Effects of Strong Cross Winds on High-Speed Trains: A methodology for risk assessment and development of countermeasures

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1 INTRODUCTION

The effect of side winds on rail transport has been investigated since the 1970s by international research, especially by the railways in Germany, England and Japan. For the DB the subject of side winds only became important with the introduction of the ICE2 with its fast, light driving trailer. Since then DB has been involved in intensive interdisciplinary cooperation to develop a generally valid method for rail transport to guarantee that railways can operate safely with a strong side wind.

A basic procedure was described and discussed in 1997 at the World Congress for Railway Research [17]. This paper describes the methodology derived from its continuous further development, as summarised in the Draft Code of Practice Ril 401 of Deutsche Bahn published in May 2000. The procedure specified in Code of Practice Ril 401 was recognised in May 2000 by the Eisenbahn-Bundesamt (Federal Railway Office - EBA) as a means of proving that railway traffic can run safely when there is a side wind and has since then become part of the vehicle acceptance procedure used by the EBA.

2 BASIC PRINCIPLES AND PROCEDURE

The effect of side wind on rail vehicles is basically determined by the following parameters:

- The vehicle properties such as shape, weight, position of centre of gravity, running gear properties, etc.
- The track parameters such as radius, cant, track bed, track bed quality.
- The meteorological conditions, especially the frequency with which strong winds occur locally on the line (this is in turn determined by the direction of the track, the conditions in the surrounding area, the position of the line whether it is on an embankment or viaducts, etc.).

These factors should be considered together not individually.

The wind dominates the side wind problem as the parameter that causes it. Because of its random occurrence it only becomes an event if three parameters occur at the same time at the same place:

- wind of a certain strength
- with the train in “critical” configuration (in general, light end vehicle at the front)
- at a certain place on the track.

The investigation of the potential danger for rail traffic produced by a side wind is, therefore, directly connected with the use of probability methods. These are described in the guidelines of the Federal Ministry of Transport (BMV) entitled “Risk orientated safety proof in railway operation” in [4] and [5] and they have already been used by DB for a considerable time [22].
Following these directives every prove of safety is based on the concept of individual and collective risks. The individual risk \( r_i \) plays the central role as it expresses the view of an individual person, who does not care how many other people besides himself are endangered in a certain situation. The collective risk integrates all individual risks, weights them depending on the degree of damage and corresponds therefore to the view of an operator of a technical system. Consequently the safety philosophy should in first place take care that the individual risks are not exceeding a certain limit (i.e. first respect the requirements of the individual). In the case of necessary countermeasures (in order to keep the \( r_i \) under a certain limit) these should then be chosen optimising the collective risk of the system (i.e. in second place to respect the economical interests of the operator). These principles should also be applied for the proof of safety in the context of side winds.

For traffic applications this individual risk \( r_i \) can then be calculated using a simple formula [34]:

\[
    r_i = N_i \cdot HR \cdot T_i \cdot C \cdot F_i
\]

With:

- \( N_i \) No. of usage by the individual per year, e.g. no. of flights per year [1/a]
- \( HR \) Hazard rate, (e.g. no. of fires in the turbine engine per year) [1/a]
- \( T_i \) Duration of stay in the „danger zone“, e.g. duration of a typical flight [a]
- \( C \) Criticality, e.g. how many times may I have a fire in the engine until the aircraft crashes [-]
- \( F_i \) Fatality; Probability, that the individual is killed during the accident [-]

In the case of the side wind problem HR can be interpreted as No. of exceedence of the permissible wind speed for the vehicle (procedure described below). But, because of the safety implicitly built into the calculation procedure and (from the statistical point of view) the small amount of service experience with light, fast driving trailers the parameters \( C \) and \( F_i \) are very difficult to be defined on an objective basis.

The same is true for the problem to define a quantifiable value for an “acceptable risk of side winds”. Even if the Target of Individual Risk (TIR) for the whole railway system may be derived on a commonly acceptable basis (e.g. by applying the MEM method of “Minimum Endogenous Mortality” a value of \( \text{TIR} = 10^{-5} [1/a] \) was found) it was not possible to define a value for the acceptable share of the side wind risk compared to the whole system. Taking together all uncertainties and assumptions, the result may vary be several orders of magnitude.

For this reason the study is based on the idea to compare the individual risk not to quantitative “generic” value, but to a reference traffic which, because of the amount of positive service experience, can be regarded to be safe in terms of side wind stability. Under the precondition that the reference traffic is representative for the traffic of evidence (i.e. that \( N_i, T_i, C \) and \( F_i \) are likely the same for both traffics), then the individual risks can be compared directly. Then it applies:

\[
    HR_{\text{ref}} \geq HR_{\text{proof}}
\]

where \( HR \) is the exceedence rate of the permissible wind speed on the vehicle.

## 3 Reference Traffic

It is obvious that the assessment of all the types of traffic using only one reference scenario can hardly be sufficient, since not only the vehicle properties (for example a “Silberling“ N
driving trailer would be compared with an ICE3) but also the operating conditions for the different types of vehicle are significantly different.

It is, therefore, sensible to divide the various trains and vehicles into different classes and to compare the same types of vehicles within these classes. A suitable parameter to differentiate between vehicles is their speed respecting that physical, operational and infrastructural parameters are significantly changing when operational velocities are increasing.

Current railway operation can be divided into 4 classes:

1. “Suburban” with a maximum speed below 140km/h.
2. “Regional traffic” with a maximum speed of 160km/h. Into this class fall all freight wagons and combined traffic (KLV) units.
3. “Intercity traffic” with a maximum speed of 230km/h. In this class double deck vehicles are also included.
4. “High speed trains” with a maximum speed >230km/h. The same method as is used for high-speed traffic is also used for all tilting body vehicles.

The choice of reference vehicle for each class is made on the criterion of which has the longest possible operating experience on the DB system (or comparable systems in other countries) and the representation for the respective traffic in respect of the vehicle technology and method of operation.

For the class of “suburban vehicles”, in general, no explicit investigations are necessary. The vehicles of this class have been in service for decades in very large numbers almost everywhere in Europe without any accidents occurring due to side winds.

In the “regional traffic” class the “Silberling“- driving trailer (BR 738, 739, 740) can be used as the reference vehicle. The study of the “reference risk“ [6] could, without doubt, show that in spite of a distance run of almost 1 billion train km in the speed range 100-140 km/h over the whole of the DB network in the course of several decades no incidents have occurred due to side winds during a period of several decades. It is, therefore, proved in the statistical sense that the vehicle is safe regarding its behaviour in respect of side winds.

The greatest service experience on DB for “Intercity-traffic” is with the Inter-Regio driving trailer. The distance run by this class is not as great as that of the “Silberling“ driving trailer, however several series of vehicles with similar properties have been successfully introduced in other European countries (however,most of them are tilting trains like ETR450, ETR460/480, Intercity 448, Alaris, X2000, etc.). The IR driving trailer is technically representative for a series of vehicles already in service on the DB as well as new vehicles (IR, IC Series 1 to 3 and Metropolitan).

With high speed trains the ICE2 driving trailer is the only vehicle in Europe that can be considered for the reference, since all other vehicles have run a smaller distance and/or have a design that is not representative for the problem (e.g. power car design, locomotives). Vehicles from non-European countries such as, for example, the Japanese Shinkansen run under other operating conditions and their technical design has not been published in sufficient detail for them to be directly included in the DB checking process.

4 PROCEDURE FOR THE SAFETY CHECK

As already explained in the previous sections it is not appropriate to assess all classes of traffic with one standard procedure.

For the classes that run in Regional trains it is possible to look, for example, at the large distances run by the reference traffic and thus to assess the operational safety of the traffic with a high degree of statistical safety. In addition the vehicle designs are comparatively simple and the vehicle dynamics at lower speeds simpler than in high speed vehicles.
However, for these the service experience is comparatively low, the vehicle design very modern and the vehicle dynamics more complex because of the higher speeds. Thus starting from relatively simple, proven procedures at low speeds, with increasing speed it is necessary to use more comprehensive methods for the safety check.

The basis procedure to prove that the vehicle is safe to run with a side wind is however the same for all classes of vehicle (figure 1):

1. Calculation of the vehicle reactions to strong side winds
2. Comparison with the respective reference traffic, assessment
3. Derivation of measures to produce the reference level

Figure 1: Schematic procedure for the safety check with extreme side winds

This approach corresponds to EBO§2 (“Proof of equal safety”) and has been used e.g. by British Railways [25] and Swedish Railways [15] for many years. A similar procedure is also used in other disciplines.

For each vehicle class the individual steps are processed in various depths or with different methods which have been co-ordinated with one another. These always represent the state of the art and are based on proven methods that have already been used.

The methodic approach and the procedure for the individual traffic classes will be discussed below with some examples. The complete description of the calculation procedure is contained in the DB Code of Practice Ril 401 [3].

4.1 Calculation of the vehicle reactions to strong side wind

According to the state of the art the calculation of the vehicle reactions, bearing in mind all the boundary conditions, delivers the most reliable results for the side wind problem. For model tests the technique of using models for scale modelling of vehicle properties is not available. In 1:1 tests it is almost impossible to get the suitable meteorological boundary conditions at the time of the test.

The result of the calculation of the vehicle reactions for all classes of vehicle is the so-called wind characteristic curve (WKK) of the vehicle, that is to say the description of the permissible wind speed depending on the operating condition (speed or transverse acceleration on defined track bed quality) of the vehicle (figure 2). The permissible wind speed is then reached when the vehicle dynamic parameters or those of the interaction between vehicle and track that have been set in other investigations of vehicle running are exceeded.

The limiting values for these parameters are, as is normal in railway technology, so set that should they be exceeded in no case will this lead immediately to a safety endangering condition.
The entry data for any calculation of the vehicle reactions caused by the side wind is the determination of the aerodynamic properties of the vehicle lift, resistance, side force, roll, pitch and yaw moment. These six so-called "aerodynamic coefficients" are generally obtained in a wind tunnel test [1, 2, 23, 24]. As computer simulation CFD has made great strides in the last few years in this connection [8, 11, 15, 19, 21], further work is under way in co-operation with Bombardier to validate CFD tools for the purpose of side wind calculations as an alternative method.

The calculation of the vehicle reactions is done in a graduated way for each class of vehicles:

Regional traffic
The calculation of the vehicle reactions is done by the method of the "extended static tipping" (EST). This is the analytical solution of a mathematical physical method, which has been used in a modified form by Japanese Railways since the 1960s for all the types of train put into service since then [12, 13, 32].

British Railways have also used a similar simplified method for the side wind safety check [25].

The "extended static overturning" EST basically describes that wind speed at which the vehicle tips over when running in a curve with a simplified modelled trackbed quality.

All the important parameters which affect the behaviour of the side wind are contained in the method, only the method is easier to use in comparison with the MKS procedure described later.

Intercity-traffic
The method of extended static tipping is supplemented by the method of the multi body simulation (MKS). This is generally recognised in the state of the art as the best and most reliable method for the calculation of the vehicle reactions [10, 26, 29, 16]. In the MKS method all vehicle properties (dampers, springs, stops, component masses and mass distri-
...butions etc.), the track behaviour as well as the wheel rail contact are reproduced in detail. Thus a calculation done by the MKS method is correspondingly expensive.

This method has already been used for several years internationally to simulate the ride properties (wheel/rail forces, ride comfort) of vehicles. These calculations are extended further for the side wind problem by the introduction of wind forces.

Since the calculation of a complete wind characteristic curve takes a long time, only a few points on the curve are determined. The curve is supplemented by the results of the EST method. The vehicle specific variables of the EST method are in this way so adapted, that both methods give coincident results at the calibration point.

High speed trains

Since with increasing speed the dynamic effects of line features, track deviations and side wind become ever stronger, particularly accurate investigation methods must be used for vehicles that belong to the high speed traffic class. Therefore all wind characteristic curves are calculated complete with the MKS method and the boundary conditions and evaluation procedures of the simulation adapted to the requirements of the increasing influence of the dynamic effects.

4.2 Comparison with the reference traffic

Also when comparing the traffic to be investigated with the reference traffic a process should be used that is graduated in its depth depending on the service experience with the reference vehicles.

For the regional traffic class of vehicle it has been proved that the reference vehicle can be safely operated over the complete DB rail system even under the most unfavourable conditions. To this extent an analysis of the operation of other "equally good" vehicles is unnecessary, since also for these the operation is safe at all times on the complete network (in the statistical sense).

For the regional and Intercity traffic (large operating experience) it is, therefore, sufficient to carry out the assessment of the safety of operation using the wind characteristic curves. If the wind characteristic curve of the new vehicle calculated according to the same method is better or as good as that of the reference vehicle, it can be assumed that the new vehicle can be safely operated everywhere. If this simple criterion is not achieved then more extensive statistical considerations are necessary similar to the high-speed traffic.

This high level of (statistical) service experience is not yet available for the class of high speed train vehicles. In addition the operation takes place mainly on the high speed lines, that is to say relatively few lines. It cannot, therefore, simply be assumed that a new vehicle can safely be run everywhere, even if it has comparable riding properties. In this case it is necessary to investigate the operation of a new vehicle on the line on which it will run (or known vehicles on new lines) and thus to support the service experience which is not yet sufficient by a detailed line analysis.

For the class of high speed train vehicles the comparison between the different vehicles is done on the basis of the risks likely to arise when the vehicle is operated on the line where it will work. The methodology for this was developed by the DB in conjunction with the German Weather Service DWD and the firm of Ernst Basler + Partner EBP in the years between 1997 and 2000 starting from the Federal Ministry of Transport (BMV) guidelines mentioned above.

SNCF works in co-operation with DB and Siemens in the DeuFraKo project to develop a method suitable for the situation in France and Germany. Integration of the method into the
The reference traffic for the class of high speed trains is taken from the services worked by the ICE2 with driving trailers initially running at 200km/h on the new high-speed line from Hanover to Würzburg [7]. The method is briefly described below.

5 METHOD TO ASSESS THE SAFETY OF HIGH SPEED TRAINS IN RAILWAY SERVICE WHEN SUBJECTED TO SIDEWINDS

The methodology for the high speed train traffic follows the procedure below:

1. Determining the vehicle reactions to side wind as described above and determination of the wind characteristic curves WKK (“what wind speed is generally permitted for the vehicle for each running condition?”)
2. Analysis of the lines to be used to determine the locally permitted wind speed (“how high is the permissible wind speed for the actual operation of the vehicle at a given point of the line?”). The result is the so-called “service curve” for the operation of the vehicle on the respective line where it is used.
3. Meteorological investigation to determine the frequency of occurrence of strong wind for each point on the line (“How frequently does this permissible wind actually occur on the line?”)
4. Integration of the local frequency of occurrence of the permissible wind speed over the complete line where the vehicle runs (= “cumulative frequency of occurrence” of the permissible wind speed) and comparison with the reference value determined by the identical method for the statistical frequency of exceeding the WKK.

5.1 Calculation of the wind characteristic curves for the vehicle

The calculation of the wind characteristic curves is done by the method of multi-body simulation. A detailed survey of the application of the MKS method was given during this symposium by other authors. On DB all relevant running gear parameters are modelled with their (non-linear) dynamic properties, including all dampers, springs, stops, active elements, and couplings between the vehicles. The wagon body is assumed to be a rigid body. The dynamic behaviour of the superstructure, as well as the wheel/rail contact are modelled. The Simpack programme is used as the simulation tool, however other systems deliver comparable results.

In this method the journey of a vehicle according to the scenario shown in figure 3 is investigated by computer. The track bed corresponds to measured real values in a representative section of line. The vehicle runs out with constant speed from behind the protection of an obstacle (e.g. wall or tunnel) into the side wind. This impinges on the vehicle initially with a ground wind speed. The train then runs into a curve. The radius of the curve for various radius classes is R= 5 500m, 7 000m and infinite (straight track). When the vehicle is in the curve a gust is applied after the subsiding of the transient effect. This gust is 1.8 times stronger that the basic wind and is iteratively increased until the limit values for the wheel-rail contact are reached. The gust factor was determined from measurements on a representative section of new line.

The result of the calculation is filtered up to 200 km/h with 1.5 Hz low pass, up to 250 km/h the filter frequency increases linearly to 30 Hz. This increase allows for the increasing significance of the dynamic effects with increasing speed and considers the possibility proved in
test runs, that the wheel on the inside of the curve has to take over the job of guiding the vehicle temporarily if there are certain track irregularities.

In the calculation each wheel is monitored independently. The criterion for the maximum permissible side wind speed is reached when on one wheel one of the following values is exceeded:

\[ Q_{\text{min}} = 0.1Q_0 \]

The residual-wheel contact force must be at least 10% of the wheel contact force that occurs when stationary. This considers that due to the manufacturing tolerances a centre of gravity displacement in the transverse direction of up to 5% is tolerated from vehicle to vehicle.

\[ Y/Q \leq 0.8 \]

This term describes the possibility of the wheel climbing up the rail. The value of 0.8 corresponds to UIC 518.

These criteria correspond widely to those used for tests of running stability.

### 5.2 Line investigations

In a detailed investigation of the line characteristic, the local maximum permitted wind speed is determined (figure 4) for each point on the line for the proposed operation using the wind characteristic curves as the input parameter. The operating curve produced as a result is shown graphically as “maximum permissible wind speed plotted against line kilometres”.

The maximum permissible wind speed for a given type of train depends on the following parameters:

- Vehicle properties (aerodynamics, ride performance) which are expressed in the wind characteristic curves,
- The track used (radii, cant, track bed quality),

![Figure 3: Scenario for the side wind simulations with MKS](image)
The method of operation (train speeds), which can be different for each direction of travel,
and the wind direction (wind from the inside or outside of the curve).

The line is divided into sections each about 100 m long, and for each section the relevant parameters are determined. Radius, cant and local speed give the uncompensated transverse acceleration $a_q$. From the matching wind characteristic curve (depending on the radius class and track bed), the local maximum permissible wind speed can now be read for wind from right and wind from left.

![Figure 4: Example of an operating curve](image)

5.3 Analysis of frequency distribution of side winds

In the next step the records of the German Weather Service from wind measuring stations close to the line which extend over many years were examined to see how frequently wind of a certain strength occurred at each point on the line. In this connection all the wind directions that were found were converted to two wind direction vectors at right angles to the track and values given based on a height of 2.5 m above rail level.

All the relevant parameters which can affect the local situation on the line, such as environmental irregularities, woods, developments, orography, track bed on embankments or bridges, etc are considered. In the same way, as in the determination of the line curves, the line is divided into calculation sections about 100 m long and for each section the frequency of strong wind of specified wind speed classes calculated in tabular form.

5.4 Risk assessment and measure planning

When the frequency of occurrence of the locally permitted wind speed is superimposed on the service curves the frequency of exceeding the permissible wind speed for each 100 m
line section can be calculated. This shows a measure for the local risk due to the side wind. The results are displayed graphically by plotting the frequency of exceeding the critical wind speed against the line kilometre post. The critical factor for safe operation from A to B is, however, less the local amount of risk, but much more the total risk experienced on the whole of the journey.

The value used for the risk assessment for a given train service on the line A-B is obtained, therefore, as the integration of the individually calculated frequencies of exceeding over the whole length of the route investigated. To ensure the comparability of different traffics this value is standardised at 1 million train kilometres.

This complete method was first used for the reference traffic ICE2 with a speed of 200 km/h on the high-speed line Hanover-Würzburg. The result is the reference frequency of exceeding \( H_{bez} \). If the frequency of exceeding \( H \) of the traffic that is now to be assessed (e.g. ICE2 on other lines or another high speed train vehicle on a high-speed line) is smaller or equal to the reference value \( H_{bez} \), then this vehicle may be operated in the planned form on the line (figure 5). If the figures stay below the reference level, measures must be taken until the reference frequency is reached.

![Figure 5: The operation of a train XYZ on the line A-B can be done in the planned way, if its safety level regarding side wind reaches at least the reference level.](image)

The following methods can be used to achieve the reference level
- measures on the vehicles (ballasting, modifications of the body shape or the running gear),
- measures on the infrastructure (wind protection walls or fences) and
- operating measures (permanent or depending on the wind speed temporary reduction of the speed).

The effect of these measures regarding the vehicle behaviour to side winds was investigated in a series of studies [1, 8, 9, 11, 19, 20, 23, 26, 30, 31] and confirmed in international research.

Modification of the vehicle characteristics, e.g. the vehicle mass or the running gear parameters, leads directly to a modification of the wind characteristic curves of the vehicle (figure 6). These then have to be determined again.

Operating measures, that is to say a temporary or permanent local speed reduction of the train must be considered in a new calculation of the service curves thus the calculation of the permissible wind speed at each point on the line (figure 7).

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**Figure 6:** Example: A modification of the shape of the vehicle causes smaller wind forces on the vehicle. Therefore, the wind characteristic curve is also displaced upwards and the permissible wind speed increases.

**Figure 7:** Example: Because of the characteristic shape of the wind characteristic curves, a higher wind speed is almost always permissible with lower train speeds. This then affects the service curve.
Track measures such as walls or fences are only specified as wind breaks if the wind frequencies on the line require them to be considered, since they reduce the wind speed that locally affects the vehicle.

Various measures can be combined to achieve a given increase in safety, in order that an economically optimum result is obtained. For example at a certain place, instead of a 2 m high wall, it is possible to specify a 1 m high wall, and a speed restriction.

The optimum measure in the sense of the cost/benefit effect is that with which the reference value is just achieved with the lowest expenditure/costs/journey time loss (figure 8).

![Figure 7: An optimum measure joins the smallest expenditure to the costs, or journey time with the maintaining of the reference level](image)

6 PERSPECTIVE

The DB Code of Practice 401 specifies the procedure to be used to demonstrate safe operation when there are side winds, as a self contained generally valid procedure. The methodology has been applied on a number of lines and vehicles on the German high speed line and can be regarded as state of the art for these sorts of investigations.

Nevertheless, the weaknesses of the methodology are based in it’s complexity, which requires relatively big efforts and expertise. On the other hand other procedures exist in Europe, which are much more simple, but do not necessarily fulfil the requirements of the big variety of German railway traffics, from low-speed regional traffic over tilting trains up to high speed trains with 300km/h. What European railways are facing is a wide gap: Very complex methods as the one of DB and SNCF, relatively simple methods as the English or the Swedish one, and several railway companies who do not need such a method at all.

Consequently the challenge for the very next future will be to put every effort in harmonising the different European approaches rather than trying to increase the accuracy of the individual methods by a few percent.
This process is forced and pushed forward by the realisation of the European high speed network which has already started between several countries (albeit with relatively low speeds on at least one side of the border). Is would not be understandable, if a train would be judged as “safe” on one side of the boarder and “not safe” on the other.

The basic requirements of the common methodology are

- Simple; it must find acceptance by the users as well as by the supervisory bodies. Together with simplicity come transparency and cost effectiveness.
- Robust: Small errors in the procedure must not effect the general findings.
- Reliable: Several users must come to the same results.

The activities in normative groups like TSI and CEN as well as bi- and multilateral co-operations are focussing on these aspects.

7 BIBLIOGRAPHY


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