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RISK ANALYSIS OF CROSS WIND ON HS/HC ROME-NAPLES RAILWAY LINE

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Abstract. *This paper describes a comparison between two new methodologies to perform the cross wind risk analysis on railway lines, developed within the European project Aerodynamic in Open Air (AOA, WP2). The study consists in the evaluation of the probability of rail vehicle overturning when it is running on a railway line under the action of cross wind. According to both the methodologies, the cross wind risk analysis is based on a meteo study and on the determination of Characteristic Wind Curves (CWC). The meteo study provides the probability of occurrence of wind gusts on a specific point of a railway line while the CWC computation allows to evaluate the gust wind speed that leads the vehicle to overcome the specific safety limits. The cross wind risk is defined as the combined probability of the wind gust velocity occurrence and of the overcoming of the safety limit adopted for the definition of the CWC. The two methodologies mainly differ in the calculation of the CWC, since one adopts a deterministic approach while the other is based on a stochastic procedure. This paper reports and compares the application of these new methodologies to the two samples of Rome-Naples high speed railway line.*

1 INTRODUCTION

When a train is running on a railway line, one of the most critical problem, related to safety, is the risk of overturning, associated to the cross wind action.

Within the new European Technical Specification for High Speed Interoperability (TSI), the cross wind represents one of the main themes: the standard defines the limit values for the Characteristic Wind Curves (CWC) that represents the wind speed that leads the vehicle to the overcoming of specific safety limits. From the infrastructure point of view, the TSI requires the infrastructure manager to identify the most critical sections of the line and to choose the actions to be undertaken (lowering the train speed, wind barriers, etc) in order to keep the probability of cross wind problems under a given threshold. Nevertheless, for this analysis, no specific methodologies are defined by standard in Italy.

In order to analyse the problem from the rolling stock point of view, a risk analysis, based on the study of the wind-train interaction, is needed. This study depends on both the wind characteristics along the line and the dynamic and aerodynamic properties of the considered train. The second part of the European project "Aerodynamic in Open Air" (AOA), was specifically oriented to assess the risk analysis on high speed lines related to cross wind effects (Ref. [5]). Within the AOA project, for the meteo analysis, specific numerical tools, with different degree of complexity, have been developed but, at the present, a common standardized method has not been assessed. Concerning the train stability, the CWC are a commonly accepted method to define the overturning limit even if uncertainties remain if they have to be computed through stochastic or deterministic approaches. The definition of the risk consists in combing the information coming from the meteo analysis and from the CWC's.

This paper leads to the comparison between two approaches for the risk analysis developed within the AOA project: a stochastic methodology (STM, Ref. [1]) and a deterministic methodology (DEM, Ref. [8]). The two methods will be applied to the risk analysis study of two samples of the new Rome-Naples high speed line, in the south of Italy, in order to evaluate the most important parameters for the definition of the risk associated to the cross wind.

2 THE RISK ANALYSIS

The risk analysis consists in the evaluation of the rail vehicle overturning probability when the train is running on a railway line under the action of cross wind.

Fig. 1 shows the flowchart of the general procedure, common for both the methodologies described in this paper.

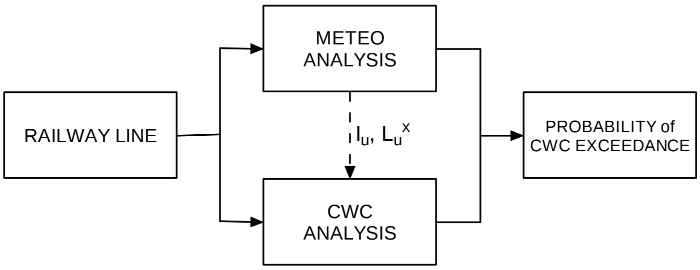

Figure 1. The risk analysis flowchart.

The first step consists in the definition of the line properties, both in terms of topographic layout (global coordinates, orientation to the north, height of the track with respect to the sea) and in terms of local characteristics (infrastructure scenario, curve radius, cant deficiency, design speed, …). According to this line description, the samples of the overall line has been divided into homogeneous sections. Moreover, the line analysis provides the inputs that are required to carry out both the meteo study and the CWC calculation. The same infrastructure database has been adopted for both the methodologies.

The meteo analysis allows to define the wind characteristics in each homogeneous section of the line. In particular, in this paper, the same meteo study, carried out by the University of Genoa (Ref. [3]), for the RM-NP line, has been adopted for both the DEM and the STM. Starting from the meteo databases of anemometric stations of the Italian Air Force (AM), located in the neighbourhood of the line, a probabilistic analysis of the wind speed and wind direction along the line was performed. The final outputs of the meteo analysis are the distributions of the directional cumulative probability $\mathbf{p_w}$ of the mean and gust wind speed (isoquantile), defined on each homogeneous section of the line (Fig. 2).

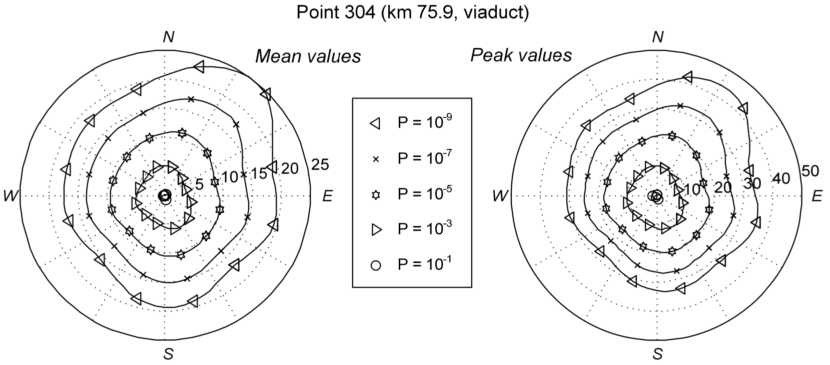

Figure 2. The cumulative probability distributions $\mathbf{p_w}$ of mean and gust wind speed.

The Characteristics Wind Curve (CWC) are evaluated in this paper using two different alternative procedures: a stochastic methodology (STM), developed by the researchers of the Mechanical Department of Politecnico di Milano, and a deterministic methodology (DEM), based on a procedure proposed, within the AOA project, by the SNCF group.

The calculation of the probability of CWC exceedance (POE) along the line is carried out, according to both STM and DEM, by combining the wind probability of occurrence, evaluated through the meteo study, and the wind speed that leads the vehicle to overcome the safety limit (CWC). Both the wind and the CWC distributions are treated as stochastic variables according to STM while, according to DEM, the CWC represents a deterministic threshold.

3 THE CWC CALCULATION

For each homogeneous section of the line, both the methodologies, described in this paper, compute the Characteristic Wind Curves (CWC) through MultiBody Simulations (MBS) of the train dynamic response under aerodynamic cross wind forces (Ref. [1], Ref. [5]).

The main difference between the two methodologies is that while, with the STM, the wind-train interaction is considered as a random process, with the DEM, the dynamic response of the train to turbulent wind is evaluated through a deterministic approach.

According to the STM, different CWC can be defined (Ref. [1]) for the same wind scenario. With this procedure, in each point of the line, a distribution of CWC is calculated accounting for the statistical wind properties of the considered section (turbulence intensity, I_u, and integral length scale, L_u^x), evaluated through the meteo analysis (dashed line, Fig. 1).

On the other hand, according to the DEM, the CWC is evaluated with the TSI approach (Ref. [2]), where the effect of turbulent wind is modelled through an equivalent impulsive input gust (Chinese hat profile). According to this methodology, the wind properties are fixed

(I_u=24.5% and L_u^x=96m) and only one CWC is calculated through the simulation of the dynamic response of the vehicle (the same adopted for the STM) to this equivalent gust.

The second difference between the two approaches consists in the application of CWC to the whole line. From a theoretical point of view, for the risk analysis, the CWC should be evaluated, in each point of the line, accounting for the specific aerodynamic effects induced by the infrastructure characteristics of the site through the aerodynamic coefficients (Ref. [1]). Anyway this should lead to a lot of wind tunnel tests to estimate the aerodynamic coefficients of the considered train with all the possible infrastructure scenarios (flat ground, viaducts and embankments of different geometries). Obviously, this approach is not feasible. The methodologies described in this paper propose different approaches, both based on empirical formula, that allow to extrapolate all the real infrastructure scenarios present along the line relying on two standard scenarios (flat ground and 6m high embankment, Ref. [2]).

In particular, for the embankment/cut scenarios, the STM considers that the aerodynamic forces acting on the train can be computed using the coefficients measured on the flat ground scenario in the range 0°-30° of angles of attack[1], if the accelerated wind speed on top of the scenario (at an height if 2 m over the track) is adopted (Ref. [4]). As a consequence, according to the STM, the aerodynamic coefficients are evaluated only for the flat ground scenario, demanding to the meteo study the task to calculate, through empirical formula, related to the geometry of embankment/cut, the wind speed over the track, in correspondence of the train position to account for different infrastructure scenarios. The wind speed, at an height of 2m over the track, is evaluated by two different methods: starting from the wind speed calculated, in undisturbed flow, at an height of 4m over the terrain, or starting from the wind speed at 10m over the terrain, and considering the effect of the atmospheric boundary layer (Ref. [3]). The highest wind speed value (that is the most critical one) is then adopted.

Moreover, with the STM, the actual non compensated acceleration in each point of the line is considered through the MB simulation.

On the contrary, the DEM takes into account the infrastructure scenario effects and the non-compensated acceleration starting from the deterministic CWC calculated, through the TSI approach (Chinese Hat, Ref. [2]), for the standard 6m-high embankment in alignment. In this case, empirical transposition coefficients are directly applied to the CWC so that they are suitably scaled in order to consider the different embankment/cut geometries (Ref. [5]) and the actual non compensated acceleration associated to the considered curve. As a consequence, no comparison are possible between the methodologies in terms of CWC for all the sections of the line characterized by embankment/cut because the STM CWC are related to the wind speed measured over the embankment while the DEM CWC refer to the wind speed of undisturbed flow, away from the scenario.

For the viaducts, on the contrary, both the methodologies adopt the CWC calculated starting from the flat ground aerodynamic coefficients. With this scenario, according to both the procedures, the wind speed is evaluated, through the meteo analysis, at the viaduct height, accounting for the atmospheric wind profile boundary layer but neglecting the scenario effect.

In Fig. 3 a comparison between the CWC calculated with flat ground by both the methodologies is reported. The CWC calculated through STM are represented in terms of mean value and corresponding spread band and they are calculated for different statistical wind characteristics. The deterministic CWC, defined for a fixed wind scenario (I_u=24.5% and L_u^x=96m), is contained, at all angles of attack, within the spread band of the stochastic curve but it does not necessarily correspond to its mean value neither to the lower value.

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[1] This range represents the interesting values for the cross wind analysis of high speed trains.

In Fig. 4 the application of the CWC to the railway line is presented. For a specific section of the line (km 75.61 – viaduct), the wind properties are extracted by the meteo analysis and the STM CWC is calculated as a function of the wind direction. On the other hand, the DEM CWC is calculated, independently from the site properties, for the standard wind scenario (I_u=24.5% and L_u^x=96m). The line direction is highlighted by a black line. It is possible to see that the larger differences arising for wind aligned to the line are due to the fact that the CWC calculated by the DEM are limited to a maximum value (saturation at 45 m/s). This discrepancy is not significant in terms of probability of CWC exceedance because, at these velocities, the corresponding probability is extremely low.

On the other hand, at the angles of attack corresponding to the wind about perpendicular to the line (about 70° and 250°), we can also see that while, for wind coming from the inside of curve (250°), the DEM CWC is similar to the mean value of the CWC distribution calculated through the STM, for wind coming from outside the curve (at 70°), the DEM CWC lies in correspondence of the upper limit of the spread band associated to the STM CWC.

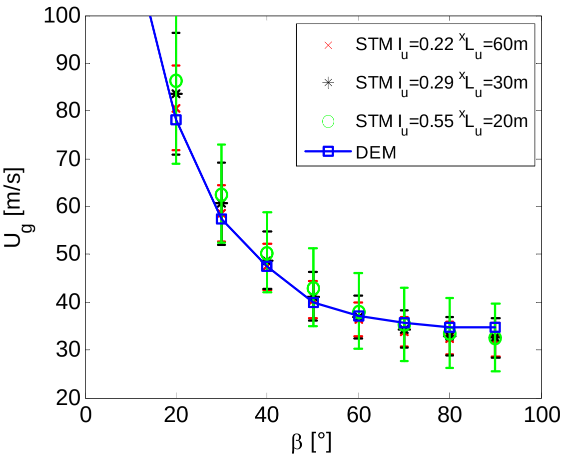

Figure 3. CWC as a function of wind angle β, (V_{tr}=300 km/h) on viaduct, alignment: STM with different wind scenarios vs DEM.

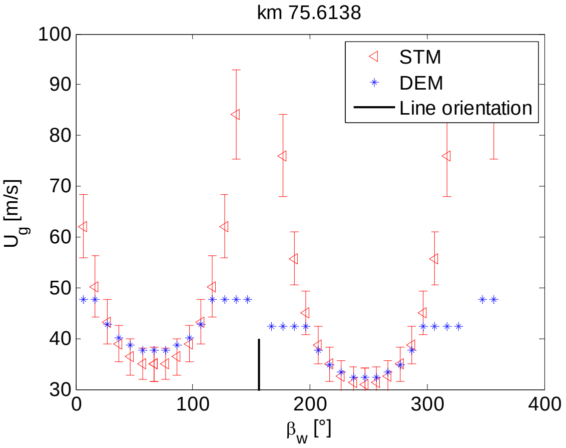

Figure 4. CWC as a function of wind coming direction for the km 75.61 of RM-NP line: STM vs DEM.

4 PROBABILITY OF CWC EXCEEDANCE (POE)

According to the STM, the probability of exceedance (POE) of CWC is evaluated as the combined probability that two events contemporary occur:

1. the gust wind speed coming from the β direction is higher than a threshold $\bar{U}_g$;
2. for a gust wind speed equal to the threshold $\bar{U}_g$ and coming from the β direction, the limit of stability of 90% unloading of the wheels (that is the safety limit for the CWC definition) is overcome.

The combined probability of the two events $\mathbf{p_{i,\beta}}$, for the a specific wind direction **β** and an homogeneous section **i**, is calculated through the following formula:

$$p_{i,\beta} = \int_{-\infty}^{+\infty} p_w\left(U_g, i, \beta\right) * p_{cwc}\left(U_g, i, \beta\right) dU_g \qquad (1)$$

representing the integral of the product between these wind speed cumulative probability distribution $\mathbf{p_w}$ (defined through the meteo study) corresponding to the probability of the first event, and the CWC distribution $\mathbf{p_{CWC}}$, associated to the probability of the second event. The POE for the ith section along the samples is:

$$p_i = \int_0^{360} p_{i,\beta} d\beta \tag{2}$$

the integral over all the angles of the calculated combined probabilities $\mathbf{p_{i,\beta}}$.

According to the DEM, the CWC does not represent a stochastic distribution but a fixed threshold and, therefore, the POE corresponds to the probability that the wind speed, coming from the β direction, is higher than the CWC value ($\bar{U}_g$) calculated for that wind direction (β). Since the output of the meteo study are the directional cumulative probability distributions for discrete probability values (iso-quantile $\mathbf{p_w}$), for each wind direction **β** and section **i**, the POE $\mathbf{p_{i,\beta}}$, related to the specific CWC value $\bar{U}_g$, is evaluated by means of a linear interpolation between the probabilities of the two closest values of the CWC $\bar{U}_g$. Also in this case, the POE for the ith section along the samples ($\mathbf{p_i}$) is the integral, over the angles, of the calculated $\mathbf{p_{i,\beta}}$ (eq. 2).

Fig. 5 shows, as an example, the POE evaluated on all the points of sample1 (km 72.82-77.32) of the RM-NP line through the stochastic (STM) and the deterministic (DEM) methodology. The infrastructure characteristics along the sample are indicated through a symbol (E=embankment, V=viaduct, C=cut) followed by the height of the scenario (expressed in meters), positioned over an arrow that corresponds to the scenario extension. From Fig. 5 it is possible to observe that the main differences between the two methodologies arise in correspondence of the embankments 2.5m high (from km 77 to km 77.3) and 7.5m high (from km 73.2 to km 74 and from km 77.3 to km 77.5): in all these points, the probability assessed by the STM is higher than the corresponding value calculated by the DEM. On the other hand, in correspondence of most of the 7.5m high embankments and in correspondence of the 12.5m high embankments, there is a good agreement between DEM and STM.

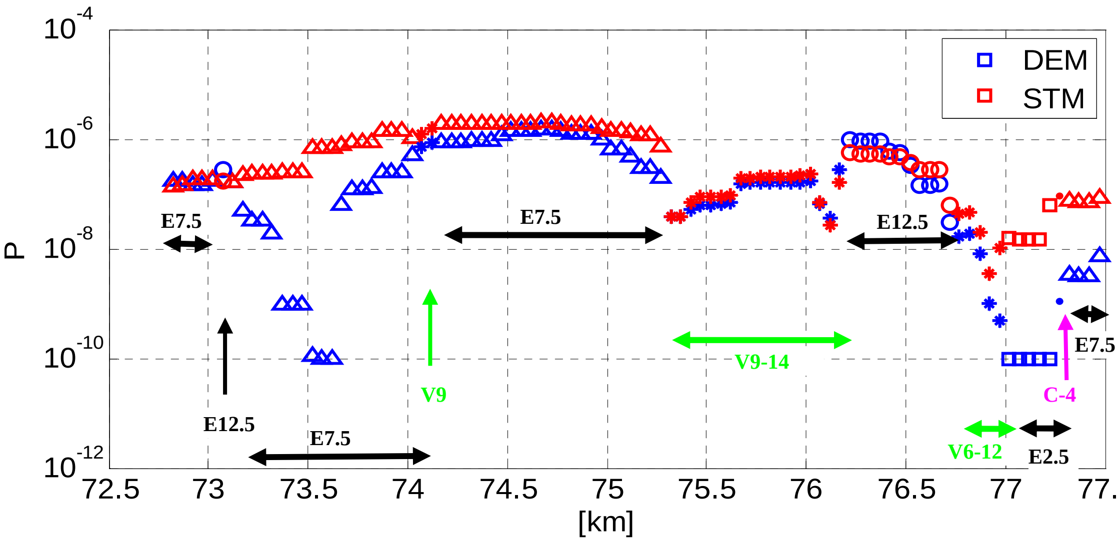

Figure 5. Probabilities of CWC exceedance for sample 1
of RM-NP line: DEM vs STM.

In order to better understand the reasons of the differences between the methodologies results, in Fig. 6 and in Fig. 7, respectively for the km 73.5 and 74.5, the CWC and the wind cumulative probability functions p_w are shown for both DEM (on the left) and STM (on the right). The two analysed sections are characterized by the same infrastructure scenario and curve radius and by the same wind properties. According to the DEM, the wind speed cumulative functions are evaluated in undisturbed flow (without accounting for the infrastructure effect) while, according to the STM, the wind speed cumulative functions are calculated over the track, in correspondence of the train position. As already underlined in the previous paragraph, the wind speed at an height of 2m over the track (STM) is evaluated, through empirical formula (that allow to account for the speed up effect associated to the geometrical characteristics of the embankment/cut), by two different methods: or, starting from the wind speed calculated, in undisturbed flow, at an height of 4m over the top of the scenario, or starting from the wind speed assessed at 10m, by considering the effect of the atmospheric boundary layer (Ref. [3]).

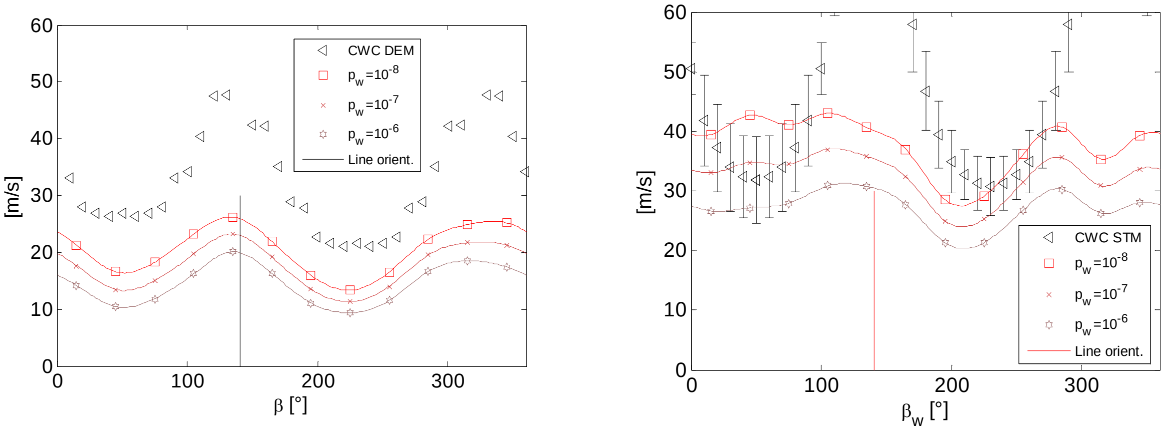

Figure 6. Section km 73.5, 7.5m high embankment, CWC and wind cumulative probability functions p_w: DEM (left) vs STM (right).

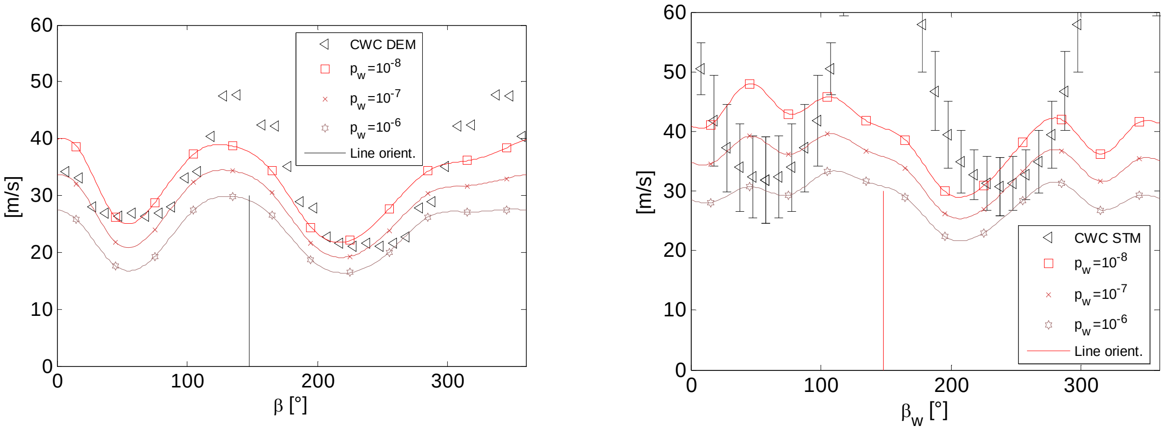

Figure 7. Section km 74.5, 7.5m high embankment, CWC and wind cumulative probability functions p_w: DEM (left) vs STM (right).

By considering the wind speed cumulative probability functions in both Fig. 6 and Fig.7, it is possible to see that the wind speed calculated over the top of the scenario (right) is higher in modulus and it has a different distribution with respect to the wind in undisturbed flow (left). Nevertheless, the increment of the wind speed from undisturbed flow (DEM, left) to above the track (STM, right), associated to the infrastructure, is much more significant at km 73.5 (Fig. 6) than at km 74.5 (Fig. 7). This discrepancy is associated to the two different ways of calculating the wind speed over the top of the scenario.

By looking again at Fig. 5, it is possible to observe that the agreement in correspondence of the viaducts of different heights is very good: in this case no corrective empirical formula associated to the scenario geometry are adopted in the calculation of the wind speed cumulative probability functions because both the methodologies adopt the flat ground CWC and the wind speed is evaluated at the height of the viaduct but without accounting for the scenario effect. In these sections, the differences between DEM and STM are due only to the effects of the wind properties on CWC (that are considered by the STM but not by the DEM) and to the different definition of the CWC, as probability distribution or a threshold, in the calculation of POE. From Fig. 4 we have observed that, where the CWC are lower, in correspondence of the most significant values for the calculation of the probability of CWC exceedance, i.e. when the wind is perpendicular to the line, coming from inside the curve (at about 250°), the CWC evaluated by the DEM exactly corresponds to the mean value of the CWC distribution calculated through the STM. This result allows to justify the good agreement found between DEM and STM in terms of probability of CWC exceedance.

From these observations it is possible to conclude that the differences in correspondence of the embankments (2.5m and 7.5m high) are mainly due to the different ways of applying the empirical formula to correctly accounting for the embankment geometry.

Nevertheless, despite of the differences, the trend of probability found with both the methodologies is very similar and, according to both the approaches, the most exposed zone of the considered sample is the embankment 7.5m high, around the km 74.5.

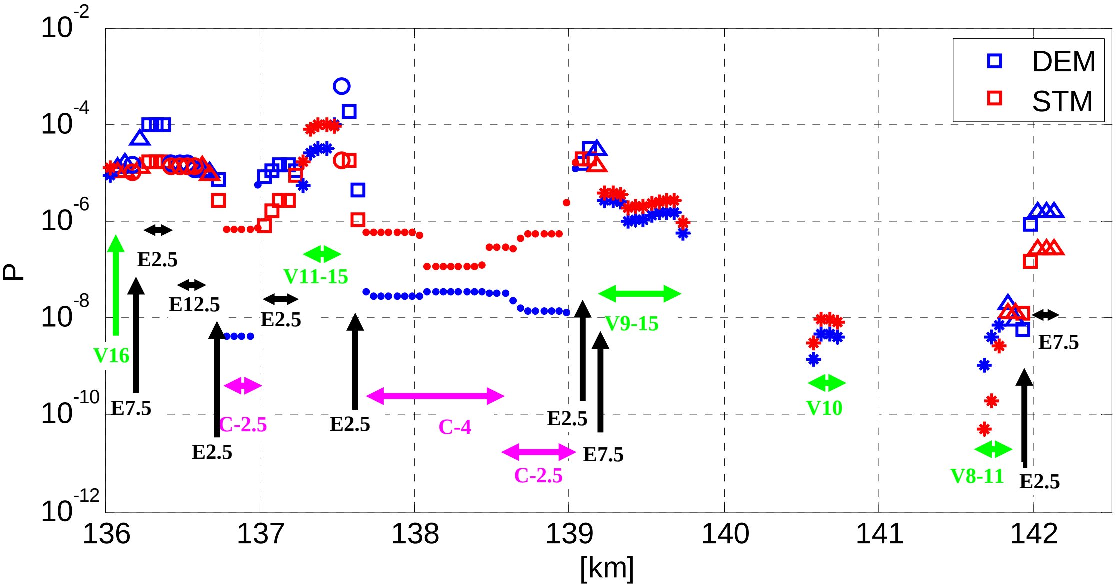

Figure 8. Probabilities of CWC exceedance for sample 2
of RM-NP line: DEM vs STM.

Fig. 8 shows the POE evaluated for the sample 2 (km 136-142.3) of the RM-NP line through the stochastic (STM) and the deterministic (DEM) methodology. Also for this sample, the symbol (E=embankment, V=viaduct, C=cut) followed by the height of the scenario (expressed in meters) allows to know the geometrical characteristics of the infrastructure in the considered point. From Fig. 8 it is possible to see that the main differences are in correspondence of cuts while, also in this case, there is a very good agreement between the results of the two methodologies in correspondence of the viaducts.

If we deeply investigate for example the point at km 139 (Fig. 9), it is possible to see that while the wind speed cumulative probability functions, evaluated according to both DEM and STM, are almost equivalent, the CWC evaluated with the two approaches are very different. In this case it is possible to deduce that, in correspondence of the cut, the two empirical formula adopted, within the DEM, for the transposition of CWC and, within the STM, for the calculation of the wind speed over the track, are not equivalent.

From the comparison carried out on both the samples we can conclude that the most important differences between the two methodologies are associated to the different ways of applying the empirical formula to account for the speed up/speed down effects related to the embankment/cut geometries. On the other hand, the trend of POE, calculated through both the methods along the two considered samples, is qualitatively very similar.

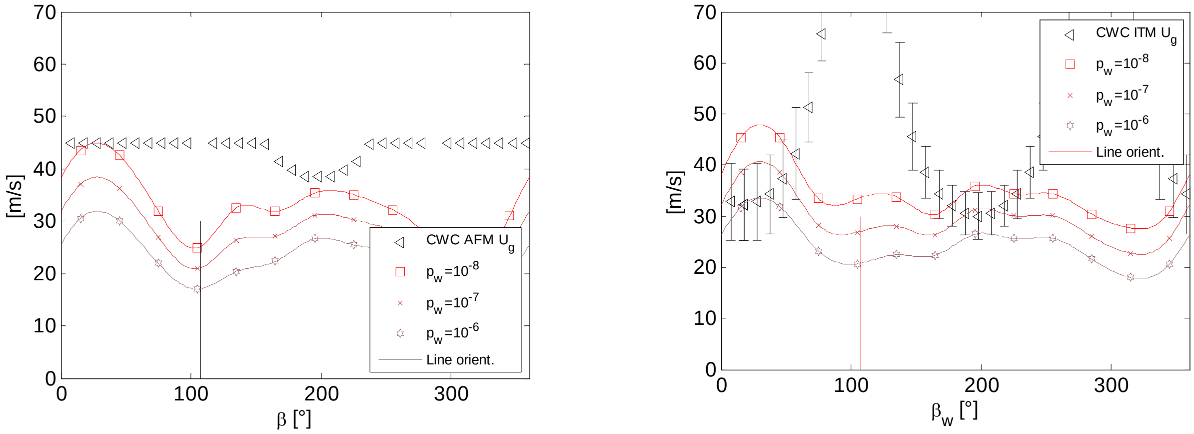

Figure 9. Section km 139, -2m dept cut, CWC and wind cumulative probability functions p_w: DEM (left) vs STM (right).

CONCLUSIONS

Two different methodologies, for the cross wind risk analysis on high speed railway lines, developed within the AOA project, have been compared.

The stochastic methodology (STM) is based on both a meteo study, providing the probability of occurrence of wind gusts on the specific considered site, and a stochastic approach for the evaluation of the Characteristics Wind Curve (CWC) probability distribution. The infrastructure effects are accounted for the wind speed that is evaluated not in free stream but in correspondence of the train position (at 2m height from the track).

On the other hand, according to the deterministic methodology (DEM), while the wind speed data are evaluated through the same meteo analysis, the CWC are defined starting from the TSI standard and in modifying it through empirical formula that account for the speed up/speed down effects associated to the embankments/cuts.

The probability of CWC exceedance is then calculated, according to both the methodologies, as the combined probability of the wind gust velocity occurrence and of the overcoming of the safety limit adopted for the definition of the CWC.

A comparison between the two methodologies has been carried out analyzing two samples of the Rome-Naples high speed railway. The results show a good agreement between the two methods: the trend of POE, calculated by STM and DEM along the two considered samples, is qualitatively very similar. Small discrepancies are probably due to the application of the empirical formula that allows to account for the scenario effect on the wind speed.

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REFERENCES

[1] G. Diana, M. Burlando, F. Cheli, A. Freda, C. F. Ratto, D. Rocchi, G. Solari, M. Testa, G. Tomasini. A new methodology to perform the risk analysis of cross wind on high speed lines. Proceedings of the 8th WCRR, May, 18-22, COEX, Seoul, Corea, 2008.

[2] *Technical Specification for Interoperability*. Draft Revised HS RST TSI.

[3] Solari, G. , Ratto, C.F., Buonanno, A., Testa, M., Freda, A., Burlando, M., Mancini, M. Probabilistic analysis of the wind speed along the Rome-Naples HS/HC railway line. Proceedings of the 12th Int. Conf. on Wind Engineering, Cairns, Australia, 2007.

[4] F. Cheli, R. Corradi, D. Rocchi, G. Tomasini. Wind tunnel tests on train scale models to investigate the effect of infrastructure scenario. Proceedings of the BBAA VI, Milano, Italy, July 20-24, 2008.

[5] H. Quentin, P.Da Costa. HST TSI’s CWCs transposition. DeuFraKo AOA report, WP2.2, 2007.