1st MSC.ADAMS European User's Conference

London, November 13-14 2002

Multi Body System – Computational Fluid Dynamics (CFD) integration

IDIADA Automotive Technology SA

http://www.idiada.com

Salvador Ruiz <sruiz@idiada.com>
MBS and CFD coordinator

Jordi Arbiol <jarbiol@idiada.com>
Vehicle Dynamics Simulation

Alexandre Català <acatala@idiada.com>
Product Manager of Vehicle Dynamics

Rubén Marí <rmari@idiada.com>
Computational Fluid Dynamics

Alex Punset <apunset@idiada.com>
Computational Fluid Dynamics

1. Introduction

A forward-moving vehicle in still air has symmetrically applied longitudinal and vertical reactions due to aerodynamic forces. Crosswind gusts apply forces not in alignment with the path of the vehicle. These forces cause aerodynamic side forces, yawing moments and rolling moments that affect the handling qualities and lateral stability of the vehicle.

Under crosswind gust conditions the vehicle is affected by lateral excitation that leads to a sudden change on its direction –an undesirable effect. Therefore, it is very important to be able to evaluate the vehicle's crosswind sensitivity, which is an important aspect of the active safety level.

In order to achieve a quantitative criterion for rating the crosswind sensitivity of vehicles, different kinds of tests are conducted. One widely used method is to measure the lateral deviation of a vehicle driving along a crosswind track under fixed control conditions.

For the virtual analysis of this test, we have used a tool for evaluating vehicle dynamics behaviour (Multi Body System simulation) a together with a tool for the analysis the aerodynamic characteristics of a vehicle (Computational Fluid Dynamics) under a longitudinal or crosswind sine.

In this paper we consider the integration of MBS models (ADAMS) and CFD analysis (STAR-CD) in order to have a correct analysis of the vehicle dynamics behaviour under complex aerodynamic excitation.

This paper details the different steps of the methodology, from the correlation of the MBS model to the complete integration of CFD analysis.

2. The object of the study

It has been proven that aerodynamic forces greatly affect a vehicle's behaviour. The influence of this effect has been traditionally evaluated using a simplified formula:

$$L = c_L \cdot \frac{r}{2} \cdot A \cdot v^2$$

Where c_L is the experimental aerodynamic coefficient that define the vehicle's sensitivity to the wind pressure.

This expression could be used with a reasonable level of accuracy in straight driving or steady state conditions. Although, the more complex driving circumstances of cross-wind testing force to develop and use a more sophisticated approach to this phenomena: the integration of Multi-body and CFD simulation tools.

3. Modelling the vehicle with ADAMS

To run this investigation a realistic and well-correlated model of a passenger car was used. The model of the vehicle was done taking experimental data of the different components mounted into the test vehicle. So, springs, shock absorbers, bump stops and main suspension bushings were measured and then modelled with non-lineal elements into the ADAMS model.

Some flexibility on the main suspension parts was also considered with beam elements, though the body of the vehicle is considered as a rigid body.

The influence of the different model refinements introduced could be evaluated in the correlation process. The final model resulting from this analysis showed a remarkable level of correlation in the following circumstances:

- Kinematics and elastokinematics tests of isolated axles
- Steady state behaviour at low to mid speed
- Severe lane change test at mid speed

The kinematics and elastokinematic test results obtained from an accurate hydraulic test rig from MTS® installed at IDIADA, were used to correlate the chassis performance on the main force and displacement ranges that will result from the road tests of interest.

With the virtual K&C implemented on ADAMS/Vehicle we obtained the results used to evaluate the correlation of the model.

All this data is obtained at very low speed, steady-state response, however in further activities the same tests run under dynamic excitation will be used.

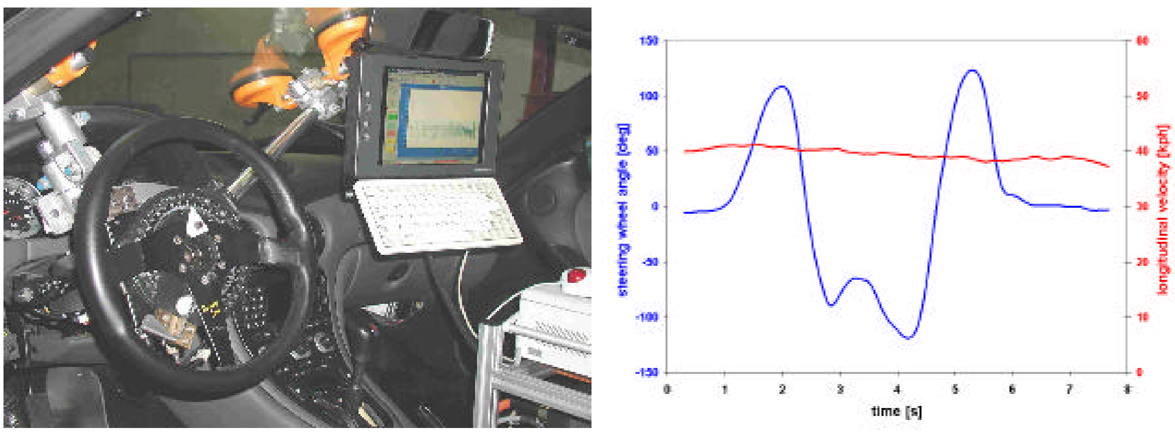
The first step of road test simulation was don with the steady-state test at constant speed: 60 km/h. The data of the tire performance used in the model was tuned in order to achieve a good correlation level with the test data.

The evolution of the steering wheel angle, and the slip angles reduced to the centre of the axle showed a very good matched with the real performance of the vehicle on the track.

Finally, the dynamic response of the vehicle was evaluated using a well-known manoeuvre: Severe lane change test, avoidance manoeuvre. This test permits to evaluate the transient response of the vehicle at different speed and acceleration levels. At this point, the low speed and high acceleration levels was of particular interest because of:

- minimal aerodynamic effect on the vehicle response
- wide range of forces applied into the vehicle

The correlation process started with the test, as we used the driver inputs obtained on the track for simulating the manoeuvre with ADAMS. The inputs used were the steering wheel angle and the longitudinal velocity of the vehicle during the test.

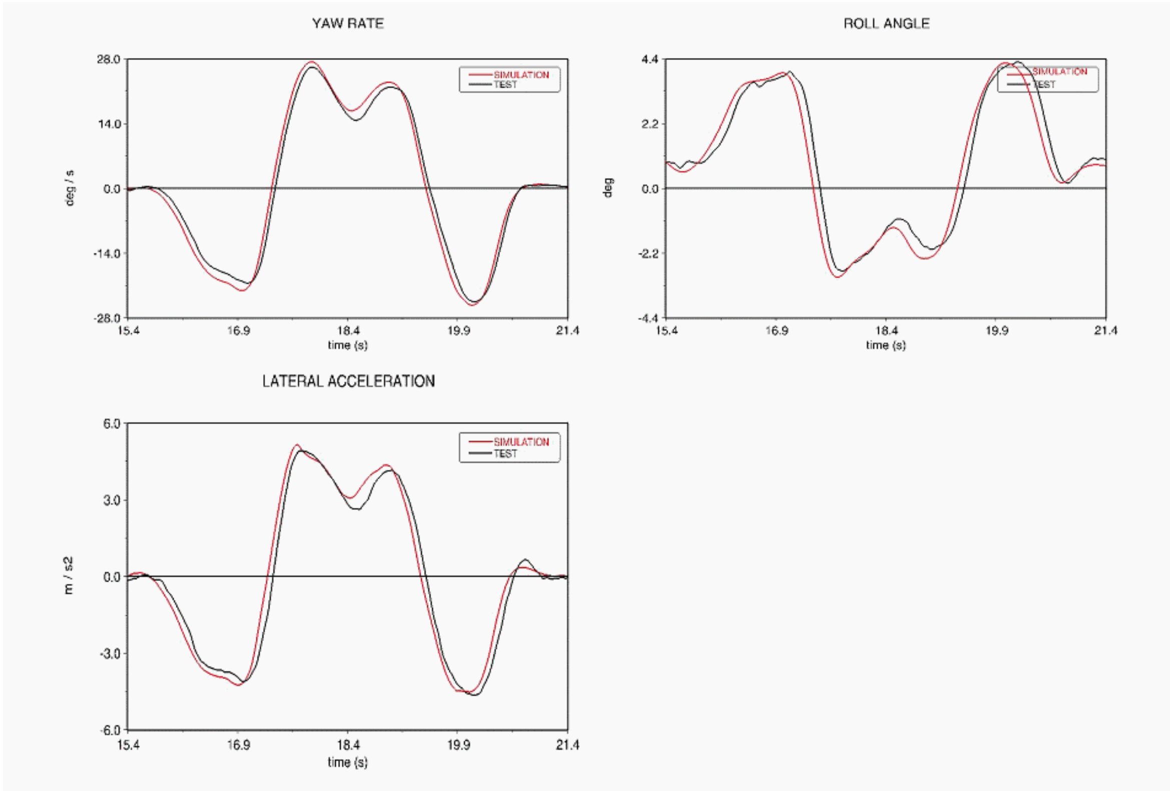


Instrumentation on the vehicle and recorded driver inputs during the test

Three general and descriptive variables of the vehicle during the manoeuvre are presented to indicate the correlation level of the vehicle during a transient disturbance:

- Lateral acceleration at the centre of gravity
- Yaw rate
- Body roll angle

The comparison between simulation and the data obtained with the real vehicle is shown below:



Comparison of virtual and real data

Both amplitude and phase levels are very similar in all variables shown for this test. The evolution of the front and rear slip angles from the model coincides with the measured variables. The final ADAMS model obtained from this process permitted to investigate aerodynamic effects with a solid level of confidence on the results obtained, as the handling dynamic performance was well correlated.

4. Integration methodology

The MBS model of the vehicle needs to be linked with the results obtained with the CFD analysis. Both techniques linked will permit to assess the vehicle response at higher speeds or special wind gust conditions obtained realistic results.

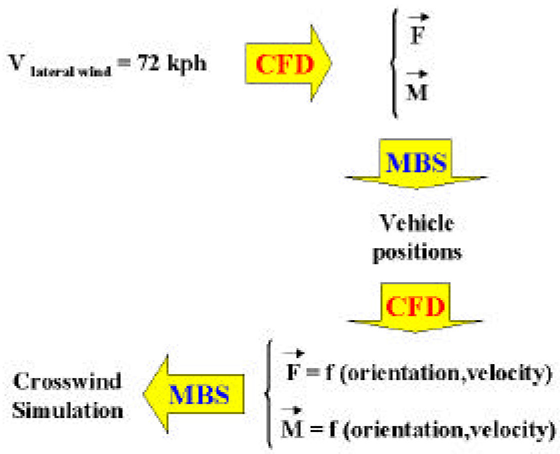
In order to run the CFD calculations, we need to know the possible positions and velocities of the vehicle during the simulation. An initial CFD simulation with a lateral wind velocity of 72 km/h gave us a lateral force and a yawing moment that we applied to the ADAMS model (with no drag and lift forces). By using this, we can estimate the possible positions of the vehicle during the crosswind.

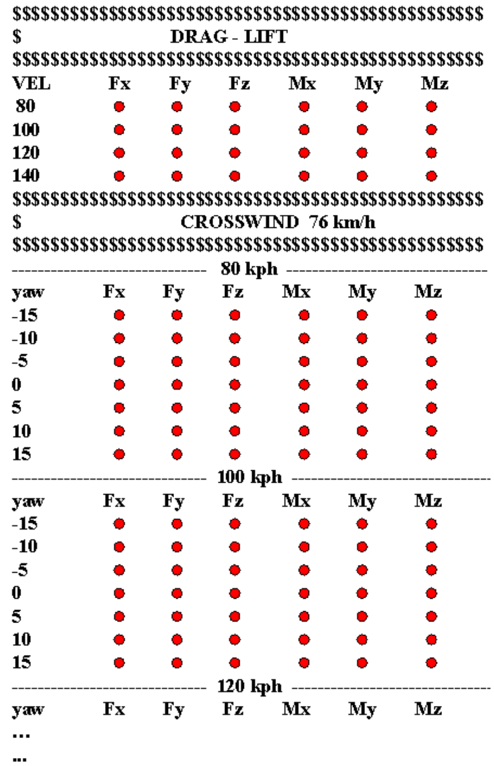
We need to know all the aerodynamic forces in all these cases in order to be able to apply them to the ADAMS model.

To do this we have to calculate the forces in STAR-CD into the range of the possible positions of the ADAMS model. These forces are different for each vehicle velocity. Then we generate a Matrix which includes all these values.

During a typical simulation of ADAMS, whether the model was affected by aerodynamic excitation and in which direction was essential information needed to complete the calculation in the right way.

The aerodynamic forces are applied to the ADAMS model using an external subroutine that takes into account the Matrix.





$$
$ DRAG - LIFT
$$

VEL	Fx	Fy	Fz	Mx	My	Mz
80	●	●	●	●	●	●
100	●	●	●	●	●	●
120	●	●	●	●	●	●
140	●	●	●	●	●	●

$$
$ CROSSWIND 76 km/h
$$

---------------------------- 80 kph ----------------------------

yaw	Fx	Fy	Fz	Mx	My	Mz
-15	●	●	●	●	●	●
-10	●	●	●	●	●	●
-5	●	●	●	●	●	●
0	●	●	●	●	●	●
5	●	●	●	●	●	●
10	●	●	●	●	●	●
15	●	●	●	●	●	●

---------------------------- 100 kph ----------------------------

yaw	Fx	Fy	Fz	Mx	My	Mz
-15	●	●	●	●	●	●
-10	●	●	●	●	●	●
-5	●	●	●	●	●	●
0	●	●	●	●	●	●
5	●	●	●	●	●	●
10	●	●	●	●	●	●
15	●	●	●	●	●	●

---------------------------- 120 kph ----------------------------

yaw	Fx	Fy	Fz	Mx	My	Mz
...						
...						

Lay-out of the methodology used **Matrix of Aerodynamic forces**

5. Influence of the aerodynamic forces

To evaluate the influence of the aerodynamic forces on the vehicle and using the integration process explained before, the study concentrated on three simulations of different tests:

- Straight line driving at constant speed
- Steady-state at constant speed and increasing wheel angle
- Single lane change

5.1. Straight line driving at constant speed

This simulation was done to obtain the weight distribution of the vehicle without any lateral and longitudinal force applied unless the needed to maintain the constant speed. At this stage we performed three simulations:

– Static simulation with the vehicle stopped (S1)
– Straight line driving at 100 km/h with no aerodynamic forces (S2)
– Straight line driving at 100 km/h including aerodynamic forces (S3)

Simulation		Front axle [kg]		Rear axle [kg]		Total weight [kg]	
S1	Static	684		562		1246	
S2	At 100 km/h without aerodynamic forces	667	*-2.55 % compared to simulation S1*	579	*+3.10 % compared to simulation S1*	1246	*0 %*
S3	At 100 km/h with aerodynamic forces	665	*-0.24 % compared to simulation S2*	536	*-7.50 % compared to simulation S2*	1201	*-3.61 % compared to simulation S2*

Weight distribution during the different tests

The weight distribution of the S2 differs from the S1 because of the torque applied on the front axle. This torque resulted from the resistance forces mainly due to the tires. The total weight was the same (1.246 kg) because of no external forces applied to the vehicle.

When the aerodynamic influence (S3) is introduced, the vehicle results with a new weight distribution. Comparing S2 with S3, we can see that the weight on the front axle is almost the same and the weight on the rear axle is 7.5% less in S3 compared to S2. This is the main important effect observed with this vehicle. The pressure differences between the vehicle's upper-side and underside produce a rear lift (L), or a pitch moment (M) applied to the gravity centre that lifts the rear part of the body.

To analyse the influence of these aerodynamic forces into the handling behaviour of the vehicle, we simulated two different manoeuvres:

- Steady-state at constant speed and increasing wheel angle
- Single lane change: transient manoeuvre

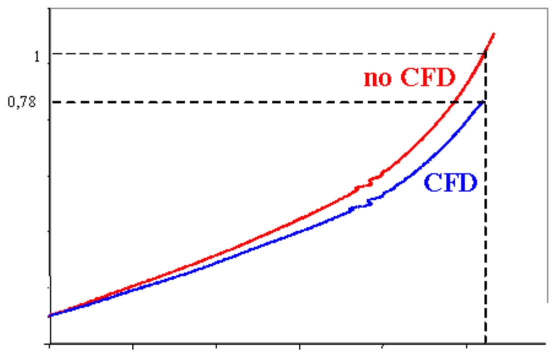
5.2. Steady-state at constant speed and increasing wheel angle

On this test the vehicle runs at a constant velocity, 100 km/h, while and increasing wheel angle evolution is applied at a very low rate, so to have quasi-steady state situation during the test.

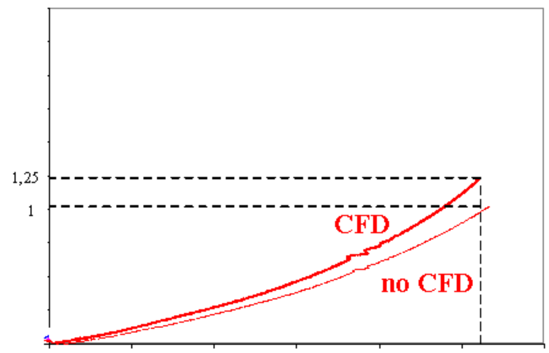
The parameters to be analysed and compared in this test are:

- Lateral acceleration
- Yaw rate
- Roll angle
- Side slip angle of the vehicle
- Reduced slip angle of both axles

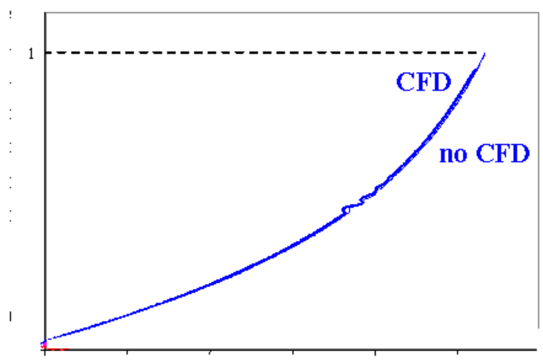
The aim is to compare the results coming from the ADAMS model without the aerodynamic forces (no CFD) and the ADAMS model with the aerodynamic forces (CFD). Next figure shows the comparison between these two configurations calculated:



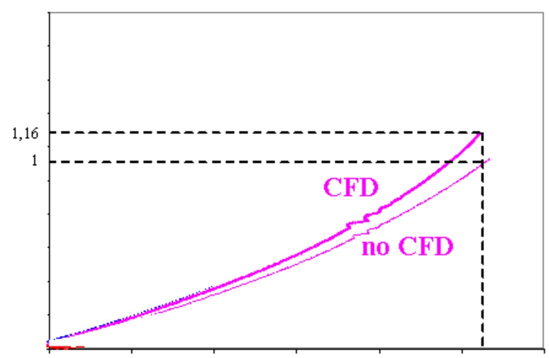
Steering wheel angle as a function of the lateral acceleration



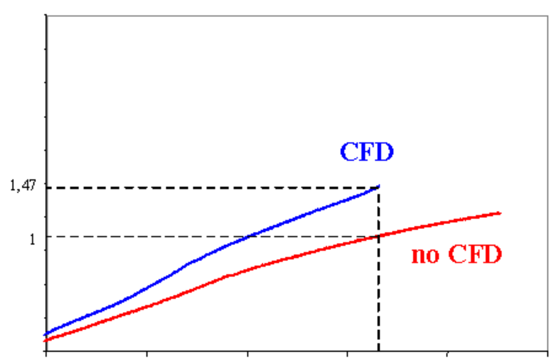
Side slip angle of the vehicle reduced as a function of the lateral acceleration



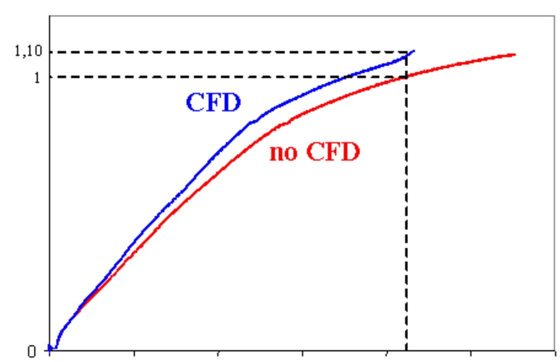
Side slip angle of the front axle as a function of the lateral acceleration



Side slip angle of the rear axle as a function of the lateral acceleration



Side slip angle of the vehicle as a function of the steering wheel angle



Yaw rate of the vehicle as a function of the steering wheel angle

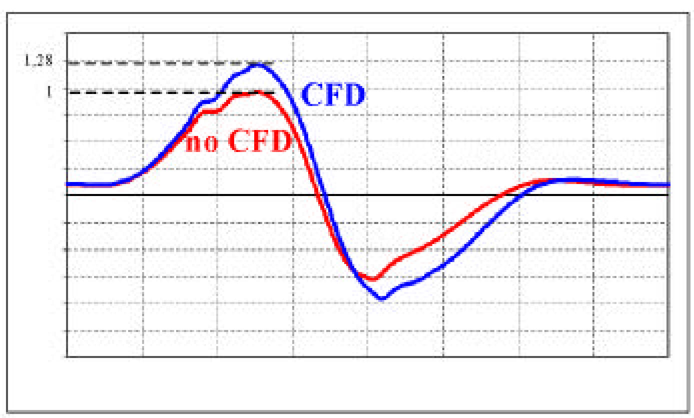
From this results we can summarise the following conclusions:

- The simulation with no aerodynamic influence shows a greater under steering tendency than the model that considers the CFD coefficients. For similar levels of lateral acceleration, the "no CFD" model has a greater side slip angle than the "no CFD" one.
- The slip angles at the front axle are very similar for both models, and corresponds to the results obtained from the previous test.

- However, the rear axle shows a significance difference between the models. The influence of the aerodynamic lift decreases the reduced cornering stiffness of the rear axle, therefore increasing the slip angles for the same lateral acceleration levels.

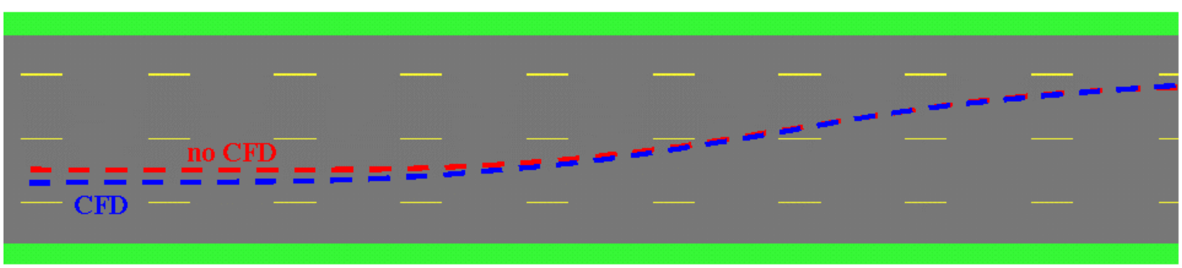
5.3. Single lane change

Finally, the same models were used for evaluation of the transient response with a single lane change at 100 km/h. Next figure shows the side slip angle during the manoeuvre.



Side slip angle during the single lane change

This results clearly shows that the "CFD" model slips more than the "no CFD". The next figure presents the lateral deviation of the first with respect to the second.



Trajectory of the vehicle model during the single lane change

5.4. Conclusions

The results from these simulations show that:

- The weight on the rear axle of the vehicle considering aerodynamic effects changes (-7.5 %) at a relatively moderate speed: 100 km/h
- The cornering stiffness of this axle is also affected to a significant level that influences the vehicle dynamic response.

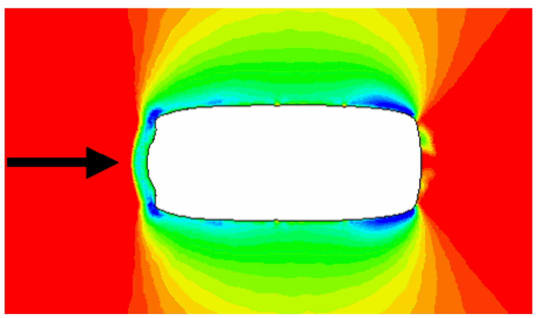
6. Crosswind simulation as a case study

The methodology that is used to integrate the aerodynamic forces into the characteristics of the ADAMS model, allows to contemplate complex wind disturbances as the ones resulting from a cross wind excitation.

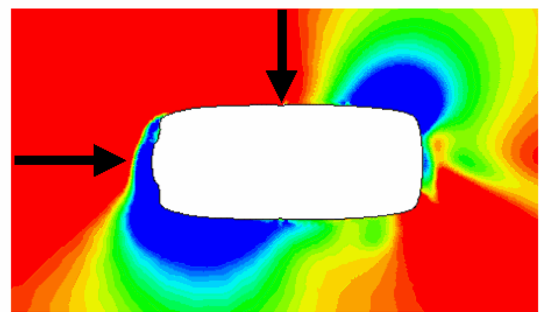
The fact that the centre of gravity and the centre of pressure of the aerodynamic forces are not located in the same position means that the wind effect will create a lateral force plus a significant bending moment. The aerodynamic forces and moments depend on the longitudinal velocity of the vehicle, the yaw angle respect to the wind source, and obviously the lateral shape of the vehicle.

These dependencies are well contemplated with the matrix imported from the CFD calculations.

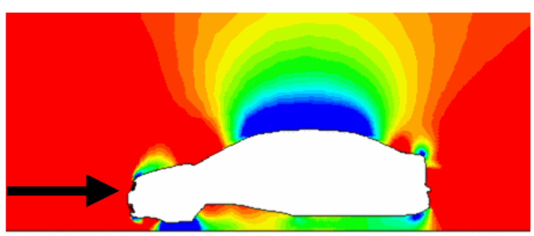
The software we used to calculate the forces of the wind was STAR-CD. Next Figure shows the pressure distribution for the model at 140 km/h (a and c) and a crosswind speed of 72 km/h (b and d). We can see that the vertical force greatly increases its value.



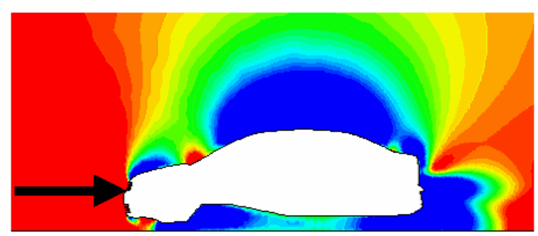
a) Pressure distribution on a horizontal vehicle section due to the velocity.



b) Pressure distribution on a horizontal vehicle section into the crosswind zone



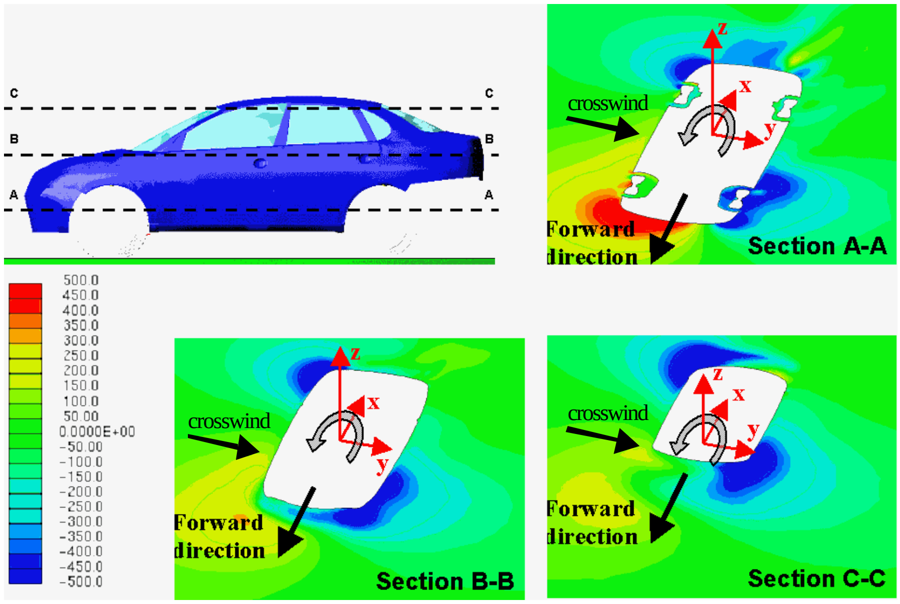
c) Pressure distribution on a vertical vehicle section



d) Pressure distribution on a vertical vehicle section into the crosswind zone

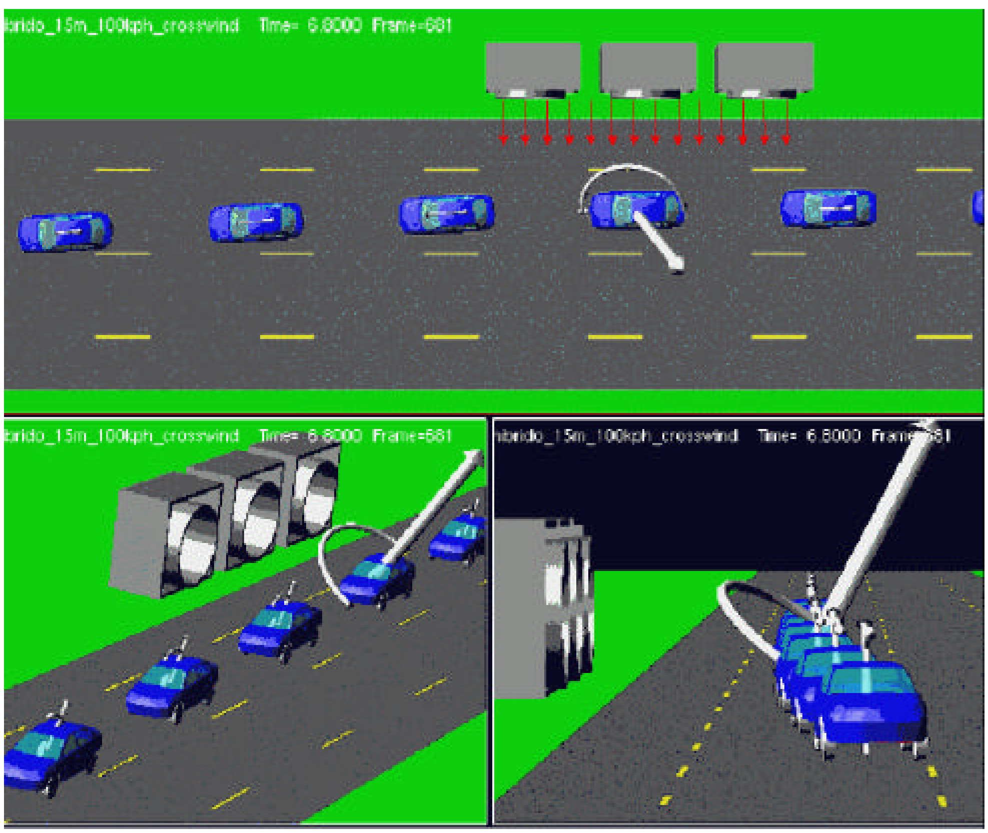
Pressure distribution. Results from STAR-CD Software.

Next Figure shows an unsymmetrical pressure distribution that causes a yawing moment.

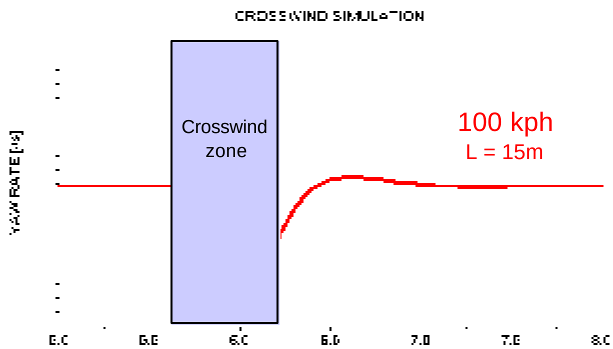


Pressure distribution into the crosswind zone at different horizontal vehicle sections. From this pressure distribution it is easy to see the yawing moment effect.

Next Figure shows the values of these aerodynamic forces in the ADAMS model.



Aerodynamic force applied to the vehicle model during the crosswind simulation.



The evolution of the yaw rate is a descriptive parameter of the vehicle response that describes the sensitivity of the vehicle in front of the cross wind excitation.

7. Further works

The ADAMS model of the vehicle is assumed to be correlated to an optimal level, however the correlation of the CFD model is also very important. The turbulence model, boundary layer and an accurate geometry of the model is important. The location y of the cell centroids in the near-wall layer, and hence the thickness of that layer, is usually determined by reference to the dimensionless normal distance y^+ from the wall. If we wish a wall function to be effective, the distance must be:

– Not too small, otherwise, the "bridge" might span only the laminar sub-layer;

– Not too large, as the flow at that location might not behave in the way assumed in deriving the wall functions.

Ideally, y^+ should lie in the approximate range 30 to 150.

Finally, the results from the simulation of the cross wind manoeuvre using the combined ADAMS and CFD software need a correlation study with real test data, in order to be fully confident with the results obtained with this technique.

8. Conclusions

This paper shows that:

- Comparison between a vehicle with aerodynamic forces (model A) and a vehicle with no aerodynamic forces (model B) is possible by using the integration of ADAMS and a CFD software
- The influence of the aerodynamic forces with the vehicle used at a moderate speed is significant during:
    - Straight-ahead driving with an important rear axle lift, that decreases the dynamic load by 7.5%. This impairs the directional stability and increases the sensitivity of the steering response to small disturbances.

  - The variation of the rear dynamic load is the origin of the decrease of the cornering stiffness of the rear axle that affects:
    - Steady state and transient response of the vehicle
  - The vehicle presents less understeer gradient, and higher levels of rear slip angles in all situations. The most critical of this phenomenon is that increases with the vehicle longitudinal speed.
- The methodology allows the analysis of a complex manoeuvre like crosswind stability. Under this type of excitation most passenger vehicles have the centre of pressure located ahead of the centre of gravity. Therefore, it appears to be advantageous to move the centre of gravity forward or to push the pressure point farther rear (by reducing the side force at the front or increasing it at rear). An increase of the yawing moment causes an increased steering wheel angle required for course correction, while a reduction of the yawing moment reduces the required steering angle. A simultaneous reduction of the rear lift further reduces the necessary steering correction.

Typically in the past the evaluation of crosswind stability at high speed has been done using prototype vehicles and road testing. For considerations of the influence of body design changes, applied to existing chassis layouts a simulation methodology like the presented in this paper is essential in order to save time and development costs.

This paper also demonstrates the need to include the aerodynamic effect into every ADAMS model that aims to correlate well at different speed ranges.

This method permits the prediction and close analysis of the stability at high speed on the earlier stages of vehicle design.

9. Bibliography

1. STAR-CD User Guide v.3.15
2. Aerodynamics of road vehicles. Wolf-Heinrich Hucho
3. Automotive aerodynamics. SAE/PT-78/16
4. Competition Car Downforce: A Practical Guide -- by Simon McBeath
5. Fundamentals of Aerodynamics. John D., Jr. Anderson
6. Low-Speed Aerodynamics (Cambridge Aerospace, 13). Joseph Katz, Allen Plotkin