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Aerodynamic Effects of Different Car Body Configurations in a Conventional Train under Crosswinds

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Abstract

Crosswind stability represents a continuous topic of research. For high-speed trains the regulations for crosswind assessment includes a set of Characteristic Wind Curves (CWC) given as reference limits that new trains need to be compliant with. On the other hand, for conventional trains, the European standards only supply guidelines lacking reference limits that train constructors can follow at the design phase of the vehicles. In this work, it is analysed how different roofs and underbodies designs of a conventional train impact the overall vehicle behaviour to cross winds. The tested train corresponds to a CAF vehicle with maximum speed of 200 km/h and the safety assessment to crosswind for different configurations has been evaluated following the procedure described by TSI and the European Standard. Aerodynamic coefficients were measured in wind tunnel tests at Politecnico di Milano, on a modular scaled model able to replicate the different aerodynamic configurations. CWC were computed using time-dependent multi-body simulations with "Chinese Hat" wind gust model. Results show that a fully covered roof with respect to a standard open configuration, could lead to an improvement, in terms of characteristic wind speed at 90°, higher than 5 m/s. Finally, the comparison of CWCs obtained for the conventional train with the CWC of ICE3 high-speed train confirms the necessity of defining reference limits also for low-speed trains.

Keywords: Train aerodynamics, crosswind, CWC, wind tunnel.

1 Introduction

A train running in open field is exposed to overturning risk due to the action of strong crosswinds, defined as any wind blowing in a different direction than the one travelled by the train.

With the constant development of high-speed trains, studies on this subject represent a continuous topic of research, as trains become faster and lighter. In the past decades, methodologies able to evaluate the level of safety of a rail vehicle in terms of overturning risk have been proposed and standards defined [1,2]. The complete regulations for the assessment to crosswinds of trains with top speed higher than 250 km/h are provided in the TSI [3] which refers, for technical items, to the EN14067-6 [4]. Characteristic Wind Curves (CWC), which represent the limit wind speed causing a vehicle to exceed safety limit (such as wheel unloading) are given as reference limits for the assessment of new high-speed trains. However, for conventional trains, the norms only supply guidelines lacking reference limits to be followed by the train constructors at the design phase of the vehicles.

At national level, only UK, Germany and France have set rules for trains running below 250 km/h. However, the work of the AeroTRAIN project, presented in [5], showed how the safety to crosswinds is a crucial problem also for conventional trains. To fill this lack in the regulations, different projects at national level and in the EU recently started, like for example the SAFIRST project, launched in 2019 by UIC and still ongoing [6].

The main goal of this work is to analyse how different roofs and underbodies designs of a conventional train impact the overall vehicle behaviour to crosswinds. The tested train is a CAF vehicle with maximum speed of 200 km/h and the safety assessment to crosswind for different configurations has been evaluated by following the procedure described by the TSI [3] and by the EN 14067-6 [4].

The aerodynamic coefficients were obtained by wind tunnel tests carried out on a reduced scale model with different roofs and underbodies. The results of the trials were used as input to estimate the corresponding CWCs by using multi-body simulations and the ideal deterministic wind speed time history named "Chinese Hat".

Lastly, it will be shown the importance of defining reference CWCs also for conventional trains by comparing the values of the CWCs for the CAF train and for a high-speed train.

2 Methods

According to the standard EN14067-6:2018 [4], for a train with maximum speed from 140 km/h to 200 km/h, the full proof of stability shall be done using time-dependent multi-body simulations as according to the following steps:

1. Determination of aerodynamic coefficients in wind tunnel test with reduced-scale model.
2. Determination of the time history of wind using the "Chinese Hat" model.
3. Calculation of aerodynamic loads adopting the quasi-steady theory.
4. Computation of the dynamic response of the vehicle using multi-body simulations.
5. Evaluation of the wheel unloading criteria to obtain the Characteristic Wind Speed.

Aerodynamic coefficients were obtained from experimental tests carried out in the low turbulence test section (dimensions 4 × 4 m^2, maximum wind speed 55 m/s) of the Politecnico di Milano wind tunnel using 1:20.6 scale models of CAF train. Tests were performed on a single-track ballast and rail (STBR) compliant with CEN standard using a 3-car vehicle: first and second vehicles were instrumented with dynamometric balances to measure forces and moments; the third car only reproduces the proper boundary conditions. To replicate all the variations applied, cars were designed in a modular way, to easily change roof and underbody equipment (see Figure 1).

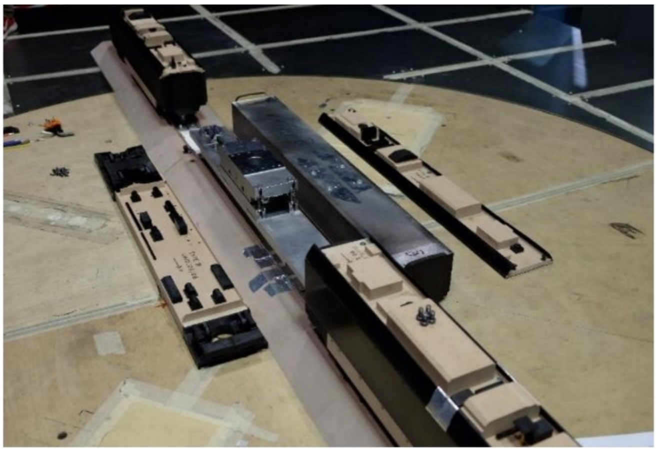
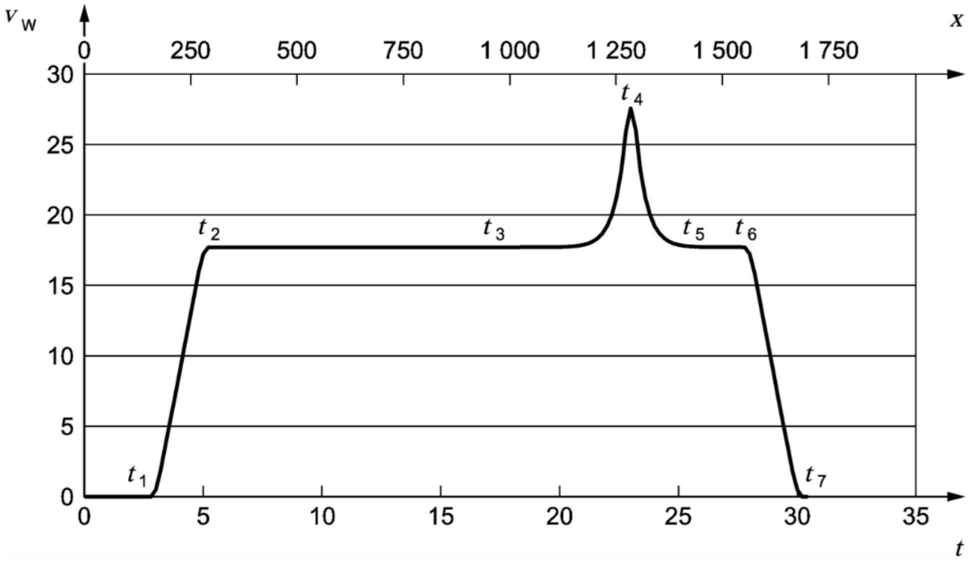


Figure 1: Exploded view of the part conforming the modular scaled model.

As previously mentioned, different configurations were studied. They can be grouped in:

- Different vehicles roofs, with both covered and exposed elements.
- Different vehicles underbodies, again with covered and exposed configurations.

The non-dimensional aerodynamic coefficients were defined according to the CEN standard normalisation. The reference frame system is fixed to the car body and its origin is coincident with the car body centre, at ground level.



Key

x in m

v_w in m/s

t in s

Figure 2: "Chinese Hat" wind speed profile.

From the "Chinese hat" wind scenario shown in Figure 2, forces are computed using the quasi-steady theory and given as input to MBS.

Characteristic Wind Curves were computed with Multi-body Simulations (MBS) using the multi-body code A.D.Tre.S developed by the Mechanical Department of Politecnico di Milano. From the results of MBS, the wheel unloading criteria is evaluated and compared to an average limit for wheel unloading of 90% to determine the CWC.

For a better understanding, this analysis is focused on the six most representative configurations out of the 42 tested in the wind tunnel. Meanwhile, the studied speed range was delimited to 80-160 km/h, that can be considered the usual operational range for conventional trains, even if top speed of the CAF train is higher.

3 Results

The effects of the enclosed and open configurations on both roofs and underbodies are examined. Figure 3 shows the $C_{Mx,lee}$ coefficients (normalised to $C_{Mx,lee}$ at 90° of Configuration 1) obtained with wind speed U_w = 50 m/s measured on the first vehicle of every configuration in which the head car was modified.

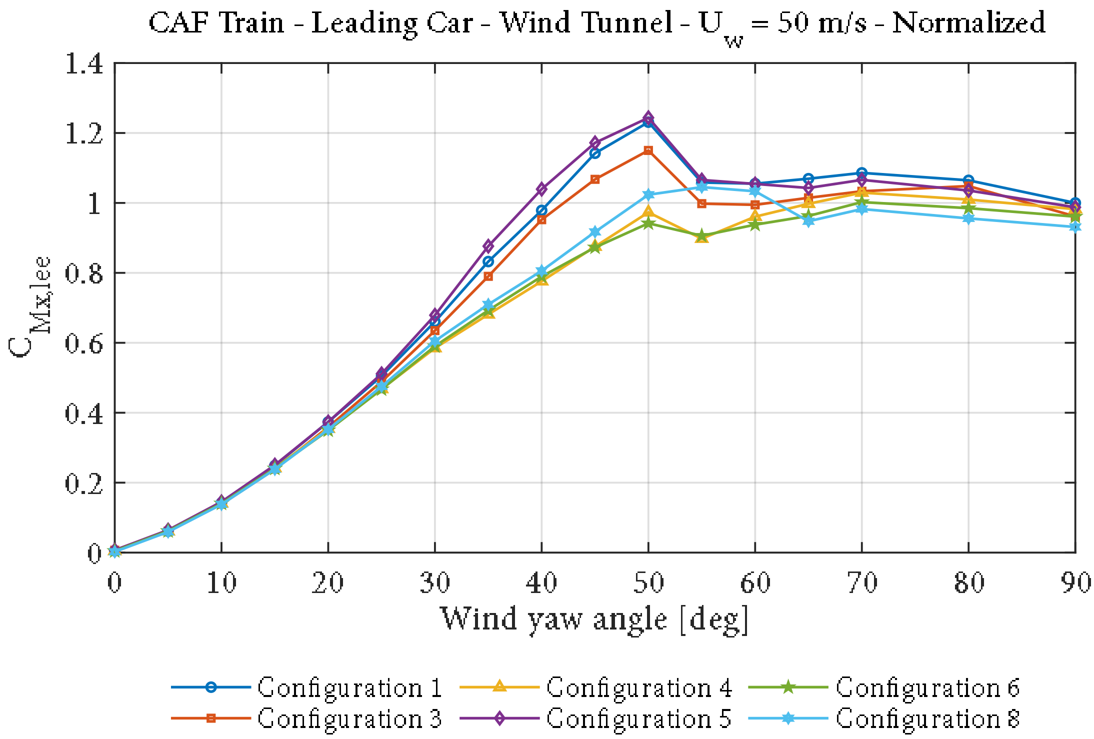
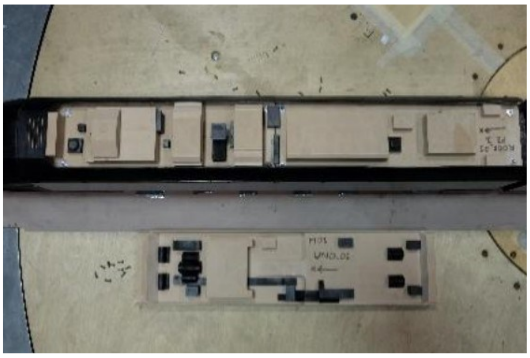
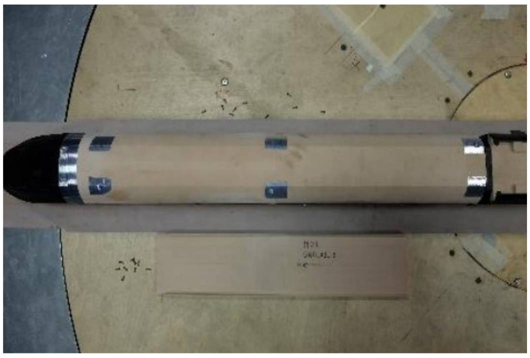


Figure 3: $C_{Mx,lee}$ leading car of CAF train for six different configurations. Wind tunnel test: STBR, U_w = 50 m/s, 1:20.6 scaled model. Coefficients are normalized to value at 90° of configuration 1.

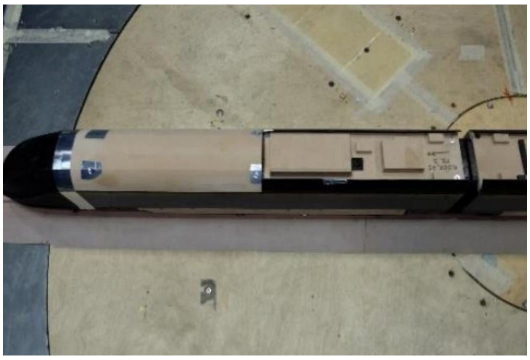
Coefficients shown in Figure 3 refer to the following configurations:

- Configuration 1: roof and underbody open (Figure 4.a).
- Configuration 3: roof half covered (Figure 4.b) and open underbody (see configuration 1).
- Configuration 4: roof completely covered (Figure 4.c) and open underbody (see configuration 1).
- Configuration 5: open roof (see configuration 1) and smooth underbody (Figure 4.d).
- Configuration 6: roof completely covered and smooth underbody (Figure 4.c).
- Configuration 8: roof completely covered (see configuration 6) and closed smooth underbody (Figure 4.d).





a) c)



b) d)

Figure 4: Different vehicle configurations. Details of roofs and underbody parts mounted on the modular scaled model.

Figure 3 shows that the variations on roofs have a bigger impact on results: a smooth continuous roof led to a significant reduction of lee-rail rolling moment coefficient. Indeed, underbody variations did not give, in general, significant effects on coefficients, except configuration 8, with higher $C_{Mx,lee}$ *at* yaw angles up to 60°.

Figure 5 shows the CWCs evaluated for the first vehicle of every configuration as a function of train speed for absolute wind angle β_w = 90°.

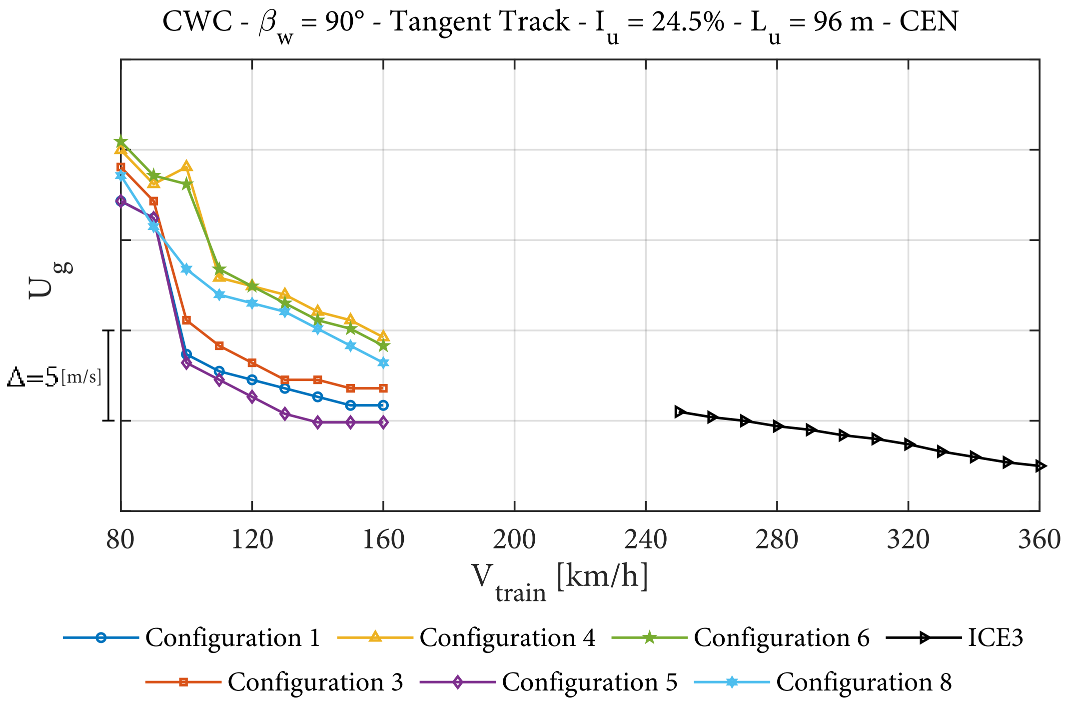


Figure 5: CWC for leading car of CAF train in six different configurations and for ICE3 high-speed train as function of train speed. MBS with 'Chinese Hat' wind gust model.

The CWCs are consistent with the results obtained by the wind tunnel tests. It is possible to observe higher characteristic wind speed values for configurations 4, 6 and 8 (with continuous closed roof). Configurations 4 and 6 have a very similar trend while configuration 8 shows a different behaviour at low train speed values due to the fully closed underbody.

A further consideration can be made by comparing the CWCs in Figure 5 for first vehicle of high-speed ICE3 and CAF trains. It can be observed that calculated characteristic wind speed of the conventional train at 160 km/h is similar to that computed for the ICE3 with the later running 100 km/h faster, at 260 km/h.

For a high-speed (HS) train β_{rel} values are in the range from 10° to 25°, while for a lower-speed (LS) train are located around 50°. This can be intuitively understood by looking at Figure 1, which provides a vectorial representation of the velocities and the angles involved in the calculations: being the value of $V_{tr,LS}$ much lower than $V_{tr,HS}$ the resulting angle $\beta_{rel,LS}$ will be much higher than $\beta_{rel,HS}$, assuming to have the same U_g.

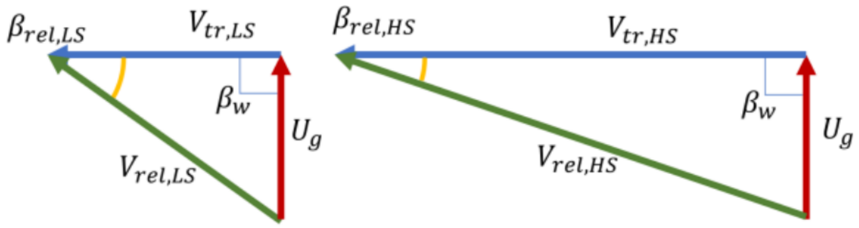


Figure 1: Vectorial composition of the velocities involved in CWC computation for $\beta_w = 90°$, on the left: for conventional train (LS); on the right: high-speed train (HS).

4 Conclusions and Contributions

In this work, the effects of shape modifications of a low-speed train have been investigated following the procedures defined by European standards [4]. The full proof of stability requiring wind tunnel tests for the measurement of aerodynamic coefficients and time-dependent multi-body simulations for the calculation of the limit wind speeds causing a vehicle to exceed its safety limits, providing the Characteristic Wind Curves (CWC) was applied.

The aerodynamic coefficients were obtained with tests performed at Politecnico di Milano wind tunnel. These experimental tests evidenced that modifications on the roofs and underbody of the convoy models have a significant aerodynamic impact.

Configurations with a smooth, fully covered roof appears as the most promising option to improve the aerodynamic behaviour under crosswind. The results show an increment of almost 5 m/s in the characteristic wind speed at 160 km/h.

Furthermore, by comparing the CWCs of the CAF low-speed train with the CWC of the ICE3 high-speed train, the safety evaluation to crosswind has been proven to be fundamental also for low-speed trains, emphasizing the necessity of reference values and limits that are not provided by the standards for conventional trains.

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