

Dynamic Response of Vehicle-Driver Couple to the Aerodynamic Loads due to the Crossing of a Bridge Tower Wake

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ABSTRACT

In the paper, a procedure to assess the quality of the shielding effect of wind barriers to protect large sided vehicles crossing the wake of a bridge pylon under cross wind conditions is proposed. The methodology is based on Multi-Body simulations of the response of the vehicle-driver system when it is subjected to the sudden change of the aerodynamic forces due to the wind-tower interaction. The aerodynamic forces that are instantaneously acting on the vehicle are computed according to a force distribution approach that relies on wind tunnel tests that may be performed on still scaled models. From the knowledge of the aerodynamic force distribution along the vehicle at different yaw angles and of the mean wind profile across the tower wake, the aerodynamic force, acting on the moving vehicle, is reconstructed at each time step taking into consideration the actual vehicle-driver dynamics. The numerical procedure is applied to compare the different responses that the vehicle-driver system exhibits in presence or absence of wind barriers close to the tower. In particular the two situations are compared by computing the characteristic wind curves and considering synthetic indexes that are able to contemporary consider the risk of lane change or vehicle overturning, for different conditions of vehicle loading.

CITATION: Sabbioni, E., Sbrosi, M., Rocchi, D. and Galeotti, R., "Dynamic Response of Vehicle-Driver Couple to the Aerodynamic Loads due to the Crossing of a Bridge Tower Wake," *SAE Int. J. Commer. Veh.* 5(1):2012, doi: 10.4271/2012-01-0214.

INTRODUCTION

It is well known that high sided vehicles can experience a sudden change in the aerodynamic forces when passing through the wake of towers of large exposed bridges under cross wind [1],[2],[6]. This represents a problem in the design and managing of the bridge since in the most dangerous conditions, a very skilled reaction is required to the driver to avoid undesired lane changes and/or rollover. In order to shield the vehicle from high cross winds and thus to give time to the driver to react to changes in the aerodynamic forces, specific fences are placed both at the edges of the bridge deck and close to the tower [3],[4]. The design of these devices requires taking into account driver-vehicle-wind interaction to choose the best performing solution in terms of safety. To address this issue its necessary to define which are the most important parameters to be investigated and which are the thresholds of these parameters that does not have to be exceeded to guarantee the running safety. Although some studies can be found in the literature experimentally investigating the changes in the aerodynamic loads on the

vehicle due to the presence of a bridge tower and also considering the vehicle motion [3],[6],[10], only a few attempts have been made to model their interaction with the vehicle dynamics and with the driver behavior. In [6] a methodology for analytically evaluating the aerodynamic forces acting on a moving vehicle passing through the wake of a bridge tower has also been proposed based on wind tunnel experiments carried out in steady state conditions with a static vehicle model. The comparison of the results with wind tunnel tests performed with a moving vehicle model stated the capability of the proposed approach to qualitatively capture the asymmetry of the variation of the aerodynamic loads when the vehicle approaches or leaves the tower wake. The interaction between vehicle dynamics and aerodynamic forces variation was however not investigated, as well their influence on the driver response. In this paper, a Multi-Body (MB) vehicle model able to simulate the vehicle handling dynamics coupled with a simple driver model [5] has been integrated with a model for reproducing the aerodynamic loads acting on the vehicle when passing through the wake of a bridge tower. The characteristics of the aerodynamic forces

acting on a vehicle are reproduced through a force distribution method relying on wind tunnel tests carried out in steady state conditions with a static vehicle model [10].

Final goal of the activity is in fact the possibility to use the implemented tool for evaluating the effectiveness of wind fences to be added close to the tower, in shielding the vehicle from cross winds. The vehicle+driver model response, with and without near tower fences, will be compared through proposed accident risk indexes.

THE VEHICLE AND DRIVER MODELS

In order to analyze the vehicle dynamic response to changes in the aerodynamic loads due to the presence of a bridge tower in cross winds, a Multi-Body (MB) model implemented in MatLab/SimuLink/SimMechanics environment has been used (Figure 1, [5]). The vehicle is composed by a tractor and semi-trailer. The MB model has 22 degrees of freedom (dofs) and it is suitable for fully describing the dynamics of a tractor semi-trailer combination. Vehicle suspensions are modeled in great detail also taking into account the viscoelastic behavior. The engine is introduced through its characteristic curve, i.e. driving torque versus angular speed, while the deformability of the driveline is neglected. The tires behavior is described using MF-Tyre model version 2002 [7].

A simple driver model is coupled with the vehicle model to allow closed loop maneuver simulations and thus making it possible to compare results for fixed vehicle trajectory and variable mean wind speed. The driver model calculates the steer angle demand according to the following logic:

- the error between the vehicle position (linearly extrapolated) and the desired path in three preview points is evaluated (see e_1 , e_2 , e_3 in Figure 2);
- the steering angle δ is calculated as:

$$\delta_{demand} = \sum_{i=1}^3 \left(P_i e_i + D_i \frac{de_i}{dt} + I_i \int e_i dt \right) \quad (1)$$

- where P_i , D_i , I_i are the regulator gains and e_i is the path error relative to the i -th preview point.

The controller proportional gains have been tuned by assigning the highest gain to the closest preview point; the proportional gains value is then decreasing with the distance of the preview point from the vehicle cog.

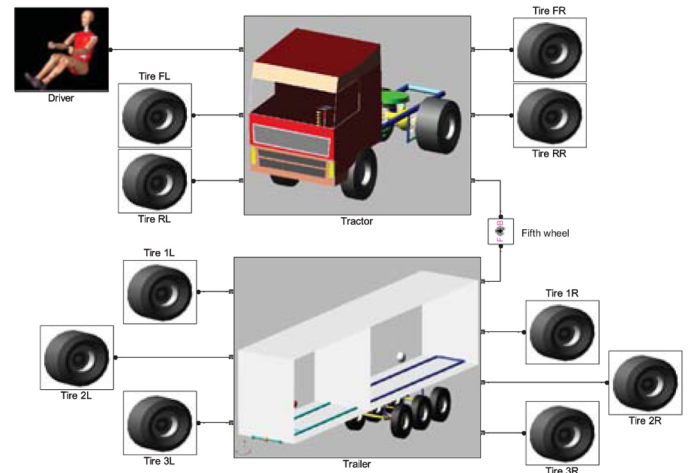


Figure 1. The vehicle model.

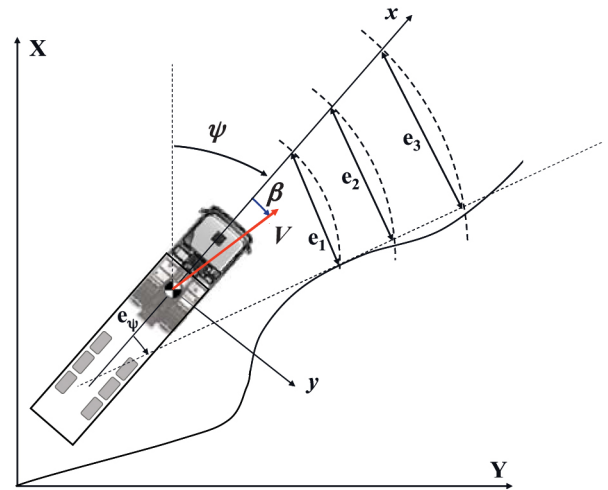


Figure 2. The driver model.

A neuromuscular model has been introduced to account for driver reflex and muscles dynamics in the steer angle (δ) definition process. The model adopted in this paper is the Hoult and Cole model [11], which is represented in Figure 3. Muscles contraction signal passes through the reflex dynamics block, which includes a delay, in agreement with physiological observations.

According to [11], stretch reflex dynamics, $H(s)$, can be modeled using a phase compensator in addition to time delay, T_r . Parameter k_T is used to adjust the gain of the stretch reflex block:

$$H(s) = \frac{30 k_r (s+5) e^{-sT_r}}{s+30} \quad (2)$$

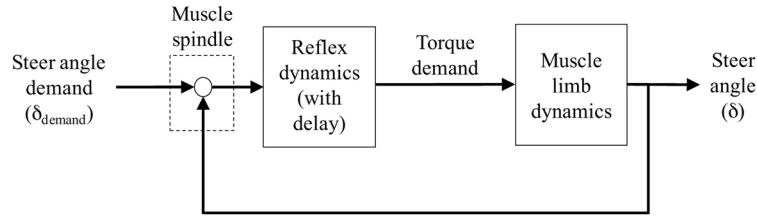


Figure 3. Driver neuromuscular model.

Table 1. Parameters characterizing the neuromuscular response of the driver model.

J_{dr} [kg m ²]	B_{dr} [Nm s rad ⁻¹]	K_{dr} [Nm rad ⁻¹]	K_{odr} [Nm rad ⁻¹]
0.098	0.55	3.7	0.25

Steering column and limb dynamics are represented by a second order system, $G(s)$:

$$G_s(s) = \frac{K_{odr}}{J_{dr}s^2 + B_{dr}s + K_{dr}} \quad (3)$$

Parameters of transfer functions $H(s)$ and $G(s)$ have been taken from the literature and they are summarized in Table 1.

AERODYNAMIC FORCES CALCULATION

The mean aerodynamic forces and moments acting on the vehicle during the crossing of the wake of the bridge tower have been computed using a force distribution approach [6]. At the purpose, the vehicle has been divided into 5 cross-plane slices along its lengths as shown in Figure 4 (see also Figure 10 and Figure 11). The aerodynamic forces and moments acting on each vehicle subsection have been computed using different aerodynamic coefficients (see equation (5)) for each slice and considering the instantaneous relative wind speed (U_{ri}) experienced by each slice during the tower wake crossing (Figure 4). The aerodynamic coefficients ($C_{Fk,i}$, $C_{Mk,i}$) of each slice have been experimentally obtained through wind tunnel tests using a vehicle model instrumented with pressure taps (see next section). The relative wind speed of each slice (U_{ri}) is calculated by combining the vehicle speed (V) and the cross wind velocity profile (U).

Two different horizontal wind speed profiles are considered in the simulations corresponding to the configurations with and without wind barriers close to the tower.

Figure 5 shows the non-dimensional wind speed horizontal profiles, $\gamma(x)$, in absence (Config. 2) and in presence (Config. 1) of fences near the bridge tower [4],[10]. The wind profile has been made non-dimensional by dividing it with the wind speed far from the tower. In absence of fences near the tower, speed ups are present at the tower enter/exit, while the wind speed becomes almost equal to zero at the tower center. No speed ups can instead be notice when

fences are placed near the tower. The non-dimensional wind profiles take also into account the effect of wind fences at the edges of the bridge deck by means of a scaling factor. The wind speed acting on each slice U_i is calculated accounting for the i -th slice position along the estimated horizontal profile, x_i , at each time step:

$$U_i = U(x_i) = U\gamma(x_i) \quad (4)$$

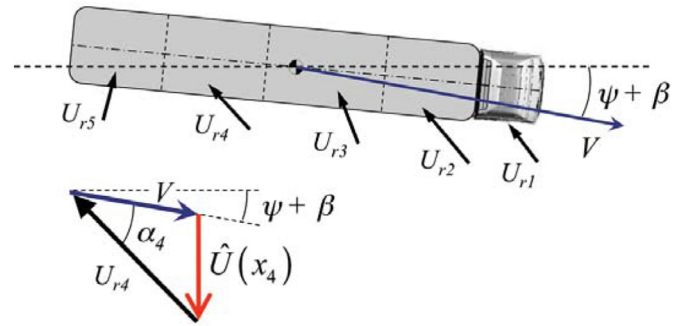


Figure 4. Relative wind speed on the subsections.

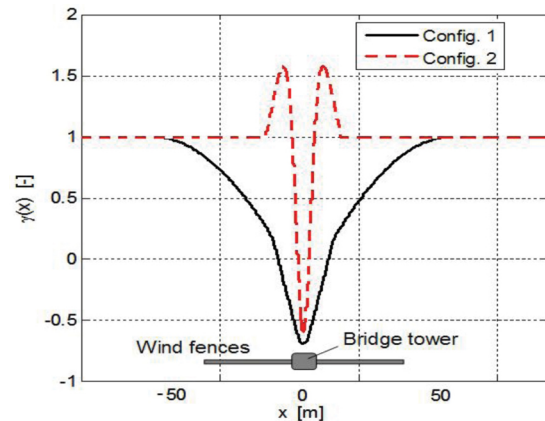


Figure 5. Estimated non-dimensional wind profiles.

Assuming that the speed of each slice is equal to the one of the vehicle V , the overall aerodynamic forces and moments acting on the truck during the tower wake crossing are thus given by:

$$\begin{aligned} F_k &= \frac{1}{2} \rho L H \sum_{i=1}^5 C_{Fk,i}(\alpha_i) U_{ri}^2; \quad (k = x, y, z) \\ M_k &= \frac{1}{2} \rho L^2 H \sum_{i=1}^5 C_{Mk,i}(\alpha_i) U_{ri}^2; \quad (k = x, y); \\ M_z &= \frac{1}{2} \rho L H \sum_{i=1}^5 b_i C_{Fy,i}(\alpha_i) U_{ri}^2 \end{aligned} \quad (5)$$

where α_i is the relative angle of attack (Figure 4) experienced by each slice during the vehicle motion, which can be obtained by combining the slice and the cross wind velocities and taking into account the vehicle yaw (ψ) and sideslip (β) angles, according to Figure 4, [2]. In the following section the experimental tests performed to define the aerodynamic coefficients are described.

WIND TUNNEL EXPERIMENTAL TESTS

Experimental tests have been carried out at the Politecnico di Milano wind tunnel, in the boundary layer test section (14m $\times$ 4m), using 1:40 models, under uniform turbulent flow ($I_U=5.5\%$). Two different scenarios have been considered during the tests: flat ground (Figure 6) and bridge (Figure 8). The flat ground scenario consists of an instrumented heavy vehicle model placed on a 1m wide, 0.039m thick and 6m long table whose upper surface is at a height of 0.86m above the wind tunnel ground. In order to evaluate the mean aerodynamic coefficient of the vehicle for different exposure angles, the vehicle model can be rotated with respect to the wind direction.



Figure 6. Vehicle model behind on the flat plate during wind tunnel tests.



Figure 7. Flat plate section (dimensions in full scale).

In the bridge configuration the same instrumented heavy vehicle model (see next section) used in the flat ground scenario is instead placed on a rigid bridge deck whose section is shown on the left of Figure 9 (200m long and 41.6m wide, full scale). A central tower 10m long and 8.5m wide (full scale) is placed in the middle of the deck (Figure 9 right). It is worth noting that the tower never completely shields the truck, which is 16.65m long in full scale. Wind fences are present along all the edges of the deck and additional wind shields can be placed near the tower (Figure 14). All the wind fences are characterized by a porosity of 45%.

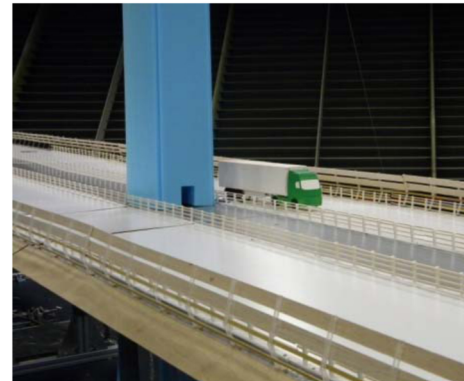


Figure 8. Vehicle model behind the bridge tower during wind tunnel tests.

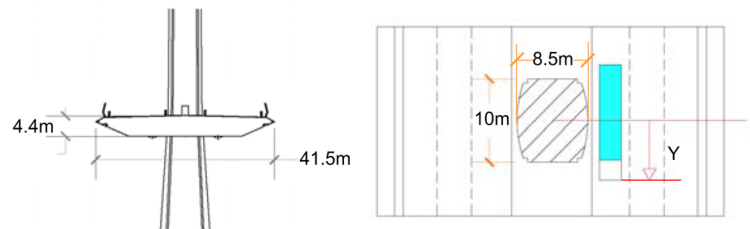


Figure 9. Deck and tower sections (dimensions in full scale) with truck-tower relative position.