

Use of Full Coupling of Aerodynamics and Vehicle Dynamics for Numerical Simulation of the Crosswind Stability of Ground Vehicles

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ABSTRACT

The prediction in the design phase of the stability of ground vehicles subject to transient crosswinds become of increased concern with drag reduced shapes, lighter vehicles as well as platooning. The objective of this work is to assess the order of model complexity needed in numerical simulations to capture the behavior of a ground vehicle passing through a transient crosswind. The performance of a full-dynamic coupling between aerodynamic and vehicle dynamic simulations, including a driver model, is evaluated. In the simulations a feedback from the vehicle dynamics into the aerodynamic simulation is performed in every time step. In the work, both the vehicle dynamic response and the aerodynamic forces and moments are studied. The results are compared to a static coupling approach on a set of different vehicle geometries. Five car-type geometries and one simplified bus geometry are evaluated. The aerodynamic loads and moments are obtained using Detached Eddy Simulation (DES) where the motion of the vehicle is enabled using an overset mesh technique. This motion is calculated with a single-track model, including a driver model and handling two degrees of freedom, namely lateral translation and yaw motion.

The results show that for vehicles undertaking large yaw moments and therefore large yaw motions, like the bus-type geometry, the full dynamic coupling is beneficial. In this case, a static coupling overestimates the aerodynamic loads and in turn the vehicle motion. On less crosswind sensitive vehicles, like the car-type geometries, the full-coupling approach does not modify the results in a significant way compared to a static coupling.

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1. INTRODUCTION

Transient crosswinds are common sources of discomfort in ground vehicles. Any experienced driver has been confronted to the side force that it creates, and to the necessity to correct the trajectory against it. In fact, while driving an automobile on motorway lateral wind speeds of only 2.5m/s to 10m/s can force the driver to steer [1]. Such lateral winds can be due to atmospheric turbulence, landscape variations, tunnel exits or when overtaking another vehicle. Although it is rarely a problem of safety for cars, it can become a major issue for buses or trains, as reported by Juhlin [2] and Diedrichs [3]. Furthermore, in order to reduce the fuel consumption, automotive companies tend to produce lighter cars with drag reducing designs. As a consequence, the center of pressure is often moved forward [4], increasing the tendency to yaw under the effect of a crosswind. Further, the increasing power of engines allows vehicles to reach higher speeds, causing the vehicle to be more sensitive to transient crosswind. Finally, thorough understanding of a vehicle's sensitivity to transient crosswinds will also have to be obtained when developing automated driving.

Crosswind stability is the result of complex interactions between aerodynamics, vehicle dynamics and the driver. To assess crosswind stability the whole system has to be considered, as shown in Figure 1.

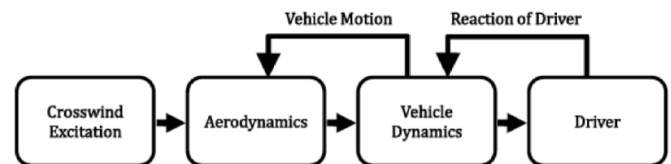


Figure 1. View of the complete system including aerodynamics, the vehicle dynamics and the wind disturbance. Figure based on the work in [5].

Unsteady effects due to the unsteadiness in the wind conditions as well as the vehicle's own motion are dominant in this system. Hence, today's development tools like experimental crosswind-testing facilities, with a constant relative yaw angle flow will not fully replicate real-world conditions. For example, when the vehicle enters a crosswind passage, the front of the vehicle can be affected by the crosswind and undertake a side force, while the back is still in an unperturbed flow situation, which tends to yaw the vehicle away from its path [6][7]. On-road experiments on the other hand enable a realistic description of the problem but are often taking place only in a late stage of the development cycle of a vehicle. Therefore, modeling the right physics in a numerical approach is of interest, especially as the liability of Computational Fluid Dynamics (CFD) improves and the accessible computational power increases.

Both experimental and numerical approaches have been investigated to simulate the physics of a transient crosswind event. However, the focus has generally been on reproducing realistic transient inflow conditions. Only recent numerical studies account for the motion of the vehicle in the aerodynamics. In [8], the motion was imposed using the Arbitrary Lagrangian-Eulerian (ALE) approach to alter the aerodynamic domain for the yaw motion and the Navier-Stokes equations were expressed in a non-inertial reference frame to consider lateral translation. More recently, Winkler et al. [9] performed a full dynamic coupling using a two-degree-of-freedom vehicle dynamics model and an overset mesh technique. It was concluded that the motion of the vehicle has an influence on the aerodynamics when the amplitude of the yaw motion is important. The method was tested on a bus-type geometry undertaking high yaw moment.

The aim of this work is to investigate the need to perform a full dynamic coupling of the aerodynamics and the vehicle dynamics including a driver model when predicting vehicle sensitivity to transient crosswinds through numerical simulations. The method used in [9] is tested on a set of car-type geometries and compared to three less advanced methodologies: two approaches using steady-state analysis and one using static coupling. Hence, both the robustness of the full coupling approach and the gain in terms of physical modelling are tested. The results are also related to the study on the bus-type geometry of [9]. This work is an important step in the process to develop a virtual development tool, where the effect of different vehicle designs on safety, comfort and energy efficiency can be evaluated in an early phase of vehicle development.

In the first section, the state of the art concerning the different approximations that have been made to simulate a vehicle going through a crosswind are presented. At each level of approximation, new sources of unsteadiness are introduced. The test-case is then described including the geometries and the type of crosswind used in the simulations. In the following section, the methods used to set up the numerical simulations and the vehicle-dynamics model are presented. Finally, the results concerning the comparison of the fully-coupled approach with the three previous approaches are shown and the performance of the fully-coupled simulation is discussed in regards to the studied case (bus-type or car-type geometries).

2. UNSTEADY AERODYNAMICS AND TIME SCALES

2.1 Oscillation of the Wake and Steady-State Approach

A crosswind gust creates a change in the incidence angle of the wind, which is the origin of undesired aerodynamic loads like side force and yaw moment. A natural way to study those loads, called the steady-state approach, is to impose a steady incidence angle on the vehicle in a wind tunnel and measure the loads. When the loads are known for all incidence angles, they can be used as input to predict the forces during a crosswind event. An experimental study using this approach has for example been performed by Howell [1] in order to identify the geometry parameters that influence crosswind sensitivity. Numerical simulations can also be performed using the same method.

Even in steady inflow conditions, the flow around the vehicle will be unsteady due to vortex shedding in the wake. A characteristic time scale τ_1 for these oscillations is related to the Strouhal number (St) as $\tau_1 = hSt/u_\infty$, where h is the height of the vehicle and u_∞ its velocity. In [10] the Strouhal number measured at the start of the vortex shedding behind a bluff body is found to be of order of magnitude 1. τ_1 is then of the same order of magnitude as h/u_∞ . In order to get reasonable values of aerodynamic loads, it is therefore necessary to perform time-resolved simulations or wind tunnel experiments. However, as reported by Theissen in [5] the resulting oscillations of the aerodynamic loads are small and, due to the vehicle's high inertia, they should not influence its maneuvering.

The steady-state approach will be used in this study as a reference to observe the benefits of more advanced methodologies.

2.2 Time-Dependent Inflow Conditions

Crosswind velocities can vary rapidly when driving on a motorway. Wojciak et al. [11] gathered experimental data from on-road measurements in gusty conditions, between 4 and 7 on the Beaufort scale [12]. The data was captured using multi-hole pressure probes mounted to the front of a test vehicle running at 140 km/h. It was observed that lateral wind speeds vary from 4 m/s (36% of the collected data) up to 8 m/s. The length scales most often observed of transients gusts were between 20 and 40 meters, which is around 4 to 10 vehicle lengths for a car-type vehicle and around 1.3 to 3.4 vehicle lengths for a bus (see Table 2). Moreover, the length scales reported as relevant for the crosswind stability were between 10m and 80m, corresponding to 2 to 20 vehicle lengths for a car-type vehicle. These length scales correspond to situations where the changes in aerodynamic loads are strong enough to demand an active steering from the driver [5]. They also correspond to time scales where the aerodynamics are likely to be unsteady and can create higher loads on the vehicle, like peaks of yaw moment as reported in [6][7]. In the study of McAuliffe et al. [13], measurements are made in more usual wind conditions and in various conditions of traffic, and terrain. The measured winds lead to a target length scale for lateral wind of 1.9m which is much smaller than in [11]. However, that target length scale doesn't take into account which amount of steering is needed from the driver. Hence, the time scales and wind velocities measured by Wojciak et al. [11] were chosen as a reference for this study. In such time varying inflow conditions, the relative incidence angle of the wind varies along the vehicle, as shown in Figure 2.

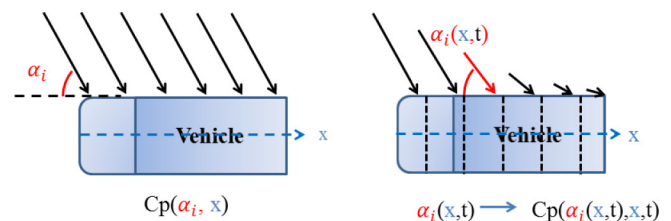


Figure 2. Left: the steady-state case. The profile of coefficient of pressure C_p can be measured for any incidence angle. Right: a transient crosswind case.

The aerodynamics of such a situation can hardly be predicted by steady-state measurements. For example, a yaw moment overshoot at the entrance of a gust was reported many times in the literature [2] [6], occurring when the front of the vehicle is affected by the crosswind before the back of the vehicle. There are actually two effects that make the aerodynamic forces different than their steady-state equivalent.

First, at a given time t , the incidence angle $\alpha_i(t, x)$ is not constant along the vehicle. At the entrance of a gust for example, the incidence angle is higher at the front of the vehicle than at the rear. This logically leads to a higher coefficient of pressure C_p at the front of the vehicle and a peak of yaw moment. Hence, this effect is essential and was the subject of focus since the first studies on crosswind stability. In the late 1960's Larrabee and Hawks [14] took both the vertical and horizontal gradients of velocity into account in their study. In 1973, Hucho and Emmelmann [15] developed an analytical model based on the slender body theory that takes into account the crosswind velocity profile. This model predicted an overshoot at the entrance of the gust compared to steady-state values, both in the yaw moment and the side force. A more recent approach from the work of Diedrichs [3], named the Quasi-Transient Gust Modeling (QTGM) assumes that the pressure coefficient along the vehicle reach its steady-state values instantly, according to the local angle of incidence. It only takes as input steady-state results, and can therefore be interesting because of reduced computational costs and feasibility in a wind tunnel. Moreover, in the study of Diedrichs [3], this approach successfully predicted the expected yaw-overshoot at the entrance of a gust for a train geometry. The QTGM approach is the second approach that is used in this study to predict the behavior of vehicles under crosswind. The characteristic time scale of this unsteady effect is linked to the length of the transient area of the crosswind to the length of the vehicle, which in this study will be of about 1.5 vehicles lengths. This leads to a time scale $\tau_2 = 1,5L/u_\infty$, similar to τ_1 , in Sec 2.1.

Secondly, within a transient crosswind, the incidence angle will also vary rapidly in time. The aerodynamics around the vehicle is then likely to be history dependent and delays in the pressure coefficient may appear. The QTGM approach will not be able to take these effects into account. An estimation of time scale for these unsteady effects can be given through the time taken by the crosswind to run over the width of the vehicle: $\tau_3 = w/u_{cross}$, where w is the width of the vehicle and u_{cross} is the crosswind velocity. In order to observe this unsteadiness, one has to put the vehicle in realistic transient crosswind conditions. This has been the subject of many experimental studies using various setups. Specific wind tunnels have been developed where the flow upstream is deflected using oscillating devices such as flaps [16] or airfoils [17], or using an auxiliary jet branched to the main wind tunnel [18]. Rotating models have also been studied, where the motion of the vehicle creates an unsteady relative inflow on the vehicle [5]. Finally, scaled model translating on an axis can be propelled through a wind tunnel exit [6].

This latter experimental setup has the advantage of reproducing a typical crosswind scenario (see Figure 3) that can be created by embankments or hills, which is thought to be particularly hazardous in terms of driving stability.

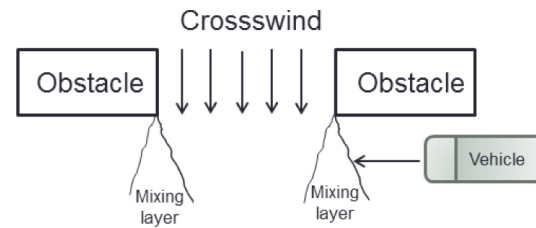


Figure 3. Typical crosswind scenario created by embankments.

Favre [7] reproduced such experiments in simulations using time-dependent boundary conditions and a fixed vehicle. This is the so-called one-way coupling approach, which is the third approach used in this study.

2.3 Motion of the Vehicle and Fully-Coupled Simulation

The final unsteady effect that can play a role is the motion of the vehicle itself. In terms of relative inflow conditions, the motion of the vehicle can have two effects. First, the lateral velocity or the yaw rate of the vehicle can create a relative wind that will influence the aerodynamics. Second, if the vehicle undertakes a large yaw motion, the crosswind will affect the vehicle with a modified angle ψ , thus changing the aerodynamics around the vehicle. These two effects are illustrated in Figure 4.

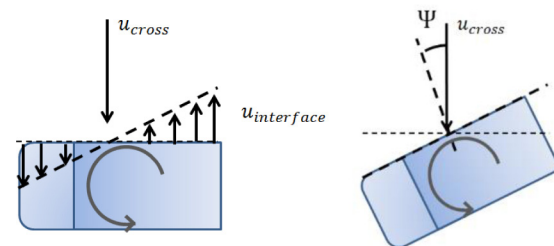


Figure 4. Two effects of the motion of the vehicle on the aerodynamics.

Due to the inertia of the vehicle, we can expect the velocity of the vehicle to stay low compared to the velocity of the crosswind. This implies that the first effect is always likely to be negligible. The second effect however, may become important as the yaw angle increases. From the results of Winkler et al. [9] on the bus geometry, we can expect this effect to have a larger time scale than τ_1 , τ_2 or τ_3 .

On-road experiments enable a full description of the behavior of a vehicle under a transient crosswind. However, their results and interpretation is limited by the fact that natural crosswinds are never exactly the same, and that measurements of the flow field around the vehicle are difficult. Mounted fans at the side of the road can be used to produce a more repetitive and controllable crosswind [19]. However, fans will give a swirling flow, which may give different flow behaviour over the vehicle than atmospheric crosswinds and in worst case an erroneous response to design alterations. The fully-coupled approach developed by Winkler et. al [9] using an overset mesh technique is also used in this study.

To conclude, four unsteady effects have been presented: oscillation of the wake, non-constant incidence angle, delays in the aerodynamics and vehicle motion. For each effect, a modeling approach exists.

steady-state simulation, QTGM, one-way coupling approach and fully-coupled approach. Performing these approaches on the same test case will enable studies of the unsteady effects independently and a better comprehension of the improvement between the approaches.

3. TEST-CASE: VEHICLES AND CROSSWIND

3.1 Geometries and Scaling

Five geometries derived from the so-called Windsor model are studied. This model was chosen for two reasons. First it has been used both in an experimental study of Chadwick et al. [6] and in a previous numerical study [7]. Second it is a simple geometry on which changes are easily implemented. The angle of the windshield at the front of the car is modified to create two other geometries, introducing the length parameter δ as shown in Figure 5. For the second set of geometries, a concavity is introduced, using the angle parameter α . No changes in the radius of curvature of the frontal edges were performed. The geometry changes were adjusted to create significant differences in the yaw moment under steady crosswind at 20 degrees of incidence, in order to observe different dynamics of the vehicle.

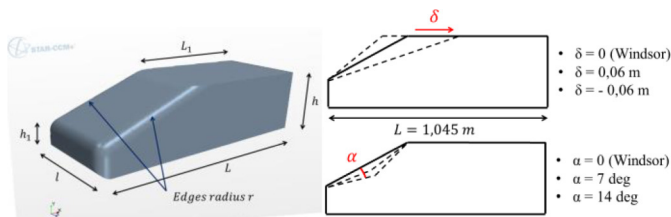


Figure 5. The Windsor model and different tested geometries.

The Windsor geometry is a 25% scale model compared to a realistic car (see Table 1). The scaled vehicle runs at a velocity of 27m/s. This choice induces a Reynolds number of 2×10^6 based on the length of the vehicle, which is smaller than in realistic conditions but identical to the experimental study of Chadwick [6]. The ground clearance is of 0.05m.

Table 1. Dimensions of the Windsor model (25% scale model).

Length, L	1.045 m
L ₁	0.645 m
Height, h	0.29 m
h ₁	0.12 m
Width, w	0.39 m
Edges radius, r	0.05 m



Figure 6. Bus geometry from Winkler et al. [9].

The work of Winkler et al. [9] on a bus presented in Figure 6 is used in this study as reference and the results obtained in the Windsor case are compared to that case. The geometry is a 12.5% scale model based on the experimental study of [20]. Its dimensions are detailed in Table 2.

Table 2. Dimensions of the bus in [9] (12.5% scale model).

Length, L _{bus}	1.525 m
Length wheel base, L _{bus,wb}	0.738 m
Height, h _{bus}	0.45 m
Width, w _{bus}	0.325 m

3.2 Crosswind Model

As explained in Section 2.2., crosswinds vary in length, intensity, and frequency domain. These parameters certainly have an influence on the resulting aerodynamic forces and moments. However, in order to compare the different models and different geometries on the same test-case, we focus on one crosswind model derived from the experiment of Chadwick [6] and meant to reproduce the natural crosswind scenario of Figure 3. This crosswind doesn't vary vertically so the effect of a possible presence of an atmospheric boundary layer is not included. The horizontal profile of the crosswind is presented in Figure 7.

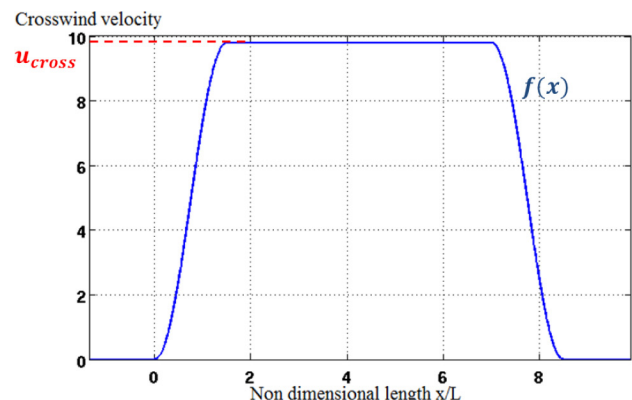


Figure 7. Shape of the crosswind used in the whole study. x is the coordinate in the forward direction.

The transient parts of the gust are modeled by a sinus curve with a period of 3 vehicle lengths, which yields a gust entrance and a gust exit of 1.5 vehicle lengths. This period is, as described in Section 2.2., a relevant length scale for the study of crosswind stability. Once the vehicle is in the steady crosswind, a transient time of at least 3 vehicle lengths is expected before the steady-state values are reached [21]. From the study of Chadwick et al. [6], this transient period could be even longer than 5 vehicle lengths. Following the study of Favre [7] and Winkler et al. [9] the length of the gust was set to 5 vehicle lengths with a maximum lateral velocity of $u_{cross} = 9.8 \text{ m/s}$ leading to a maximum incidence angle of 20° .