Designing a Wind Alarm System for the TGV-Mediterranée

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ABSTRACT: This paper presents the studies that have lead to the definition of the wind-alarm system for the TGV-Méditerranée, particularly on the meteorological and statistical aspects: characterization of the wind along the line, procedure to make the link between an overturning probability level, the wind predicted at anemometric sites, the dynamical response of trains;

KEYWORDS: wind, wind alarm, side-wind effects, climatology, trains

1 INTRODUCTION

1.1 *Cross-Winds protection strategies*

For some years, the problem of the effects of high crosswind on railway and road vehicles has been studied and it has been shown that the vehicle speed has generally an incidence on the induced loads [1-4]. The use of lighter materials for trains and the increase of their operational speed make this problem more and more sensitive, and current studies have shown that this question cannot be neglected at present, particularly for high-speed trains. In addition to other safety measures, wind alarm systems aiming at reducing the train speed for high wind conditions, have been developed in Germany, Japan, and France [5-7]

The TGV-Mediterranée line being particularly exposed to strong wind, a protection strategy has been defined by SNCF in order to guarantee the safety of passengers with regard to the cross-winds effects. In complement to the erection of wind screens on the most exposed sites, it has been decided to settle a « wind alarm system » in order to reduce the trains speed in case of strong wind conditions.

The aim of this paper is to describe the studies that have allowed to define this wind alarm system, particularly from the meteorological and statistical aspects.

1.2 *The TGV-Méditerranée wind alarm system*

The line, between Valence and Marseille, and between Avignon and Nïmes (fig.1) is divided into twelve zones of 5 km to 30 km length, each of them monitored by an anemometric station continuously measuring both wind speed and direction. Measurements are made at the immediate vi-

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cinity of the track, at a height of 4 m above the rails (fig.1). The track lies generally over an embankment which is between 5m and 25 m high.

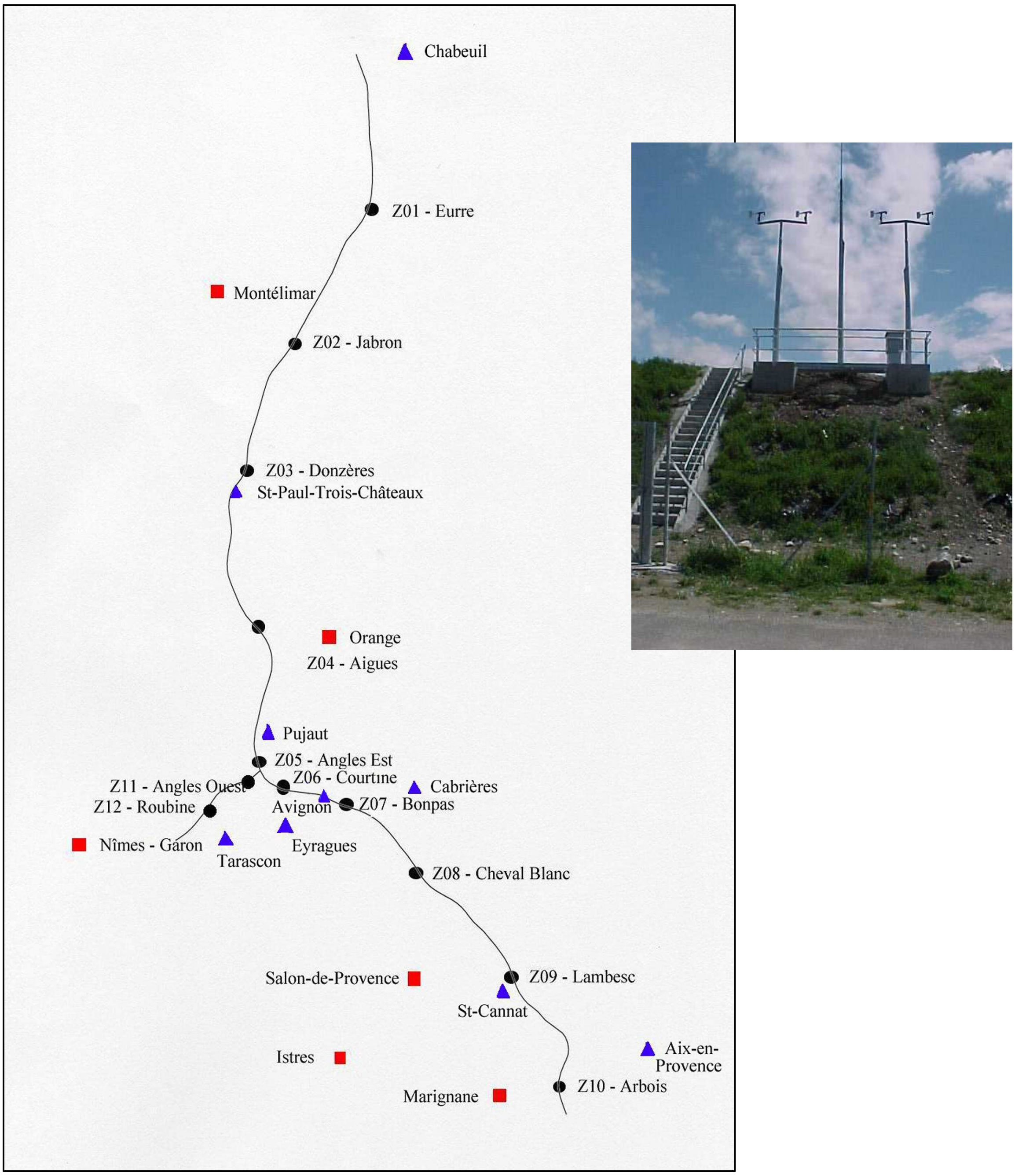

Figure 1 : The TGV-Méditerranée line and the wind measurement sites (circles: SNCF anemometric sites, squares : Meteo-France main stations, triangles : Meteo-France secondary stations) – *map scale : frame height = 150 km.* (photograph : SNCF anemometric site for zone monitoring)

In order to slow down the trains before they enter the zone, the wind variations are anticipated on the basis of a 4-minutes forecast at the monitoring site . When the predicted wind speed at this site exceeds wind direction-dependent threshold values previously defined, the wind alarm is activated in order to reduce the train speed from 300 km/h to 170 km/h, or even 80 km/h.

We call "Zonal Threshold Wind Curve"', hereafter noted ZTWC, the chart of 36 values V_i of windspeed (one for each 10 deg. wind direction sector), which activate the wind alarm in the zone according the following condition :

D and *V* being respectively the predicted 10-min mean wind direction and speed at the anemometric station, the call of slowing down the train is given if $V > V_i$ when *D* belongs to the i^{th} sector. Two ZTWC are defined :

- The ZTWC 300 for a train running at a speed of 300 km/h, used for a speed reduction to 170 km/h.
- The ZTWC 170 for a train running at a speed of 170 km/h, used for a speed reduction to 80 km/h.

2 PRELIMINARY STUDIES

2.1 *Train sensitivity to the wind*

Wind-tunnel measurements of the train aerodynamic coefficients, in different configurations (flat ground, embankments, bridges ...) have been carried out in the CSTB wind-tunnel [8]. The wind-tunnel methodology leads to the assessment of the aerodynamic coefficients with a reference wind speed defined at a height of 4 m (or deck height in cases of bridges) and upstream the line. Consequently the reference wind speed is not influenced by possible embankment effect, as this effect influences the aerodynamic coefficients themselves.

A dynamical multi-body simulation (code VAMPIRE [9]), allows to determine the train response, considering nonstationary effects by the mean of a spatial gust model. This gust model derived from previous works [10], has been tested and validated against measurements on the line. It allows to characterize joint probability densities of the gust amplitudes, durations, and characteristic dimensions as a function of the classical parameters of the atmospheric turbulence : turbulence intensity, turbulent length scales, coherence functions. An exponential spatial shape of the gust has been chosen. This approach is confirmed by recent works by Bierbooms et al. [11]. Dynamical computations have also been done using generated spatio-temporal series of wind [12] as input. These tests have permitted to check the realism of the gust model approach.

In this way, considering line characteristics every 50 m, it has been possible to build for each site, « 90% limiting wind curves » which give in each wind direction (every 10 degrees), the instantaneous wind speed that induces a 90% unloading of the vehicle wheels.

As the risk analysis considers overturning as the critical event, it was necessary to make the link between overturning and the 90% unloading. As dynamical computations are not able to simulate full unloading, tests were carried out in the CSTB climatic wind-tunnel, on a 1/10 scale model, with dynamical and wheel-rail contact characteristics allowing an extrapolation to the full-scale. A margin on the wind speed was observed between the 90% unloading and the overturning of the model. This value of the margin was added to the « 90% critical wind curves » in order to get the « overturning critical wind curves ».

2.2 *Wind characteristics along the line*

The protection of a zone is ensured by means of measurement at the anemometric site, so that it is necessary to be able to characterize the wind on the whole zone, as a function of the wind at the anemometric site.

As the spatial extension of each zone is short regarding to the synoptic scale, we assumed that, besides the random spatial fluctuations linked to the large turbulence scales, the variations of the mean wind and turbulence characteristics inside a zone, are only dependent on topographical effects i.e. terrain roughness and orography. The roughness effects were evaluated by using an atmospheric boundary layer model for flat terrain [13] , while the orographic effects were assessed by solving the linearized Navier-Stokes equations via the code BZ [14]. Corrections of turbulence due to orography were also considered following the effective roughness approach of Taylor et al. [15]. More than 35 measurements points along the line were used to validate and to calibrate the modeling (fig.1)

In addition to the evaluation of the topographic influence along the line, measurements at the anemometric site must be corrected to take into account, the embankment effects: These effects have been evaluated from wind-tunnel measurements and also field measurements on a ideal site at Donzères (fig. 3). Previous experiments by Baker [16] were globally confirmed by our measurements.

Then, it has been possible to evaluate both the ratio between the wind speed at the anemometric site with the wind speed on the line, and the deviation of the mean wind direction between the two sites. This has been done every 500 m on the line, and up to 100 m when the orographic effects imposed a finer resolution. The computed values were then interpolated every 50m.

Eventually at each site (every 50 m) and for each wind direction D at the anemometric site, were computed 4 parameters : a "transfer coefficient" $C_s(D)$ of the mean wind speed, the mean wind direction $D_s(D)$, the turbulence intensity, the standard deviation of the wind direction

In order to take into account both the mean wind variability (turbulent time scales greater than 10 min.) and the model uncertainties, standard errors on the coefficient $C_s(D)$ and the mean wind direction $D_s(D)$ were evaluated by field experiments : comparisons were made between mean wind measurements at different sites standing at distances varying from 500 m to 8 km.

2.3 *The wind forecast model*

The wind forecast model is based on the extrapolation of moving 10 min-average wind speed with a horizon time of 4 min. Different prediction models have been tested using wind series measured at the anemometric sites during one winter. The choice has been made to use an auto-regressive model of a second order. After a first fitting of the model coefficients, leading to a least-square minimization of the prediction error, a constant value was added to the best fit prediction in order to minimize the probability of under-estimation of the wind [7].

Besides the determination of the model coefficients, data have allowed to compute at each anemometric site, the cumulative function of the prediction error, noted $F(V_p\text{-}V)$, where Vp is the predicted wind speed and V the real wind-speed. It has been observed that the distribution of the error could be considered in a first approximation as a gaussian function. The mean (bias) and the standard deviation of the prediction model error were determined at each anemometric site and these parameters are taken into account in the evaluation of the train overturning probability.

3 DESIGNING THE WIND ALARM SYSTEM

3.1 *Principle of the ZTWC determination*

The main criterion for the determination of the zone threshold wind curves is the probability level P of overturning for a train during its passage all over the zone, i.e. the probability that the train encounters at least at one site, an instantaneous wind speed above the overturning critical wind curve at this site.

However this criterion is not sufficient to define the 36 threshold windspeeds V_i, because there are an infinity of combinations of the V_i, leading to a same value of P. Therefore a complementary criterion aiming at sharing the risk between wind directions has been used: We consider that the conditional probability $p(V_i,D_i)$ of overturning, when the wind speed V_i and direction D_i at the anemometric site are given, is identical for all directions D_i.

For a given wind speed and direction at the monitoring site, this conditional probability p is computed by using a Monte-Carlo simulation method : Taking into account topographical influences and turbulent fluctuations, speed and direction profiles of the instantaneous wind encountered by a train running all over the zone are simulated. The overturning critical wind curves at each site crossed by the train are compared to the simulated wind, so that it can be observed if the overturning occurs somewhere during the simulated run. By performing a great number of such simulations, the probability p is given by the percentage of simulations for which this event occurs.

Then, the computation of the overturning probability P is performed in two steps : Firstly, the time prediction uncertainty is not taken into account, and the probability p is integrated over all the directions and wind speeds lower than the threshold value. Secondly, the computed probability is corrected by considering the distributions of the prediction errors. The computation is then done iteratively according to the following procedure:

1 Choice of a p_o value.
2 Computation of the 36 V_i with the relationship $p(V_i,D_i) = p_o$
3 Computation of the associated global risk P
4 Return to step 1, with a lower (higher) p_o if the computed P is greater (smaller) than expected.

The figure 2 gives examples of such zonal threshold wind curves, for speed reduction to 170 km/h (ZTWC 300) and to 80 km/h (ZTWC170)

3.2 *The Monte-Carlo simulation*

The aim of the Monte-Carlo simulation is to compute the conditional probability (the windspeed and direction at the anemometric site being known), of overturning for a train running all over the zone. For that, a great number of instantaneous wind speed and direction series are generated every 50 m along the line with an hypothesis of windspeed V and direction D at the anemometric site. This distance of 50 m is representative of the lateral turbulence length scale, so that it can be admitted that the turbulent part of the wind is not correlated between two sites. However, the method could be improved by taking into account spatial correlations between sites.

During the crossing of the zone, the train is successively exposed, during very short lapse time to the wind at each site. Then, the spatially simulated wind can be considered as a wind series “seen” by the train. One wind series corresponds to one train run, and then the probability of overturning is given by the frequency of series for which at least one of the sites is affected by a wind speed greater than the overturning threshold.

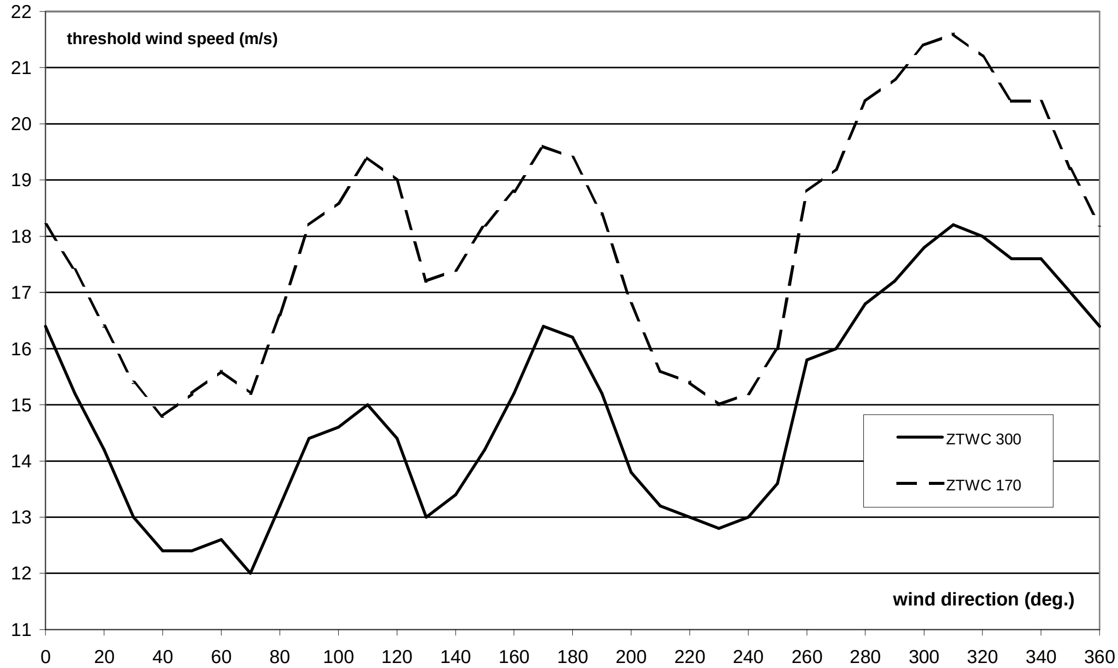

Figure 2 : An example of Zonal Threshold Wind Curves

The instantaneous wind speed and direction at each site are considered as gaussian random variables which are defined by their mean and their standard deviation. The meteorological analysis of the line has permitted to determine the relationship between the mean wind at each site and the mean wind at the anemometric site, and also the turbulence intensity and standard deviation of the instantanous wind direction.

Finally, at a given moment, the instantaneous wind speed at an elementary site *s* is linked to the mean windspeed *V* and winddirection *D* at the anemometric site according to the relationship:

$$v_s = C_s(D)C_t(D)V \qquad (1)$$

In order to take into account the variability and the uncertainty of the transfer, $C_s(D)$ is a random variable with a mean given by the modeling and with a standard deviation deduced from the variability in the 10-min value transfert, as it was measured along the line.

$C_t(D)$ is the turbulence coefficient making the link between mean wind speed and instantaneous wind speed. It is a centered gaussian variable, with a standard deviation computed from the mean wind speed and the turbulence intensity.

The mean wind direction D_s on the site as well as the instantaneous wind direction d_s are also random variables whose characteristics are given by the meteorological analysis.

Then, the Monte-Carlo simulation consists in choosing at random, at each site, values of $C_s(D)$, $D_s(D)$, $C_t(D_s)$ and $d_s(D_s)$ in their distributions and to compare the instantaneous wind vector obtained to the overturning characteristic wind curve.

Practically, the probability $p(V,D)$ is computed for all mean wind speeds and 36 mean wind directions at the anemometric site. The value of the threshold wind speed for a wind direction D_i at the anemometric site is then the value V_i given by $p(V_i,D_i) = p_o$.

3.3 *Computation of the train overturning probability*

With the assumption that the *real* wind speed and direction are known at the anemometric site, the simulation method allows to compute the probability $p(V,D)$ for the train to overturn inside the zone. To get the global overturning risk, we have to integrate this conditional probability over all directions and over wind speeds inferior to the zone threshold windspeed in that direction. The integration takes into account the probability density function $f(V,D)$ of wind speed and direction at the anemometric site. This pdf was deduced from a climatological analysis including a comparison between measurements on the site during one or two years and Météo-France stations data.

However, for operational reasons, the wind alarm system is based on a predicted wind at the anemometric site, instead of the real wind. The impact on the risk is linked to the occurence frequency of two kinds of events: The “missed alarm”, which corresponds to a predicted wind speed inferior to the ZTWC and a real wind above this curve, and the “false alarm”, due to a predicted wind above the ZTWC, but a real wind inferior to the ZWTC.

If we call $F(V_p\text{-}V)$ the repartition function of this error, V_p being the predicted wind speed and V the real wind speed, the undetected or missed alarms lead to increase the risk with the following amount :

$$\Delta P = \sum_{D=D_1}^{D_{36}} \sum_{V=V_i}^{\infty} p(V,D) F(V_i - V) f(V,D) \qquad (2)$$

On the contrary, the “false alarms” decrease the risk with :

$$\Delta P = \sum_{D=D_1}^{D_{36}} \sum_{V=0}^{V_i} p(V,D) \left[1 - F(V_i - V)\right] f(V,D) \qquad (3)$$

The analysis of data on which the prediction model has been built has given the cumulative function $F(V_p\text{-}V)$. Concerning the error on the wind direction prediction, it can be shown, that due to its symmetry regarding to the persistence model, its influence on the risk is negligible.

3.4 *Computation of the wind alarms frequency*

As for the risk computation, the wind alarms frequencies are obtained into two steps:

- Firstly, the prediction model is not taken into account, so that the frequencies $f(V,D)$ are simply integrated over all directions and windspeeds above the ZTWC.
- Secondly, the prediction error is taken into account by adding the frequencies of false alarms and substracting the frequencies of missed alarms, i.e. by adding the term:

$$\Delta f = \sum_{D=D_1}^{D_{36}} \left[\sum_{V=0}^{V_i} (1 - F(V_i - V)) f(V,D) - \sum_{V=V_i}^{\infty} F(V_i - V) f(V,D) \right] \qquad (4)$$

When the wind speeds are high, with a return period greater than 1 year, the estimation of the frequencies $f(V,D)$ has a high uncertainty. In this case, an analysis of the kind “annual extreme values” is applied to the long wind time series generated at the anemometric site on the basis of data at Meteo-France stations.

4 CONCLUSION

From the wind engineering point of view, the design of the Wind Alarm System for the TGV-Méditerranée is an interesting case study, because it requires a global approach including wind-tunnel, numerical, and field studies. Various domains of wind engineering have been considered : determination of aerodynamic coefficients, dynamical response, gust modeling, wind simulation, topographical effects, statistical prediction, stochastic analysis...

The system has been operating since October 2001. Further improvements are planned in function of new data and operational feedback. As well, running on from these studies, a common approach on cross-wind protection strategy has been carried out in 2002 with Deutsche Bahn in the framework of the " Deufrako" project.

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