values or the measured values exceeds the control value. Therefore, we consider for all intents and purposes instantaneous wind speed measured with a single anemometer in any case. Introduction of the strong wind

warning system started in August 2005 and has been completed for all sections subject to operation control under wind.

**2 The Kunieda formula developed by Dr. Masaharu Kunieda at the Technical Laboratory of JNR in 1972 is used for theoretical analysis on the mechanics of overturn of rolling stock.³⁾ The formula gives practical calculation results in a relatively easy manner by setting some assumptions in the process of calculation. It has thus been used for many years in area such as designing rolling stocks and tracks.

***3 After the accident on the Uetsu Line, early control has been applied to all sections subject to operation control under wind, except sections provided with windbreak fences. General control is applied in those sections.

2.2 Past Developments

(1) Wind Observation Method

It is said that the introduction of anemometers into railways in Japan dates back to around the early 1920s. Anemometers at that time were called wind run anemometers, and those calculate by a conversion formula the number of rotation of cups in a specified period of time into the average wind speed. Operation control then was implemented according to average wind speed because visual wind speed measurement, a method applied before the introduction of anemometers, also determined average wind speed. Thus, even after the introduction of more modern anemometers that could measure instantaneous wind speed as is presently done, operation control was still implemented upon conversion of instantaneous wind speed into average wind speed.

The Amarube Bridge accident in December 1986 triggered application of instantaneous wind speed to operation control. In this accident, an out-of-service train running on the Amarube Bridge between Yoroi and Amarube stations on the San'in Line received a gust of more than 30 m/s, and all seven cars of the train other than the locomotive overturned and fell from the bridge. For technical identification of the cause of the accident and development of appropriate countermeasures, an accident investigation committee consisting of railway and academic experts was set up in February 1987, conducting an investigation of the causes and studying countermeasures⁹⁾. Concerning wind observation, the investigation results revealed that instantaneous wind speed greatly affected overturning of vehicles. Accordingly, the committee found that train operation control should be based on instantaneous wind speed instead of average wind speed.

JR East therefore confirmed that all of anemometers in its operation area were of a type that could measure instantaneous wind speed. And we decided to apply instantaneous wind speed measured with anemometers directly to operation control from October 1987 on.

(2) Calculation of Critical Wind Speed of Overturning for Rolling Stock

The Kunieda formula has been used as the basis for safety assessment on overturning of vehicles since its publication. JR East also has a regulation that specifies to confirm that critical wind speed of overturning is greater than 30 m/s using the

Kunieda formula.

As mentioned above, the Kunieda formula was made public as a paper in 1972. However, the formula it was based on seems to have already been created in the 1930s. For example, we can see some results of calculation of critical wind speed of overturning after train derailments and overturn accidents in the Muroto typhoon that hit the Kinki region in September 1934. As there was a report in a related study at the time stating that wind speed in excess of 30 m/s presents a risk of overturning, that calculation would be one of the reasons for the operation control rule to stop train operation at wind speed of 30 m/s.

(3) Operation Control Rules

In light of the research above, some regional offices of JNR stipulated a rule of operation suspension at 30 m/s wind speed in 1930's. In August 1948, the rule was nationally standardized as the operation management instruction and put into full-scale application. The instruction stipulated to monitor the situation at wind speed of 20 m/s, to prohibit coupling of lightweight cars and, depending on the situation, temporarily suspend operation at 25 m/s, and to stop operation at 30 m/s. Rules similar to those are still in use.

JNR era operation control rules were for the most part inherited by JR East after the breakup and privatization of JNR in April 1987. In August 1989, based on a study by an internal committee, the rules were amended to the current operation control rules with 1) early control sections introduced where operation is stopped at wind speed 25 m/s, 2) new slow-down control at 25 km/h set up at 5 m/s lower wind speed than that for operation suspension, and 3) a 30-minute rule set up for lifting and easing control. (At the introduction of the strong wind warning system, 3) was abolished on conventional lines except in case of anemometer failure.)

2.3 Recent Findings

In this section, we will introduce new findings on aerodynamic force and the method for calculating the critical wind speed of overturning and the background of those gained from accident investigation and research results of recent accidents caused by strong winds.

There are three external forces that greatly affect overturning of vehicle: aerodynamic force of crosswinds, excess centrifugal force when passing through curved track and inertia force by vehicle lateral vibration. Of those, aerodynamic force has the greatest effects, having a contribution rate of around 60% in critical overturning. Thus, it is quite important to accurately assess the aerodynamic force acting on the vehicle to estimate the critical wind speed of overturning. Here, the aerodynamic forces contributing to vehicle overturn include side force that acts on the vehicle laterally to the running direction, lift that acts upward and rolling moment that is the overturning moment around the center of the car body (Fig. 1). Those can be expressed in the form of proportion to the square of wind speed. The proportional constants that show the relation between those forces (moments) and the square of wind speed are called side force coefficient, lift coefficient and rolling moment coefficient respectively, and collectively they are called aerodynamic force coefficient. For example, side force can be expressed as in the following formula.

$$F_s = \frac{1}{2} C_s \rho u^2 S \quad \dots (1)$$

Here, F_s is side force, C_s is side force coefficient, ρ is air density, u is wind speed, and S is area of side of the car body.

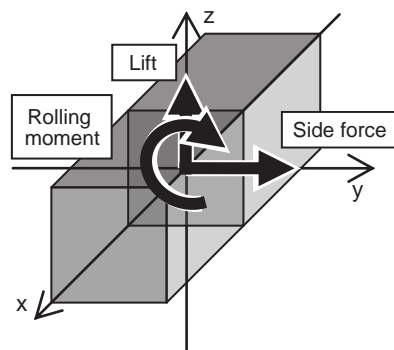


Fig. 1 Aerodynamic Forces Greatly Affecting Overturning

The Kunieda formula is distinguished by its taking into account only side force as aerodynamic force, assuming the aerodynamic force coefficient to be 1.0. This assumption was largely considered valid since the test using a Naha 10 series passenger car in the yard of Nō Station on the Hokuriku Main line demonstrated that the effect of lift on overturn was negligibly small and the side force coefficient based on the results of wind tunnel tests using a model of Naha 10 was 0.92. However, wind tunnel tests in the investigation of the cause of the aforementioned Amarube Bridge accident revealed that aerodynamic force acting on the vehicle depends not only on the shape of the vehicle, but also on the shape of wayside structures. That could increase the side force coefficient up to around 2.0 under some conditions⁴. (Note: Conditions in the above-mentioned wind tunnel test using a Naha 10 model were for middle cars on level ground. The aerodynamic force coefficient under the same conditions is evaluated to be equivalent even today.)

In the derailment accidents of the “Ozora” limited express on the Nemuro Main line of JR Hokkaido and a train on the Minami-Rias line of the Sanriku Railway Company, both of which occurred on the same day in February 1994, more than one car including the diesel lead cars overturned. The investigation of causes of the accidents proved that the aerodynamic force coefficient varies with the wind angle to the vehicle, the characteristics of which are different between a leading car and a middle car. More specifically, it was clarified that the side force coefficient of a leading car tends to be larger than that of a middle car, particularly when wind acts on the leading car diagonally from the front (Fig. 2). (Note: In cases where wind acts on a standing vehicle at a right angle, the side force coefficient of a middle car tends to be larger than that of a leading car. But wind often acts on a train diagonally from the front while running as will be explained later (Fig. 9), and in this case, side force coefficient of a leading car tends to be larger.)

Based on those findings, Railway Technical Research Institute (RTRI) conducted wind tunnel tests combining five types of car body shape and seven types of wayside structure shape to examine aerodynamic force coefficients according to wind angles in detail (Fig. 3)⁵. Furthermore, RTRI improved the estimation accuracy of the aerodynamic force coefficient as well as the analysis formula of the critical wind speed of overturning based on the Kunieda formula to achieve accuracy equivalent to that

of aerodynamic force coefficient estimation. In 2003, Hibino et al. proposed the Railway Technical Research Institute Detailed Equation that gives more consideration to the effect of suspension of the vehicle⁶. Experiments including stationary tests using an actual vehicle⁷ and field tests^{8, 9} proved the formula valid.

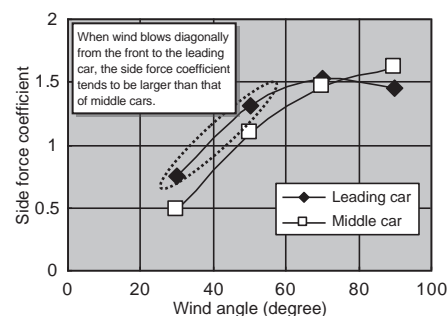


Fig. 2 Dependence of the Aerodynamic Force Coefficient on Wind Angle (Typical Example)

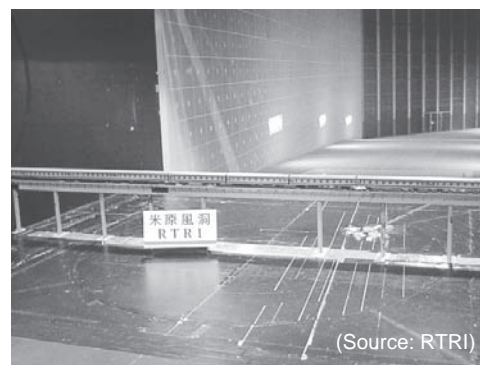


Fig. 3 Wind Tunnel Test

3 New Methods for Operation Control

3.1 Wind Observation Method

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 Fig. 4 and Fig. 5 respectively. Looking at the large —several seconds— variation of the frequency of wind speed, Fig. 5 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

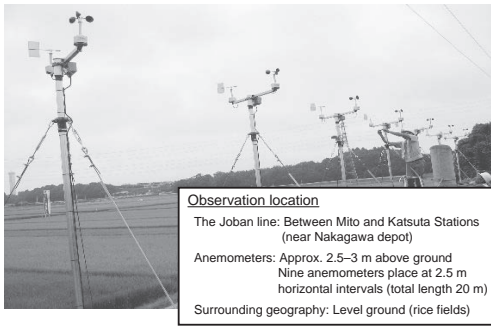


Fig. 4 Observation of Natural Wind with Nine Anemometers

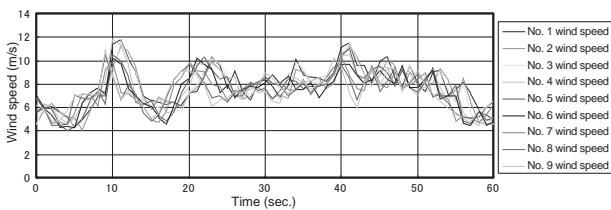


Fig. 5 Example of Natural Wind Observation Results

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). Fig. 6 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-minute data for total three hours; the same applies for Fig. 7 too). The comparison between the spatial average of the nine anemometers and the observation value of a single anemometer in Fig. 6 clarifies that both of the maximum value and standard deviation of the observation value of a single anemometer are larger, meaning that the observation value contains smaller noise-like fluctuation than the car body size. Fig. 6 also shows that Fig. 6 also shows that, by the special average of five, four, and three anemometers at a 10-m interval and two anemometers at a 20-m interval, maximum value and standard deviation can be evaluated at the same level as the special average of nine anemometers. Next, Fig. 7 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, four 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.

Table 2 Number and Interval of Anemometers

1	2	3	4	5	6	7	8	9	
○	○	○	○	○	○	○	○	○	Nine (at 2.5 m intervals)
○	○		○					○	Five (at 5 m intervals)
○		○						○	Four (at random intervals)
○								○	Three (at 10 m intervals)
	○							○	Three (at 7.5 m intervals)
		○						○	Three (at 5 m intervals)
			○	○					Three (at 2.5 m intervals)
○								○	Two (at 20 m interval)
	○								Two (at 15 m interval)
		○							Two (at 10 m interval)
			○						Two (at 5 m interval)
				○					One

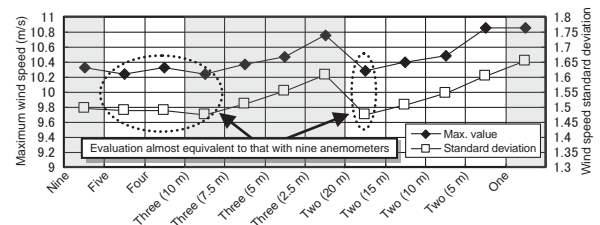


Fig. 6 Difference Between Wind Speed Statistics by Method of Spatial Averaging

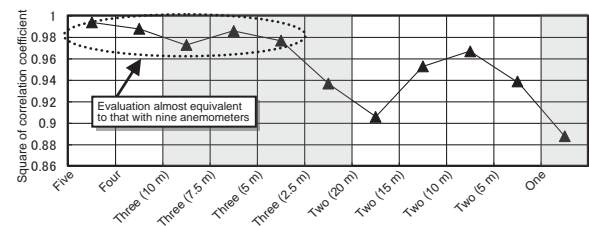


Fig. 7 Correlation to Spatial Average with Nine Anemometers

3.2 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. Fig. 8 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.

- (1) 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 (see Fig. 2 and Fig. 3).
- (2) 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 (see Fig. 1).
- (3) 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 (Fig. 9).
- (4) 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.
- (5) 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.
- (6) Values appropriate to recent vehicle and track conditions are used for lateral acceleration of the car body.

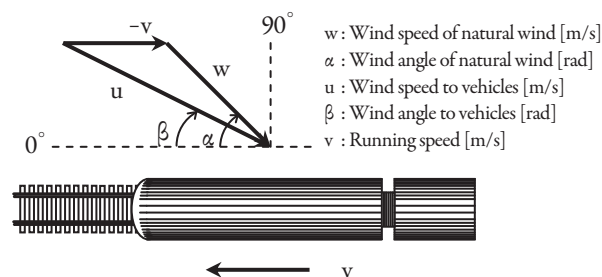


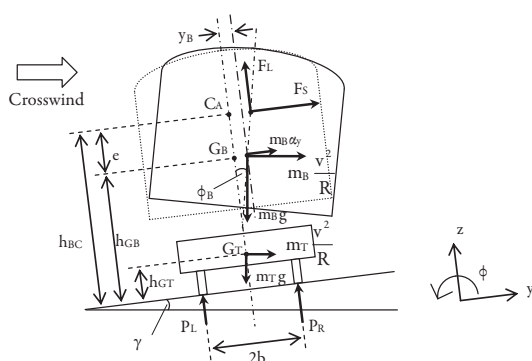
Fig. 9 Wind Acting on Running Vehicles⁹⁾

Consideration of (1)–(3) 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.

3.3 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 (Fig. 10). In the calculation, we include safety margins⁴⁾, 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 Fig. 11. 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 Fig. 11. This figure shows an example of setting running speed in operation control in two steps and setting



- | | |
|--|---|
| F_s : Side force due to crosswind [N] | h_{bc} : Height of center of wind pressure [m] |
| F_L : Lift due to crosswind [N] | h_{gb} : Height of center of gravity of car body [m] |
| m_c : Half mass of car body [kg] | h_{gr} : Height of center of gravity of bogie [m] |
| m_r : Mass of bogie | P_r : Wheel load of right wheels [N] |
| ω : Car body lateral acceleration [m/s ²] | P_l : Wheel load of left wheels [N] |
| g : Gravitational acceleration [m/s ²] | y_b : Lateral displacement of center of gravity of car body [m] |
| C_a : Center of wind pressure | ϕ_b : Roll angle displacement of car body [rad] |
| G_a : Center of gravity of car body | $2b$: Distance between wheel/rail contact points [m] |
| G_r : Center of gravity of bogie | R : Curve radius [m] |
| γ : Cant angle [rad] | v : Running speed [m/s] |
| e : Distance between center of wind pressure and center of gravity of car body [m] | |

Fig. 8 Calculation Model of RTRI Detailed Equation ⁸⁾ some description added

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.

We are currently running simulations of the effects that introducing new methods for operation control to actual line sections will have on transport. The simulations show a mix of line sections where operation control becomes stricter and where it is eased compared to current uniform operation control. Overall, however, operation disruption tends to be reduced, verifying that it is possible to establish new reasonable operation control rules while avoiding cumbersome operation instructions.

*4 An example of the method of including safety margin is adding a 10% safety margin to the risk of overturning D and calculating the critical wind speed of overturning with $D = 0.9$. This is based on the results of studies such as sensitivity analysis of uncertainties and analysis of the results of field test on a commercial line⁹⁾.

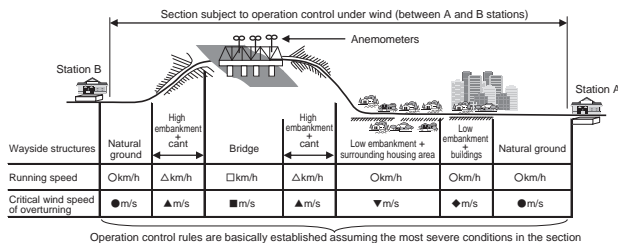


Fig. 10 Image of Critical Wind Speed of Overturning for Individual Sections

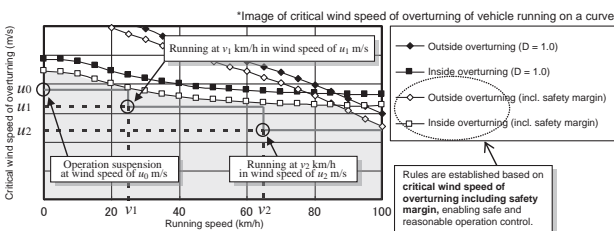


Fig. 11 Image of the New Operation Control Rules

4 Conclusion

Based on the recent results of investigations of accidents due to strong winds and results of research, we reviewed methods for wind observation and for calculating the critical wind speed of overturning to find safer and more reasonable new methods for operation control. A summary of the new methods for operation

control is as follows.

- (1) Wind Observation Method
 - Spatial average of instantaneous wind speed measured with multiple anemometers is applied.
- (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.

We introduced this new method on a trial basis from the winter of 2011 after deliberation in study meetings and committees that include external experts. In the future, further improvements will be made to the wind observation methods. We decided to apply the spatial average of multiple anemometers in this research, but if it is possible to evaluate wind speed that represents the wind acting on the whole car body using only one anemometer, that would be more preferable. So, we have started to study methods of calculating time average of measured wind speed that enable evaluation with a single anemometer that is equivalent to evaluation of spatial average with multiple anemometers. We aim to reach a conclusion before full-scale introduction of the new methods for operation control.

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