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COMPARISON BETWEEN FIELD MEASUREMENTS AND NUMERICAL SIMULATIONS OF THE WIND SPEED ALONG THE HS/HC ROME-NAPLES RAILWAY LINE

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Abstract. *Due to their very light structural weight, high-speed trains are very sensitive to the action of cross-winds. A common tool for the estimation of the safety of trains against cross-winds is provided by the Characteristic Wind Curves (CWC), that are evaluated in wind-tunnel tests and depend on the wind speed and direction at the railway line. The estimation of the wind speed and direction along railway lines is then fundamental to provide a reliable risk assessment. A new methodology has been developed for the evaluation of the wind speed along any railway line and to any context. Its current application deals with the Rome-Naples High Speed (HS)/High Capacity (HC) railway line in Italy. The present study is focused on the comparison between the probabilistic analyses carried out on data collected by anemometers placed along the line by Rete Ferroviaria Italiana (RFI) and those obtained through the application of the new methodology. The comparisons highlight both good agreements and noteworthy differences. A sound assessment of the uncertainties inherent in the new methodology points out its merits and defects, providing clear indications about its effectiveness in evaluating the wind hazard along the railway line.*

1 INTRODUCTION

In last decades, the need of faster transports by land drove to develop high-speed trains that stand out not only because of excellent aerodynamic characteristics, but also because of very light weights. They consequently became very sensitive to the action of cross-winds. Several accidents have been reported worldwide in the last years (e.g. Ref. [1]; Ref. [2]) and many studies have been carried out with reference to the aerodynamic properties of trains (e.g. Ref. [3]; Ref. [4]).

A commonly used tool for the evaluation of the safety against vehicle overturning due to high wind gusts is provided by the Characteristic Wind Curves (CWC). They are evaluated in wind-tunnel tests, and they furnish the maximum allowable train velocity depending on the wind speed and direction at the railway line.

The definition of the probabilistic distribution of the wind speed and direction along the railway lines is then fundamental to provide a reliable risk assessment. For this purpose, a new methodology has been developed for the evaluation of the wind speed along any railway line in any context. Its current application deals with the Rome-Naples High Speed (HS)/High Capacity (HC) railway line in Italy (Figure 1); it is based on the probabilistic assessment of long-term measures carried out by the meteorological stations of the Italian Air Force (AF) and of the company that provides servicing to air traffic in Italy (ENAV) in Lazio and Campania regions (Figure 1).

Figure 1: Railway line, AF/ENAV stations (indicated by names) and RFI monitoring system (stations indicated by numbers).

The developed method can be summarized in four main steps: A) line, stations and territory modeling; B) wind simulation; C) probabilistic analyses; D) comparisons and methodology assessment. Each step is organized in sub-steps as shown in Figure 2. The early 3 steps of the method, presented in Ref. [5] and in other papers currently in progress, lead to the evaluation of the probability of occurrence of the mean and peak wind speed at any point of the line, taking into account also the local features of the ground (e.g. embankments, cuts and viaducts). The peak wind velocities are then used for the risk assessment combined with the CWC.

The present study is focused on the comparison between the results of the probabilistic analyses carried out by means of the application of the new methodology and those obtained analyzing the data collected by anemometers placed by Rete Ferroviaria Italiana (RFI) along the railway line (Figure 1).

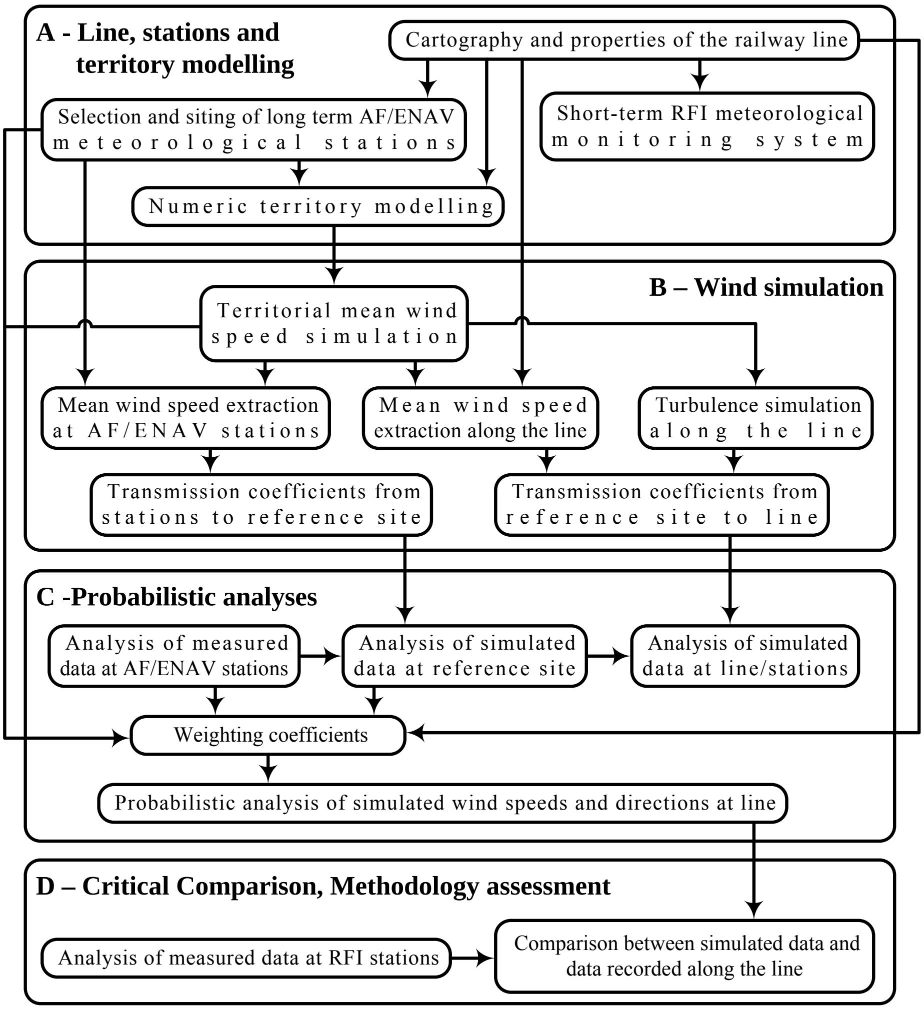

Figure 2: General scheme of the procedure adopted for the probabilistic assessment of the wind speed.

2 PROBABILISTIC ANALYSIS OF THE WIND SPEED FROM LONG-TERM MEASUREMENT STATIONS

The HS/HC railway line links Rome and Naples in central-southern Italy (Figure 1). It is 196 km long, and winds on a terrain characterized by complex orography. Seven meteorological stations close to the line have been selected to perform this study. Their data of mean wind speed and direction, averaged on 10 minutes and collected every 3 hours, were available for periods between 44 and 54 years when the study started. A new procedure has been developed to allow the wind data transfer from these long-term meteorological stations to the railway line. Such a procedure is based on numerical simulation of the wind field in the whole area where the line winds.

Three digital models have been realized involving the soil topography, the soil roughness and the displacement level of the whole area surrounding the railway line and the meteorological stations. Each digital model has been implemented at 2 different spatial scales, relative to 6 simulation domains referred to as one “macro-area” and five “micro-areas” (Ref. [6]).

The macro-area contains the main features influencing the wind speed and direction at the Rome-Naples railway line. It is extended approximately 261 km in the West-East direction and 225 km in the North-South direction, and is discretized through a regular grid with 283 columns and 245 rows of nodes, for a total of 69335 nodes. The grid step is about 920 m both along the longitude and the latitude.

The micro-areas are aimed at establishing a zooming procedure to improve the precision of the territory modeling; each micro-area is discretized through regular grid steps of about 230 m both along the longitude and the latitude. An overlapping of the micro-areas is applied in order to avoid border discontinuities in the results of the simulations.

The digital modeling has been carried out to perform the numerical simulation of the wind fields in the area by using the mass-consistent model WINDS (Ref. [6]). The model WINDS has been used to evaluate mean wind scenarios coherent with barotropic states, i.e. with uniform wind speed and direction at the top of the Atmospheric Boundary Layer (ABL). Adopting this method, physical phenomena related to actual synoptic atmospheric conditions cannot be considered, but a complete set of mean wind scenarios can be produced. Simulations have been performed under the hypothesis of neutral stability, which is appropriate for strong wind conditions, and considering 36 wind directions aloft, with uniform steps of 10°.

By means of the simulation of the wind speed at the long term meteorological stations and at the railway line, it has been possible to evaluate the transmission coefficients (i.e. the parameters expressing the change of the wind speed and directions at different locations) from the meteorological stations to the line.

The transmission coefficients have been evaluated by means of a double-step procedure: at a former step they have been calculated from the stations to reference conditions (i.e. open and homogeneous flat ground with roughness length equal to 0.05 m) and then, at the latter step, from reference conditions to the railway line. Figure 3 sketches the procedure for the transfer of the databases through the passage to reference conditions.

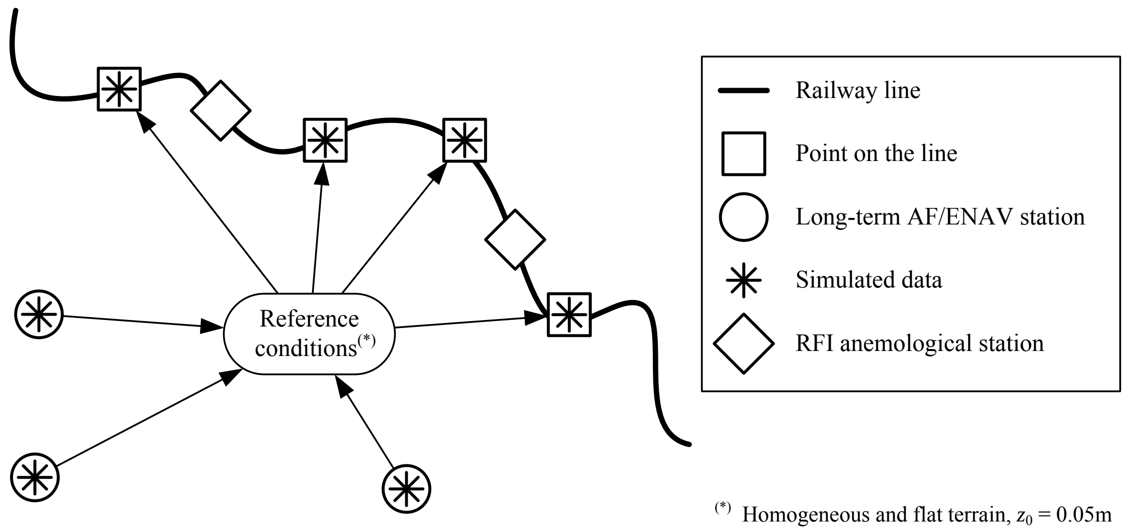

Figure 3. Two-step procedure for the transmission of wind databases from meteorological stations to the railway line.

The passage to reference conditions has been adopted to make the data of the long-term stations more homogeneous, and then to allow a former comparison of the results of the probabilistic analyses before the projection of the databases to the line.

The local features of the ground have been included in the evaluation of the transmission coefficients from reference conditions to the railway line. The wind speed and direction at the line has been calculated at a height equal to 3 m above the ground (i.e. 2 m above the track) taking into account those features – as the height above the ground for stretches on viaduct and both the height and the shape of the cross-section on embankments – that cause changes of the wind speed. When passing from reference conditions to the line, suitable transmission coefficients have been evaluated to generate also databases of the peak wind speed at the line, making use of the gust factor technique in the form proposed by Ref. [7].

All the databases of mean and peak wind speed and direction transferred from long term stations to the railway line have been submitted to probabilistic analyses. The probabilistic analyses have been carried out to derive the distributions of both the parent population and the extreme values. The parent population has been regressed by using a hybrid Weibull model (Ref. [8]). The extreme values distribution has been obtained by means of three alternative methods: the asymptotic model of the first type (Gumbel distribution), the peak over threshold Pareto technique and the Process analysis. The Process analysis has also been implemented to avoid biased values due to discontinuous acquisitions, missing data and wrong wind calms.

The final distributions of the wind speeds and directions along the line are expressed as a weighted average of the distributions of the wind speeds and directions associated with the different stations. The averaging procedure is carried out through appropriate weighting coefficients, which are functions of the relative distance between each station and each point of the railway line. The whole sequence, reported more in detail in Ref. [1], is depicted in Figure 2.

3 PROBABILISTIC ANALYSIS OF THE WIND SPEED MEASURED ALONG THE RAILWAY LINE

Besides long-term anemometric measurements, this study avails of short-term measures carried out by the network realized by RFI along the railway line. Figure 1 shows the position of these stations along the railway line. The anemometers are placed at 3 m height above the ground level (i.e. roughly 2 m over the track), on several types of line: embankments, cuts and viaducts. Figure 4 shows two typical placing of the anemometers along the line.

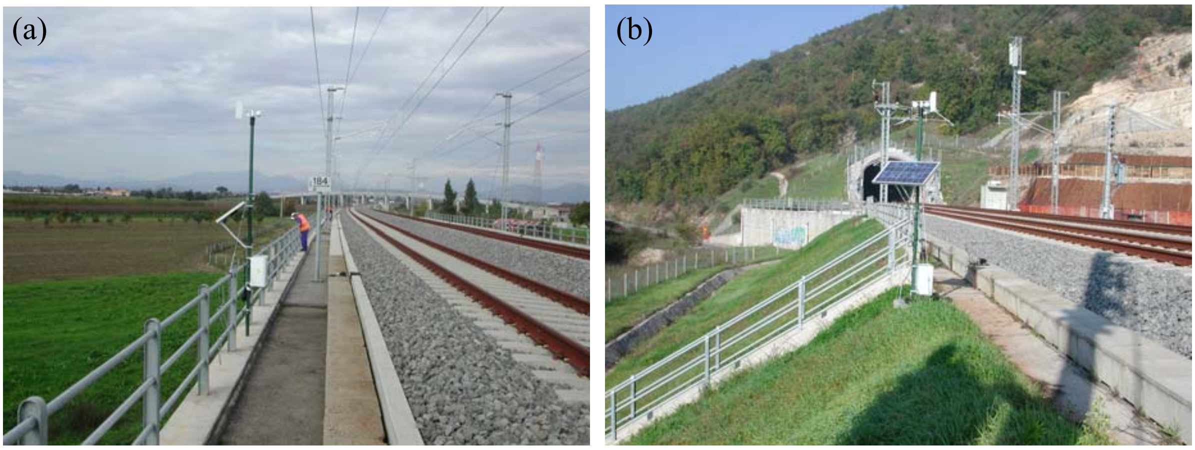

Figure 4. Anemometer 7659 (a) and anemometer 7672 (b), installed on a viaduct and on an embankment, respectively.

The analysis of the data recorded by these anemometers is used to check and up-date the probabilistic analyses introduced in the previous section and – in the meantime – for the realization of a now-cast and forecast system. The network includes 11 stations; each station registers continuously the mean value, the direction, the standard deviation, the minimum and the maximum value of the wind speed over 10 minutes.

This data is available beginning from January 2006. At the present stage, only the data collected in the year 2006 have been used to carry out the probabilistic analyses. For this reason only the regression of the populations of data has been performed; analyses have not been carried out to derive the extreme values distribution.

4 ASSESSMENT OF THE UNCERTAINTIES

The procedure developed to provide the estimation of the probability of occurrence of the wind speed and direction along the HS/HC Rome-Naples railway line is characterized by various steps: the modeling of the territory where the line is situated and of the wind fields, the probabilistic analyses of long term measures of wind speed and direction, the weighting of the results carried out starting from different databases (Figure 2). All the steps are subjected to assumptions regarding the modeling, uncertainties (e.g. in the estimation of the model parameters), and might even be affected by systematic errors (e.g. if original databases of wind speed are biased). A critical approach to the estimation of the uncertainties, of the systematic errors and of the assumptions is therefore fundamental to provide an assessment of the procedure.

The first uncertainties of the procedure are related with the statistical inference of databases of long term measurements, and then with the transfer of the databases to the railway line.

The transfer of the databases from meteorological stations to the line involves a detailed modeling of both the territory and the wind field. This notwithstanding, it cannot perfectly reproduce the natural environment due to several reasons. On the one hand, simulations are not carried out solving the Navier-Stokes equations, but under the only hypothesis of mass consistency; on the other hand, the mesh grid resolution – equal to 230 m – causes a smoothing of the orography and of the roughness length models. Simulated mean wind scenarios are then derived under the assumption of uniform wind speed and direction at the top of the ABL, that is as valid as the size of the simulation domain is small, and under neutral atmosphere conditions, that are certainly appropriate for strong winds, but might be not accurate and therefore questionable for the transferring of low values of the wind speed.

It's also timely to observe that digital models do not consider changes of the land cover that might have taken place in 50 years, but – from a theoretical point of view – they should be taken into account when transferring wind databases of long-term meteorological stations.

Last but not least, the mass-consistent model WINDS can process correctly winds at the synoptic scale, but not local wind systems like daily breezes, thunderstorms and foehn winds. Local phenomena can be found in data recorded by several RFI anemometers instead.

Besides the approximations related to the wind field simulations and physical phenomena not included in the model used to perform simulations, it should be borne in mind that the mathematical models at the roots of numerical analyses loose reliability when approaching the soil, and in any case close to obstacles. The extraction of wind speed at a reduced height above the ground implies that the model is operating in a reduced-confidence region. The extraction of the wind speed in locations characterized by smooth orography and large height above the ground (e.g. on viaducts and high embankments) provides more reliable results.

On the other hand, RFI anemometers are placed at 2 m above the track, often in areas with complex orography and high roughness length. This type of installation, that has been chosen to record the wind effectively acting on trains, implies that measurements are rather conditioned by local ground characteristics that cannot even be introduced in the numerical models.

Moreover, the very short period of available data should also call for caution about the representativeness of the results of their probabilistic analyses. Due to the limited time of observations and the presence of seasonal phenomena, preliminary checks highlighted that the results of the probabilistic analyses were still strongly dependent on the number of observations. New probabilistic analyses should be carried out when more data will be disposable.

Besides several uncertainties that characterize the procedure, it's also timely to remark that the comparison of the results of the probabilistic analyses of databases transferred to reference conditions highlights a general homogenization with respect to the same analyses on original wind data. This fact suggests the robustness of the methodology when dealing with territorial features that do not cause enhanced reductions of the wind speed.

On the other hand, a more detailed modeling of the wind fields by means of refined numerical analyses (e.g. using CFD) could be possible. However, at present, this approach on a large domain of simulation implies excessive costs due to the computational time, the troubles related with the assignment of correct boundary conditions and the difficulties in creating thicker mesh grids with detailed modeling of the territory.

5 COMPARISON BETWEEN SIMULATED AND REGISTERED DATA

Several checks have been carried out to compare the results of the analyses of data collected along the line by RFI anemometers and those obtained by the analyses of databases transferred from long-term meteorological stations to the line. The comparisons are aimed at providing an assessment of the whole methodology.

For all the anemometers placed along the line by RFI and used in the present study, Table 1 summarizes the adirectional values of the mean and peak wind speed ($\overline{V}$ and $\hat{V}$ respectively) with assigned exceedance probability P and the corresponding simulated data from AF/ENAV stations. The relative percentage difference ε between recorded and simulated data is also reported for every anemometer and two different exceedance probabilities. As expected, the uncertainties that are intrinsic in the whole procedure (Section 4) lead to a rather variable agreement between the analyses carried out on recorded and simulated data. It's timely to observe that the percentage differences between simulated and recorded data generally achieve the highest values for the anemometers that are not subjected to strong winds. A rough estimation of the windiness of the places where anemometers stand is provided in Table 1 by the value $\tilde{V}$, expressing the threshold that defines the 90% of records (i.e. the 10% of measures of each anemometer exceeded such a value in one full year); high values of $\tilde{V}$ correspond to windy sites.

It's also timely to point out that the percentage differences relative to mean and peak wind speeds do not remain constant for each anemometer and each exceedance probability. Some anemometers show a better agreement for the mean values of the wind speed, others for the peaks. However, the gust factor technique used to generate the databases of peak wind speed at the line is suitable to be applied to intense mean wind speeds. The peak wind speed distributions are therefore more significant for the anemometers placed in windy sites, where the percentage differences between mean and peak values are always roughly in the same ranges indeed.

Since the adirectional values of wind speeds with assigned exceedance probability are obtained as superposition of the directional distributions, significant errors in the estimation of the adirectional wind speed do not necessarily correspond to large errors in the evaluation of the wind blowing from critical sectors (and vice versa). For the RFI station 7658, that is installed on an embankment and in open terrain, Figure 5 shows the comparison between the mean wind velocities with assigned exceedance probability P (equal to 0.01 and 0.001) obtained from the analysis of the data recorded along the line (RFI) and those obtained by numerical simulations (AF/ENAV). The left panel shows the polar representation of the results of the analysis carried out on the mean values of the wind speed. The right panel shows the results of the same analysis on the peak wind speed values. In this case the comparison shows a very good agreement for almost every wind direction, even if the adirectional distributions (Table 1) are characterized by noteworthy percentage differences (i.e. 23-34%).

Anemometer	$\tilde{V}$ [m/s]	P	$\overline{V}$ [m/s]			$\hat{V}$ [m/s]		
			RFI	*AF/ENAV*	ε %	*RFI*	*AF/ENAV*	ε %
7656	4.3	10^{-2}	5.9	5.2	11	9.7	9.7	0
		10^{-3}	7.8	7.7	1	12.8	14.0	-10
7657	3.6	10^{-2}	5.9	4.9	17	12.5	8.6	31
		10^{-3}	8.7	8.0	9	18.5	13.7	26
7658	4.4	10^{-2}	6.4	7.9	-23	10.9	13.6	-25
		10^{-3}	8.8	11.5	-31	14.6	19.5	-34
7659	5.4	10^{-2}	8.5	8.7	-3	13.1	14.8	-13
		10^{-3}	11.6	12.6	-9	17.6	21.1	-20
7665	2.9	10^{-2}	4.8	7.2	-50	10.0	11.9	-18
		10^{-3}	7.1	10.6	-49	14.2	17.0	-20
7670	4.8	10^{-2}	10.7	7.4	31	18.6	11.5	38
		10^{-3}	17.6	11.3	36	28.8	17.5	39
7671	4.5	10^{-2}	8.1	3.6	56	15.5	5.9	62
		10^{-3}	12.4	6.0	52	22.9	9.6	58
7672	2.0	10^{-2}	3.4	6.6	-95	7.1	11.3	-60
		10^{-3}	5.3	9.8	-85	10.6	16.5	-56
7673	2.7	10^{-2}	4.0	4.9	-22	8.1	8.9	-10
		10^{-3}	5.8	7.6	-29	11.3	13.7	-21
7674	2.1	10^{-2}	3.3	6.2	-87	8.9	10.7	-20
		10^{-3}	4.9	9.2	-87	13.4	15.5	-16
7675	2.2	10^{-2}	3.2	4.5	-38	8.6	8.7	-1
		10^{-3}	4.5	6.7	-49	11.5	12.7	-11

Table 1. Mean and peak wind speed with different assigned exceedance probability evaluated from recorded and simulated data, and percentage differences.

The same good agreement on directional distributions is not achieved for all the stations. By way of example, the results of the analyses of the anemometer 7665, that is placed on a viaduct, (Figure 6) show a quite satisfying agreement of the maximum wind speed intensities, but the polar diagrams obtained by the transmission of databases from the meteorological stations result to be rotated roughly by 60° clockwise. This also leads to large differences between adirectional distributions (Table 1).

As for the anemometer 7670, which is installed on a viaduct and in complex orography, data transmitted from meteorological stations do not simulate correctly strong winds blowing from North (Figure 7).

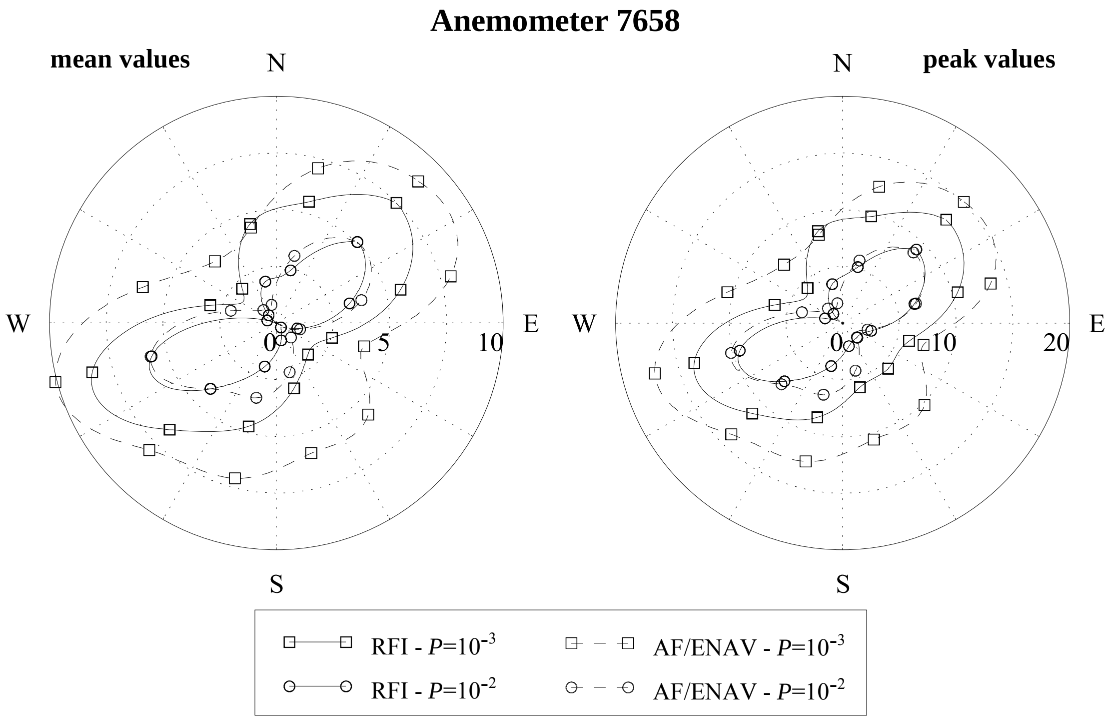

Figure 5. Comparison between the analysis of the data recorded along the line (anemometer 7658) and those obtained by numerical simulations; the left panel refers to the analysis of the mean wind speed, the right panel refers to the analysis of the peak wind speed.

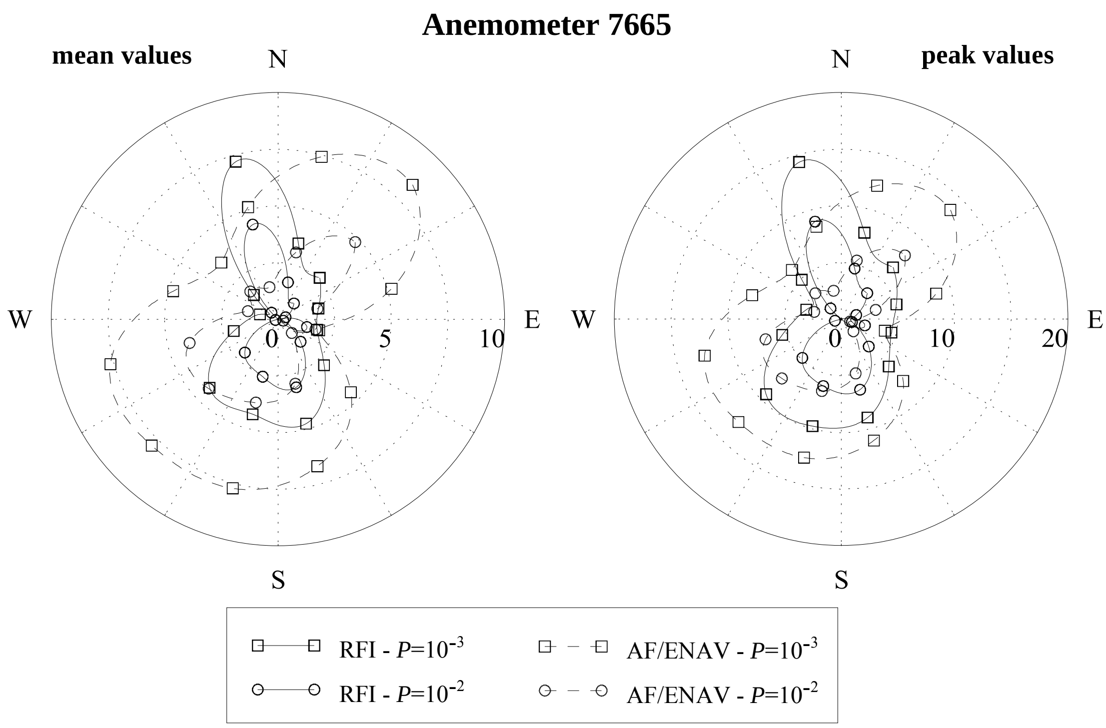

Figure 6. Comparison between the analysis of the data recorded along the line (anemometer 7658) and those obtained by numerical simulations; the left panel refers to the analysis of the mean wind speed, the right panel refers to the analysis of the peak wind speed.

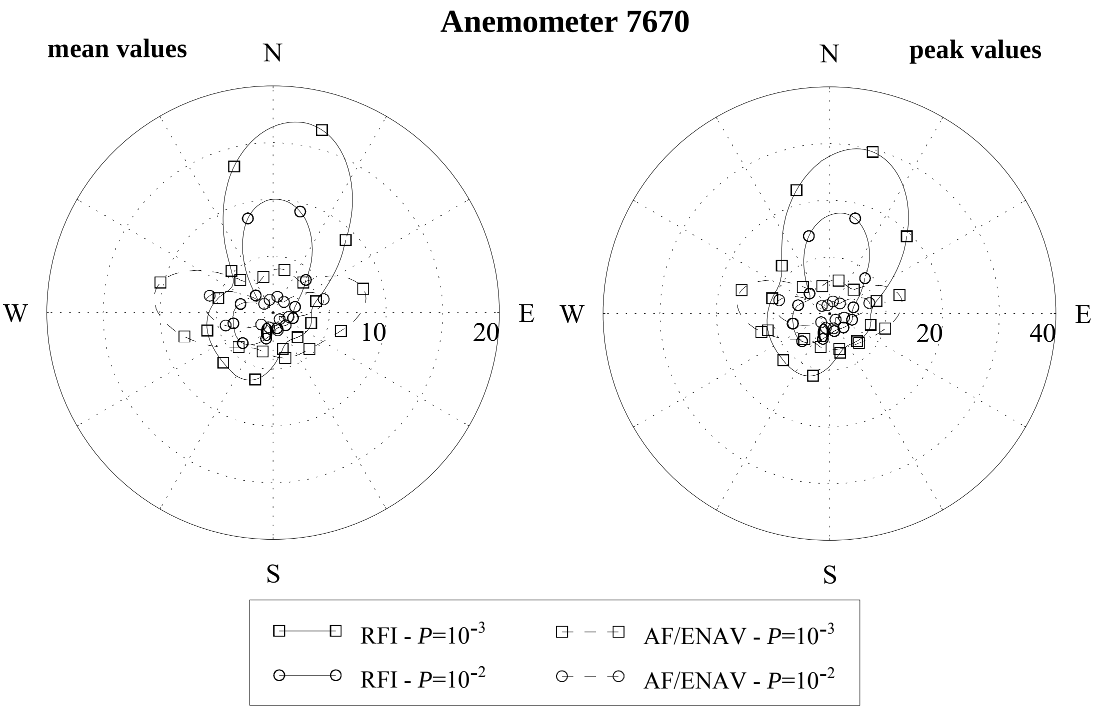

Figure 7. Comparison between the analysis of the data recorded along the line (anemometer 7670) and those obtained by numerical simulations; the left panel refers to the analysis of the mean wind speed, the right panel refers to the analysis of the peak wind speed.

As depicted by Figure 8, showing a three-dimensional representation of the area surrounding the anemometer 7670, such anemometer is screened in the North direction by a significant mountain range. Therefore, strong winds blowing from that direction are probably downhill winds (maybe catabatic winds), that cannot be simulated by the mass-consistent model. On the contrary, probabilistic analyses based on numerical simulations reach the maximum values roughly along the West-East direction, corresponding to the opening of a valley, whereas the mountains in the North direction screens the wind.

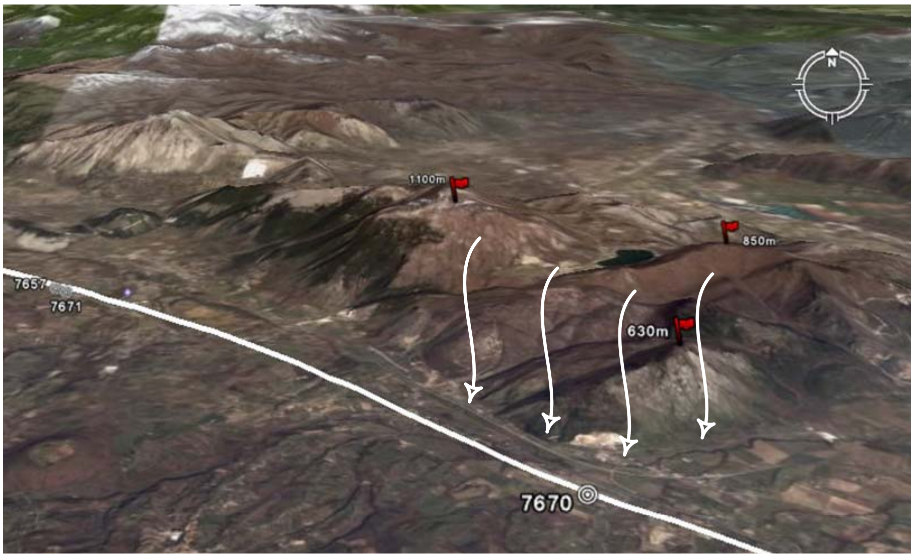

Figure 8. Three-dimensional view of the area surrounding the anemometer 7670, and schematic representation of the downhill wind from North.

As introduced at Section 4, the records of the anemometers installed along the line are also characterized by daily breezes phenomena that are not modeled by the numerical simulations. By way of example, Figure 9 shows the results of probabilistic analyses carried out on two sets of data collected by the anemometer 7658. Each set refers to the measurements collected every day on an interval equal to 5 hours, at daytime from noon to 5 pm (left panel) and in the nighttime from midnight to 5 am (right panel). The resulting polar distributions are rather different in shape and values, and this phenomenon make difficult any attempt to compare the results of the analyses on recorded and simulated data.

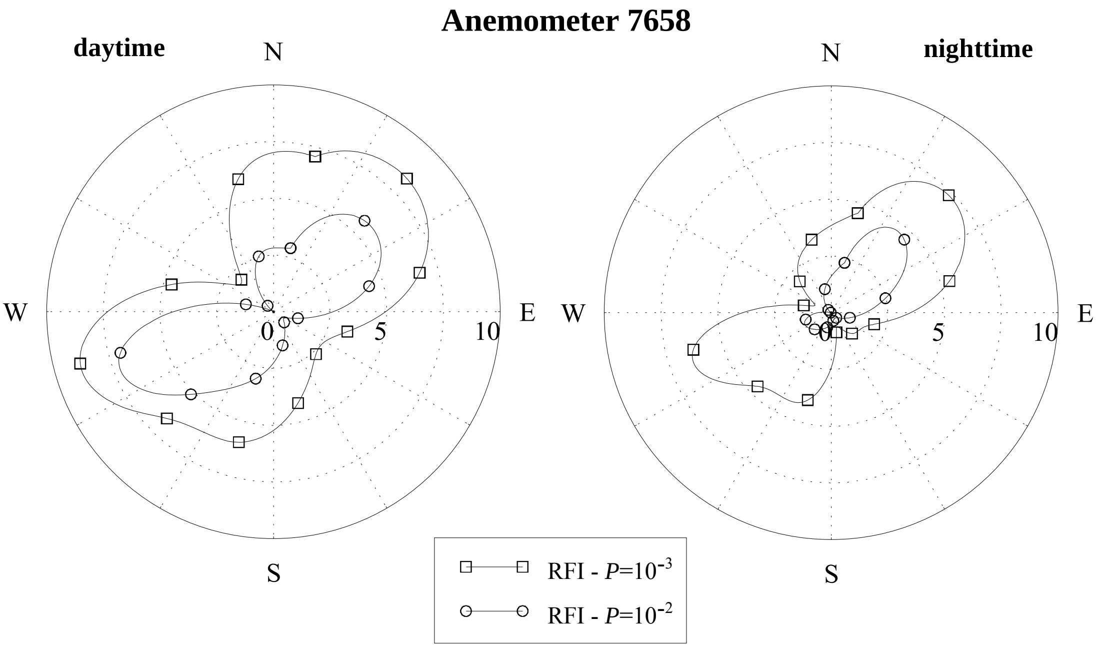

Figure 9. Polar diagrams of daytime (left panel) and nighttime (right panel) wind speed at anemometer 7658.

6 FURTHER CONSIDERATIONS AND CONCLUSIONS

The procedure adopted to derive the aforementioned method makes use of advanced tools; this notwithstanding, there are several uncertainties in the modeling chain that leads to the evaluation of the probabilistic evaluation of the wind speed and direction at the railway line.

The largest differences between simulated and recorded data are generally corresponding to zones denoted by a low windiness, though. The evaluation of the wind speed at the line by means of the developed procedure provides better results just next to places where strong winds blow. In these situations, particular attention should be paid only to local winds that cannot be included in the numerical model. To provide a better understanding of local winds, new models are going to be implemented to study the wind circulation in the area where anemometer 7670 stands. In parallel, new anemometers could be placed in the areas that numerical analyses have individuated as windy. The analysis of their data, along with the comparison of simulations with the results of probabilistic analyses carried out on updated databases of existing anemometers, could provide a better validation of the methodology.

All in all, at present, since the wind hazard has to be evaluated based on windy locations, the developed methodology can be regarded as a powerful tool to estimate the wind hazard at the railway line, and can be successfully adopted as input for the evaluation of the CWC.

The developed procedure and its further improvements are going to be applied to other high-speed railway lines.

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