Introduction

The vision to establish a fully-fledged European market for railway services and equipment requires technical regulations for interoperability. One topic to be regulated is the safety of railway operation under cross wind conditions. Based on the first German approach (Ril401 [1]) and the results of the DEUFRAKO research project [2] a new method calculating characteristic wind curves (CWC) for passenger trains has been developed. The result is a 3-step method, where every step increases the accuracy of the CWC. These methods are harmonized with the German railway authority and defined in the new German regulation for crosswind stability (Ril807.0401–807.0449 [3]). The methodology is also in accordance with the European technical specification for interoperability (TSI) concerning crosswind stability [4]. This paper describes the German methodology for calculating the characteristic wind values and curves for passenger railway vehicles.

Overview

To analyse the cross wind behaviour of a vehicle several aspects have to be considered. Due to the characteristics of the vehicle (maximum speed, masses, aerodynamics, suspension) the cross wind behaviour of each vehicle type is different. Likewise the infrastructure (track alignment and direction, bridges, embankment) has to be taken into account. The following parameters vital affects the cross wind characteristics of a traffic:

- Vehicle characteristics (masses, aerodynamics, suspensions)
- Current vehicle velocity
- Current wind speed and direction at the track considering track environment (bridges, embankment, wind fences)

Thus it appears that the analysis of the cross wind aspects is linked to the vehicle and the infrastructure. To reduce the complexity of the investigations, a separate treatment for the admittance of lines and vehicles was one important aspect in the development of the cross wind calculation. The calculation is based on a risk assessment for cross wind with reference vehicles and lines with longtime operational experience. For the admittance of new vehicles or lines the cross wind characteristics have to be as good or better as the reference to take no higher risk.

The division into vehicle and line has been done in such a way, that the operation of an vehicle on an approved line is safe. If the cross wind properties of one part (vehicle or line) are worse than the reference, a risk analysis of the vehicle on the line where the operation is planned is needed. In this paper, the German methods for calculating the cross wind behaviour of passenger railway vehicles are described (upcoming Ril 807.0401 – 807.0449 [3]).

Calculation of the cross wind characteristics for railway vehicles

As described in Ril 807.0401 – 807.0449, a future operational traffic has to meet the cross wind risk of the reference vehicle or line. Figure 1 shows the process flow for the cross wind investigations of the vehicle. The first step is to classify the vehicle (see table 1) on the criteria of the maximum speed and the vehicle operation mode (conventional/tilting). Tilting trains always belong to class E, but can have an additional class, if in conventional operation mode the maximum speed is above 140 km/h (e. g. \(v_{\text{max}}\) (conventional)=230 km/h results in class E and B). Depending on the classes, different reference vehicles are defined.
After the classification a pre-assessment of the vehicle with a simple P0-method is done. The validity of the method is restricted by the vehicle design and the class. Result of the P0-method is a characteristic wind value (CWV), that is compared with the reference value of the associated vehicle class. If the value is equal or higher than the reference value, the vehicle is graded to be cross wind stable. This method is in particular useful for heavy vehicles, like locomotives. If the vehicle is potentially unstable, than the calculation with P1- or P2-method has to be done.

Results of the P1- and P2-methods are characteristic wind curves (CWC). CWC’s are tables including the different train speeds, different wind angles and the characteristic wind speed at which the train reaches the criterion for crosswind stability. The scenario for crosswind stability is the overturning of the train, so the criterion for the CWC is an unloading of 90% Q-forces on the windward wheels for each bogie. The following part of the safety verification is the comparison of the CWC’s with the CWC’s of a reference vehicle of the class.

The P1-method is a quasi-static method without considering dynamic effects, where a moment equilibrium of the aerodynamic forces and the mass forces (90% unloading) is reached. For a common vehicle design (vehicle with two bogies, no coupling between adjacent vehicles) the mathematical equations are described for calculating the CWC’s. For different vehicle designs the equations can be adjusted or a multi-body simulation tool can be used.

The most complex method is the P2-method, which considers the dynamic effects on cross wind. Starting at the wind scenario, the reaction of the vehicle and the time history of wheel forces is calculated and assessed. This method requires a multi-body simulation.

If the CWC is smaller than the reference CWC, a speed reduction or an individual risk analysis for the vehicle on the specific line is the fallback option to admit the vehicle.

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<table>
<thead>
<tr>
<th>Class A</th>
<th>230 km/h &lt; v &lt;= 350 km/h</th>
<th>conventional</th>
<th>TSI HS RST class 1, high-speed trains</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class B</td>
<td>200 km/h &lt; v &lt;= 230 km/h</td>
<td>conventional</td>
<td>low HST / fast IC-trains</td>
</tr>
<tr>
<td>Class C</td>
<td>160 km/h &lt; v &lt;= 200 km/h</td>
<td>conventional</td>
<td>IC-trains, fast IC-trains</td>
</tr>
<tr>
<td>Class D</td>
<td>140 km/h &lt; v &lt;= 160 km/h</td>
<td>conventional</td>
<td>Fast regio trains</td>
</tr>
<tr>
<td>Class E</td>
<td>140 km/h &lt;= v &lt;= 160 km/h</td>
<td>tilting mode</td>
<td>Tilting trains</td>
</tr>
</tbody>
</table>

Table 1: Classification of vehicles.
The advantage of this 3-step approach is, that for cross wind stable vehicles a very simple calculation is possible, while for vehicles with a potential low cross wind stability more complex methods are provided. Due to the simple P0-method the reference values have a large safety margin. The reference CWC’s for the P1- and P2-methods are identical. For all investigated cases the CWC’s coming from the P1-method are lower than the CWC’s resulting from the P2-method due to the quasi-static approach. So, calculating CWC’s with the P2-method benefits the vehicle (see table 2).

<table>
<thead>
<tr>
<th>method</th>
<th>description</th>
<th>input data</th>
<th>quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>P0</td>
<td>simple static approach</td>
<td>mass, side area, vehicle length and height</td>
<td>poor</td>
</tr>
<tr>
<td>P1</td>
<td>static approach including main information about the vehicle using full aerodynamic data set</td>
<td>aerodynamic data, masses, stiffness (nonlinear), bump stops</td>
<td>good</td>
</tr>
<tr>
<td>P2</td>
<td>considering dynamic behavior with full multi-body simulation wind scenario: Chinese hat using full aerodynamic data set</td>
<td>aerodynamic data, full vehicle data set (masses, damping, stiffness etc.)</td>
<td>excellent</td>
</tr>
</tbody>
</table>

Table 2: Comparison of the methods.

**P0-method**

The P0-method is used to proof, if the vehicle is cross wind stable or not. Result of the method is the characteristic wind value (CWV) that is compared with the reference value associated with the vehicle class.

The mathematical method is based on the tilting or aerodynamic moment $M_A$ and the restoring moment $M_R$ due to the vehicle mass on a straight track without cant deficiency. When the equation (1) with the factor $f_S = 0,6$

$$M_A = M_R \cdot f_S$$

is fulfilled, the characteristic wind value can be achieved from the equations (2), (3):

$$M_R = m \cdot g \cdot b_A$$

$$M_A = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A_0 \cdot d_0 \cdot c_{Mx,lee}(\beta)$$

with $\rho = $ air density ; $A_0 = $ reference area, $d_0 = $ reference length ; $b_A = $ semi wheelbase $c_{Mx,lee}(\beta) = $ function for leeward aerodynamic rolling coefficient depending on the angle of incidence. The relative incident flow is resulting from

$$v^2 = v^2 + v^2$$

with $v_W = $ wind speed ; $v_tr = $ vehicle speed.

The angle of incidence $\beta$ can be calculated as follows:

$$\beta = \arctan \left( \frac{v_W}{v_tr} \right)$$

For the calculation of the aerodynamic moment, the aerodynamic coefficient depending on the angle of incidence is necessary. This function (6) can be derived from a universal aerodynamic function using the vehicle length $L$ (without buffers) and the vehicle roof height $H$. The derivation is described in [3].

$$c_{Mx,lee}(\beta) = f(H, L)$$
An iteration method to determine the wind speed is necessary to solve this implicit system of equations for a given train speed. The P0-method is valid for the following conditions:

- Only suitable for vehicles with two running gears (2 bogies or 2 single wheelsets)
- No mechanical coupling to adjacent vehicles with lateral- and vertical forces or moments.
- Conditions for universal aerodynamic given

Vehicles that do not satisfy these conditions are treated as vehicles with a potential small crosswind stability and have to be assessed with the P1- or P2-method.

**P1-method**

The P1-method is a quasi-static method that considers the kinematic behaviour of the vehicle neglecting any dynamic effects (e.g. dampers). For calculating the CWC’s the essential parameters are as follows:

- Unsprung masses like wheelsets and bearings (masses, center of gravity (c.g.))
- Primary suspended masses like bogies and attached parts (masses, c.g.)
- Secondary suspended masses like coach (masses, c.g.)
- Primary and secondary suspension (linear / nonlinear stiffness)
- Rolling suspension (stiffness)
- Primary and secondary bump stops in lateral and vertical directions
- Wind loads (measured aerodynamic coefficients)
- Influence of tilting mechanism on center of gravity

The mathematical equations for the CWC’s are derived from a physical equivalent model with 5 masses and 10 DOF (5-mass-model) as seen in figure 2.

![Physical equivalent model](image)

**Figure 2: Physical equivalent model (5-mass-model with 10 DOF).**

A vehicle adjusted simplified multi-body model can be used for vehicles, that can not be described by this 5-mass-model. For such a model an additional verification is necessary.

The wind load acting on the coach is calculated by aerodynamic coefficients and the wind speed. The aerodynamic coefficients are measured in a wind tunnel with a scaled model [3]. At the equilibrium between wind load and vehicle forces the wheel loads are evaluated. Then the wind speed is varied, so that the wheel loads have a remaining value of 10% of the nominal wheel loads (10% \(Q_0\) or 90% unloading). This characteristic wind speed is one point of the CWC. For getting the complete CWC’s, several calculations are necessary with different vehicle speeds and cant deficiencies.
P2-method

A multi-body simulation is used for calculating the CWC’s with the P2-method, because dynamic effects of the vehicles on a wind scenario are considered. The method has the following attributes:

- The aerodynamic coefficients are derived from wind tunnel tests with scaled models.
- The wind scenario is based on meteorological studies [2] and describes the behaviour of a gust.
- The vehicle dynamic is described by a multi-body model that is verified by measured data from the real vehicle. Thus, complex vehicle designs can be analysed.
- No track irregularities are used for the calculation.

The multi-body model is assumed to be a 3D-Model including the coach, the bogies and the wheelsets as separated masses. All elements that have a vital influence on the cross wind behaviour must be included. For example, for conventional vehicles with bogies the following elements are needed:

- Masses:
  - Coach, bogies, wheelsets and other important masses (masses, moment of inertia, c.g.)
- Suspensions (primary and secondary)
  - Geometry
  - Stiffness in x-, y- and z-direction with nonlinear characteristics
  - Damping characteristics of all relevant dampers in lateral and vertical direction
  - Geometry and characteristics of all bump stops
- Tilting mechanism
- Wheel/Rail Contact

The time history of the wind scenario is described by a mathematical model based on the behaviour of a typical wind gust, derived from meteorological measurements [2]. The scenario is used as excitation for the dynamic model and the characteristics of the scenario, also called chinese hat, can be seen in figure 3. For the simulation calculation the vehicle has a constant velocity.

Criterion for the CWC’s is the unloading of the bogie averaged wheel loads up to 10% of the nominal wheel load (10% of $Q_0$). From the simulation results, the time histories of the wheel loads are derived. The calculation of the criterion is done by the following procedure:

- Addition of the wheel loads for each bogie
- Division by the sum of the nominal wheel loads ($Q_0$) for each bogie
- Low-pass filtering with 2 Hz (Butterworth-Filter, 4th order)
- Minimum for each bogie
Example

Figure 4 shows typical results from the three methods. The left diagram shows the CWV from the P0-method (one value) and the CWC’s from the P1- and P2-method with the vehicle velocity. These values are derived for no cant deficiency (aq=0.0 m/s²). The CWC’s for the P1-method is lower than the CWC’s for the P2-method, as expected. The dotted curves and the ring represent the reference values. On the right side the CWC’s for v=200 km/h over the cant deficiency are shown. For a complete set of CWC’s the curves from v=80 km/h to v_{max} are calculated and compared with reference values for velocities of 120 km/h and above.

![Diagram of CWC and CWV](image)

Figure 4: Example of CWC and CWV.

References