

Evaluation of crosswind effects on rail vehicles through moving model experiments

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ABSTRACT: This paper presents the results obtained from two series of tests on scale-model rail vehicles, one in static and the other in moving model conditions. The experiments were carried out at the TRAIN (TRANSient Aerodynamic INvestigation) rig using the recently developed crosswind generator. A 1:25 scale model of a Class 390 Pendolino train was tested on a flat ground scenario in correspondence of a 30° yaw angle. The Reynolds number was of the order of 2×10^5 . The surface pressure on the train leading car was monitored in correspondence of 110 tapping points using a novel onboard stand-alone measuring system. An evaluation of the mean values for the local pressure coefficient shows limited differences between static and moving model tests only in correspondence of a restricted number of tapping points. A comparison in terms of overall mean aerodynamic coefficients indicates a good agreement between the two sets of results.

KEYWORDS: Crosswind, rail vehicles, moving model tests, static tests, mean pressure coefficient, mean aerodynamic load coefficients

1 INTRODUCTION

A train travelling through a natural turbulent crosswind is surrounded by a complex flow field which leads to a series of steady and unsteady aerodynamic forces and moments. These aerodynamic loads may induce significant changes in the vehicle dynamic behaviour in comparison to a no-crosswind condition and, in the presence of strong winds, serious accidents may happen because the train stability has been compromised [1]. To prevent the occurrence of such events, in the last two decades a series of specific methodologies have been developed for assessing the stability of trains in crosswinds [2, 3]. These methodologies are currently applied within the rolling stock certification process [4, 5] and rely on a numerical-experimental approach. While the vehicle dynamics and the characteristics of the natural wind are simulated numerically, the information regarding the wind-vehicle interaction is provided as an external input to the model in form of dimensionless aerodynamic coefficients. Such parameters depend on the train geometry and are typically obtained through wind tunnel experiments on static scale models, which represent the standard technique of investigation [4, 5]. These type of experiments have the significant advantage that they can be treated as conventional wind tunnel tests and, as such, can be carried out in traditional environmental wind tunnel facilities. However, by their very nature they do not simulate the movement of the train relative to the ground; the importance of this on the overall forces/moments acting on the train still remains largely unresolved [6].

Different studies have been undertaken in the past for evaluating the impact that the vehicle movement simulation has on the crosswind loads on trains. Since the mid 1980's the problem was approached from an experimental perspective and a number of moving model test campaigns were carried out [7, 8, 9, 10]. Despite the differences in these experiments, three common elements can be identified. Firstly, a test methodology based on carrying out series of multiple

runs was adopted. This was essential in order to collect a proper amount of data for enabling stable ensemble averages of the time histories to be calculated. Secondly, in the vast majority of the cases, the tests took place in existing wind tunnel facilities, where specifically designed propulsion systems (either mechanical [7, 8, 10] or gravity based [9]) had been integrated for providing the vehicle movement. Finally, the measuring systems employed during the tests all measured the overall forces and moments acting on the moving vehicle through the use of internal strain gauge balances. The outcomes from these previous moving model test campaigns do not appear to be entirely consistent. Bocciolone *et al.* [9] found no relevant discrepancies between aerodynamic loads on a train measured in stationary and moving model conditions, whereas Baker [7] and Humphreys [8] found the opposite. However, a close examination of data which did show an effect of the vehicle movement simulation yielded no definitive trends. Such inhomogeneity suggests a limited level of reliability associated with the results and was one of the motivations for the current work.

Considering the numerous issues associated with a moving model test campaign, recently, an alternative approach based on CFD analyses has been used [11]. However, before quantitative conclusions can be drawn based on numerical results, it is essential to assess the level of accuracy of CFD when applied to moving vehicles. Such a comparison requires detailed and reliable experiment data, some of which will be outlined below.

This paper presents the results obtained from a measurement campaign on scale-model rail vehicles in crosswinds, which was undertaken as part of the EU-funded AeroTRAIN project. Two series of experiments were carried out, one under static conditions and the other in moving model conditions. Contrary to previous moving model campaigns, the measuring system used for these tests monitored the local pressure distribution on the train surface rather than the overall aerodynamic loads on the vehicle. This approach enables a first comparison between static and moving tests results to be made with consideration to local values of the mean pressure in different areas of the train. By integrating the pressure distribution, a further comparison can be arranged in terms of steady overall aerodynamic loads. In what follows, the details of the examined test case, together with the characteristics of the facility, as well as of the measuring system and of the methodology, are described in section 2. Section 3 illustrates the results in terms of local values of the mean pressure coefficient and also of overall steady aerodynamic loads. Side force, lift force and rolling moment coefficients are considered and a comparison between static and moving tests is discussed. Finally, some concluding remarks are drawn in section 4.

2 EXPERIMENTAL CAMPAIGN

All of the experiments outlined below were carried out at the University of Birmingham's TRAIN (TRANSient Aerodynamic INvestigation) rig (the distinctive features of which are outlined in section 2.1). A 1:25 scale model of a Class 390 Pendolino train was used for the tests. It comprised a full reproduction of the leading car followed by a dummy half trailing car: the leading vehicle was the object of investigation, while the partial second coach was provided to ensure realistic flow around the length of the train (Fig. 1a). For the purpose of the present work a Flat Ground (FG) scenario (i.e. no representation of the ballast was included) and a yaw angle (i.e. the angle between the direction of travel and the relative impacting wind) of 30° were examined. An onset turbulent crosswind characterized both series of tests, static and moving. Such flow simulation was provided by a crosswind generator that has been developed as part of this project. A more in depth description of this apparatus, as well as of the flow characteristics, is reported in what follows. The Reynolds number, based on the train height and the wind speed relative to the vehicle, was of the order of 2×10^5 .

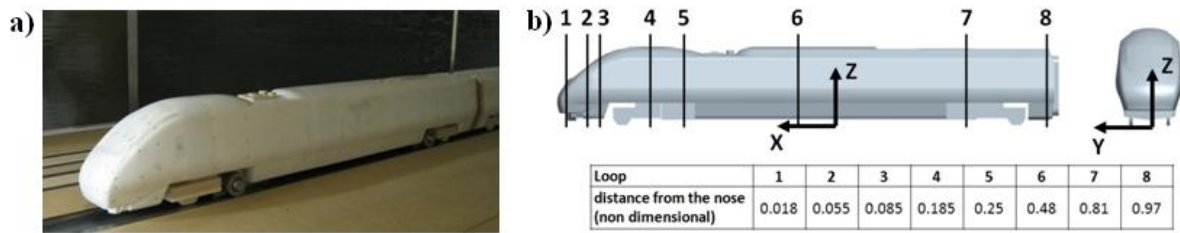


Figure 1. a) Photograph of the Class 390 Pendolino model (1:25 scale). b) Reference system and position of the loops of pressure taps on the leading car.

2.1 The TRAIN rig

The TRAIN rig is a research facility specifically dedicated to undertaking moving model tests on scale model vehicles in open-air, crosswinds and tunnels [12]. It is situated in Derby (UK) and was designed and built by British Rail Research at the end of 1980's [13]. The rig consists of a series of three straight parallel tracks, 150 meters long, equipped with a mechanical propulsion system that can catapult a 1/25 scale model up to 75 m/s. The acceleration mechanism employs a series of pre-tensioned elastic ropes driven by pulleys, while the brake is based on the use of a piston deformable tube. The facility was acquired by the University of Birmingham Centre for Railway Research and Education (BCRRE) in 2009. Since then, the capability of performing moving model experiments in crosswinds has been improved through the design and installation of a new crosswind generator.

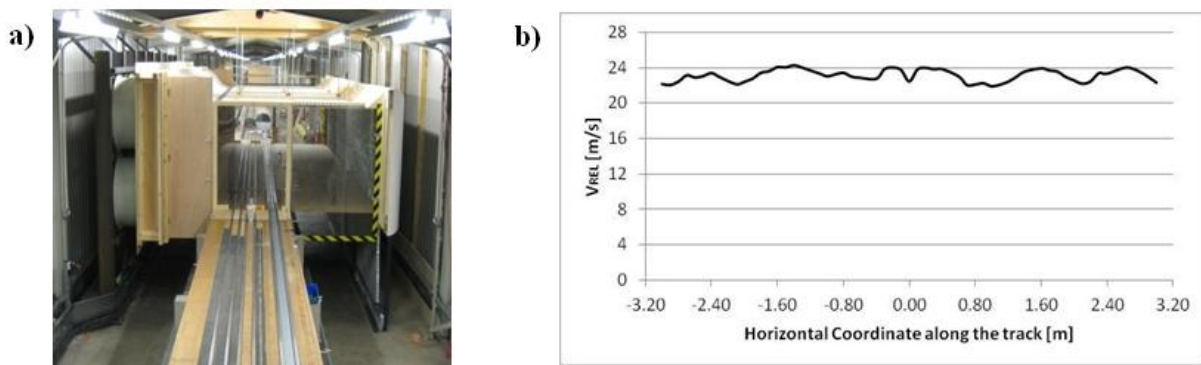


Figure 2. a) TRAIN rig internal view: new crosswind generator. b) Mean wind velocity relative to a train travelling at 20m/s c.a. and experiencing a 30° yaw angle: horizontal profile at 3m full scale equivalent height.

The new system, consists of a series of 16 axial flow fans positioned at the trackside and arranged in two rows of eight units each. The fans operate in sucking-mode and generate an air-flow directed perpendicularly to the direction of travel. Such flow is enclosed in a tests section spanning a portion of the tracks 6.4m long (indicated in what follows as L_{CW}). A photograph of the new crosswind generator is shown in Figure 2a. Before the static and moving model test campaigns started, a dedicated session was carried out in order characterize the properties of the simulated crosswind in terms of mean speed, turbulence intensity and static pressure. The spanwise average of the mean wind speed (U) and turbulence intensity (I_U), measured at 3m full

scale equivalent height, are approximately 12m/s and 16%, respectively. The mean velocity profile of the relative wind, as seen by a train travelling through the crosswind section at approximately 21 m/s (thus in correspondence to a 30° yaw angle) is illustrated in Figure 2b.

2.2 *Measuring Instrumentation*

The experimental data collected during the tests comprised of both trackside and onboard measurements. The trackside measurements included the data regarding the ambient conditions (temperature, barometric pressure and relative humidity), the crosswind properties (velocity and static pressure within the air-channel) and the train speed (for moving model tests only). The ambient conditions were monitored using an Oregon Scientific BAR208HGA weather station and a GBP3300 digital barometer. Localized measurements of the flow speed and static pressure within the crosswind section were recorded using a set of Series 100 cobra probes (by Turbulent Flow Instrumentation Ltd) and a Pitot-static tube in combination with differential pressure transducers HCLA02X5PB (by Sensortekhnics GmbH). An acquisition system run by a laptop computer was employed and data were sampled at 1KHz over a time interval of 60s. During moving model tests, the vehicle speed at the entry and exit of the crosswind generator was measured by two sets of photoelectric position finders and reflectors.

The onboard measurements consisted mainly of the surface pressures detected on the train model. For moving model tests, they included also the output signal from a light detector. The employment of an onboard stand-alone measuring system is essential in order to enable moving model experiments. Unlike what had been done in the past, the system used for these tests monitored the local pressure distribution on the train surface rather than the overall aerodynamic loads on the vehicle. It is a purpose-built measuring system, which employs a series of miniaturized ultra-low differential pressure transducers HCLA12X5PB (by Sensortekhnics GmbH) in combination with a stand-alone data logger. The data logger has a 16-bit resolution, is capable of monitoring 16 channels at a maximum sampling rate of 4KHz and presents an extremely compact design that makes it suitable to be accommodated inside the scale train model. The surface pressure was measured only on the first vehicle, which was equipped with eight loops of pressure taps distributed along its length for a total of 110 measuring positions (Fig. 1b). A series of silicon tubing connected the tapping points to the pressure ports of the transducers. Having 15 channels of the data logger available to pressure measurements, the same number of transducers was used. This enabled the pressure taps of each single loop to be monitored simultaneously. A light detector was connected to the sixteenth channel of the data logger. Having set a series of light sources at specified locations along the track, during the moving model tests the signal from such sensor provided a number of 'position markers'. They were used while post-processing the data for trimming the records from the raw data and thus isolate the portion of time histories associated to the train travelling within the crosswind section.

2.3 *Experimental setup and test methodology*

The test procedure for static tests was similar to the standard methodology commonly adopted for wind tunnel experiments. The train model was mounted statically inside the air-channel and rotated with respect to the oncoming wind in order to simulate the required yaw angle (30°). Time histories of the surface pressure on the train were recorded during a time window of 60s at a sampling rate of 4KHz. It is worth noting that, having the design of the crosswind generator optimized for moving model tests, a number of restrictions were imposed on the static tests. The dimensions of the model coupled with the limited extension of the air-channel in the along-wind direction (i.e. transversally to the track) meant that the nose of train was positioned close to the

channel inlet (i.e. at a distance of approximately 0.2m). This positioning compromised the possibility of a freestream flow upstream the model and determined a high sensitivity of the pressure field on the nose of the train to minor alterations in the environment external to the air-channel. In addition, a gradient in the along-wind direction was identified by the experimental data collected during the flow characterization, either for the streamwise mean wind velocity (negative gradient) or for the static pressure (positive gradient). All these aspects were taken into account during the data processing and also within the uncertainty analysis. They led to an estimate of the experimental error for the static tests slightly larger than in moving model conditions (Fig. 6).

During the moving model experiments the train was run through the crosswind section at approximately 20.8m/s (± 0.6 m/s). For analysis purposes the wind velocity was doubled averaged, i.e., both in time (averaged over the measurement time) and spatially (spanwise) along the measurement domain, yielding a value of 12m/s. Hence, the required yaw angle was $30^\circ \pm 1^\circ$. Considering a total span of the air-channel (L_{CW}) of 6.4m, a train travelling at the specified speed spent approximately 0.3s within the crosswind section. With an acquisition data rate of 4 KHz, this corresponded to approximately 1200 samples. A high variability was observed in the time histories of the surface pressure associated to different runs (Fig. 3b). This suggesting that no reliable indication could be obtained from the analysis of individual runs, a data analysis method based on ensembles of runs was adopted for the moving model tests [14]. For the experiments reported in this paper, a sensitivity study indicated that 15 runs were required for obtaining stable ensemble averages. Figure 3 presents an example of the results obtained by applying this moving model test procedure, with consideration of one single pressure tap on loop 2 (on the nose of the train according to Figure 1b).

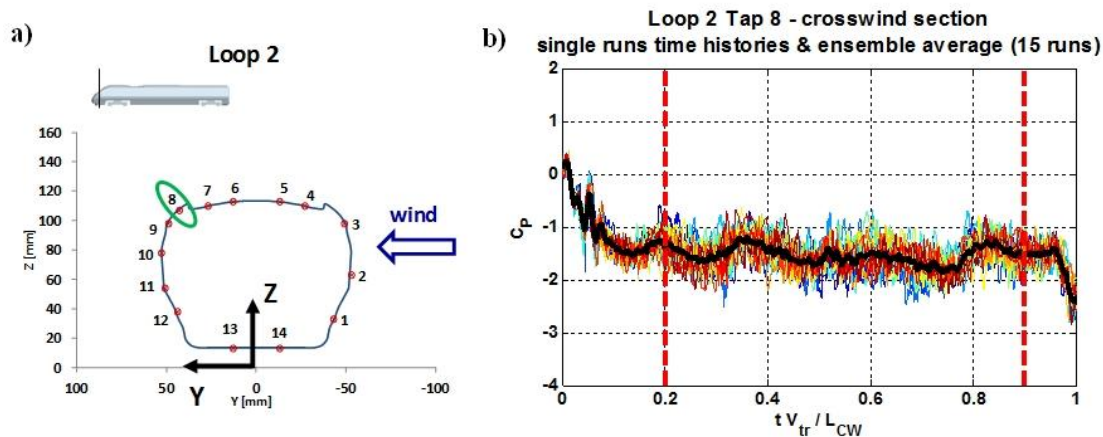


Figure 3. a) Loop 2: cross-section and taps' distribution. b) Single runs time histories (thin lines in grey colors) and ensemble average time history (thick line in black) trimmed within the crosswind section: C_p with respect to non-dimensional time (the vertical dotted lines denote the portion of time history considered for calculating the mean pressure coefficient).

3 RESULTS AND DISCUSSION

3.1 Stationary pressure distribution

In this section the data concerning the pressure distribution on the train are presented in terms of non-dimensional pressure coefficients. Considering each tapping point i on the train surface, the

instantaneous value of the pressure coefficient at a generic time t is indicated as C_{Pi} and defined as:

$$C_{Pi}(t) = \frac{P_i(t) - P_0}{0.5\rho V_{rel}^2} \quad (1)$$

where $P_i(t)$ is the instantaneous value of the actual pressure, measured at the tapping point i , P_0 is the reference pressure, ρ is the crosswind air density and V_{rel} is the reference wind velocity relative to the train.

The reference pressure (P_0) adopted in this study, either in static or moving conditions, consists in the estimated double average static pressure: during any single run, the wind static pressure at a number of measuring positions were recorded over a 60s time interval. Selecting one of these positions as a reference, and averaging the data over the entire time interval, a local mean value for the static pressure during each run was calculated. The reference pressure P_0 , as defined in the above, corresponds to the spanwise average extrapolated from such local mean value. It was obtained using a spanwise average-to-local ratio based on data obtained during the full flow characterization. For static tests only, an additional correction was applied to the reference static pressure calculated as explained in the above. Considering that different loops of tappings were at considerably different distances from the inlet, such correction was adopted to take into account the along-wind static pressure gradient (see Section 2.3). For the moving model experiments, the Cobra probe used for monitoring the reference wind conditions was positioned 0.2m upstream the track centreline, at 3m full scale equivalent height. During the static tests, although still at the same height, the probe was set close to the channel inlet and on the side with respect to the model.

For static tests, the relative wind corresponds to the absolute crosswind. Hence, the reference relative wind velocity (V_{rel}) coincided with the reference crosswind streamwise velocity, indicated as U . Both the definition and the process according to which U was calculated were consistent with those for the reference pressure. A local mean was calculated time averaging the 60s velocity time history recorded by the reference Cobra probe (the same that provided the data for the crosswind static reference pressure). The reference crosswind streamwise velocity (U) is the spanwise average extrapolated from such local mean velocity. Once again it was based on a spanwise average-to-local ratio obtained from the flow characterization data. An along-wind velocity gradient correction was applied when processing the data from static tests.

The results reported in what follows are relative to a stationary aerodynamic condition. Hence, they are expressed in terms of a mean pressure coefficient, $\bar{C}_{Pi}$, where i corresponds to a particular tapping point. For the static tests, the average was calculated over the entire 60s time interval, which corresponded to the full length of time histories recorded for the surface pressure. For the moving model tests, it was obtained considering only the central portion of the ensemble average time history relative to the crosswind section (noted by vertical dotted lines on Figure 3b). The transitions experienced by a running train at the entry and exit of the crosswind section determined a series of unsteady fluctuations respectively in the initial part and in the tail of the ensemble average time history. As not representative of a stationary aerodynamic condition, such effects were not taken into account in the analysis reported here.

Figures 4 and 5 present the mean pressure coefficient distribution in correspondence of two loops of pressure taps, loop 2 on the train nose and loop 6 approximately in the centre of the leading car. A comparison between static and moving tests results is outlined. Error bars are included in the figures to represent the experimental error that has been estimated through an uncertainty analysis (not discussed in the current paper). As specified above, experimental data for the surface pressure were collected for all the eight loops of tappings shown in Figure 1a. For

purposes of discussions, however, two cross-sections were selected to provide a significant example of different surface pressure conditions experienced along the vehicle.

On the nose of the train (Fig. 4) positive values of $\bar{C}_p$, which indicate a stagnation region, are shown on the windward side and also on the roof windward corner. Negative values of $\bar{C}_p$, which instead indicate suction, characterize the leeward side, the underbody region and also the roof leeward corner, with an evident suction peak arising in correspondence of the latter. Significantly reduced magnitudes of $\bar{C}_p$, for both positive and negative values, and also a partially different trend are outlined at the centre of the train leading car (Fig. 5). Similarly to what observed for loop 2, the results relative to loop 6 show areas of suction that embrace both the leeward side and the underbody region. A stagnation region is still present on the windward side, within which a uniform surface pressure is indicated by the very similar $\bar{C}_p$ values in correspondence of taps 1 and 2. The pressure distribution on the roof presents the main variations with respect to what found on the train nose: in the centre of the leading car the roof is entirely characterized by an area of suction, which shows a peak in correspondence of the windward corner.

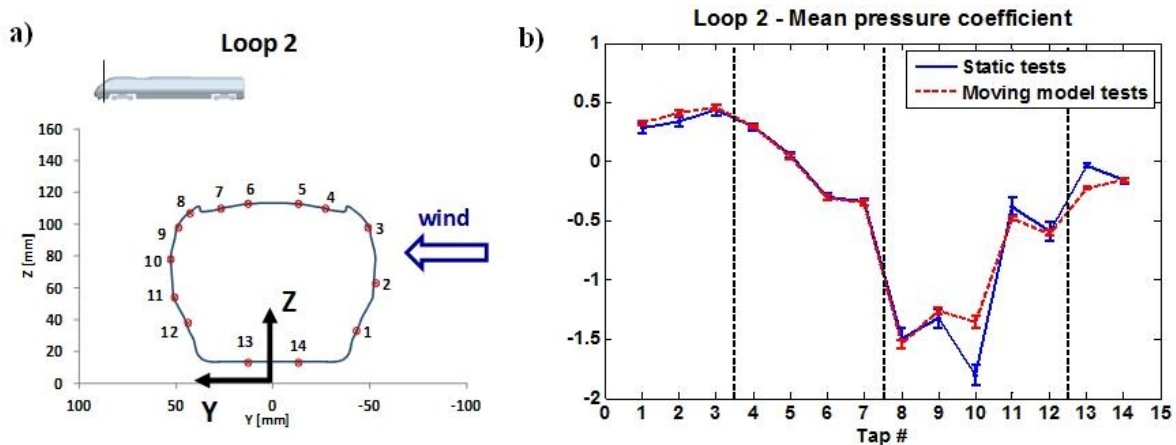


Figure 4. Mean pressure distribution over loop 2 on the nose of the train: Static vs Moving model tests comparison (Class 390 Pendolino, 1:25 scale, 30° yaw angle, FG scenario)

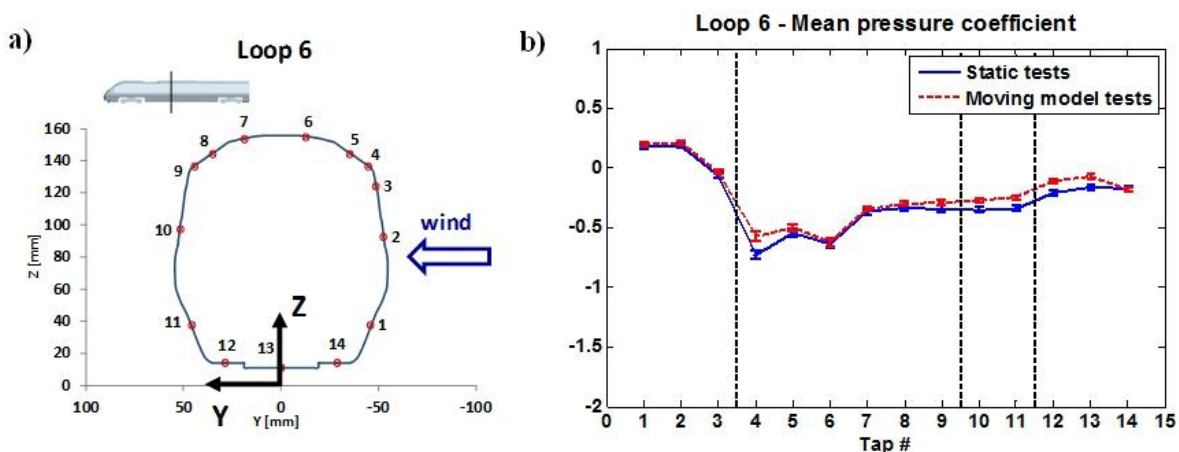


Figure 5. Mean pressure distribution over loop 6 in centre of the leading car: Static vs Moving model tests comparison (Class 390 Pendolino, 1:25 scale, 30° yaw angle, FG scenario)

These results appear consistent with those reported by previous studies on trains which presented similar streamlined designs and were investigated at a 30° yaw angle [11, 15]. The stagnation on the windward side, which on the nose extends also to part of the roof, is determined by the relative crosswind directly impinging the train surface. The suction peak on the nose leeward side is compatible with the presence in that area of one (or more) vortex attached to the train surface. This being supported not only by the magnitude of the suction highlighted in Figure 4 on tap 8, 9 and 10, but also by the fluctuations observed in the time histories of the surface pressure and reflected by high values of standard deviation (not shown here). Moving towards the rear of the train, the data for the adjacent loops of tapings (not shown here) denotes a progressive attenuation in the intensity of this low pressure peak. Such a trend supporting the hypothesis of the vortices mentioned in the above progressively rolling up and moving away from the train surface. A smooth pressure distribution on the leeward side, still associated to a suction region but showing no peak, is reached already in correspondence of loop 4 (Fig. 1a) by where, hence, a complete detachment of the vortical structures seems to have occurred. A region of uniform low pressure is maintained on the leeward side from that section up the rear of the leading vehicle, as reflected by the results relative to the centre of the first car (Fig. 5). The suction peak observed on loop 6, in correspondence of the roof windward corner, suggests in that area the presence of a further vortex. The data from adjacent measuring sections seems to indicate that this vortex is rolling up on the roof. While moving towards the rear, it is drifting progressively from the windward edge to the centerline of the roof, and then it detaches from the train.

The comparison between static and moving model tests indicate good correspondence between the two cases. If the estimated measurement accuracy is taken into account, the majority of the data show a level of agreement that appears somehow remarkable. There are local differences that do not fall within the margin of experimental error. They tend to occur in correspondence of the suction peaks. Nevertheless, it is worth noting that they can be found only for a limited number of tapping points. The trend of the pressure distribution shows a good agreement between static and moving model test results. In correspondence of all the examined loops of pressure taps, the position and extension of the stagnation regions and of the suction peaks are very similar, and also the magnitude of such peaks is comparable. No major differences, hence, can be inferred with regard to the characteristics of the flowfield surrounding the train.

3.2 Mean aerodynamic load coefficients

The mean aerodynamic load coefficients for the side and lift forces, and for the rolling moment are presented in this section. Such coefficients are indicated in what follows as $\bar{C}_Y$, $\bar{C}_Z$ and $\bar{C}_{Mx}$, respectively. They were calculated by discrete integration of the pressure distribution over the entire leading car, according to the following equations:

$$\bar{C}_Y = \frac{1}{A_{ref}} \sum_i \bar{C}_{Pi} A_i (\mathbf{n}_i \bullet \mathbf{y}); \quad \bar{C}_Z = \frac{1}{A_{ref}} \sum_i \bar{C}_{Pi} A_i (\mathbf{n}_i \bullet \mathbf{z}); \quad \bar{C}_{Mx} = \frac{1}{A_{ref} H_{ref}} \sum_i \bar{C}_{Pi} A_i |\mathbf{d}_i \times \mathbf{n}_i| \quad (3)$$

In Equation 3, $\bar{C}_{Pi}$ is the mean pressure coefficient as defined in the previous section. A_i and $\mathbf{n}_i$ represent, respectively, the area and the normal unit vector associated to each flat surface into which the train geometry has been discretized. The discretized geometry adopted for the integration was the same for both the static and moving model tests pressure data. $\mathbf{d}$ is the vector directed from the longitudinal axis X to the center of such flat surfaces i , while $\mathbf{y}$ and $\mathbf{z}$ are the unit vectors associated to the Y and Z axes, respectively (Fig. 1b). A_{ref} is the reference area, assumed as the nominal side area of the leading car and equivalent to 77m² at full scale, while H_{ref} is the reference height and corresponds to a full scale equivalent of 3.1m. The convention for positive

directions defined in accordance to the reference system specified in Figure 1a (for the rolling moment following the ‘right-hand screw rule’).

A comparison between the results obtained from static and moving model tests is illustrated in Figure 6. The differences appear to be very limited. In particular, whereas the experimental accuracy is taken into consideration (i.e. by specifying error bars on the figure), it can be appreciated how the discrepancies fall well within the estimated margin of error.

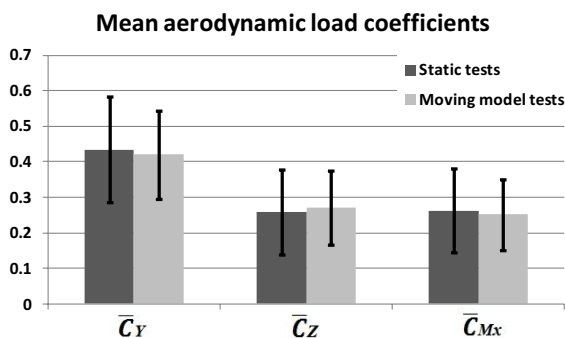


Figure 6. Mean aerodynamic load coefficients for the side force, lift force and rolling moment: Static vs Moving model tests comparison (Class 390 Pendolino, 1/25th scale, 30° yaw angle, FG scenario)

4 CONCLUSIONS

This paper has presented the results from an experimental campaign aimed to assess the effect of the vehicle movement simulation on the train aerodynamics in crosswinds. The existing TRAIN rig moving model test facility was updated by installing a new crosswind generator. A novel test methodology based on the use of an onboard pressure measuring system was developed. The combination of such factors enabled a rather extensive set of data to be collected through both static and moving model experiments. A Class 390 Pendolino scale model was tested on flat ground scenario at a 30° yaw angle. A first comparison, concerned with the mean pressure coefficient on the train leading car, shows limited differences between static and moving model tests. A second analysis, focused on the mean aerodynamic load coefficients, indicates non-significant impact of the vehicle movement on such parameters. Additional studies are ongoing. A further data analysis is investigating the unsteady aerodynamic effects. Also, the experimental results are being shared and used within the AeroTRAIN consortium for CFD benchmarking.

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6 REFERENCES

- 1 Baker, C.J., Cheli, F., Orellano, A., Paradot, N., Proppe, C., Rocchi, D., 2009. Cross-wind effects on road and rail vehicles. *Vehicle System Dynamics: International Journal of Vehicle Mechanics and Mobility* 47, 983 - 1022.
- 2 Cheli, F., Corradi, R., Diana, G., Ripamonti, F., Rocchi, D., Tomasini, G., 2007. Methodologies for assessing trains CWC through time-domain multibody simulations, in: *Proceedings of the 12th International Conference on Wind Engineering*.
- 3 Baker, C.J., 2010. The simulation of unsteady aerodynamic cross wind forces on trains. *Journal of Wind Engineering and Industrial Aerodynamics* 98, 88-99.
- 4 CEN, 2010. *Railway Applications - Aerodynamics - Part 6: Requirements and test procedure for cross wind assessment*, EN 14067-6, Brussels.
- 5 EC, TSI - Technical Specification for Interaoperability of the trans-European high-speed rail system, in 'Rolling stock' Sub-System. 2008, Official Journal of the European Union. p. 193-195.
- 6 Baker, C.J., Humphreys, N.D., 1996. Assessment of the adequacy of various wind tunnel techniques to obtain aerodynamic data for ground vehicles in cross winds. *Journal of Wind Engineering and Industrial Aerodynamics* 60, 49-68.
- 7 Baker, C.J., 1986. Train aerodynamic forces and moments from moving model experiments. *Journal of Wind Engineering and Industrial Aerodynamics* 24, 227-251.
- 8 Humphreys, N.D., 1995. *High Cross Wind Gust Loads on Ground Vehicles from Moving Model Experiments*. University of Nottingham, Nottingham, UK.
- 9 Boccione, M., Cheli, F., Corradi, R., Muggiasca, S., Tomasini, G., 2008. Crosswind action on rail vehicles: Wind tunnel experimental analyses. *Journal of Wind Engineering and Industrial Aerodynamics* 96, 584-610.
- 10 Li, Y., Hu, P., Zhang, M., Liao, H., 2009. Wind tunnel tests with moving vehicle model for aerodynamic forces of vehicle-bridge systems under crosswind, in: *Proceedings of the The Seventh Asia-Pacific Conference on Wind Engineering, APCWE-VII*.
- 11 Cheli, F., Rocchi, D., Schito, P., Tomasini, G., 2011. Steady and moving high-speed train crosswind simulations. Comparison with wind-tunnel tests, in: *Proceedings of the 9th World Congress on Railway Research, WCRR 2011*.
- 12 Quinn, A.D. The TRAIN (Transient Railway Aerodynamics INvestigation) Rig. 2009-2011 19/02/2012]; Available from: <http://www.windresearch.org/mmr.html>.
- 13 Pope, C.W. The simulation of flows in railway tunnels using a 1/25th scale moving model facility. in *Aerodynamics and Ventilation of Vehicle Tunnels*, p 709-737, edited by Alex Haerter, published by Elsevier, 1991.
- 14 Baker, C.J., et al., The slipstream and wake of a high-speed train. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 2001. 215(2): p. 83-99.
- 15 Hemida, H., Krajnovic, S., 2009. Exploring flow structure around a simplified ICE2 train subjected to a 30 degrees side wind using LES. *Engineering Applications of Computational Fluid Mechanics* 3, 28-41.