Evaluation of Critical Wind Speed of Overturning Considering Measured Lateral Vibrational Acceleration

Yu HIBINO

Hiroyuki KANEMOTO

Vehicle Mechanics Laboratory, Railway Dynamics Division

The critical wind speed of overturning obtained by RTRI's detailed equation tends to be lower than the empirically estimated speed, because it assumes the superposition of the worst conditions. In order to improve the accuracy of the evaluation, previous research has focused on the evaluation of aerodynamic forces that have the greatest influence on calculation results. Only few studies however, have been conducted on the lateral vibrational inertia force. Therefore, in order to evaluate the critical wind speed of overturning reflecting real conditions, an examination was made of the evaluation method based on the measured values of the lateral vibrational acceleration.

Keywords: crosswind, critical wind speed of overturning, RTRI detailed equation, lateral vibrational acceleration, frequency distribution, probability

1. Introduction

In order to evaluate more accurately the critical wind speed of overturning of a railway vehicle, the Railway Technical Research Institute (RTRI) created what has been termed 'the RTRI detailed equation' [1] which was based on the conventionally used Kunieda equation [2] and also reflects recent research results. However, the equation produces results which tend to be lower than empirically estimated values, because it assumes a superposition of the worst conditions, creating the need to obtain more accurate evaluations which reflect real conditions. Research to improve evaluation accuracy, however, focused on the aerodynamic forces that have the greatest influence on the calculation results, whereas little was done to study lateral vibrational inertia forces, except during a series of on-track tests which were conducted to validate assumptions about lateral vibrational acceleration, and a study on the influence of the frequency of lateral vibrational acceleration on wheel load variation. Thus, in order to evaluate the critical wind speed of overturning reflecting actual conditions, an evaluation method based on the measured values of the lateral vibrational acceleration was examined.

2. Assumption of lateral vibrational inertia force in the RTRI detailed equation

In the RTRI detailed equation, three forces are taken into consideration as the external forces which exert significant influence on overturning, namely, (1) aerodynamic forces due to crosswinds, (2) unbalanced centrifugal forces in curves, and (3) lateral vibrational inertia forces. With regards to (1), it became clear from previous research that aerodynamic forces depend largely on the shape of the car-body, the shape of the ground structure, the wind direction angle relative to the vehicle, etc. It was therefore recommended that the aerodynamic force coefficients should be obtained wherever possible through wind tunnel tests using models of the vehicles and ground structures to be investigated. For cases where individual wind tunnel

tests are unfeasible, previous wind tunnel test results [3] might be applicable, from tests conducted by RTRI using combinations of 5-types of car-body shapes and 7-types of ground structure shapes. With regards to (2), once the curve radius, cant, mass of the vehicle, and train speed are set, unbalanced centrifugal force is determined uniquely. In the case of (3), although lateral vibrational inertia force can be obtained by the product of the mass of the car-body and the lateral vibrational acceleration, the value of lateral vibrational acceleration can be largely changed depending on conditions such as vehicle, track, and running speed. Therefore, in Reference [1], a linear equation is assumed where the lateral acceleration increases proportionally to the running speed, for which the maximum value is 0.98 m/s^2 at the maximum running speed (Equation (1)).

$$\alpha_y = 0.98v/v_{\max} \quad (1)$$

where α_y is the lateral vibrational acceleration (m/s^2), v is the running speed (km/h), and $v_{\max}$ is the maximum running speed (km/h).

Equation (1) is an assumption that was derived from a series of on-track test results, that is, after excluding high-frequency components of about 2Hz or more that do not affect vehicle overturning, while taking into account maximum half-amplitude values. On-track tests were recently conducted to confirm the generality and application range of (1) for measuring lateral vibrational acceleration generated on a running vehicle. It was reported that less than 1% of the measured data exceeded the values estimated through (1) [4]. Therefore, (1) can be considered to be generally appropriate as an assumption which falls on the safety side. However, it is possible that the proportion of lateral vibrational inertia force values exceeding actual conditions, might be greater, as compared to the case of aerodynamic force and unbalanced centrifugal force. Further, Reference [1] recommends that when estimating the critical wind speed of overturning for a specific event such as for an accident investigation, the lateral vibrational acceleration measured at that point which corresponds to

actual track conditions, should be used. Therefore, in the following chapters, in order to generalize the procedure using measured acceleration and to evaluate the critical wind speed of overturning reflecting actual conditions, an examination is made of the evaluation method based on measured values of the lateral vibrational acceleration acquired through on-track tests using several types of vehicles traveling on different lines.

3. Measurement of lateral vibrational acceleration

3.1 Outline of measurement tests

The measurement tests were conducted by the Rolling Stock Design Office of the West Japan Railway Company (JR-West) Rolling Stock Department, which then sent the measurement data to RTRI. The measurement tests were conducted using standard commuter type vehicles or limited express type vehicles on tracks with different levels of maintenance. Table 1 gives details about each of the measurement test conditions, such as vehicle type and track grade. Track grades were classified into two groups based on the company's standards, for convenience, called group A and group B. The measurement items were lateral vibrational acceleration at the center of the car-body floor and running speed. In the case of measurement tests on meter-gauged railway lines, the roll angle and the yaw angular velocity of the car-body were also measured.

Table 1 Measurement test conditions

Condition	Track grade	Vehicle type	Approximate running distance	Target vehicle
Condition 1	Group A	Limited express	540 km	3 cars / 3 car train
Condition 2	Group A	Commuter	440 km	4 cars / 4 car train
Condition 3	Group B	Pendulum limited express	660 km	Leading car / 2 car train
Condition 4	Group B	Standard	570 km	Leading car / 2 car train
Condition 5	Shinkansen	Shinkansen	1240 km	Leading car / 16 car train

3.2 Primary data processing

The measurement data was subjected to the following primary processing: First, 2 Hz low-pass filter processing was performed in order to remove noise or high-frequency vibration components not affecting overturning. Next, in order to remove steady lateral acceleration in curved sections, a 3-sec moving average (average of the data for the preceding and succeeding 1.5 sec) was subtracted from the time-series data resulting from the 2 Hz low-pass filter processing. In other words, the time-series data were prepared at a sampling rate of 100 Hz by extracting only the pure variation component (deviation component) with respect to vibrations below 2 Hz. Based on this, the relationship between the running speed and the lateral vibrational acceleration (absolute value) and the frequency distribution of the lateral vibrational acceleration were obtained.

3.3 Results of data analysis

3.3.1 Relationship between running speed and lateral vibrational acceleration

(1) Comparison of all data

Figures 1 (a) to (d) show the relationship between the running speed and the lateral vibrational acceleration (absolute value) under the conditions 1 to 4 shown in Table 1. In each figure, the currently assumed equation (Equation (1)) in the RTRI detailed equation is also shown by a solid line. Although each figure shows in common that the lateral vibrational acceleration tends to increase as the running speed increases, it can be seen that in most cases this increase is generally smaller than the outcome estimated using (1). However, in the middle to low speed range of about 50km/h or less, there are some cases where the measured values exceed the estimated values obtained using (1).

By comparing Figs. 1 (a), (b) and Figs. 1 (c), (d), as a whole, the maximum value at each running speed in group A tends to be smaller than that in group B. Consequently, it can be seen that the generated tendency in lateral vibrational acceleration depends on track grade. Moreover, in the case of the same track grade, while there is no great difference between the commuter type vehicle and the limited express type vehicle based on a comparison of Figs. 1 (a) and (b), a slight difference can be seen between the standard type vehicle and the pendulum limited express type vehicle in the high speed range based on a comparison of Figs. 1 (c) and (d). Nevertheless, in all Figs. 1 (a) to (d), the measured values of the lateral vibrational acceleration are generally smaller than those estimated using (1), and the percentage of data exceeding the assumption in the middle to low speed range was less than 1 % in all cases. This tendency is the same as that reported in Reference [4]. Apart from the above, data for the Shinkansen tested under condition 5, was not directly compared with other conditions in this paper, because track maintenance standards, vehicle specifications, running conditions, etc. are very different from those of meter-gauged railway lines. Nevertheless, the tendency for maximum values of lateral vibrational acceleration to be generally proportional to the running speed resemble the tendency found on meter-

Fig. 1 Relationship between running speed and lateral vibrational acceleration

gauged railway lines, although the maximum values were about half those reported for the meter-gauged railway lines. In addition, given that the mechanism whereby lateral vibration excited by track irregularity affects the overturning of the vehicle is the same for Shinkansen lines and meter-gauged railway lines, the procedure for evaluating the critical wind speed of overturning of vehicles on both types of lines is identical, and is described later.

From the results mentioned above, regardless of the track grade (or track maintenance standard) and vehicle type, it was reconfirmed that the currently assumed equation (1) of the RTRI detailed equation is generally valid as a safe side assumption. In addition, it became clear that if there are differences in measured lateral vibrational acceleration data due to track grade or vehicle type, evaluation of the critical wind speed of overturning reflecting actual conditions was possible by using either measured data or the assumed equation based on measured data, without compromising the safety.

(2) Excluding data collected when passing through turnouts

The data exceeding the assumed equation mentioned above, in the middle to low speed range (hereinafter referred as extremal value), was empirically assumed to occur mainly when the vehicle was passing through a turnout, although this has not been investigated in detail. This paper, therefore re-analyzed the data collected under condition 1 (Fig. 1 (a)) after excluding the data collected when the vehicle was passing through a turnout. More specifically, the route taken by the test vehicle was provided by JR-West, and the locations where the test vehicle passed the branch side of turnouts were confirmed. Then, from the time-series waveform of the car-body yaw angular velocity, the points where large fluctuation were observed (where the vehicle changed running direction left and right largely) within a short time of about 1 to 2 seconds were extracted. If these points were identified as turnouts, the corresponding lateral vibrational acceleration data was excluded. The re-analyzed results following the exclusion of this data is shown in Fig. 2. Figure 2 shows that the extremal values observed in the middle to low speed range were almost eliminated, and the acceleration data was below the values obtained through the currently assumed equation.

These results confirmed that most of the extremal values found in the middle to low speed range were due to the influence of the vehicle passing through a turnout. Although only the results of condition 1 were re-analyzed in detail, similar tendencies are expected with the other conditions, because the characteristics of time-series waveforms of the lateral vibrational acceleration under the other conditions did not differ much from those obtained

Fig. 2 Re-analyzed result after excluding data collected from vehicles passing through turnouts

under condition 1. Therefore, when evaluating the critical wind speed of overturning in a general section, such as when considering operational control in strong wind, it is thought to be appropriate to use the assumed equation based on measured data after excluding those extremal values. On the contrary, if the extremal values observed when passing through turnouts are included in the evaluation of lateral vibrational acceleration, the calculation results of the critical wind speed of overturning are affected by these extremal values which only account for less than 1 % of all data. In this case, there is a possibility that the safety margin will be over-estimated. In addition, for the method used to exclude data collected as vehicles pass through turnouts, it is best to remove the data individually after confirming the time-series waveform one by one, as mentioned in this paper, however this might be difficult in practice. Therefore, in practice, for all data including data collected vehicles passing through turnouts, the assumed equation for lateral vibrational acceleration is estimated by including almost all the extremal values in the high speed range, and by automatically neglecting those in the middle to low speed range. By adopting this approach, it is thought that almost the same result can be obtained.

With regards to running safety in crosswinds when passing through turnouts, which is neglected here, it is considered that the assessment of safety in such conditions should be conducted on a case-by-case basis, only if required. However, the need for such assessment is generally considered to be low. This is because even if the influence of running through turnouts is not included, the general safety evaluation will not be affected. This is because turnouts are mostly located near main stations which are surrounded by tall buildings, and the situation subjected to strong winds are presumably rare. Furthermore, running speeds on the branch side of turnouts are relatively low, which means that the critical wind speed of overturning will be relatively high. Nevertheless, in opposite situations, i.e., if the location of turnout is exposed to possible strong wind, and if the running speed through the turnout is relatively high, the critical wind speed of overturning should be evaluated individually. And if necessary, it is desirable to take countermeasures, such as strengthening wind observation systems, installing windbreak fences, and reducing running speed.

3.3.2 Occurrence frequency analysis of lateral vibrational acceleration

(1) Frequency distribution at each running speed

In order to clarify the influence of the running section and the running speed on the occurrence of lateral vibrational acceleration, a frequency analysis was conducted using data after exclusion of values collected when a vehicle was passing through turnouts, as mentioned above. That is, after dividing the running test data into 15 sections separated by stops, the occurrence frequency distribution of the lateral vibrational acceleration was obtained for every 10 km/h range in running speed and with a class width of acceleration of 0.03 m/s^2 . Among these results, the relative occurrence frequencies for the section with the longest running distance, and speed ranges of 0 to 10 km/h, 40 to 50 km/h, 80 to 90 km/h, and 120 to 130 km/h are shown in Figs. 3 (a) to (d) respectively, as an example. In each figure,

Fig. 3 Occurrence frequency distribution of lateral vibrational acceleration (Condition 1)

the standard deviation σ obtained from each set of lateral vibrational acceleration data is indicated, and a normal distribution with mean value 0 and standard deviation of the above value is also indicated by a solid line. From each figure, it can be seen that the occurrence frequency of the lateral vibrational acceleration generally follows a normal distribution, and there is almost no difference between the vehicles. Although all data cannot be shown due to space limitation, similar trends were observed in other sections and for different running speeds.

(2) Relationship between running speed and standard deviation of acceleration

The relationship between the running speed and the standard deviation of acceleration in each section obtained from the above-mentioned analysis result is shown in Fig.4. From Fig.4, it can be seen that the standard deviation of the lateral vibrational acceleration tends to increase proportionally to the running speed, and the difference between the sections is relatively small. Therefore, considering the result of discussion in Section 3.3.1 (2), when evaluating the critical wind speed of overturning in general sections based on the measured values of the lateral vibrational acceleration, it is appropriate to assume a linear equation for the relationship between the running speed and the lateral vibrational acceleration. That is, if a linear equation is assumed to include the maximum values of the measurement data (but excluding the extremal data collected from vehicles when passing through turnouts in the middle to low speed range), it is considered possible to obtain an evaluation which is safe and reflects actual conditions.

Fig. 4 Relationship between running speed and standard deviation (Condition 1)

4. Case study of critical wind speed of overturning based on measured lateral vibrational acceleration data

4.1 Assumption of lateral vibrational acceleration based on measurement data

This chapter examines the influence of the difference in the assumed equation for lateral vibrational acceleration on the calculation results of the critical wind speed of overturning. Table 2 shows the calculation conditions. The vehicle specifications used for the calculation were the standard values (approximate values) for a relatively light-weight recent commuter vehicle, and the mass of the vehicle was assumed to be 30 tons. Wind tunnel test results [3] performed on the leading car of a commuter vehicle on a double track viaduct with a girder thickness of 1 m, were used to obtain the aerodynamic coefficients. Different track alignments were considered, namely straight and curved lines. For curved lines, sections with high running speeds and large cant deficiency in particular were selected, since these are the most severe conditions for overturning due to crosswind. As for the lateral vibrational acceleration, besides the currently assumed equation (Equation (1)), the following linear equation was assumed, which was derived from the measurement data of the lateral vibrational acceleration under condition 1, as shown in Fig. 2.

$$\alpha_y = 0.5v/v_{\max} \quad (2)$$

Note that the above assumed equation is applicable to the measurement result of condition 1 in this paper, and if the conditions such as track maintenance are different, the assumed equation could be also different.

Table 2 Calculation conditions

Vehicle	Commuter type (Leading car) *presumable specification
Ground structure	Double track viaduct (girder thickness 1 m)
Track alignment	① Straight, ② Curve (R=500 m, C=105 mm)
Lateral vibrational acceleration	① Current assumption (Equation (1)) ② Measurement-based assumption (Equation (2))
Running speed	0 ~ 100 km/h

4.2 Calculation results of critical wind speed of overturning

The calculation results are shown in Fig. 5. From Fig. 5, in both straight and curved sections, it can be seen that by using the assumed lateral vibrational acceleration based on measurements, the critical wind speed of overturning is calculated to be 2 to 3 m/s higher than when using the current assumption. Therefore, the calculated results of the critical wind speed of overturning by using the current assumption are thought to be evaluated to be below the actual critical speed, which means a safe-side assumption.

Additionally, even when the calculation is performed by using the measurement-based assumption of the lateral vibrational acceleration as described above, it can be said that the assumption is still on the safe side, because it is assumed so as to include the maximum values of the measurement data. Moreover, it can be easily estimated from

Fig. 5 Relationship between running speed and critical wind speed of overturning

Fig. 3 that the occurrence frequency of such values close to the maximum value is quite low. For example, in Fig. 3(d), the maximum value (absolute value) of the lateral vibrational acceleration was 0.32 m/s^2 from the analysis result of the measurement data, which corresponds to 4.6σ in the normal distribution in the figure. In the measurement-based assumption (Equation (2)), 0.5 m/s^2 is assumed at the maximum running speed, which corresponds to 7.2σ .

Therefore, by interpreting these safety margins probabilistically, it may be possible to consider operation control under strong wind that achieves both running safety and transportation stability at a higher level. In the next chapter, assuming that the lateral vibrational acceleration follows a normal distribution, the calculation results of the critical wind speed of overturning will be interpreted in a probabilistic manner.

5. Critical wind speed of overturning considering occurrence frequency of lateral vibrational acceleration

5.1 Probabilistic interpretation of critical wind speed of overturning

On the premise of static analysis such as the Kunieda equation or the RTRI detailed equation, a linear relationship exists between lateral vibrational acceleration and the critical wind speed of overturning (Fig. 6). Therefore, it is possible to consider that the critical wind speed of overturning has a probability distribution corresponding to the above-mentioned probability distribution of the lateral vibrational acceleration. That is, the horizontal axis of the frequency distribution shown in Fig. 3 may be substituted by the critical wind speed of overturning using the relationship shown in Fig. 6. As an example, a schematic diagram in which the probability distribution shown in Fig. 3(d) is replaced with the probability distribution of the critical wind speed of overturning is shown in Fig. 7. Note that the calculation conditions of the critical wind speed of overturning are virtual. From Fig. 7, it can be seen that the calculation result of the critical wind speed of overturning by using the measurement-based assumption that was described in the previous section corresponds to a phenomenon that occurs with quite low probability. If the current assumption (Equation (1)) is used for the lateral vibrational acceleration, the probability is further lowered. Therefore, the tendency whereby the calculation results obtained using the current assumption tend to be lower than the empirically estimated values, as mentioned at the be-

Fig. 6 Relationship between lateral vibrational acceleration and critical wind speed of overturning

Fig. 7 Probability distribution of critical wind speed of overturning (Schematic diagram)

ginning, can be interpreted to mean that it is because quite rare conditions are assumed.

5.2 Notation of critical wind speed of overturning based on probabilistic interpretation

The critical wind speed of overturning based on probabilistic interpretation is not represented by a single numerical value as in the current notation, but has a fluctuation range corresponding to the probability distribution. For example, as shown in Fig. 7, if the probability distribution of the lateral vibrational acceleration is assumed to follow the normal distribution with mean value 0 and standard deviation σ , the probabilistic distribution of the critical wind speed of overturning follows the corresponding normal distribution with mean value w and standard deviation σ_w . In this distribution, the critical wind speed of overturning is $w \text{ m/s}$ on average, and when considering the fluctuation (occurrence probability) of k times σ_w , it has a variation of $\pm k\sigma_w \text{ m/s}$. In the example of Fig. 7, if considering the occurrence probability equivalent to 3σ (that is 10^{-3} order), it can be described as “ $30.3 \pm 1.0 \text{ m/s}$ ”, and if considering the measurement-based assumed equation (2) mentioned above (in the case of Fig. 7, the occurrence probability equivalent to 7.2σ (that is 10^{-13} order)), it can be described as “ $30.3 \pm 2.5 \text{ m/s}$ ”. In conventional notation, for example, in the case of the calculation result by using the measurement-based assumed equation (2), it is described by one value as “ 27.8 m/s ” which is the lower limit value obtained by “ $30.3-2.5 \text{ m/s}$ ”. Consequently, it was not possible to distinguish between the average part (deterministic element) and the fluctuational

part (probabilistic element), so it was not possible to grasp the calculation result in accordance with the actual condition (or phenomenon). Therefore, if the new notation as described above is adopted, the distinction between them becomes clear, and the critical wind speed of overturning can be described in a form corresponding to the assumed occurrence probability. That is, the part of " $\pm k\sigma_w$ m/s" is the basis for considering the safety margin, and the value changes depending on the assumed occurrence probability. In addition, in the case of checking the validity of the current operation control rules, it will be easier to understand instinctively the possibility of encountering strong wind exceeding the critical wind speed of overturning, because the average part and the probabilistic part are clearly distinguished. However, the most important issue when considering operational control rules, "how large a safety margin should be provided," needs to be carefully further considered. For the evaluation of safety against crosswinds in Japan in particular, given the deterministic way in which safety is considered, the probabilistic discussion is immature, and there is room for research and development. Therefore, it is deemed necessary to refer to safety evaluation methods used in other technical fields such as aviation and nuclear power, or used overseas. The aim is to establish an evaluation method and apply it in practice to operations, while cooperating with researchers in the fields of vehicle dynamics, meteorology, and aerodynamics.

6. Conclusions

In order to evaluate the critical wind speed of overturning reflecting real conditions using the RTRI detailed equation, an examination was made of an evaluation method based on measured values of lateral vibrational acceleration. Results of the analysis of the measured lateral vibrational acceleration data of the car-body provided by JR-West, and the calculation results of the critical wind speed of overturning based on this data, are as follows.

- (1) Results of the analyses made of lateral vibrational acceleration measurement data collected from several types of vehicle running along different lines, made it possible to clarify the difference in resulting acceleration tendencies depending on track grade or vehicle type.
- (2) An investigation of the relationship between the running speed and the lateral vibrational acceleration, revealed that the acceleration tended to increase as the running speed increased, although in most cases they were generally smaller than those estimated by the currently assumed equation in the RTRI detailed equation. However, in the middle to low speed range of about 50 km/h or less, there were some cases where the measured values exceeded the estimated values obtained with the

currently assumed equation, though these were confirmed to occur mainly when the vehicle was passing through turnouts.

- (3) In the case of evaluating the critical wind speed of overturning in general sections based on the measurement data of the lateral vibrational acceleration, if a linear equation for the relationship between the running speed and the lateral vibrational acceleration is assumed so as to include the maximum values of the measurement data (but excluding the extremal data when passing through turnouts in the middle to low speed range), it is considered possible to obtain an evaluation which reflects actual conditions.
- (4) A frequency analysis of the lateral vibrational acceleration for every 10 km/h range in running speed, found that the occurrence frequency generally followed a normal distribution. And it was seen that the standard deviation tended to increase almost proportionally to the running speed.
- (5) By assuming a probability distribution of lateral vibrational acceleration, it was shown that the probabilistic interpretation of the calculation result of the critical wind speed of overturning is possible. In addition, by dividing the calculation result of the critical wind speed of overturning into the average part (deterministic element) and the fluctuational part (probabilistic element), it was shown that the obtaining a notation of the critical wind speed of overturning corresponding to the assumed occurrence probability was possible.

Acknowledgment

The authors would like to express their thanks to staff at the Transport Safety Department and the Rolling Stock Department of JR-West for their help and cooperation in collecting on-track measurement data of the lateral vibrational acceleration.

References

- [1] Hibino, Y. and Ishida, H., "Static analysis on railway vehicle overturning under crosswind," *RTRI Report*, Vol.17, No.4, pp.39-44, 2003 (in Japanese).
- [2] Kunieda, M., "Theoretical study on the mechanics of overturn of railway rolling stock," *Railway Technical Research Report*, No.793, 1972 (in Japanese).
- [3] Tanemoto, K. et al., "Results of wind tunnel tests for aerodynamic coefficients of railway vehicles," *Railway Technical Research Report*, Vol.27, No.1, pp.47-50, 2013 (in Japanese).
- [4] Oyama, A. et al., "Lateral acceleration for evaluation of railway vehicle against crosswind," *J-Rail 2015*, SS7-3-1123, 2015 (in Japanese).

Authors

Yu HIBINO, Dr. Eng.
Senior Chief Researcher, Head of Vehicle Mechanics Laboratory, Railway Dynamics Division
Research Areas: Vehicle Dynamics, Cross Wind Safety

Hiroyuki KANEMOTO, Dr. Eng.
Senior Researcher, Vehicle Mechanics Laboratory, Railway Dynamics Division
Research Areas: Vehicle Dynamics, Cross Wind Safety