Race Car Aerodynamics

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- Race car categories
- Aerodynamic and performance
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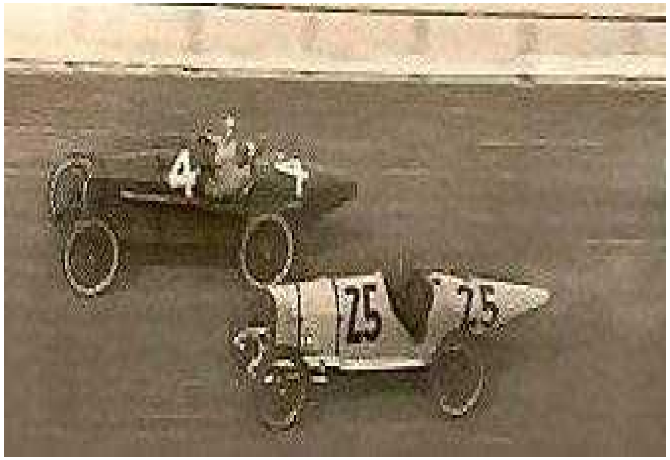
Historic overview

- First steps
  - Drag reduction: fast circuits, low power engines

1915: Indianapolis 500



1916: Indianapolis 500

Historic overview

- Race car evolution
  - Downforce research: tire and engine technology are improved

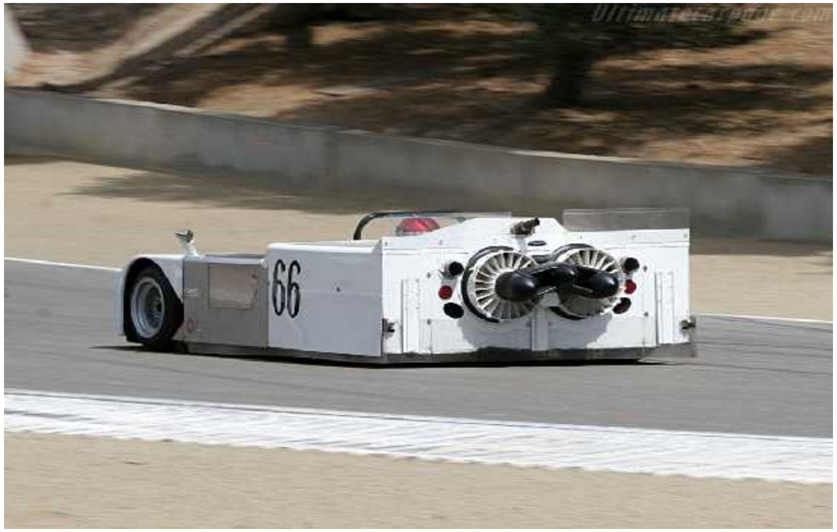
1965: Chaparral-2C

1966: Chaparral-2E

Historic overview

- Race Car Evolution
  - Extreme solution: adjustable wings, suction fans

1968: Lotus – Type 49

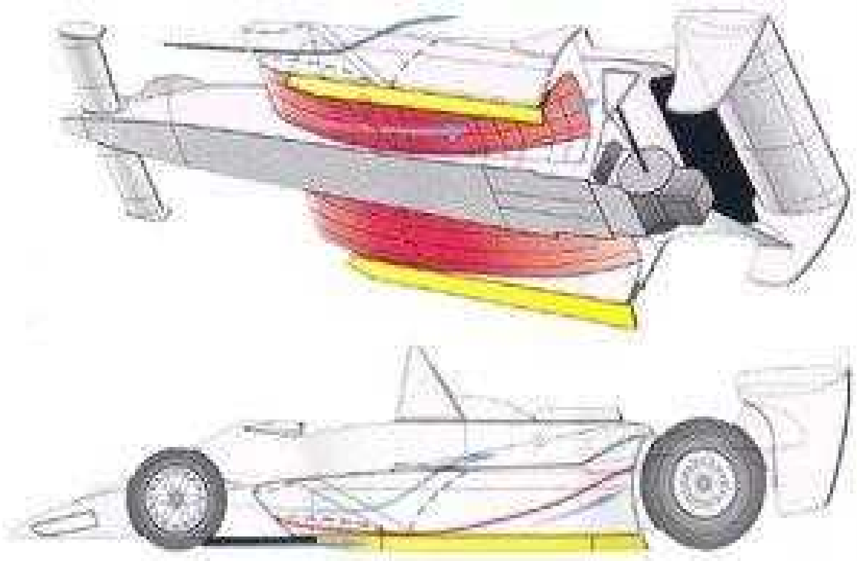


1966: Chaparral-2J (Sucker car)

Historic overview

- Race Car Evolution
  - Wing cars: reversed wing underbody and sealing skirts

1977: Lotus type 78



1977: Lotus type 78

Historic overview

- Race Car Evolution
  - Modern era: flat and "stepped" underbody

1983: McLaren MP4-1C

2004: Jordan "stepped" underfloor

Historic overview

- Sports Car
  - Apex of efficiency

1999: Mercedes CLR

1999: Toyota GT-One

1999: BMW-LMR

1999: Audi R8R

Historic overview

- Sports Car
  - Safety problems

1998: Porsche GT1

1999: Mercedes CLR

Race car categories

- Sedan-based race cars
  - WTCC, Rally, Nascar,etc.
  - Enhancements in stiffness and safety (roll-cage), minimum aerodynamic modifications

Race car categories

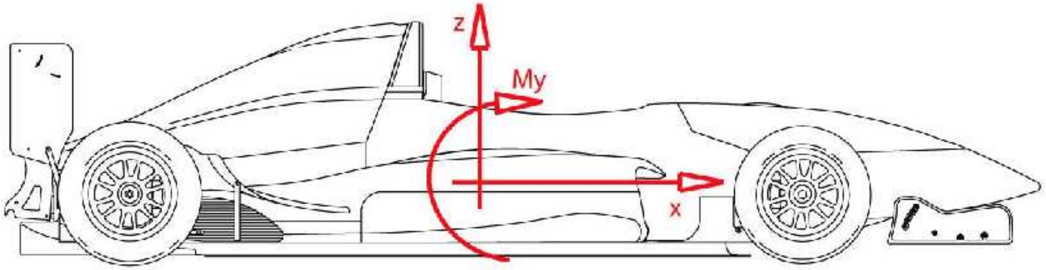
- Enclosed Wheel race cars
  - LeMans Prototypes LMP1, LMP2...
  - Free shapes, regulated underbody and complex wings

Race car categories

- Open Wheel race cars
  - F1, GP2, F3, etc.
  - Single seater, streamlined body, massive use of aerodynamic appendages

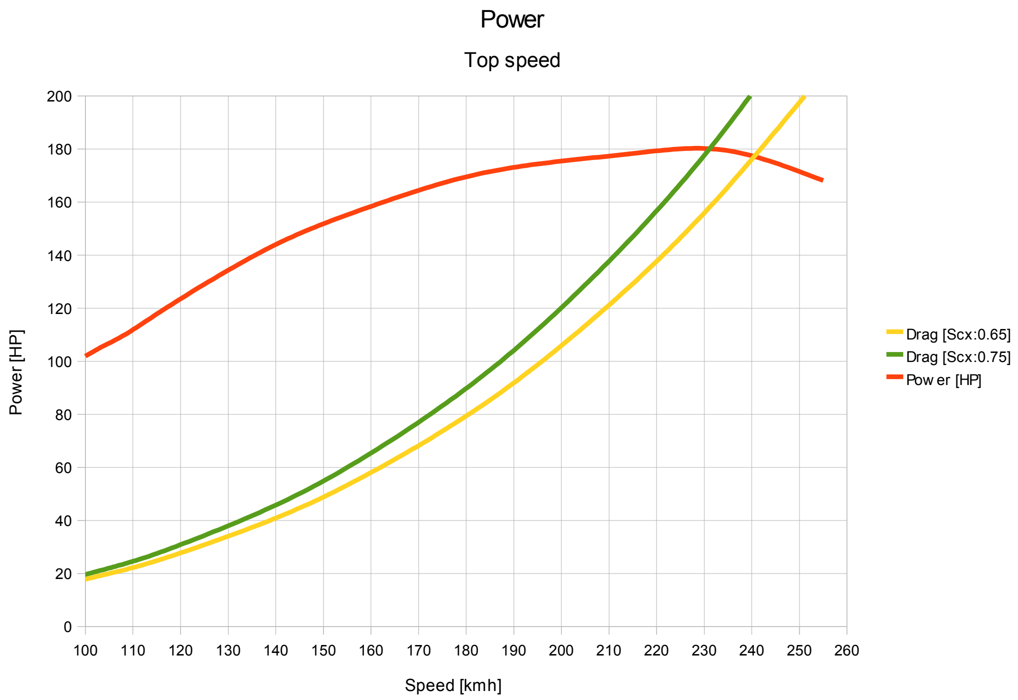
Aerodynamic and performance

- Aerodynamic forces are depending by the body shape and velocity
  - $F = \frac{1}{2} \rho v^2 SC_F$
  - $F_x = D = \frac{1}{2} \rho v^2 SC_x$
  - $F_z = L = \frac{1}{2} \rho v^2 SC_z$



Aerodynamic and performance

- Drag
  - Drag reduction is not commonly the main target of top race car aerodynamic optimisation
  - Drag reduction is still an important factor for low power vehicles (F3, electric/solar cars)

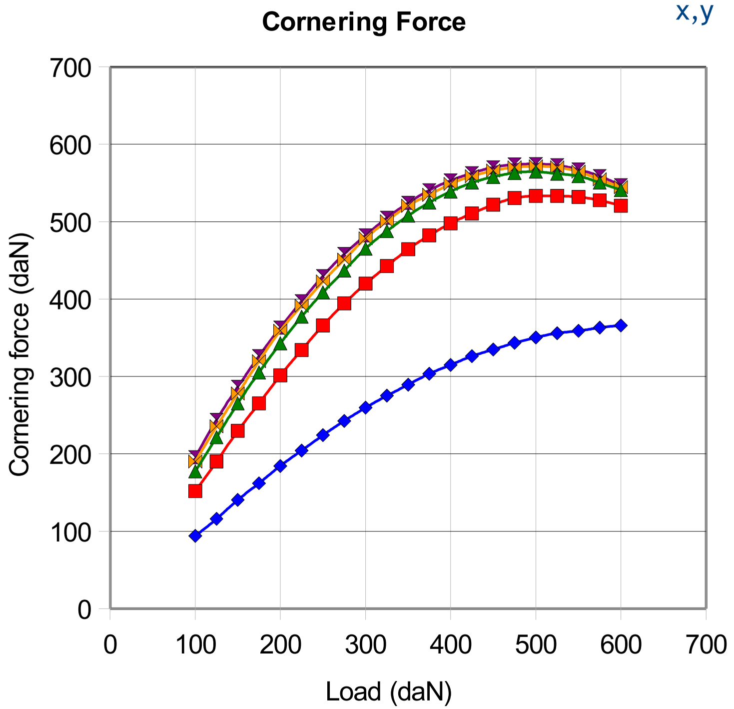


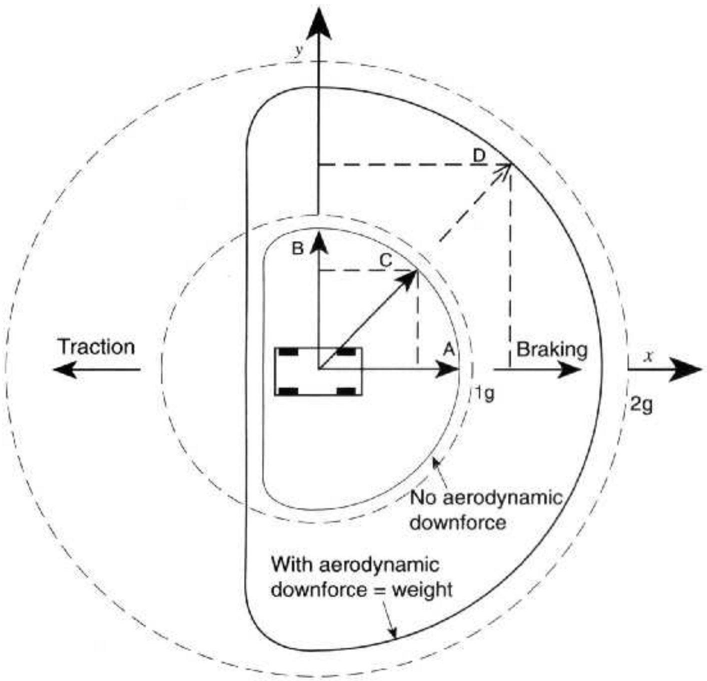
Aerodynamic and performance

- Downforce
  - Vehicle stability and handling are primarily dictated by tyre performance, but this performance is considerably related to aerodynamic loads, i.e. optimal loading of the tyres by the control of front and rear downforce can lead to:
    - Improved braking performance
    - Increased cornering speed
    - Stability (necessary to achieve cornering speed)

Aerodynamic and performance

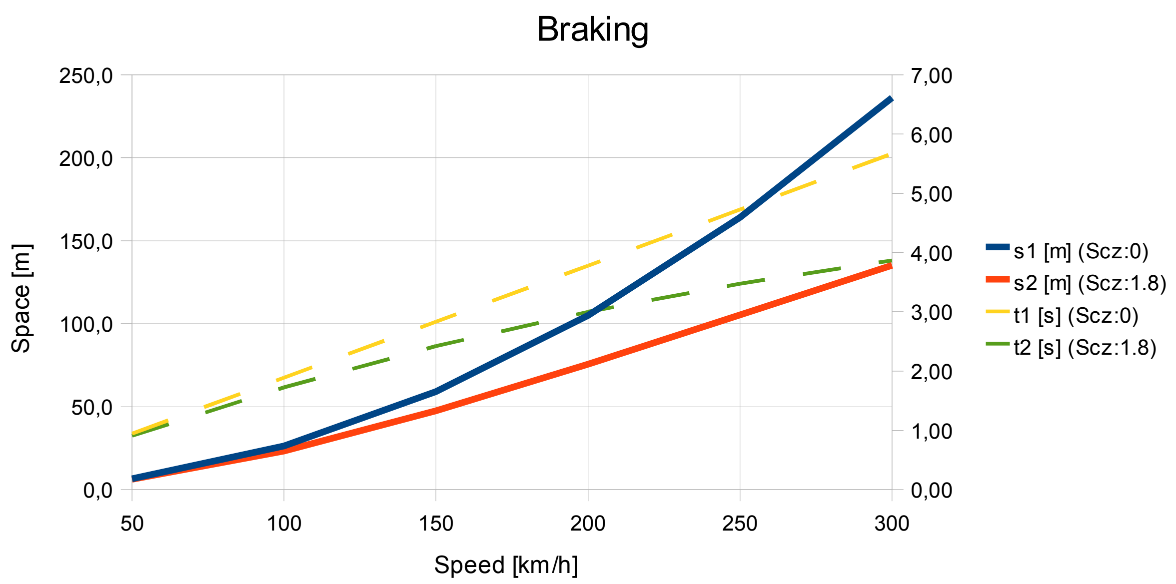
- Downforce and grip
  - The tyre can transfer a force through its contact that is a function of the vertical load (linear)
  - In the normal range of use it can be assumed: $F_{x,y} = \mu F_z$





Aerodynamic and performance

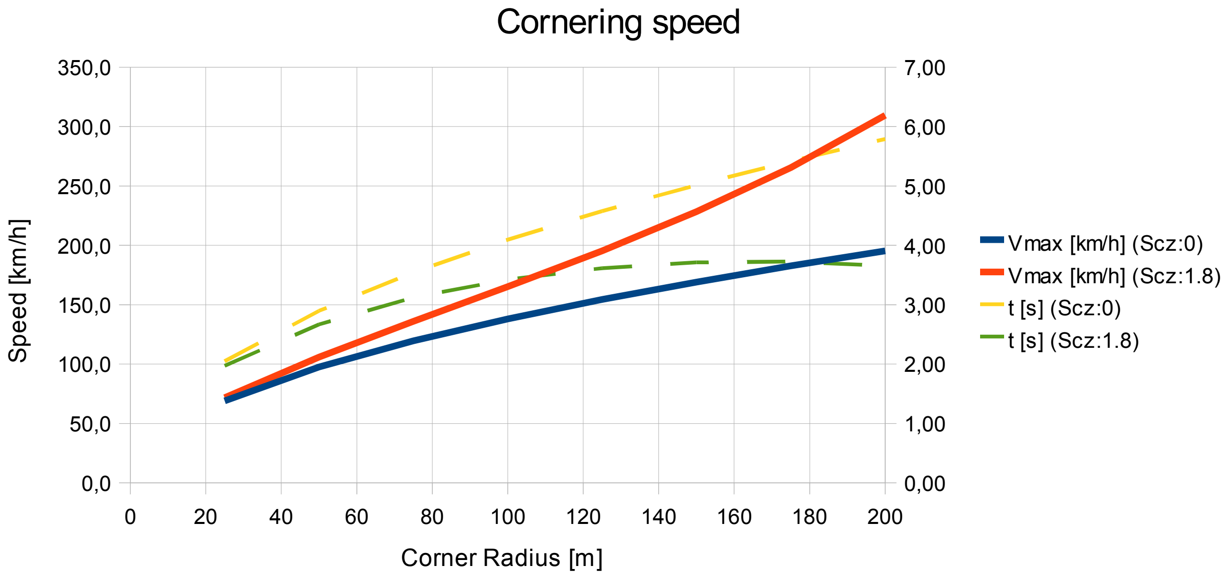
- Braking performance
  - Increased downforce reduces braking space



Braking distance to stop and braking time
versus initial speed with and without downforce

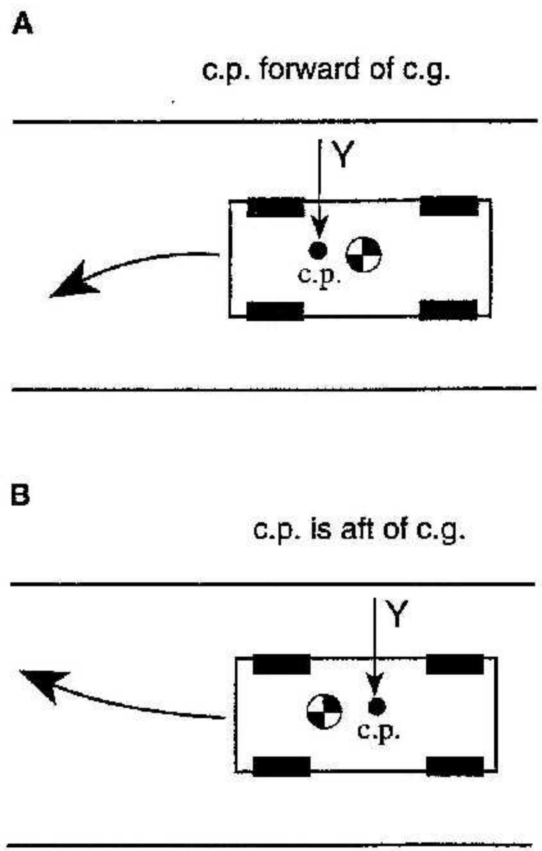
Aerodynamic and performance

- Cornering Speed
  - Steady-state turning leads to forces on the tyres which increase with downforce and to centrifugal forces which increase with cornering speed



Maximum speed and cornering time (90° corner) versus track curvature R with and without downforce

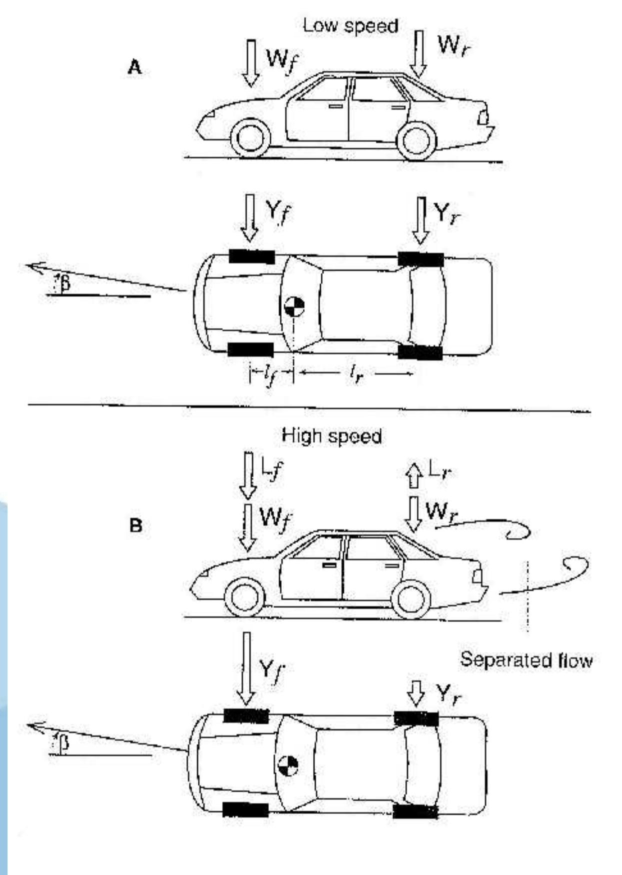
Aerodynamic and performance



Stability

- A: Centre of pressure (CP) ahead of Centre of Gravity (CG)
  - Any lateral irregularity (bump, wind gust) will cause an initial side slip that tends to generate an aerodynamic side force that tend to increase the side slip, i.e. unstable without driver correction.
- B: CP behind CG
  - Unlike most road cars, race cars have their CP behind the CG in order to have a good lateral stability at high speeds where aerodynamic forces are significant.

Aerodynamic and performance



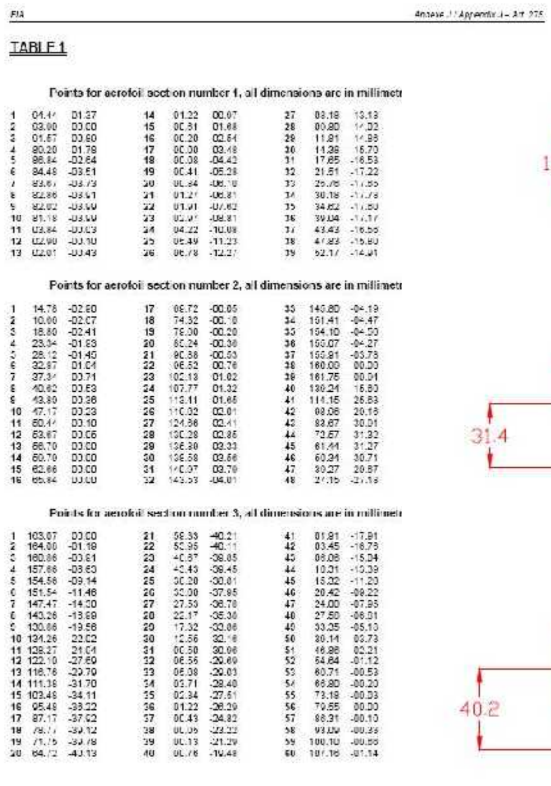
- Stability
  - A: Low-speed (negligible lift) vehicle with side slip angle β due to lateral force (wind or centrifugal)
    - The side force created by tyres is proportional to the normal load, i.e. proportional to the weight on the front (W_f) and rear (W_r) axles.
    - If the moment about the CG created by the rear tyres exceeds that created by the front tyres, such that the net moment tends to rotate the car in the direction of slip, then there is understeer (Stable).
  - B: High-speed (significant lift) vehicle with side slip angle β
    - Here the downforce is generated at the front and there is some rear positive lift (typical of some production cars)
    - If the moment about the CG created by the front tyres exceeds the rear tyre moment, such that the net moment tends to turn the car away from the side slip direction, then there is oversteer and possible vehicle spin (Unstable).

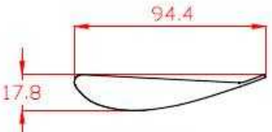
Aerodynamic and performance

- Lap-time
  - In racing top speed is often not relevant and each track requires different aerodynamic settings:
    - High speed track with serious accelerations and sharp corners (i.e. Monza) requires low drag/low downforce setting
    - High speed track with fast corners (i.e. Barcelona, Spa) requires high downforce setting
  - The overall lap-time is a result of corner, braking and top speed:
    - Due to the modern circuit layout most of the lap-time is spent in acceleration, deceleration, cornering, so downforce plays a greatest part than pure efficiency

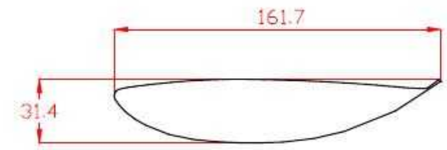
Aerodynamic Tools

- Regulations
  - Regulations are the most relevant limitation to aerodynamic design in race cars

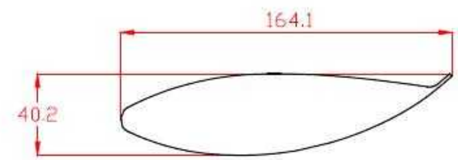




Drawing 3



Drawing 4



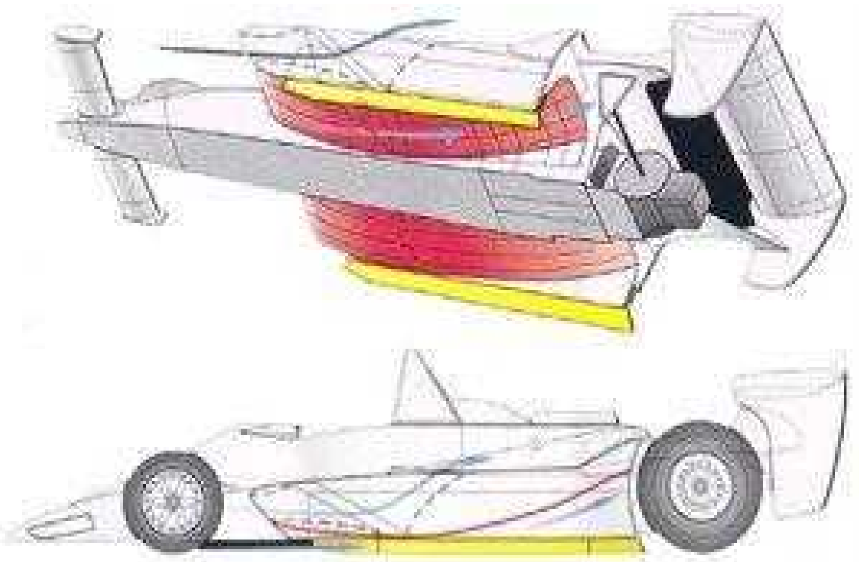
Drawing 5

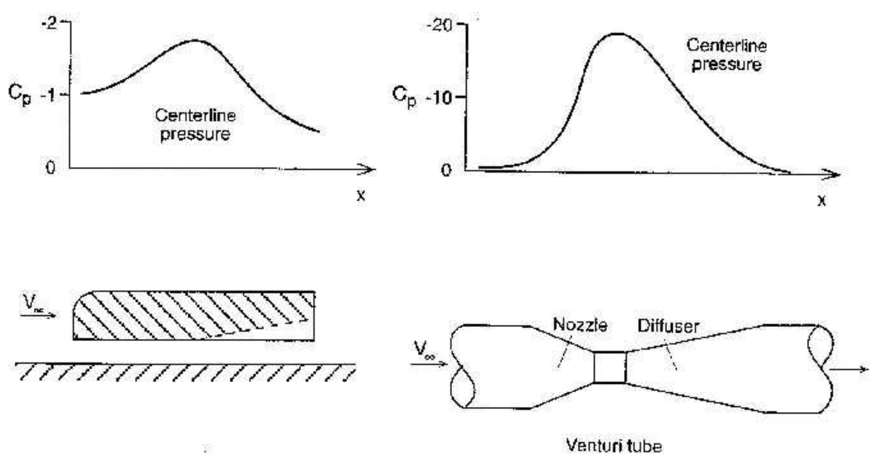
Aerodynamic Tools

- Most relevant items
  - Body
  - Wings / Endplates
  - Splitter / Spoiler
  - Appendages (barge boards, strakes, chimneys, vortex generators)
  - Wheels

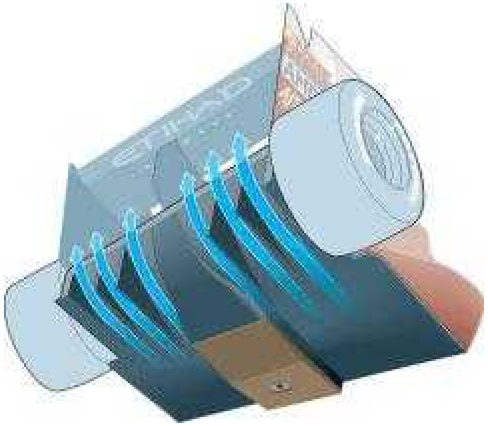
Aerodynamic Tools

- Body
  - Bodyworks and particularly underfloor are the most powerful aerodynamic devices
  - Underfloor works as a Venturi in ground effect

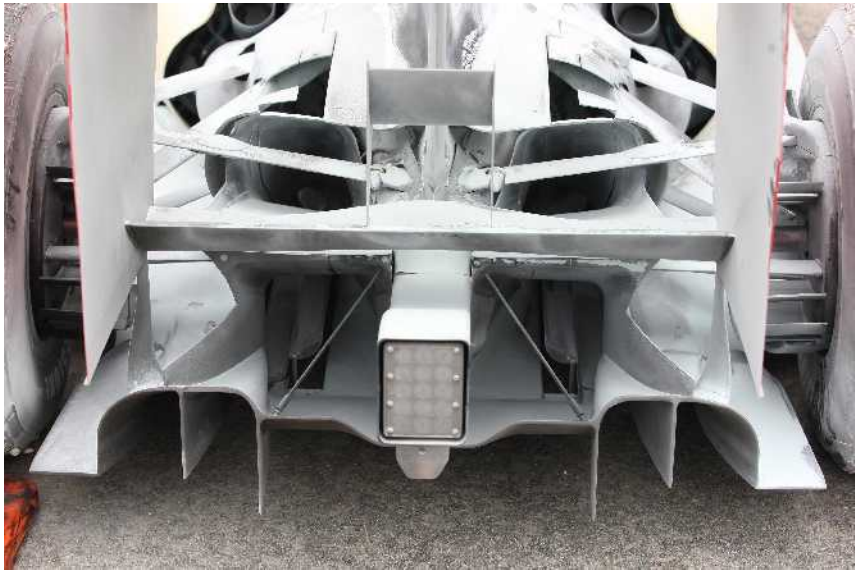




Aerodynamic Tools



- Body
  - Regulations ban underfloor shaped as an inverted wing (floor must be flat between axles) but allows a rear diffuser that massively affects the pressure under the vehicle
  - An extreme interpretation of regulations allowed in 2009 the introduction of "double deck" underfloor



Aerodynamic Tools

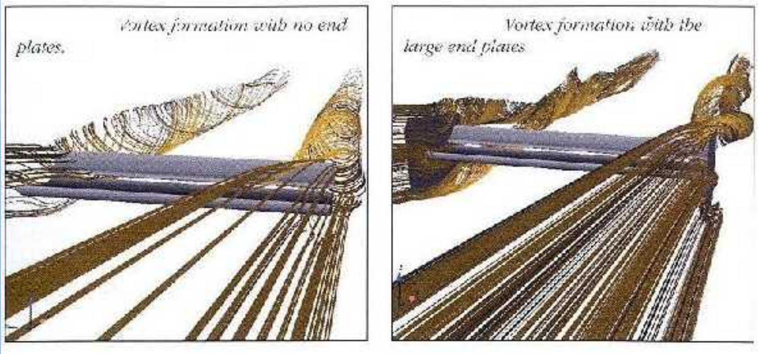
- Wings
  - Wings are the most efficient aerodynamic device
  - Open wheeled rear wings have a very small aspect ratio
  - Wings are installed far-forward far-after to enhance their balancing effect

Aerodynamic Tools

- Wings
  - Race car wings are designed to heavily interact with the surrounding bodies: e.g. the rear bottom wing works in symbiosis with the underfloor diffuser to pump air from the venturi

Aerodynamic Tools

- Wings
  - Endplates are important for lateral stability and to separate the wing from the turbulent wheel flow, big endplates are helping to restore a 2D flow
  - Front wings operate in extreme ground effect and are affected by vehicle pitch



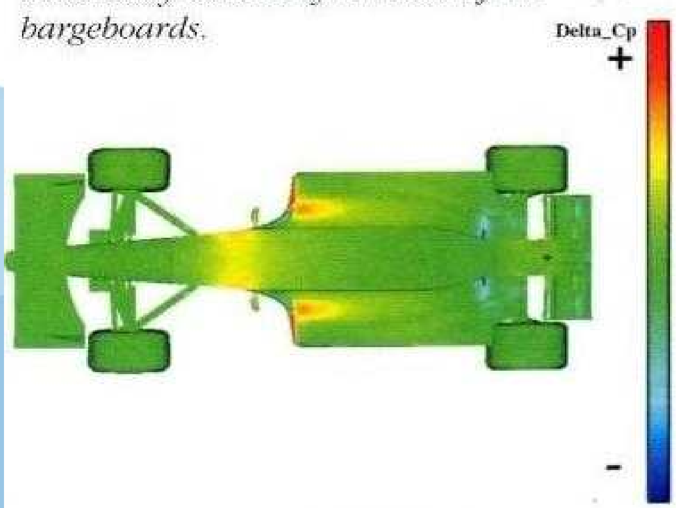
Aerodynamic Tools

- Barge boards and side boards
  - Bargeboard is a vertical panel situated longitudinally, between the front wheels and the sidepods
  - Bargeboards act primarily as flow conditioners, smoothing and redirecting the turbulent (or *dirty*) air in the wake of the front wing and the rotating front wheels

Aerodynamic Tools

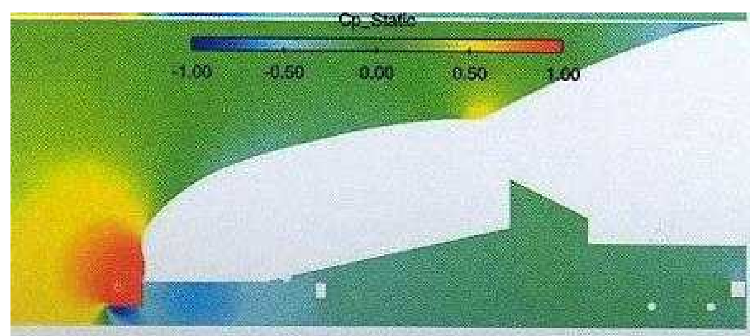
- Barge boards and side boards
  - Bargeboards act as vortex generators, redirecting and energizing airflow: the upper, downward sloping edge shed a large vortex downstream around the sidepods, where it aid in sealing the low pressure underbody flow from the ambient stream. The bottom edge of the bargeboard shed vortices that energize the airflow to the underbody, which can help delay flow separation and allow the use of more aggressive diffuser profiles

Static pressure changes to the underbody caused by removal of the bargeboards.



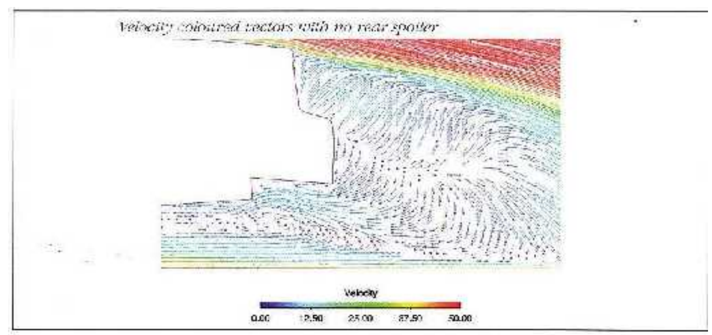
Aerodynamic Tools

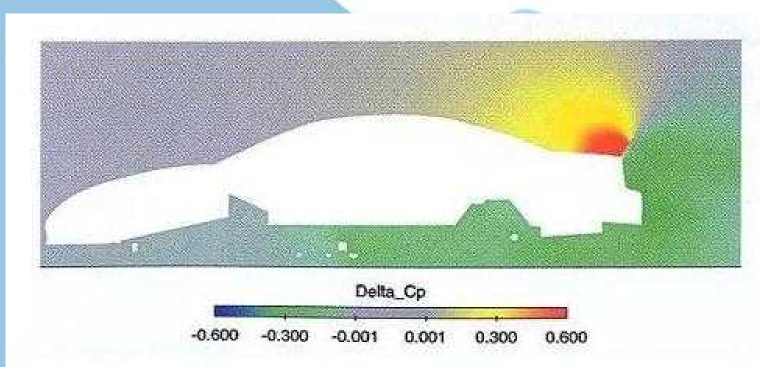
- Spoilers and splitters
  - Spoilers on the front of a vehicle are often called air dams, because in addition to directing air flow they also reduce the amount of air flowing underneath the vehicle which reduces aerodynamic lift.
  - The splitter is an horizontal lip that brought the airflow to stagnation above the surface, causing an area of high pressure. Below the splitter the air is accelerated, causing the pressure to drop. This, combined with the high pressure over the splitter creates downforce.

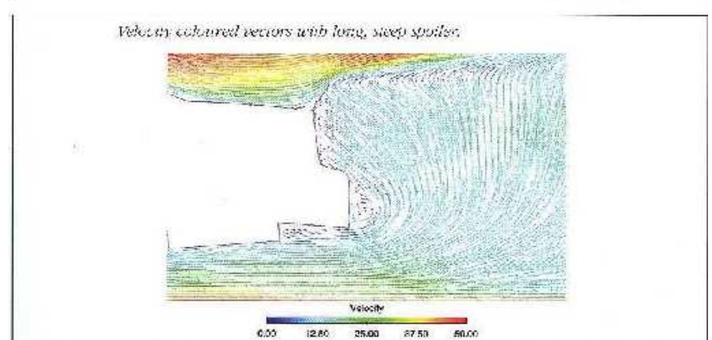


Aerodynamic Tools

- Spoilers
  - Rear spoilers act in a similar way than front, they spoil the airflow tumbling over the rear edge of the car that causes a recirculation bubble, this vortex doesn't allow a good underfloor flow increasing lift and instability

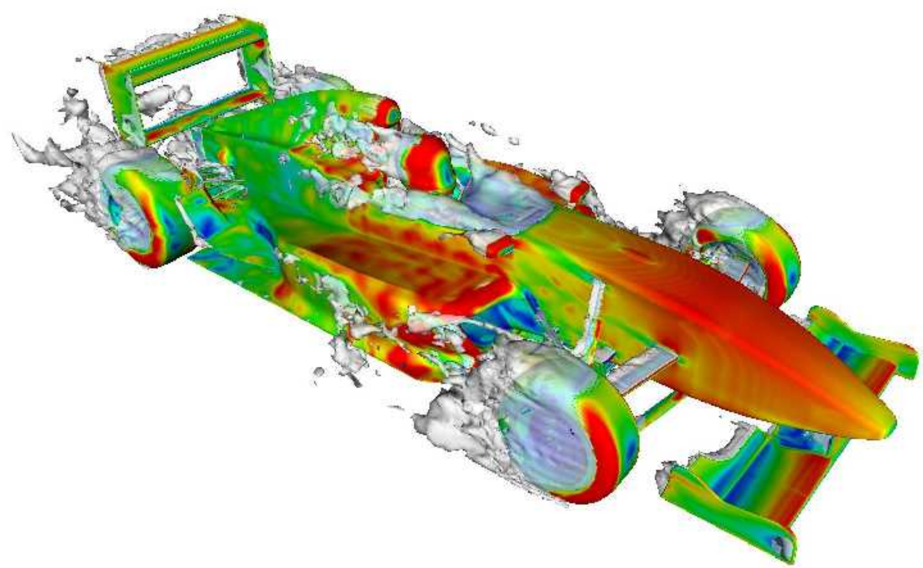






Aerodynamic Tools

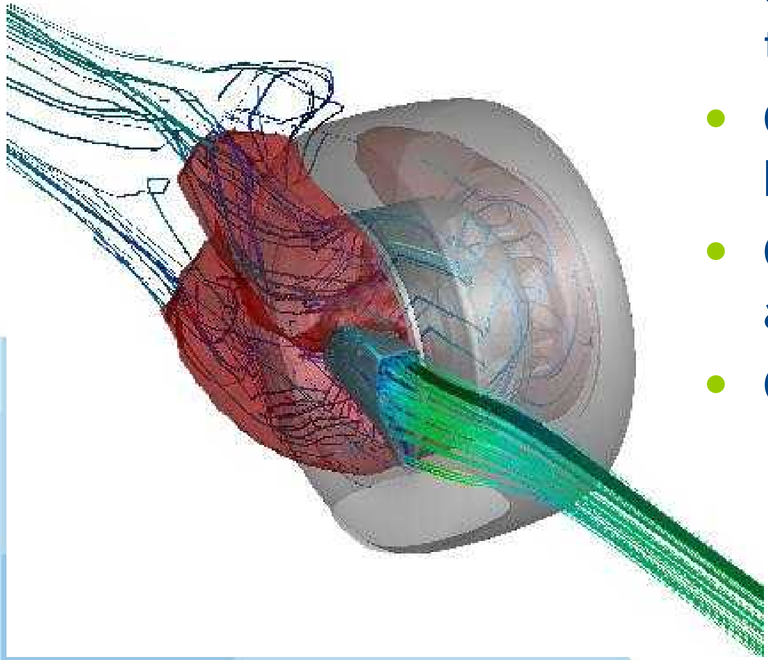
- Wheels
  - Open-wheeled race car have a very complicated aerodynamics due to the large exposed wheels
  - The flow behind wheels is completely separated
  - The frontal area of the four wheels may be as much as 65% of the total vehicle frontal area



Verification

- CFD
- Wind Tunnel
- Track Test

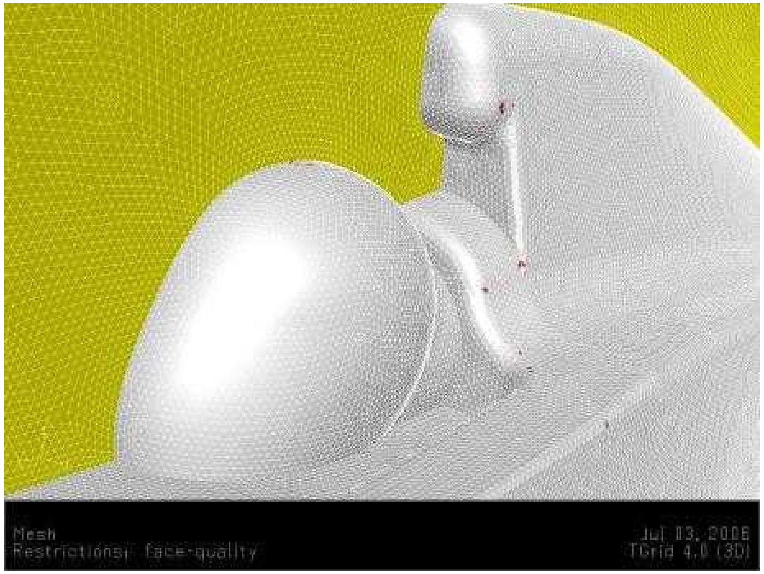
Verification



- CFD: Computational Fluid Dynamic software is the numerical approach to the aerodynamic simulation
  - CFD is a powerful tool for the first evaluation of appendages before the model manufacturing for the wind tunnel
  - CFD model allows the quick modification of the boundary condition
  - CFD allows the analysis of the complete aerodynamic field without intrusive measurement
  - CFD is a powerful tool for the design stage of:
    - Wing
    - Geometry modification
    - Vortex analysis
    - Load distribution

Verification

- CFD process iterates during the design of the vehicle
  - Neutral file are saved for the CFD analysis
  - Geometry clean-up is needed to fix CAD model geometry (holes, overlapping...)
  - Meshing is required to solve the case

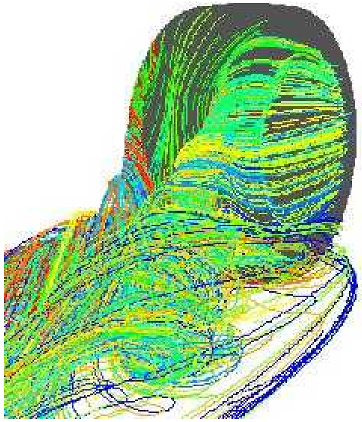


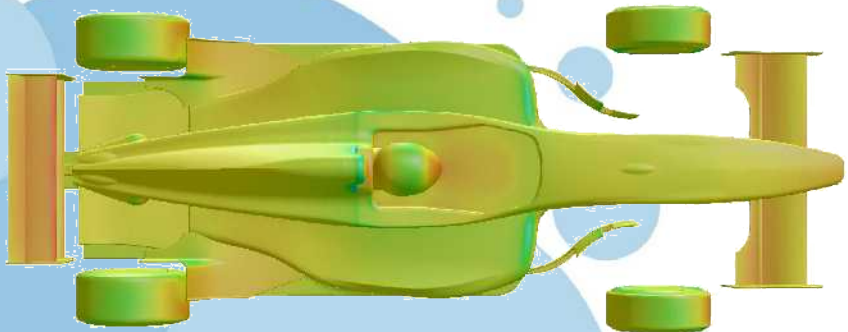
Verification

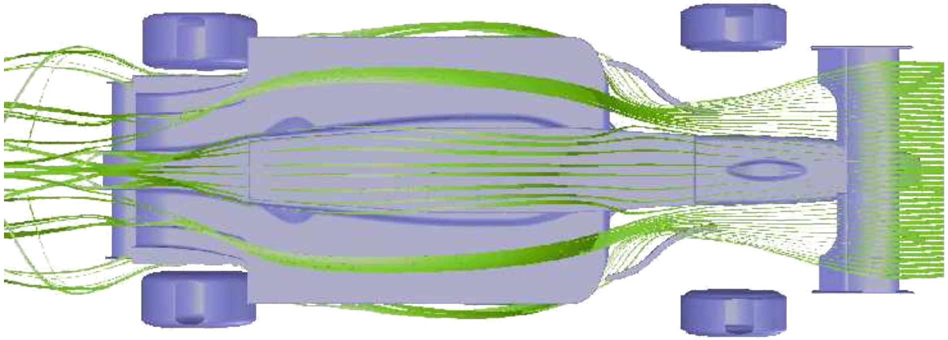
- CFD solving requires high power computing (HPC) to get a good and reliable result
  - Actual model size is about 40-60 Million volumes
  - Cluster computing allows parallel solving of the model
  - Solving time requires 8-24 hours
  - Typical cluster sizing is:
    - 32 cores CPU
    - 64 Gb RAM
    - High speed intranet

Verification

- CFD post processing is the key to iterate the CAD design process
  - Typical visualization can show
    - Streamlines
    - Pressure distribution
    - Ribbons

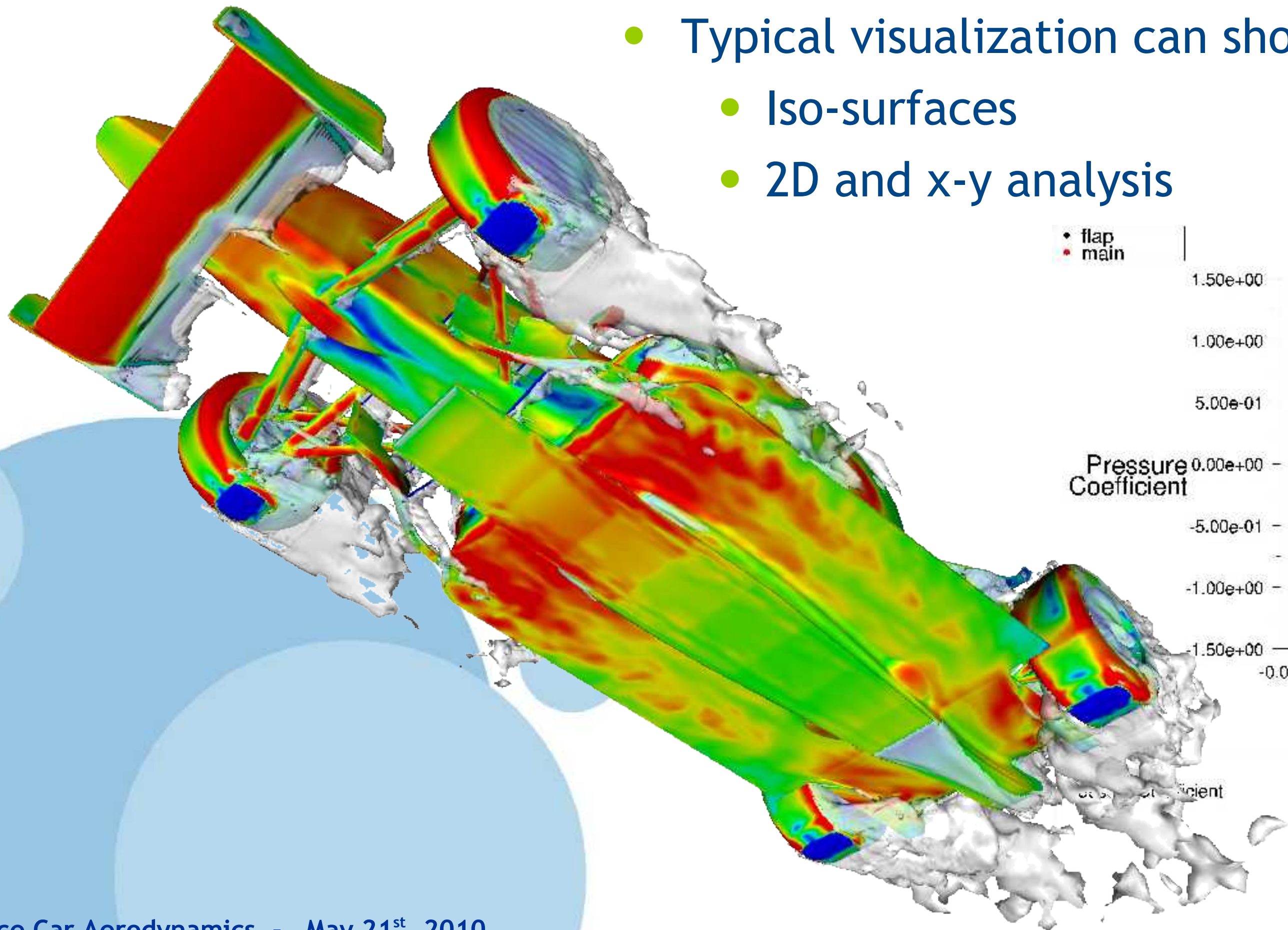


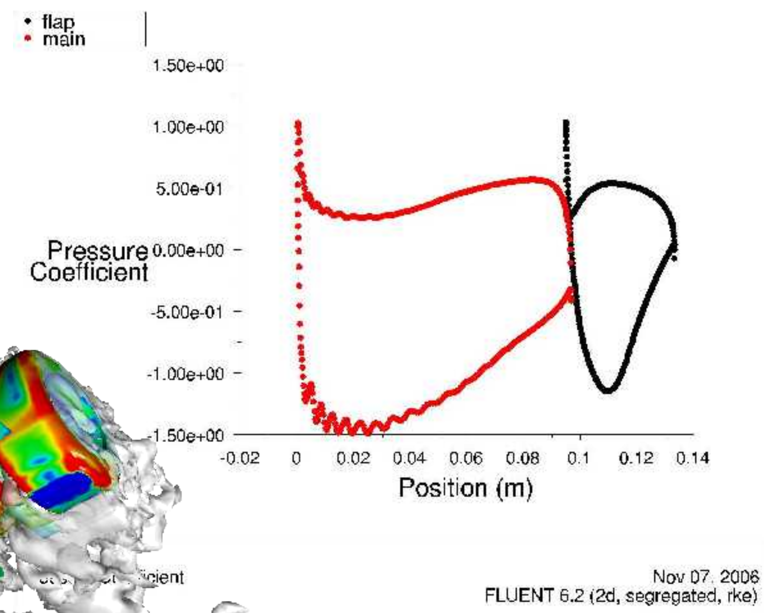




Verification

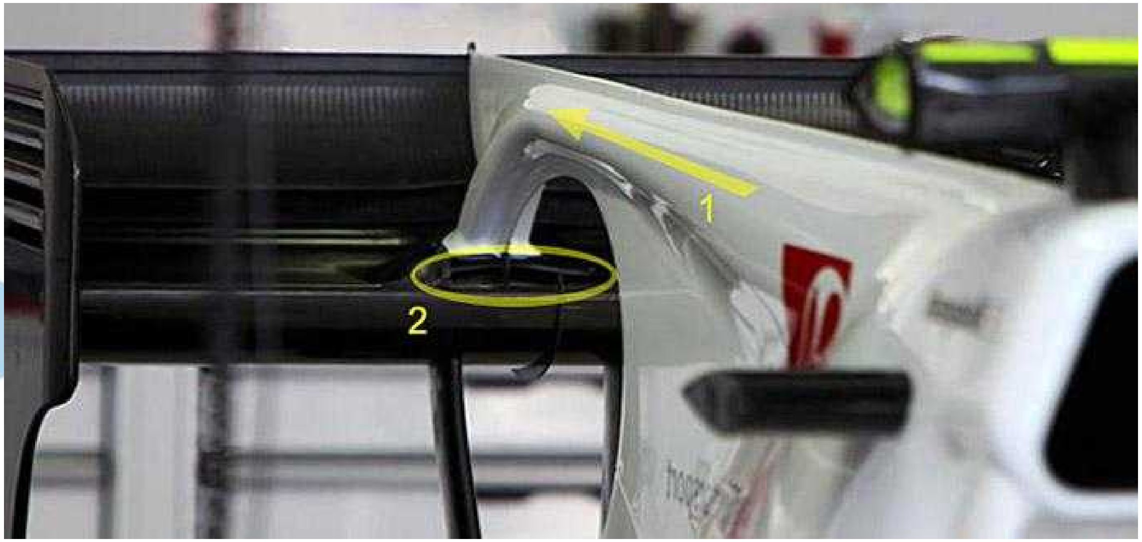
- CFD post processing is the key to iterate the CAD design process
  - Typical visualization can show
    - Iso-surfaces
    - 2D and x-y analysis





Verification

- Fluid-structure interaction (FSI) is still ongoing but the maturity of these fields enables numerical simulation
- Micro-aerodynamic optimisation are investigated



Verification

- Wind Tunnel
  - Wind tunnel is the main experimental development facility
  - Measurement in the wind tunnel are based on the reciprocity effect of the wind speed and vehicle speed (vehicle is steady, air is moving)
  - The largest test section would be desirable to reduce blockage and better simulate real condition, but operational cost of a full scale tunnel is huge

Verification

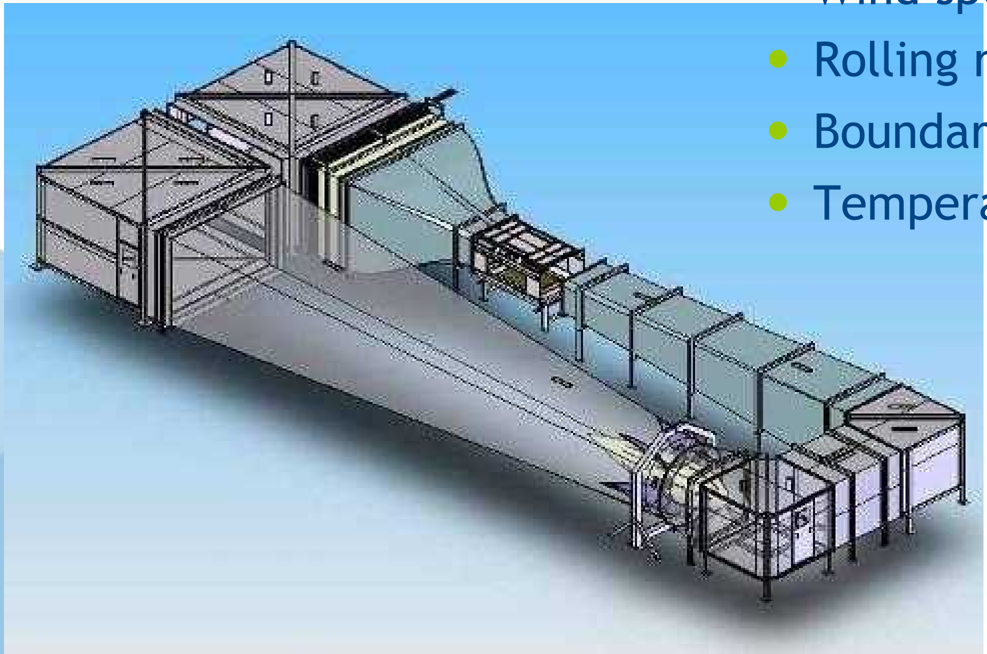
- Wind Tunnel: Scaled Model
  - Most of the wind tunnels use scaled models
  - The aerodynamic similitude is respected if coefficients are the same for scaled and real model:
    - Viscous similitude: Reynolds = $\rho v l / \mu$
    - Compressible similitude: Mach = v / a
    - Gravitational similitude: Froude = $(v^2/lg)^{(1/2)}$
  - When the model is steady and air is flowing Froude is neglected and to respect the dynamic similitude Reynolds and Mach numbers should be the same than full scale
  - In low speed tunnels Mach number is neglected and Reynolds remains the only coefficient to be targeted, in reality it cannot be matched because the air speed cannot be scaled up sufficiently (cost and transonic speed)

Verification

- Wind Tunnel: Boundary Layer
  - The control of the boundary layer thickness is crucial on the wind tunnel simulation: because of the reciprocity boundary layer grows on both model and ground (if steady)
  - The boundary layer thickness is of the same order as the ground clearance and therefore ground effect is affected, for that reason wind tunnel for racing car testing must be equipped with boundary layer control system
  - The moving ground is the most common solution

Verification

- Wind Tunnel: Typical Layout
  - A typical design of an automotive wind tunnel:
    - Model scale 40-60%
    - Contraction ratio 5-7:1
    - Wind speed: 40-60 m/s
    - Rolling road
    - Boundary layer suction
    - Temperature control

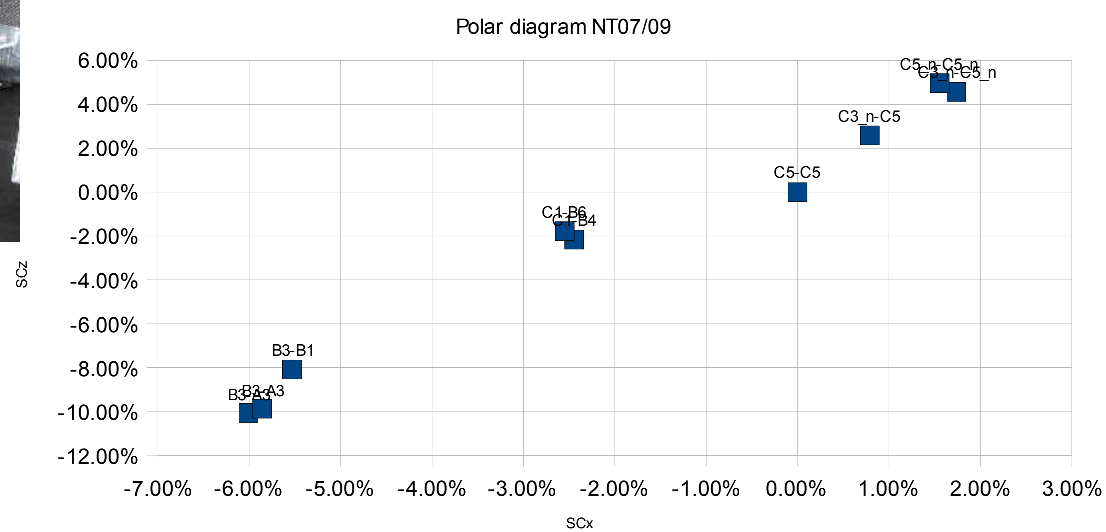


Verification

- Wind Tunnel: Model Installation
  - The rolling road causes some measurements problems:
    - The model have to be sustained by the sting that interact with the body
    - Wheels are not connected to the chassis
    - Difficulties in measuring load on rotating wheels in contact with the belt

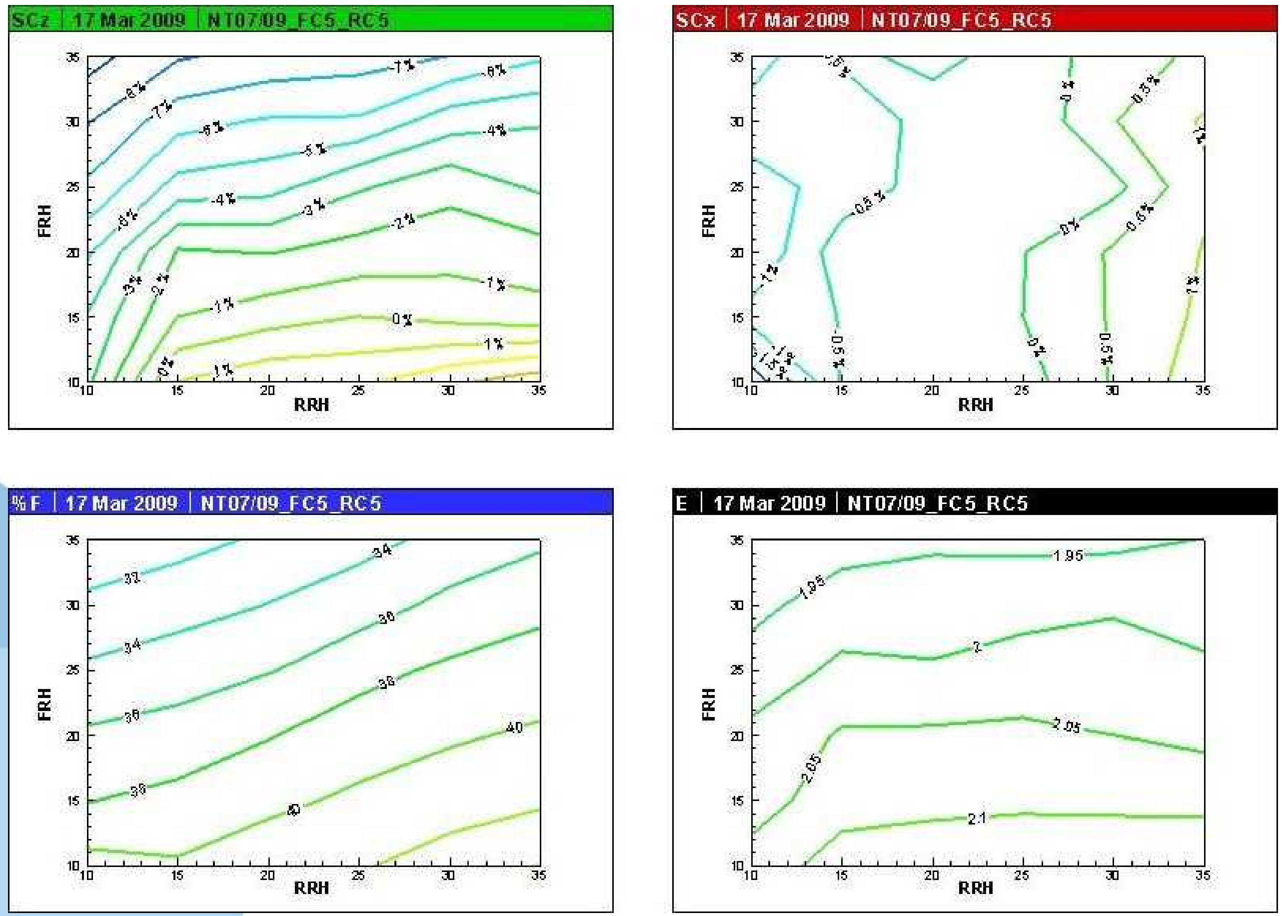
Verification

- Wind Tunnel: Data processing
  - Data are resumed in some significant diagrams: Polar diagram of the vehicle (download vs drag)



Verification

- Wind Tunnel: Data processing
  - Aero-map: a diagram that shows the magnitude of aero loads as a function of the ride height

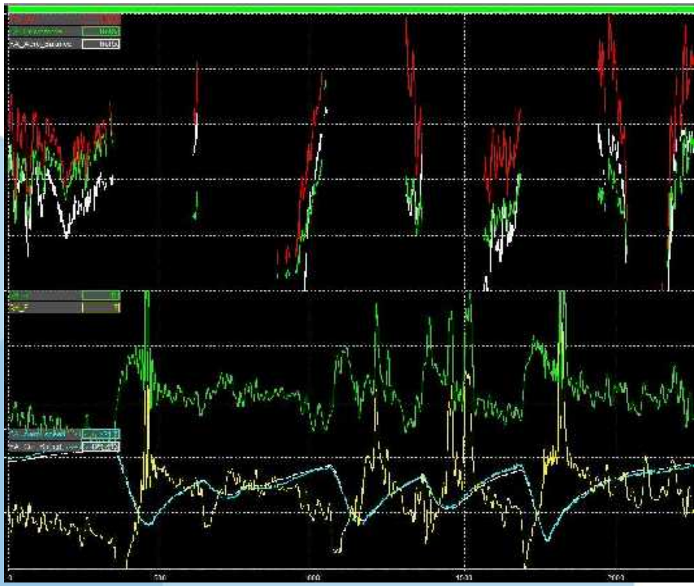


Verification

- Track Test
  - Full scale aerodynamic testing can be done on the real car running on the track: downforce, drag and aero balance (% of the downforce on the front axle) can be measured
  - Measurement are quite difficult and have poor repeatability
  - The car can be equipped with sensor that log:
    - Air speed: Pitot tube
    - Downforce: Strain gauges
    - Ride Height: Laser displacement
    - Power: Torque sensor

Verification

- Track Test
  - It is important to consider the dynamic ride height as a critical parameter for the aero measurements:
    - Ride Height can be calculated by suspension measurements (via installation ratio)
    - Real Ride Height can be measured including tyre deformation by a Laser sensor
    - Ride height oscillation can be avoided replacing dampers with solid rods (only on straight line testing)



Verification

- Track Test
  - Downforce and aero balance are measured on every wheel by the strain gauge

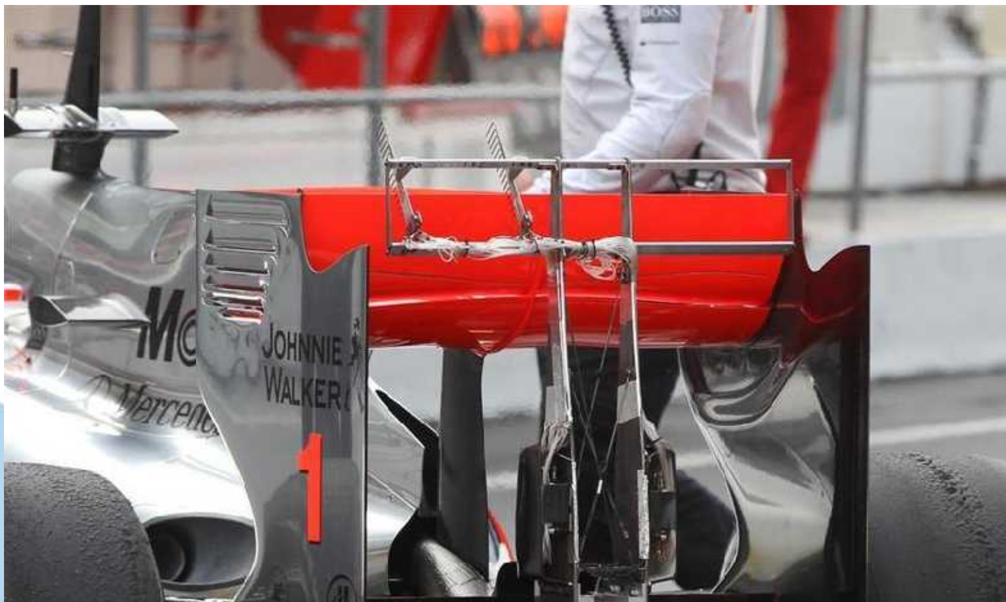
    $$SC_z = F_z\ (\text{front RH, rear RH})\ /\ p_{dyn}$$

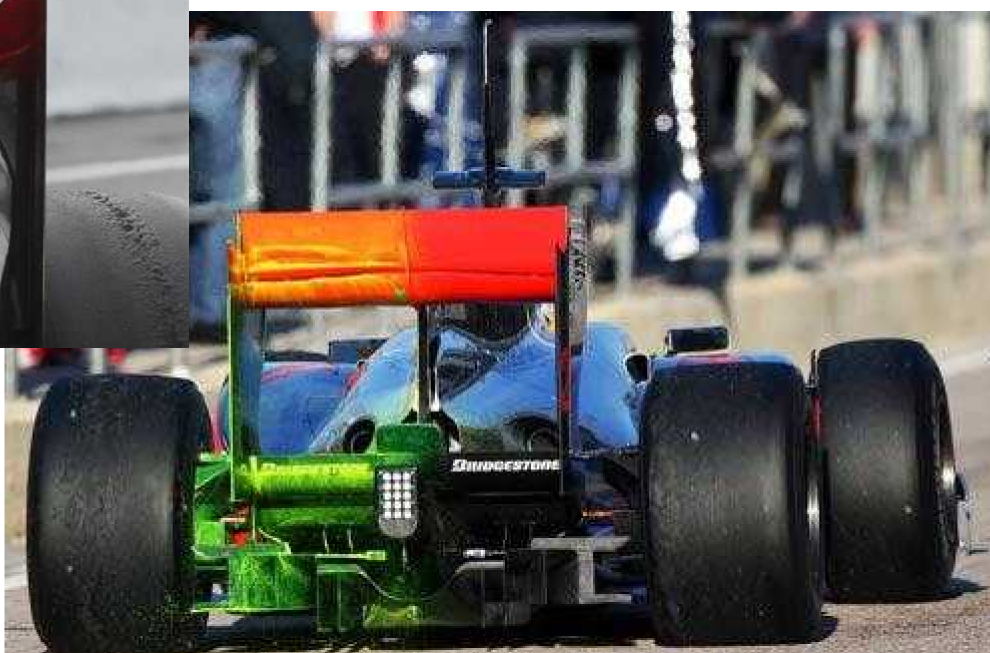
  - Drag can be measured in equilibrium condition between engine power and drag power, or calculated during a coast-down

    $$ma_x = -(SC_x\ p_{dyn} + R)$$

Verification

- Track Test
  - Flow visualisation can be done on running car





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