Experimental assessment of wind influence on high-speed train energy consumptions.

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Abstract

Ifsttar and RFF have developed an energy model of high-speed trains in order to determine the influence of infrastructure geometry and environment on train power consumptions. Validation of this model is based on full scale tests performed for the Rhine-Rhone high-speed line acceptance of work (in 2011).
This paper aims to evaluate if wind influence is a relevant parameter for the model. This involves numerical determination of aerodynamic coefficients for various wind and ground configurations and their use for the calculation of the aerodynamic efforts. Atmospheric characteristics are extrapolated from meteorological measurements thanks to the AROME numerical model, over the whole Rhine- Rhone line. Most remarkable results show for a moderate train speed (about 47 m/s), a rearward oriented wind of only 5,5 m/s lowers by 30% the power due to aerodynamic forces applied on the train, or raises it similarly if it is forwardly oriented. In conclusion, this work points out that wind influence is of first importance for computing energy consumption.
Keywords: Railways, energy consumptions, energy model, wind, aerodynamics, high-speed train.

Résumé

L'Ifsttar et RFF ont développé un modèle énergétique des trains à grande vitesse dans le but de déterminer l'influence de la géométrie et de l'environnement des infrastructures sur les consommations énergétique des trains. La validation de ce modèle est basée sur des essais grandeur nature réalisés lors de la réception de la ligne à grande vitesse Rhin-Rhône (en 2011). Cet article vise à évaluer si l'influence du vent doit être prise en compte dans ce modèle. Cela implique la détermination numérique de coefficient aérodynamiques pour plusieurs configurations de vent et de terrain et leur utilisation pour le calcul des efforts aérodynamiques. Les caractéristiques atmosphériques sont extrapolées de mesures météorologiques à l'aide du modèle numérique AROME, sur l'ensemble de la ligne Rhin-Rhône. Les résultats les plus remarquables montrent que pour une vitesse modérée de train, d'environ 47 m/s, un vent arrière de seulement 5,5 m/s diminue de 30 % l'énergie due aux efforts aérodynamiques appliqués sur le train, ou l'augmente similairement s'il est orienté frontalement. En conclusion, ce travail montre que l'influence du vent est de première importance.
Mots-clé: Voies ferrées, consommations d'energie, modèle énergétique, vent, aérodynamique, train à grande vitesse.

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1. Introduction

Railways, thanks to their low rolling resistance, overtake road and air in energy-efficiency for short and medium travel. Nevertheless, rail transportation is not always competitive in terms of travel times, compared to air transport for long travels or door to door road transport for short distances. Higher speeds are then required for maintaining railways competitiveness, but this trend paradoxically lowers its initial energy efficiency advantages (Martin, 1999), especially for short inter-stop distances (Feng, 2011). Then, the optimization of rail transportation should involve energy and mobility criteria (Coiret, 2012 ; Smith, 2012, Vandanjon, 2012).
In this context, Ifsttar and RFF have developed an energy model of high-speed trains, validated with full scale tests at the occasion of the acceptance of work of the Rhine-Rhone line (in 2011). Infrastructure geometry, train dynamics and electric consumption have been used to build an energy model but wind influence was not integrated in first attempt since local weather conditions was not continuously accessible during the tests.
This last point remained to be assessed. In this context, this work, handled by Andheo and Ifsttar, aims to determine the level of wind induced aerodynamical forces, compared to other forces including aerodynamic forces due to the train speed. Various wind conditions, train speed and topological situations are considered to assess the wind influence.

2. Aerodynamic model

2.1. Field determination of atmospheric characteristics

The wind influence was chosen to be studied on several trains running on the Rhine-Rhone high-speed line. Indeed, electrical power consumptions and infrastructure characteristics are known for these runs. An energy model has been developed and validated with these data. Wind influence could be integrated in this model.
Atmospheric characteristics (wind speed and direction, pressure and temperature) were determined over the whole Rhine-Rhone line (about 140 km) for the 25 days of tests conducted in 2011 for its acceptance of work. The numerical model AROME (Seity, 2011) was used to compute these wind fields from measurements at several surrounding weather stations (figure 1 : example of computed wind field).
The wind defined at a height of 10 meters is converted to a local wind along the train line, by applying atmospheric boundary conditions and specific environmental masks to take into account cities or forest. The equation (1) gives the wind intensity for a *z* height, relatively to the z_0 rugosity height (here 0.05m, considering mostly countryside), *d* a moving length (here equal to $0.7\times h$), and *k* the Von Karman constant (0.4). Hypothesis leads to a value of $u(3m)$ equal to $0.75\times u\ (10m)$. Land influence is later taken into account thanks to a shading criterium of less than 100 m forests or urban areas.

$$u(z)=\frac{u_*}{k}\ln\left(\frac{z-d}{z_0}\right) \tag{1}$$

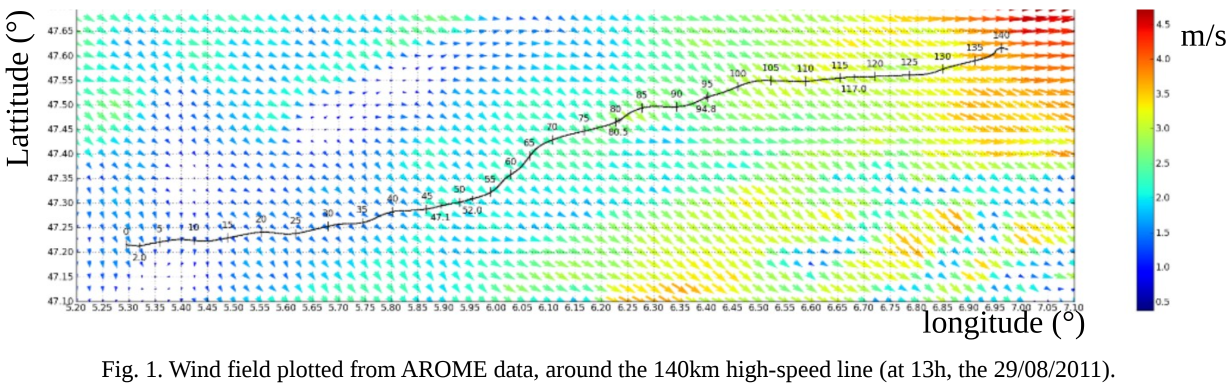

Fig. 1. Wind field plotted from AROME data, around the 140km high-speed line (at 13h, the 29/08/2011).

2.2. Run selection among wind variety and train speeds

144 runs have been performed during the acceptation of work process. It has been chosen to evaluate the wind influence for only 15 runs, to limit computational cost while ensuring sufficiently various cases, by combining various speeds and orientations of wind and various train speeds.

A classification of the whole set of run is presented on figure 2, for two variables: the "influence_vent" variable is the scalar product of the wind and train velocity vectors, divided by the train speed norm ($\vec{V}_{wind} \cdot \vec{V}_{train} / \|\vec{V}_{train}\|$). It indicates both the relative intensity and the orientation of the wind facing the train speed. The "V_moy_rel_TGV" variable is the train mean speed over the considered run (also called V_{train}).

Other classifications have led to the selection of 15 runs by considering the following mean criteria: high and low train speed, front and rear wind direction, strong or weak wind.

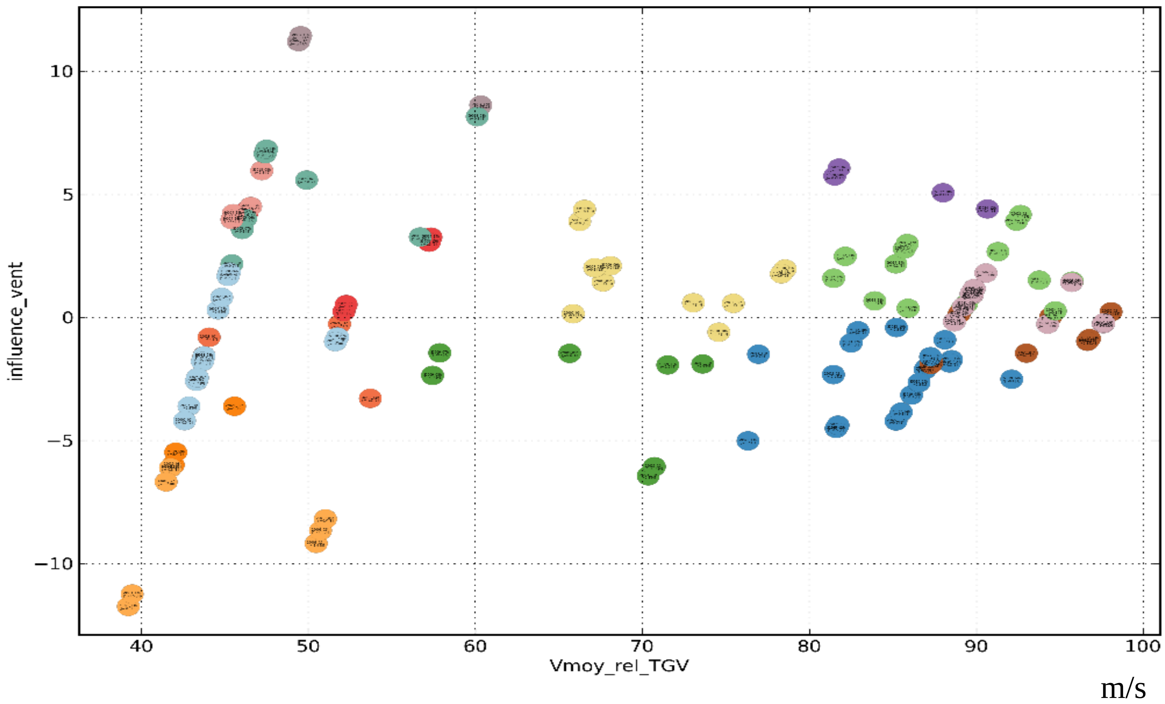

Fig. 2. Classification of the runs on the train speed, and relative wind speed (each colored spot represent a test run).

2.3. High-speed train aerodynamics modeling

In parallel, aerodynamic coefficients of the experimental high-speed train (ALSTOM TGV Duplex) were computed. Navier-Stockes equations have been resolved on a simplified geometrical model by using auto-adaptive Cartesian meshes (figure 3, table 1). The longitudinal coefficient Cx fits with the value retained by the concerned norm and other data (Raghunathan, 2002). It is of great importance since this coefficient is used for computing aerodynamic forces. Other coefficients match less the norm, for example, Cz is 56% lower than the normative value. This is due to issues of modeling the underside of the train, but it virtually does not affect the needed tractive forces, since its influence is negligible facing the Cx coefficient. Eventually, the considered Cx coefficient is a combination of data issued from literature on the detailed geometrical model and influence due to side wind as numerically computed on the simplified one.

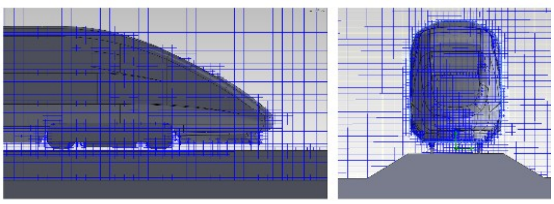

Fig. 3. Transverse and frontal views of the numerical discretization of the train.

Table 1. Aerodynamic coefficients for the trailer, with a 5 degrees wind incidence angle.

	C_x	C_y	C_z	Cm_x	Cm_y	Cm_z
Norm	0.157	0.484	-0.294	-0.317	-0.119	-1.013
Simulation	0.148	0.555	0.128	-0.334	-0.235	-1.036
Variation to the norm (%)	-6	15	-56	5	97	2

3. Results

Computed coefficients are integrated in numerical simulations for the 15 selected train runs , on a full train, for various wind angle direction and relative elevations to the natural ground. At last, power is computed all along the itineraries, while considering situations with or without wind.
The computation of the power is based on the equations (2). These equations give the aerodynamic F force and M momentum from the C and Cm force and moment coefficients, and from the air density (ρ), the S and L reference surface and length (S=10 m^2 ; L = 3 m), and from the speed of the air flow velocity (V).

$$F=\frac{1}{2}\rho S V^2 C$$
$$M=\frac{1}{2}\rho S L V^2 Cm \qquad (2)$$

The power induced by aerodynamic forces is computed as the product of the axial force Fx and the relative wind speed. The power that would have been consumed without wind is also calculated to estimate the wind effect on energy consumption. It is simply the product of the axial force without wind and the train speed. The wind effect is then the gap between the two power levels, as used on Figure 6 in ordinate.
Here, three particular runs are considered (figure 6). The green curve labelled 29034 corresponds to a train traveling at high speed in a weak mean wind. The blue and red curves, labelled respectively 29001 and 30002, correspond to a train traveling at a moderate speed for two quite different wind mean speeds (the wind and train speeds are given in figures 4 and 5 for theses two test runs).

One worthwhile result is that for a weak wind (2 m/s) and a train traveling at high speed (95 m/s), wind influence is of +5% and -5% on power due to aerodynamic forces on the train, respectively on front and rear wind sections of the itinerary (test run labelled 29034 on figure 6). This result is deduced from the analysis of the 29034 test run between the 70 and 120 km abscissae (section for which the mean speed is of 95 m/s).

Another result is that for a moderate train speed (about 47 m/s), a stronger rear wind (5.5 m/s) lowers the needed power by 30% compared to the case without wind, and a front wind of 3 m/s raises it by 20% (respectively test runs labelled 29001 and 30002 ; see figures 4, 5 and 6 at the pk distance of 70 km).

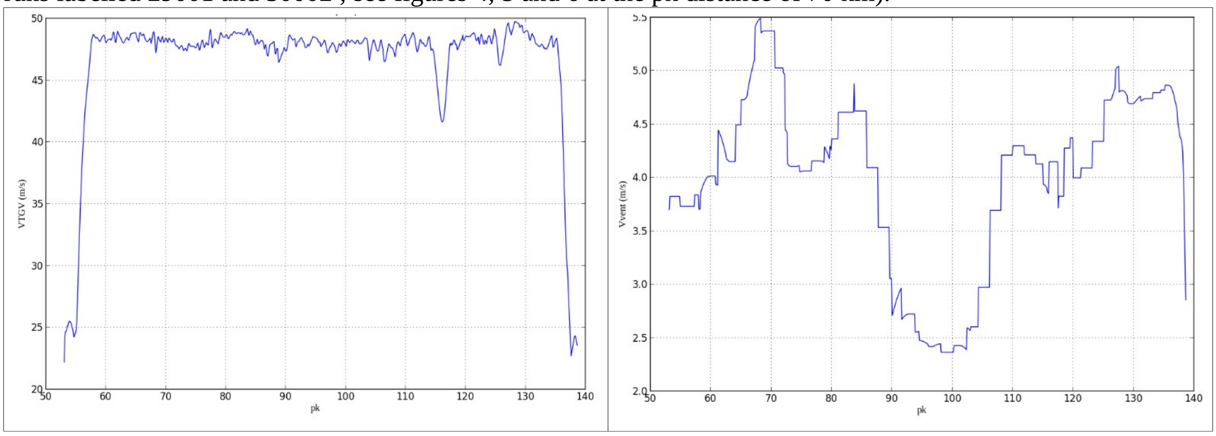

Fig. 4. Train speed (left) and computed wind speed (right) for the 29001 test run along the curvilinear distance pk (km)

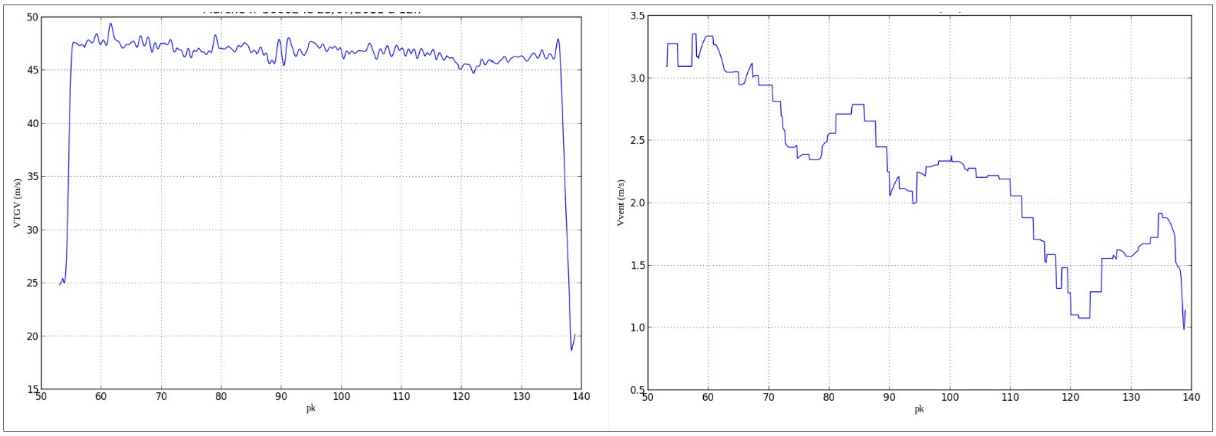

Fig. 5. Train speed (left) and computed wind speed (right) for the 30002 test run along the curvilinear distance pk (km)

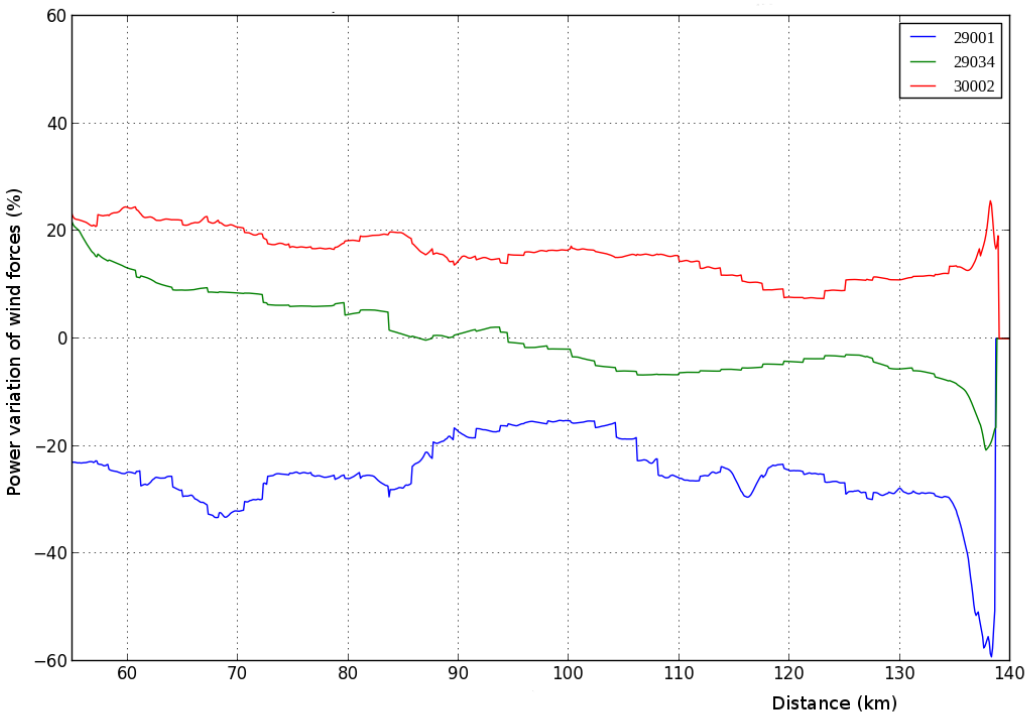

Fig. 6. Power variation of wind forces for three particular test runs (labelled 29001, 29034 and 30002).

4. Conclusions

In conclusion, this work based on a large set of full-scale experimental data, on the reconstitution of the wind field and the numerical simulation of the aerodynamic forces, points out that wind influence on total aerodynamic power consumption is of first importance.

Indeed, for the less sensible case, with a weak wind and a high train speed, wind influence has been found to be netherless noticeable, of the order of 5% of power due to aerodynamic forces on the train. For a more sensible case, with a wind speed about 5,5 m/s and a moderate train speed of 47 m/s, the wind field is accountable of variations on this power as high as 30%.

In perspective, the work will contribute to the developpement of a complete wind model as a component of the Ifsttar and RFF energy model.

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