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On the ground-vehicle induced flows and obstacle interaction for energy harvesting purposes

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ABSTRACT

CFD simulations were conducted with the aim of studying the flow field induced by a road vehicle moving at high speed for energy harvesting purposes. 2D and 3D approaches were used and focus was put on the interaction between the vehicle and an obstacle placed upon the road simulating the shape of a generic harvesting device. 2D RANS simulations have proved that a separated region forms and that a trailed flow exists upon the vehicle which thickness do not exceed 1.1 times the vehicle height. The presence of trailing vehicles was analyzed and the raising of the separation region evaluated. The 3D steady approach showed that 2D modeling did not adequately predict velocity and pressure values even if general trends were captured. Different panel shapes were then compared to assess the effect of placing an obstacle near the moving vehicle. 2D URANS simulations suggested that to overcome an obstacle placed 1 m above the vehicle roof, an energy boost is required, while 3D unsteady calculations showed negligible variations in the vehicle's drag with approaching the obstacle. Furthermore, simulation of the full 3D domain allowed to identify forces time-histories and loading directions acting on a circular cylinder, with definition of an equivalent uniform velocity to characterize the flow impinging on the obstacle. Results showed that force coefficients and equivalent velocity maximums locate in the vehicle nose region, where inviscid-like effects dominates.

1. Introduction and overview

A ground vehicle moving at high speed generates a complex flow field that greatly influences the environment nearby. For a typical Class-8 tractor-trailer of about 300 kW, Ougburn et al. (2008) pointed out that to travel at a speed of 60 mph (approximately 100 km/h) along a level and windless highway, the truck needs continuously 137 kW at the wheels, the energy spent to overcome air resistance being about 75 kW based on a drag coefficient C_d of 0.6; according to Ougburn et al. (2008), this power is relative to the aerodynamic load, amounting to the 21% of the total fuel consumption or the 47.7% of the engine net output. Therefore about half of the engine power output is directly spent to overcome aerodynamic resistance. Based on such results and according to percentages from the work of Hilliard and Springer (1984), roughly 3.75 kW out of 75 kW are spent into frictional losses, the rest of the global loss being spent to displace the air; hence air fluxes and pressure gradients of a certain strength are expected somewhere around the truck.

A question arises whether or not is possible to recover part of such an energy that would be otherwise lost. With this purpose in mind there is the need to characterize the resource, i.e. the generated flow, in terms of its pressure and dynamic contributes. Furthermore is of great interest to explore how a generic energy recovery device interacts with the truck itself; even though some energy contents are available, the presence of such a device near the truck way could improve the aerodynamic loss of the vehicle resulting in a negative energy balance for the whole system.

From this point of view, general information about the loads induced by a road vehicle come from the experimental study of Baker et al. (2000a). In this work the slipstream and wake of a 1/25 scaled model lorry is investigated with an experimental apparatus measuring velocity profiles upon and sideways of the vehicle with varying the distance from the vehicle surface. Flow velocity and time are made non-dimensional based on vehicle speed and truck length, results proving a strong correlation among the two when the vehicle model overcome the hot-anemometers rake, see Fig. 1. With these choices, the lapse between 0 and 1 represents the time interval needed to overcome the measuring station, the origin being the time the vehicle nose pass underneath. It is found that the flow trailed

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Nomenclature

L	truck length (m)
W	truck width (m)
H	truck height from street plane (m)
A_{ref}	reference area (m^2)
ρ_{ref}	reference density (kg/m^3)
p_{ref}	reference pressure (Pa)
X	axial coordinate (m)
Y	height from street plane (m)
Z	transversal coordinate (m)
ΔY	distance from truck surface in the Y direction (m)
U_0	truck speed (m/s)
V_x	absolute flow velocity X-component (m/s)
CD_0	steady truck drag ($Steady\ drag/0.5\rho_{ref}A_{ref}U_0^{2)}$
CD	unsteady truck drag ($Unsteady\ drag/0.5\rho_{ref}A_{ref}U_0^2$)
C_p	pressure coefficient ($(p-p_{ef})/0.5\rho_{ref}U_0^2$)

from the vehicle could be divided into five main regions, each characterized by specific flow features:

- *Upstream region [UR]* $t<0$
  This is the region in front of the vehicle where velocities increase smoothly and the flow behaves as it was inviscid. Side measurements show that the air feels the vehicle arriving at a time of about -1, or in terms of distance, at a fairly 1 vehicle length from the nose of the advancing model.
- *Nose region [NR]* $t\in[0,0.25]$
  In this region are located the highest values of velocity that the vehicle could reach. In a lapse, velocity values decrease hence nose and upstream regions are the zones where the highest velocity gradients, or fluid accelerations, locate. Peaks strengths depend from distance, lowering with leaving the vehicle surface.
- *Boundary layer region [BLR]* $t\in[0.25,1]$
  The potential behavior ceases here and viscous effects start to dominate, with the formation and develop of boundary layers on the vehicle body. Here velocity variations are slow hence the flow shows low acceleration terms.
- *Near wake region [NWR]* $t\in[1,10]$
  This zone starts from the vehicle base region and downwards of it velocity profiles show high non-uniformities that decrease in amplitudes with time.
- *Far wake region [FWR]* $t>10$
  The wake has uniform values of velocity at any section and gradually decay with time (not shown in figure).

Acceleration terms, hence aerodynamic forces related to the induced flow, are computed integrating the velocity time histories to give evidence about the effects on objects placed nearby the vehicle way. In reality it is expected that the presence of an object, depending on its shape and size, affects the interaction with the vehicle providing a resulting flow-field where both the object and the vehicle mutually interact exchanging forces and moments.

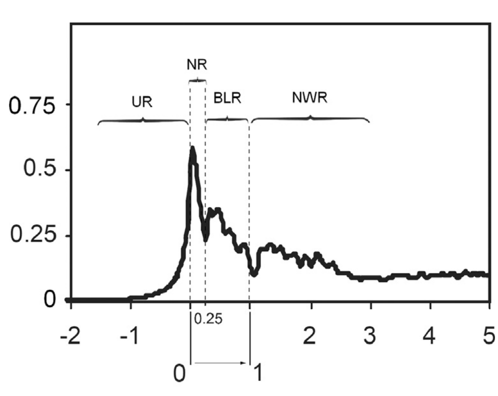

Fig. 1. Velocity time history at the model side, adapted from Baker et al. (2000a).

In terms of energy balance, this could mean a variation in the vehicle aerodynamic loss, hence interest is to be devoted in such a problem.

Details about road vehicles induced loads could be found in the pioneer works of Cali and Covert (2000) and Quinn et al. (2001), who investigated experimentally the effects of vehicles induced flows upon different kind of highway signs, with the induced loads analyzed monitoring the C_f force coefficient time histories, see Fig. 2. The total force coefficient C_f relates to the sum of each of the three load-cell contributes mounted on the sign which is placed upon and sideways of the vehicle way (positive values are in the vehicle direction). The time variable is defined as before, with the C_f load histories allowing to define different fluid regions.

Zone I is dominated by inviscid effects according to which fluid flow in front of the vehicle could be modeled by a potential approach, while the Zone II trend is governed by viscous effects related to separating boundary layers, wake formation and recirculating bubble. Moreover, different subregions could be analyzed: Cali and Covert (2000) find that Zone III is independent from vehicle length but greatly influenced by sign height and vehicle frontal shape, apart from the little frontal region, sub-Zone V, where point Z_1 moves towards the origin when the panel eight lowers. Furthermore, while P_2 is totally controlled by inviscid effects, the strength of peak P_3 comes from the direct interaction of the separation bubble formed upon the vehicle with the lower part of the sign. Hence, magnitude of P_3 lowers with streamlining the vehicle (reducing the separation bubble-formation till its complete disappearance for a very high streamlined vehicle) and/or rising of the sign. Sub-Zone IV depends from vehicle rear shape and dimensions, peak P_5 related to the recirculation flow in the vehicle base region.

Some hints about the nature of the induced flows and the load mechanism upon the signs arise from the measurements made in the full scale test, (Quinn et al., 2001). In this work, apart monitoring forces on the panels, both static pressure and wind

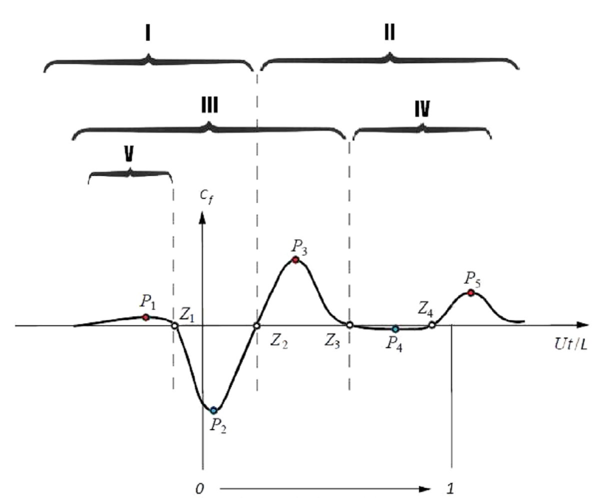

Fig. 2. Force coefficient history, adapted from Cali and Covert (2000).