

Analysis of the Impacts of Formula 1 Car Wakes on the Aerodynamic Performance of a Following Vehicle.

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Abstract: This paper investigates the impact of the wake of a Formula 1 geometry on a following vehicle. For the case considered, the vehicle downforce is seen to be reacted by the pressure force on the ground plane, resulting in little net up-wash in the wake despite strong localised up-wash on the centreline. The following vehicle loses drag and downforce, especially front downforce. Using an idealised wake model and parametric variations it is shown that generating a higher proportion of downforce using the rear wing of the upstream vehicle results in less loss of front downforce on the following vehicle.

Keywords: Aerodynamics, Wake, Wake Integral, Racing Car, Formula 1, CFD

1 Background

The lap-time performance of a Formula 1 car is a result of the high cornering forces (in excess of 4g) made possible by the high levels of downforce generated by the aerodynamic surfaces of the car, in excess of three times its own weight Zhang et al. (2006) or -4.5 to -5.0 on C_L (based on nominal frontal area).

The three principal downforce generation features are the front wing, the rear wing and the underbody. The wheels contribute lift, as well as drag. The front wing and underbody operate in ground effect and it is generally assumed that the rear wing does not. However, there is a strong interaction between aerodynamic surfaces, including between the rear wing and underbody, and so it is dangerous to consider different aerodynamic devices to be independent of each other. Very high drag is coming with drag coefficients around 1.0 (Wright (2004) & Aiguabella (2011)). High lift and drag results in a strong wake characterised by a velocity deficit, a counter-rotating vortex pair with centreline up-wash (Wilson et al. (2009) & Watts (2014)).

The effect of the wake on any following vehicle is severe, resulting in a strong obstacle to overtaking. Better understanding of the link between vehicle design (controlled by regulations), the resulting wake, and the impact on a following vehicle could facilitate future regulation design to enable easier following and hence overtaking.

2 Approach

Simulations were performed on a Formula 1 car geometry compliant with the pre-2009 Formula 1 regulations FIA (2008) (the post-2009 regulations have been shown to not significantly affect the structure of the wake, Watts (2014)). The simulation Reynolds number was 3.1×10^6 which matches that of model tests at 25% scale performed as part of a broader investigation (e.g. Newbon et al 2014). Key vehicle set-up parameters (ride height, pitch angle, front wing flap angle) were selected through wind tunnel testing but it should be recognized that the aerodynamic design of the vehicle has not been developed to the extent of that of a competitive Formula 1 car.

Simulations were performed using EXA PowerFLOW, a transient solver, utilizing the Lattice-Boltzmann Method (LBM). Turbulence modelling uses a Very-Large Eddy Simulation (VLES) model, coupled with a two equation (k- ϵ) model for sub-grid scale turbulence. Refinement of the Cartesian mesh is controlled using Variable Resolution (VR) regions, with the lattice length halving as the VR level increases. Kotapati et al. (2009) describes the numerical approach and reviews other published work using this method.

The meshes used had a minimum cell size of 1.5 mm and contained between 8 and 31 million cells, split between up to 10 VR regions. Cases were run on the Durham University High Performance Computer cluster (which has 2000 CPU cores with up to sixteen 2.6 GHz Intel Xeon processors per core). Simulations required up to 1500 CPU hours to compute 0.7s of physical time, sufficient to time-average features in the wake.

3 Results and Discussion

Baseline Vehicle in Isolation

Experimental and computational studies for the generic Formula 1 car have been performed and analysed in detail in Newbon et al. (2014) and Newbon et al. (2015) so the following is a summary of the vehicle force behaviour. With the vehicle in a clean onset flow $C_D = 0.92$ and $C_L = -0.79$ (based on nominal frontal area) with an aerodynamic balance of 68% of downforce acting on the rear axle, similar to the ideal balance of 65% shown in Agathangelou and Gascoyne (1998). The vehicle wake shows the same features as other F1 wake studies (e.g. Perry and Marshall (2008), Simscale (2015)), namely an axial velocity deficit and a counter-rotating vortex pair from the rear wing. There is a small recirculation bubble from separated flows on the rear wing centreline, as well as reversed flow in the wheel wakes, though no flow reversal remains in the wake beyond 0.1 car lengths downstream of the rear of the vehicle.

Impacts on a Following Vehicle

Two vehicles were simulated with inter-vehicle separations of one and two car lengths. A one vehicle separation (illustrated in figure 1) was considered to be the closest that a vehicle would follow another and resulted in a 20% loss of drag and a 60% loss of downforce, which was coupled with a 38% rearwards shift of the aerodynamic balance. Component forces showed that the body downforce was more adversely affected than either the front or rear wings and this was the case at both one and two vehicle separation distances.

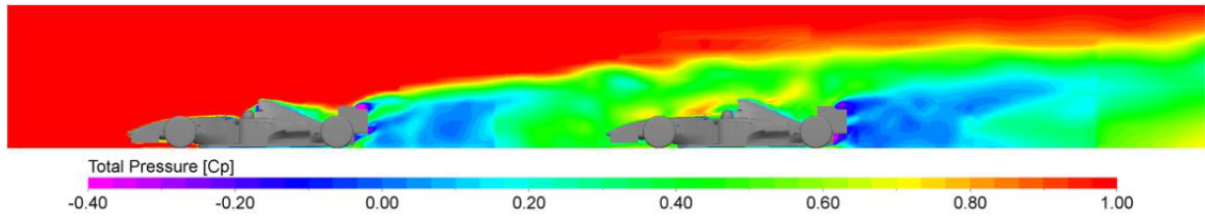


Figure 1 - Centreline Total Pressure, Two Vehicles with a One Vehicle Separation

Wake Integral Analyses

The vehicle wake is linked to the aerodynamic forces on the vehicle and on the ground plane as described by, for example, Ryan (2000). A control volume was chosen extending 0.75 car lengths upstream and 1 car length behind the vehicle with width and height four times the vehicle width and height respectively. A vehicle in “ground effect” can be expected to generate a significant pressure distribution on the ground plane. Integrating the pressure on the ground plane showed a force on the ground that was 94% of the magnitude of the downforce on the vehicle. Correspondingly, while strong up-wash was seen on the wake centreline, taken across the whole of the downstream control volume boundary up-wash and downwash essentially exactly cancel out. This is perhaps of particular interest because the centreline up-wash plays an important role in moving the vehicle wake up and over a following vehicle (further detail in Newbon et al. 2015).

Idealised Wake and Impacts on a Downstream Vehicle

An idealized wake was created composed of a rectangular region of axial velocity deficit, a uniform up-wash (approximately zero in the base case) and a pair of trailing vortices with a Rankine vorticity distribution. Figure 2 shows the wake propagation downstream from its starting point equivalent to 0.25 L behind an upstream vehicle.

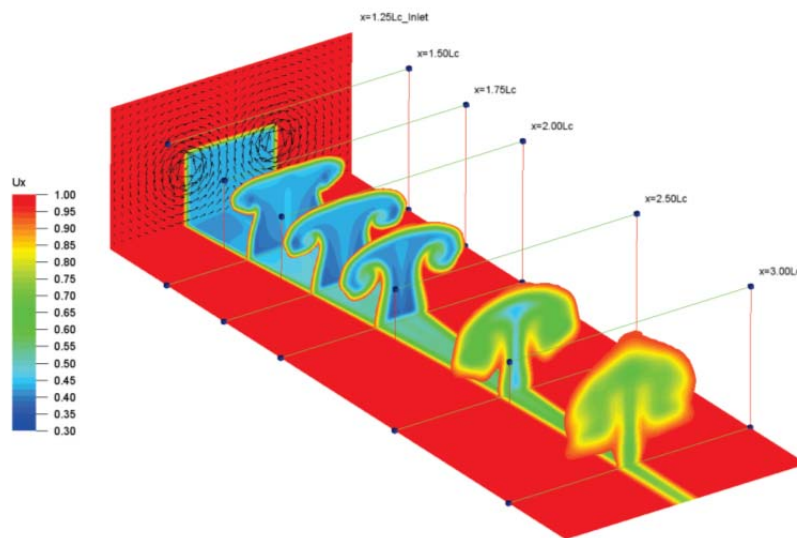


Figure 2 – Idealised Wake Propagation

The relative contributions to downforce of the rear wing and vehicle body will have different impacts on the wake. A combination of analytic theory and Taguchi analysis of small parametric changes to the upstream vehicle was used to map changes in body and rear wing downforce to revised idealized wakes. Multiple idealised wakes were created representing different proportions of lift generated by the rear wing, but based on the same overall drag and downforce.

These wakes were, in turn, imposed as the inlet condition ahead of a downstream vehicle. This showed (figure 3) that higher proportions of downforce generated by the rear wing of the upstream vehicle resulted in less loss of front downforce on the following vehicle, in particular as a result of reduced downforce loss on the front wing of the following vehicle.

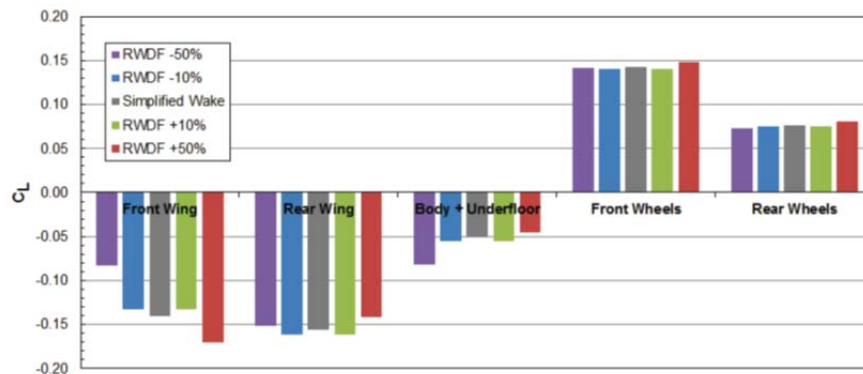


Figure 4 – Component C_L Impacts due to Wakes based on Different Rear Wing Downforce

4 Conclusions

For the case considered, the vehicle downforce is seen to be reacted by the pressure force on the ground plane, resulting in little net up-wash in the wake despite strong up-wash on the centreline. The following vehicle loses drag and downforce, especially front downforce, which will have a negative impact on handling. A higher proportion of downforce generated by the rear wing results in less front downforce loss on a following vehicle.

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