# Race Car Aerodynamics

## KTH – Royal Institute of Technology

Stockholm – April 8th, 2011

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Tatuus Racing

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- Race car categories
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- Validation: CFD, Wind Tunnel, Track Test
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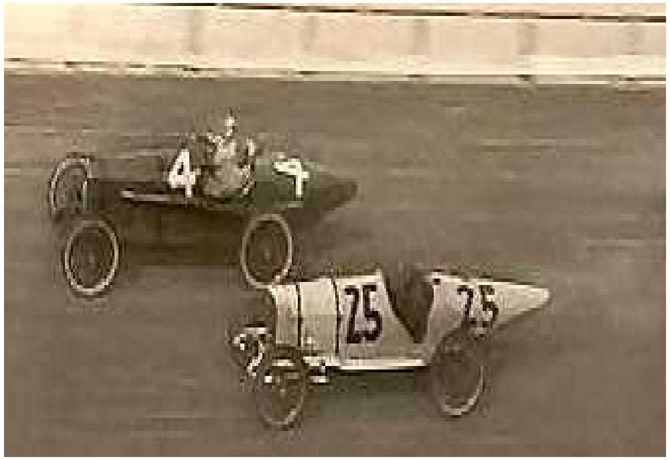
# Historic overview

- 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

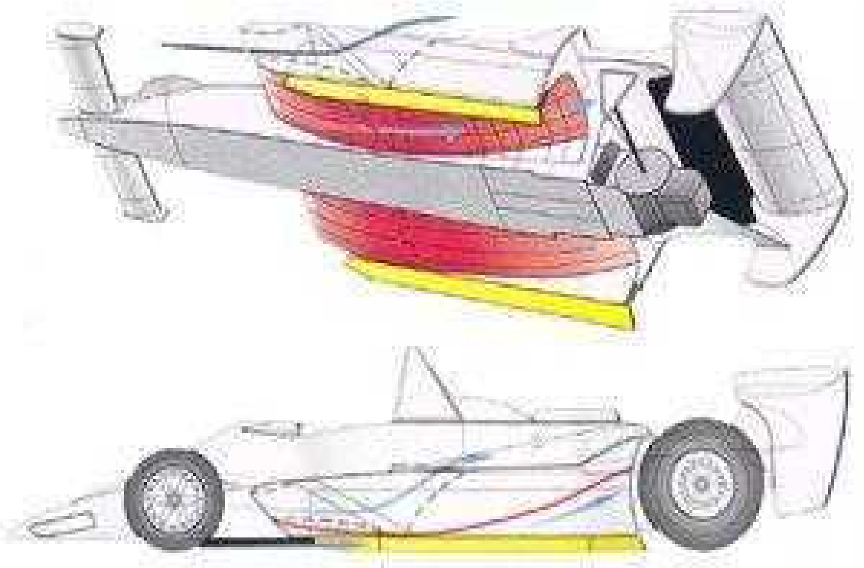
1968: Lotus – Type 49

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

© Etienne Dhont 1999

1999: Toyota GT-One

GREG COOPER © 1999

1999: BMW-LMR

James Davies 1999

1999: Audi R8R

# Historic overview

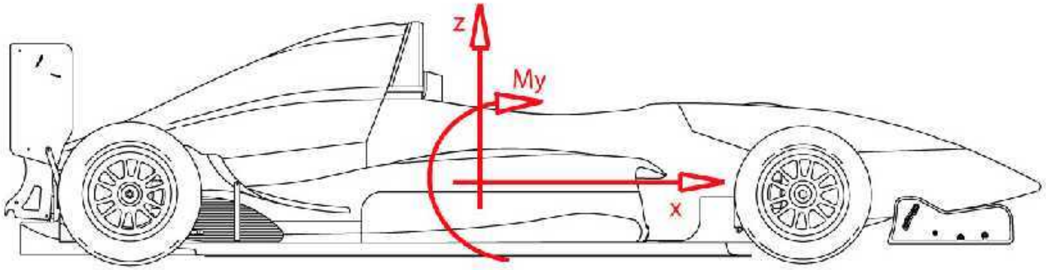
- Sports Car
  - Safety problems

1998: Porsche GT1

1999: Mercedes CLR

# Aerodynamic and performance

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



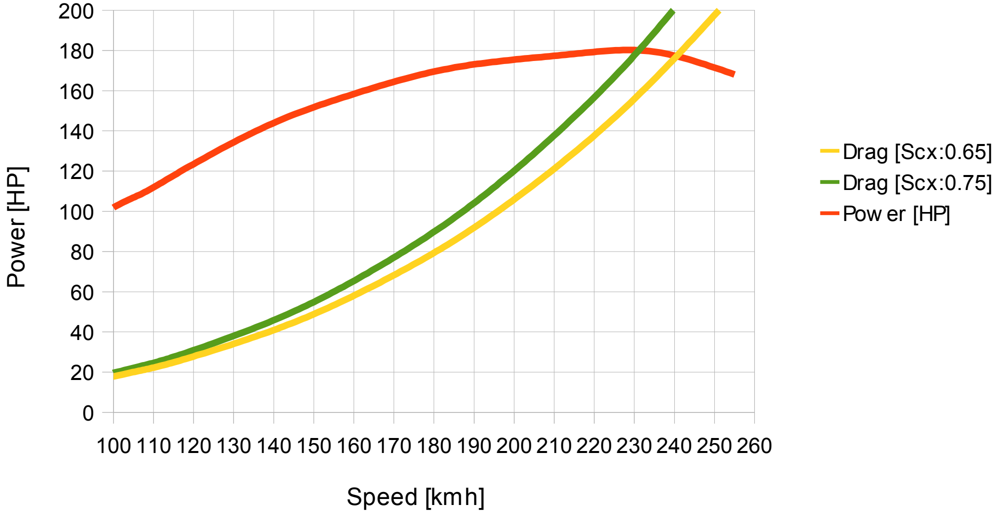
# Aerodynamic and performance

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

$$P\,(1-\eta)=1/2\rho v^2 S C_x + R\,(v)$$

Power

Top speed

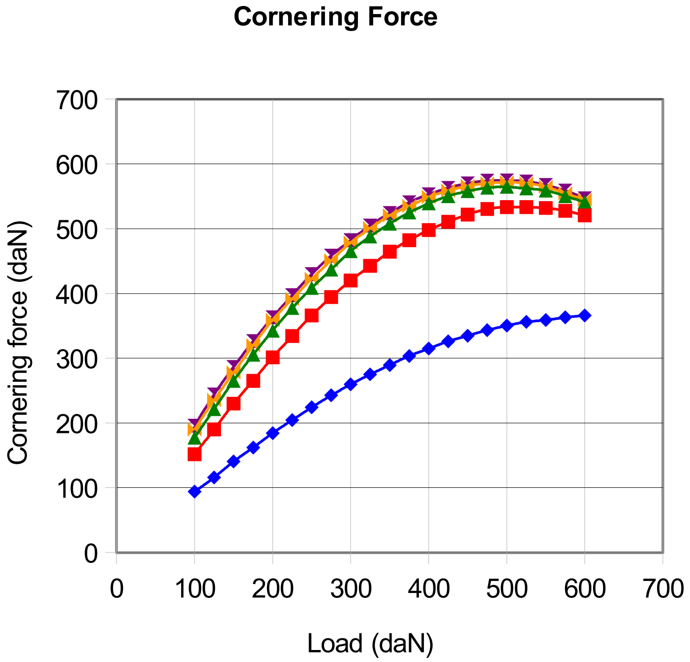


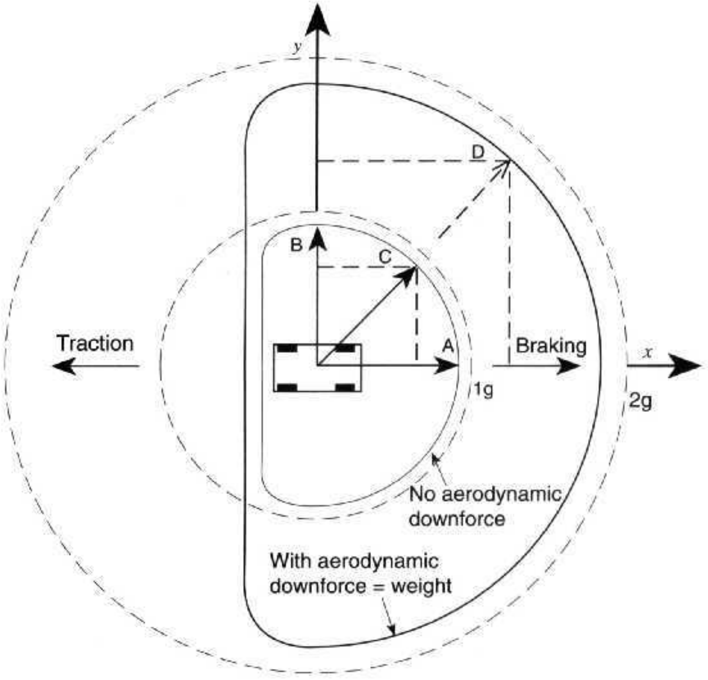
# Aerodynamic and performance

- Downforce
  - The vehicle stability and handling are primarily dictated by the tyre performance, but this performance is considerably related to the 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 through its contact patch a force that is a function of the vertical load (linear for low vertical forces)
  - To keep it simple it can be assumed: $F_{x,y} = \mu F_z$





# Aerodynamic and performance

- Braking performance
  - Increased downforce reduces braking space

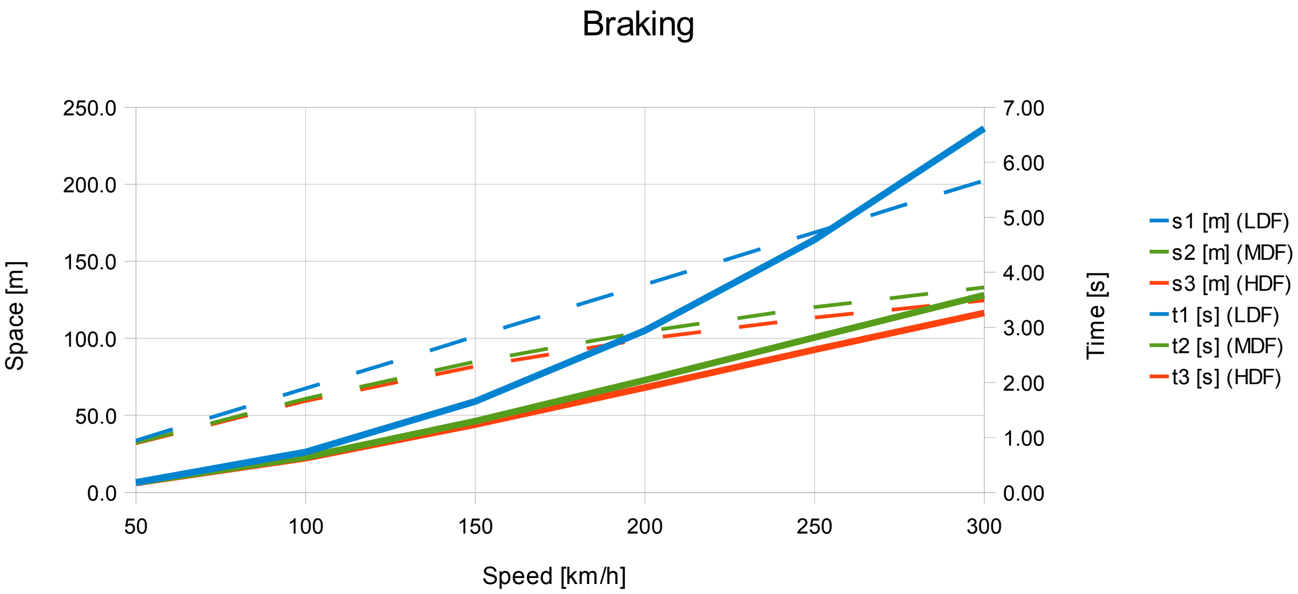
$F_x=\mu F_z$

$a_x=F_x/m$

$t=a_x/v$

$s=v_0 t-1/2 a_x t^2$

Braking



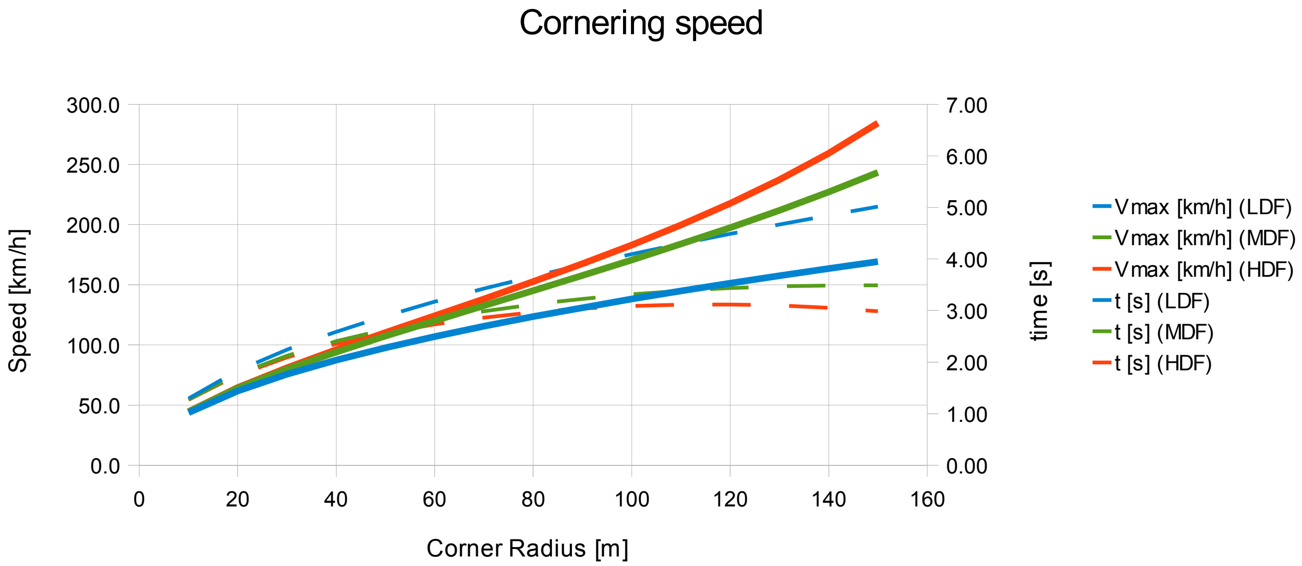
Braking distance to stop and braking time versus initial speed with low (SCz=0), medium and high downforce

# 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

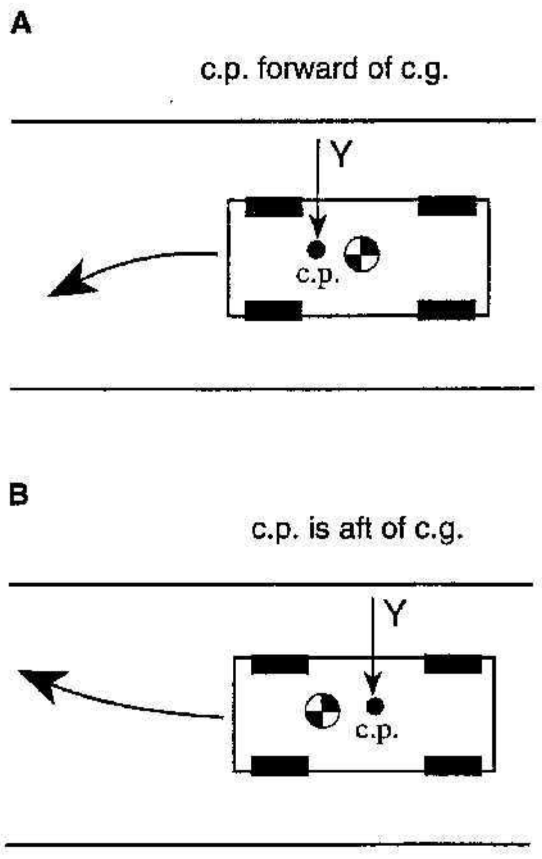
$F_y=\mu F_z=\mu \frac{1}{2} \rho v^2 S C_z$

$F_y=m v^2/R$



Maximum speed and cornering time (90° corner)versus track curvature R with low (SCz=0), medium and high downforce

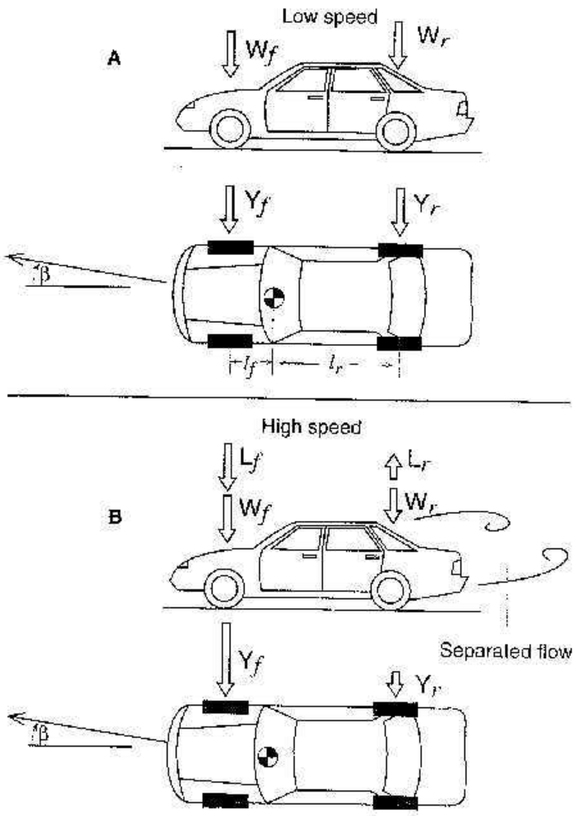
# Aerodynamic and performance



## Side wind 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.

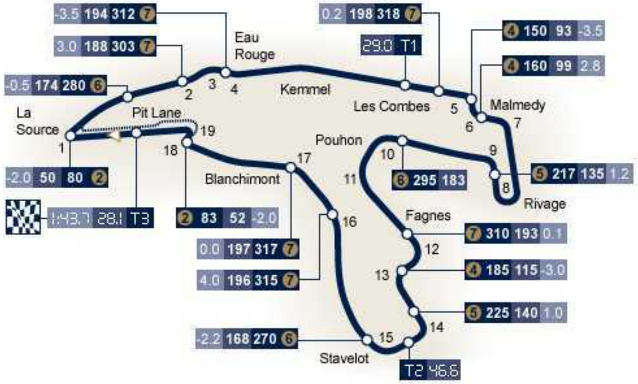
# Aerodynamic and performance



- "*Aero-balance*" 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

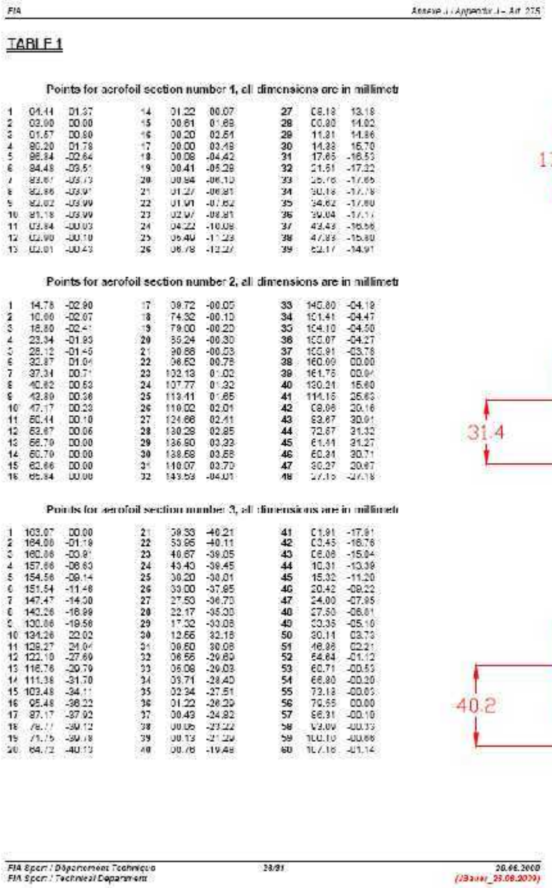
- Lap-time
  - In racing top speed is often not relevant and each track requires different aerodynamic settings:
    - High speed track with serious accelerations and sharp corners (i.e. Monza) requires low drag/low downforce setting
    - High speed track with fast corners (i.e. Barcelona, Spa) requires 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 remarkable limitation to aerodynamic design in race cars

FIA Annexe J / Appendix J – Art. 275



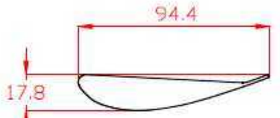
FIA Annexe J / Appendix J – Art. 275

TABLE 1

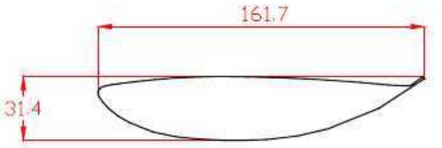
Points for aerofoil section number 1, all dimensions are in millimetr

Points for aerofoil section number 2, all dimensions are in millimetr

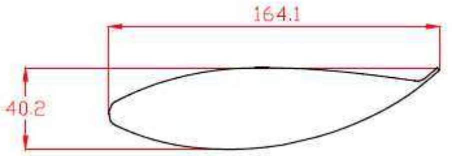
Points for aerofoil section number 3, all dimensions are in millimetr



Drawing 3



Drawing 4



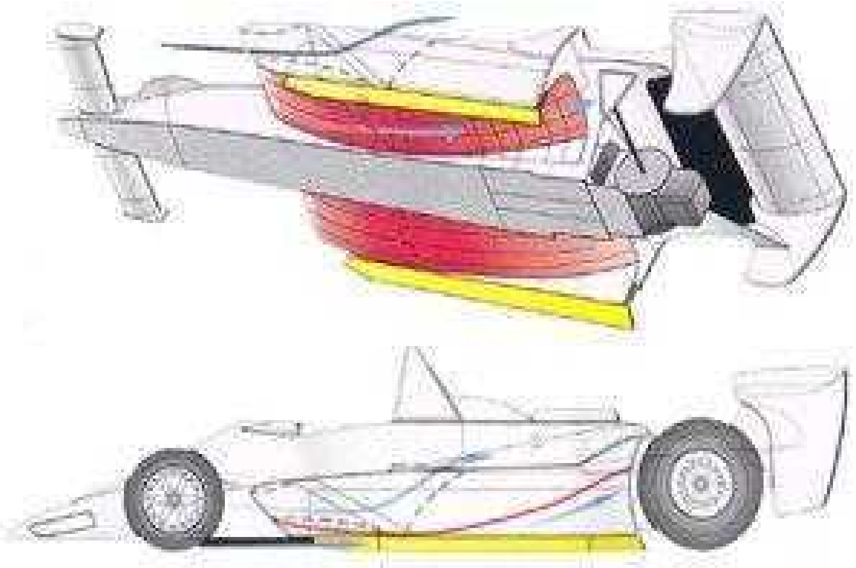
Drawing 5

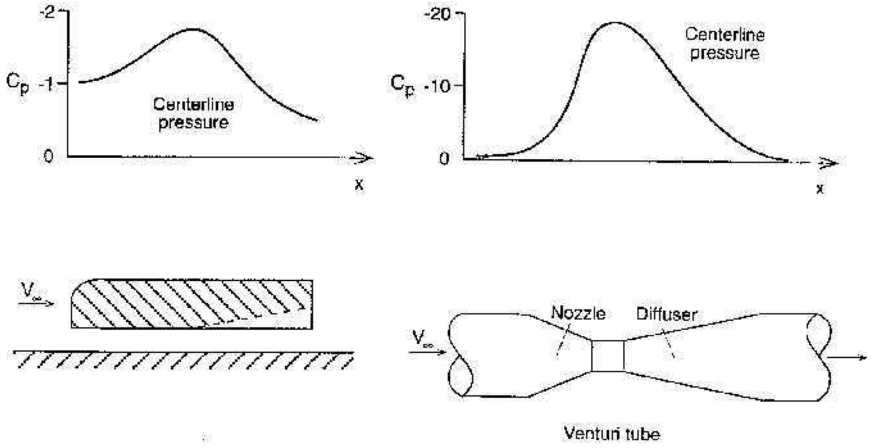
# Aerodynamic Tools

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

# Aerodynamic Tools

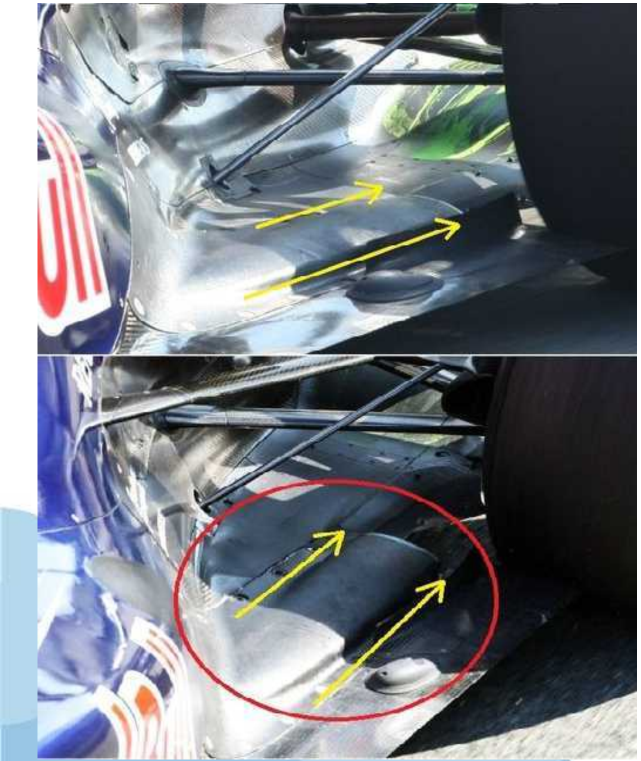
- Body
  - Bodyworks and particularly underfloor are the most powerful aerodynamic devices
  - Underfloor works as a Venturi in ground effect

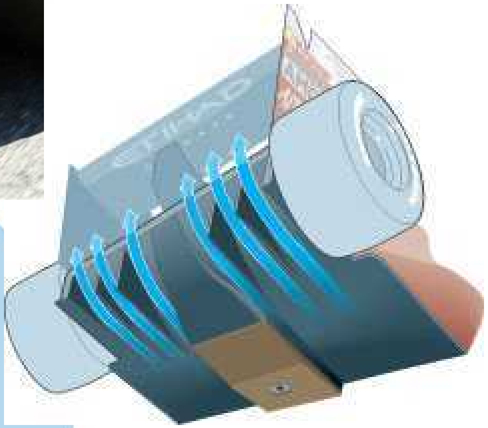


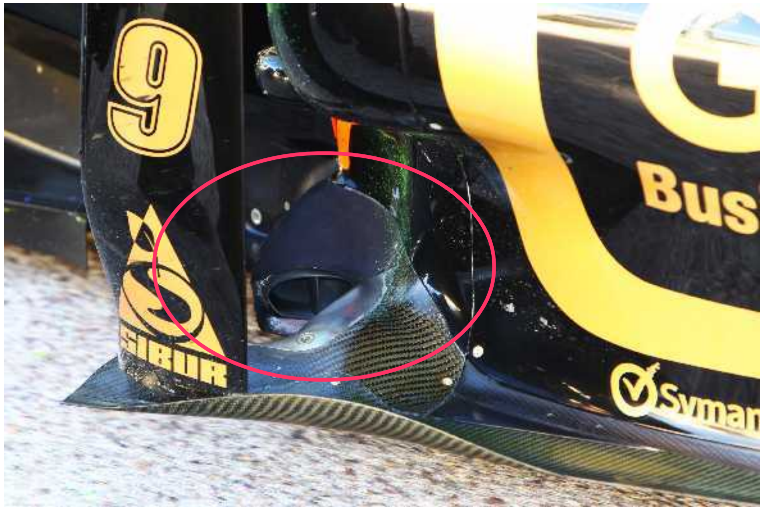


# Aerodynamic Tools

- 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
  - Rules dictate more and more limits to the diffuser design resulting in an extreme research on flow interference with exhaust, cooling ducts...







# Aerodynamic Tools

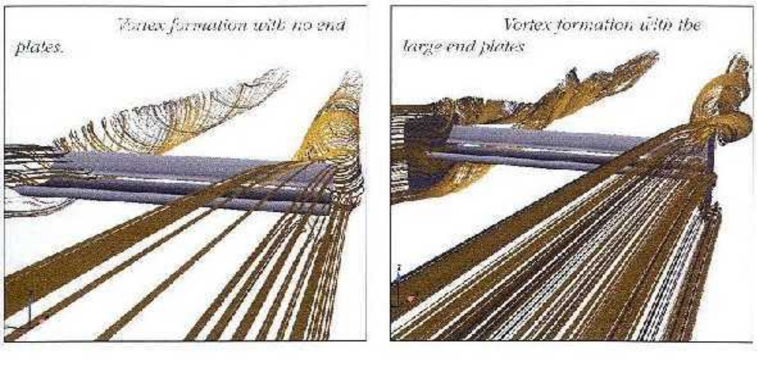
- Wings
  - Wings are the most efficient aerodynamic device
  - Rear wings of open wheel car have a very small aspect ratio
  - Wing installation (by the rules) far-forward far-after enhance their balancing effect

# 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 the 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



Vortex formation with no end plates.

Vortex formation with the large end plates

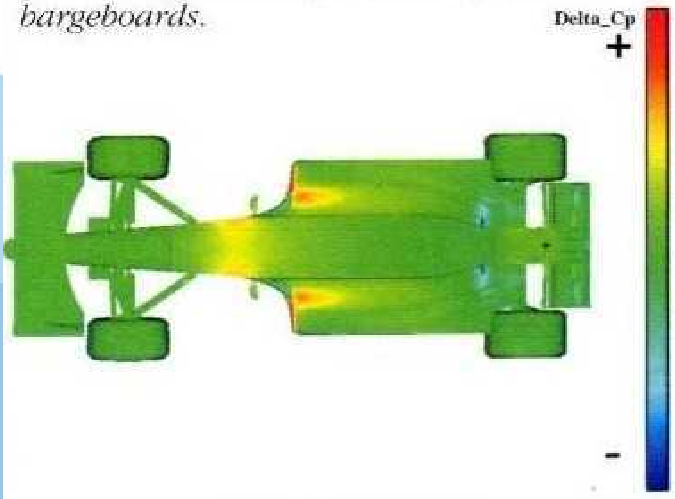
# Aerodynamic Tools

- Barge boards and side boards
  - The bargeboard is a vertical panel situated longitudinally, between the front wheels and the sidepods
  - Bargeboards and sideboards act primarily as flow conditioners, smoothing and redirecting the vortex created by the front wing and the "dirty" flow released by the rotating wheels

# Aerodynamic Tools

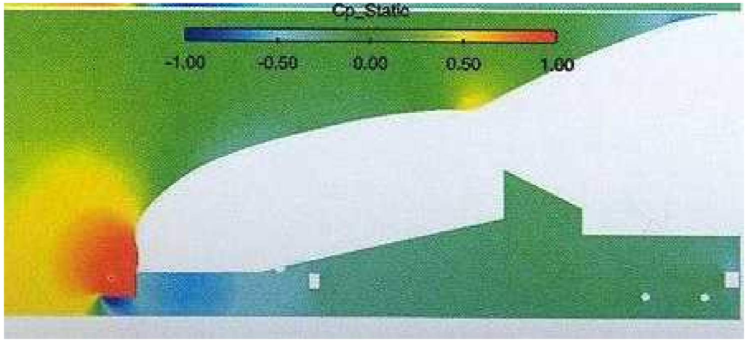
- Barge boards and side boards
  - Bargeboards act as vortex generators, redirecting and energizing airflow: the upper, downward sloping edge shed a large vortex downstream around the sidepods, where it aid in sealing the low pressure underbody flow from the ambient stream. The bottom edge of the bargeboard 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.*



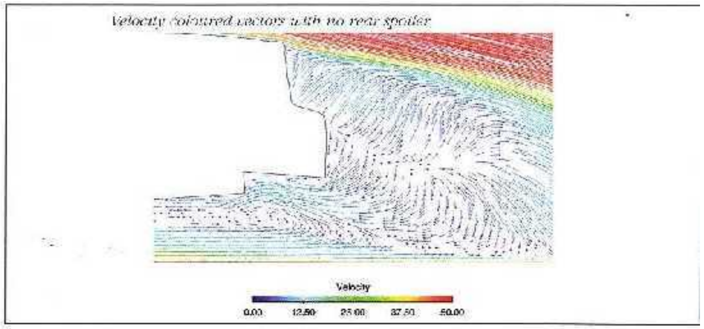
# Aerodynamic Tools

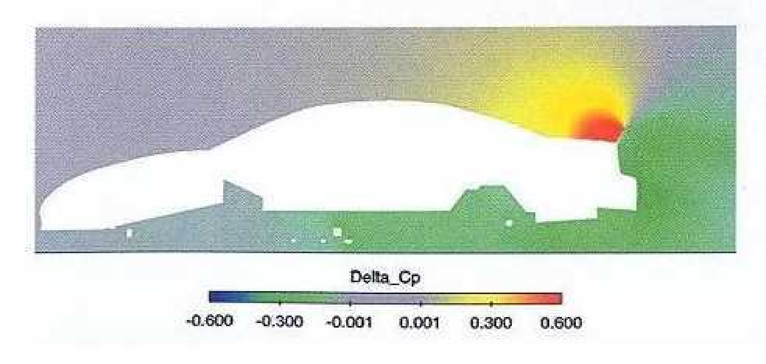
- Spoilers and splitters
  - Spoilers on the front of a vehicle are often called air dams, because in addition to directing air flow they also reduce the amount of air flowing underneath the vehicle which reduces aerodynamic lift.
  - The splitter is an horizontal lip that brought the airflow to stagnation 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.

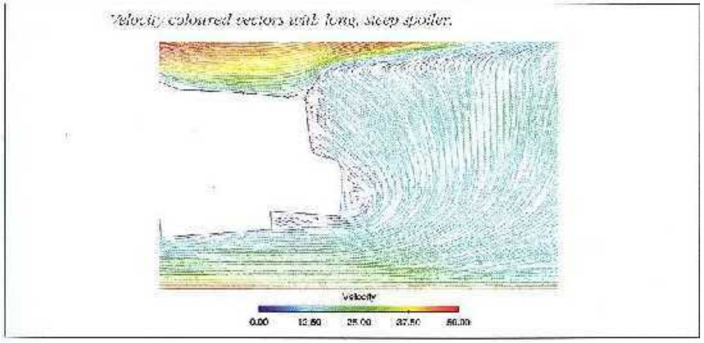


# Aerodynamic Tools

- 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

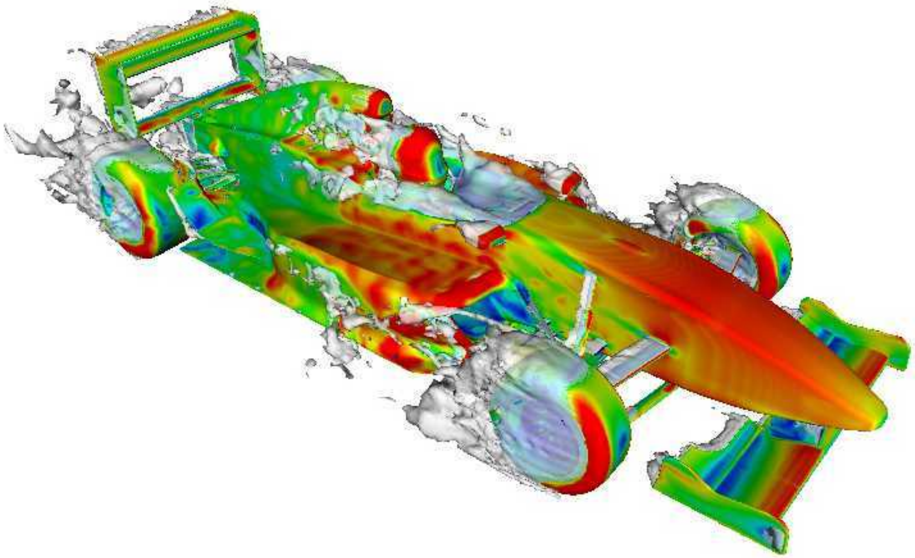






# Aerodynamic Tools

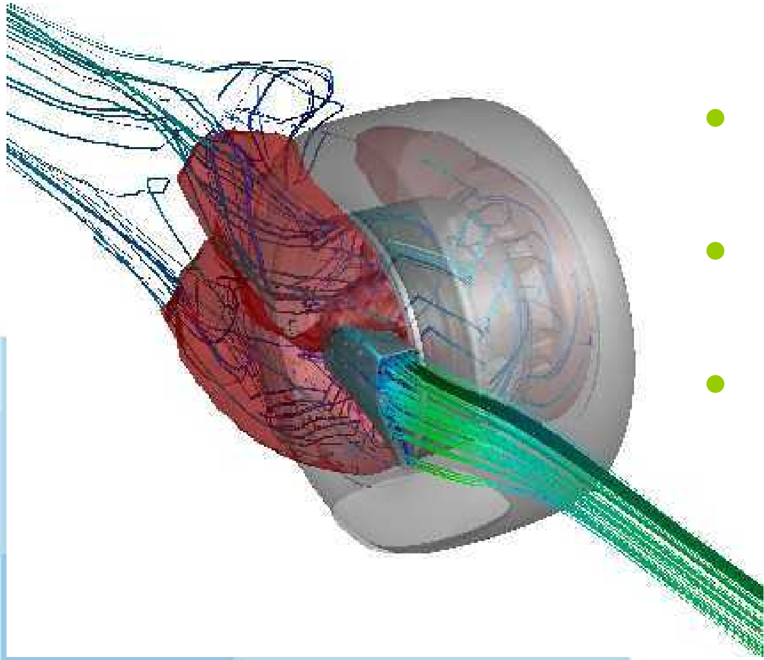
- Wheels
  - Open-wheeled race car have a very complicated aerodynamics due to the large exposed wheels
  - The flow behind wheels is completely separated
  - The frontal area of the four wheels may be as much as 65% of the total vehicle frontal area



# Verification

- CFD
- Wind Tunnel
- Track Test

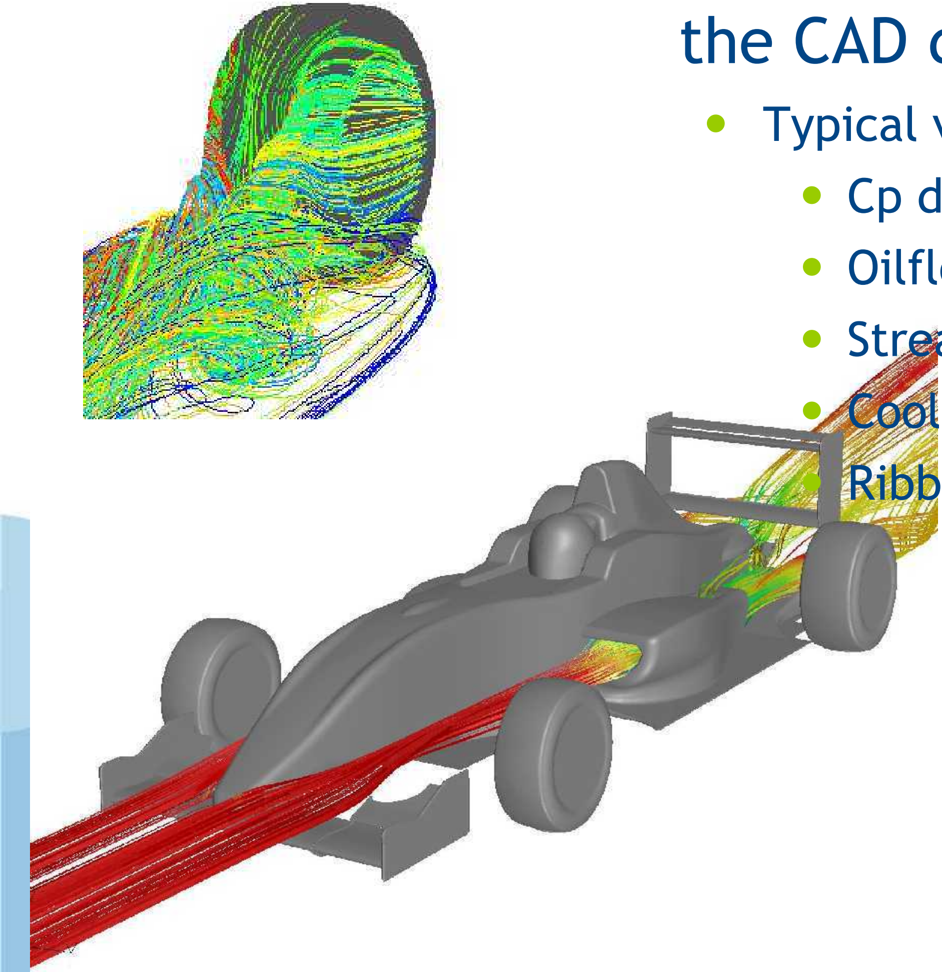
# Verification

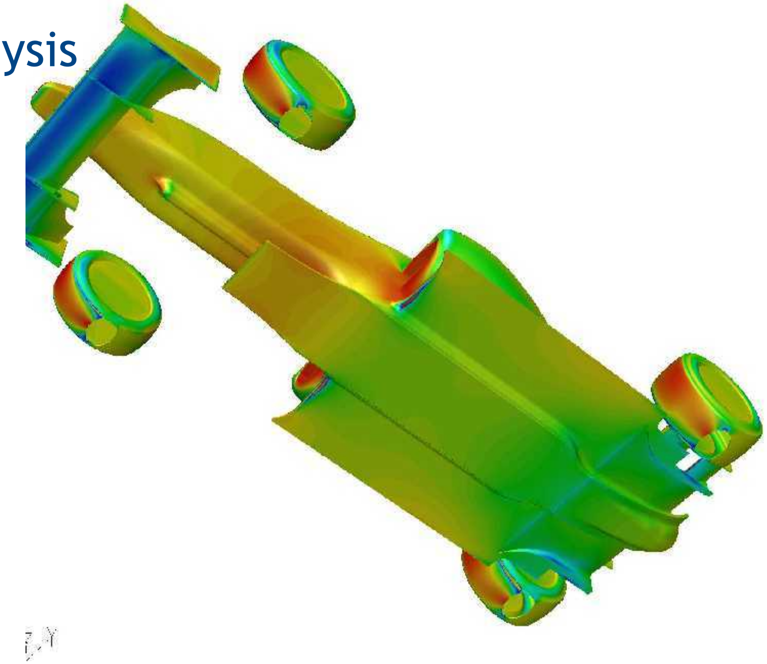


- **CFD:** Computational Fluid Dynamic software is the numerical approach to the aerodynamic simulation
  - CFD is a powerful tool for the first evaluation of appendages before the model manufacturing for the wind tunnel
  - CFD model allows the quick modification of the boundary condition
  - CFD allows 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

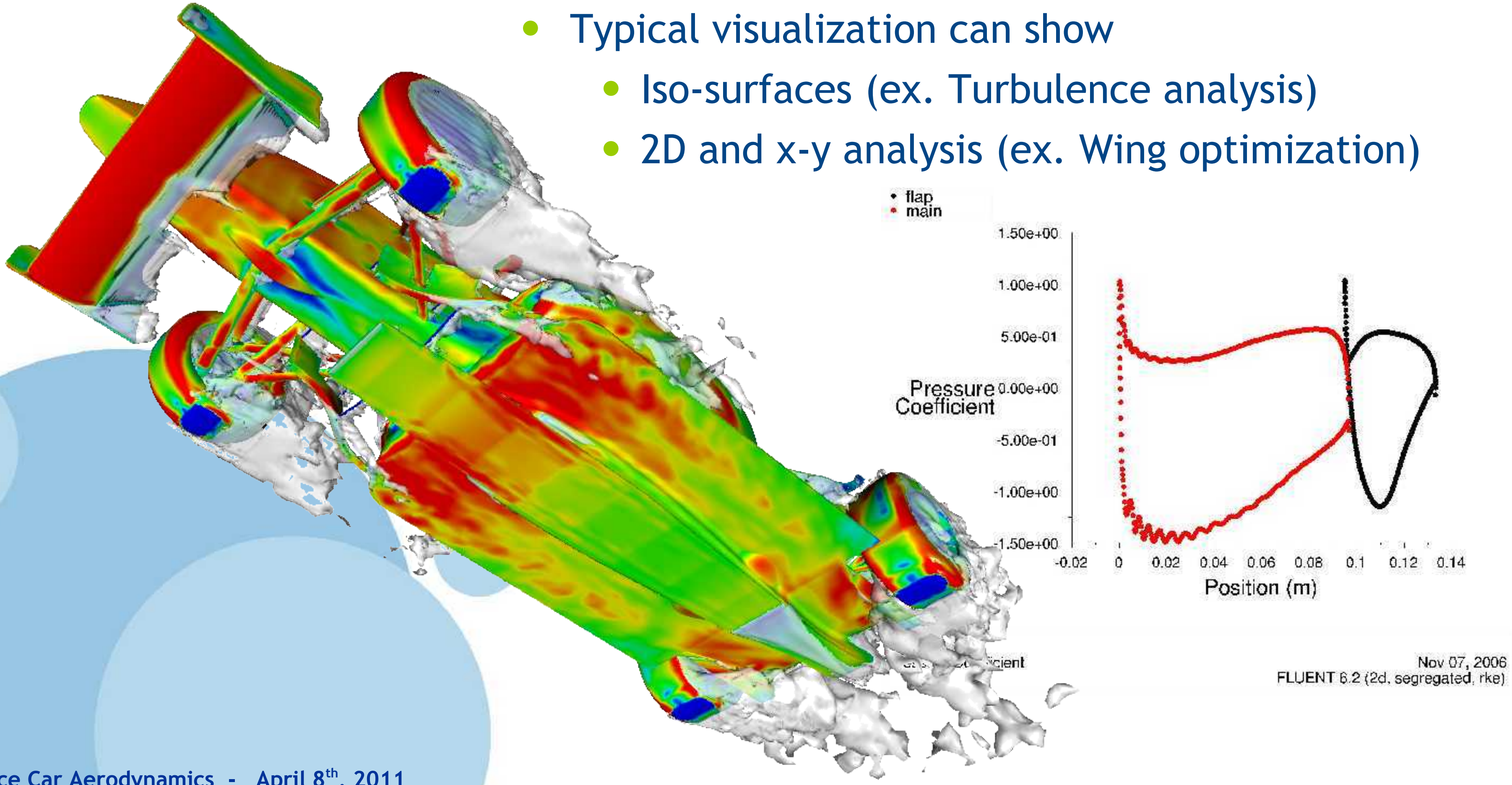
- CFD post processing is the key to iterate the CAD design process
  - Typical visualization can show
    - Cp distribution
    - Oilflow
    - Streamlines
    - Cooling analysis
    - Ribbons





# Verification

- CFD post processing is the key to iterate the CAD design process
  - Typical visualization can show
    - Iso-surfaces (ex. Turbulence analysis)
    - 2D and x-y analysis (ex. Wing optimization)



# Verification

- Wind Tunnel
  - Wind tunnel is the main experimental development facility
  - Measurements 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

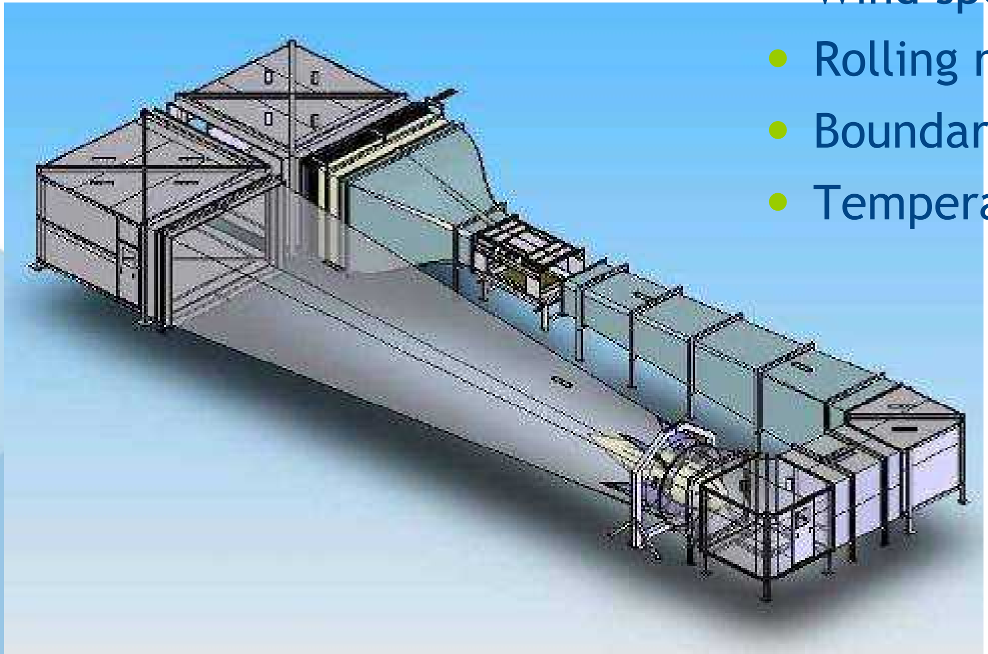
- Wind Tunnel: Scaled Model
  - Most of the wind tunnels use scaled models
  - The aerodynamic similitude is respected if coefficients are the same for scaled and real model:
    - Viscous similitude: Reynolds = $\rho v l/\mu$
    - Compressible similitude: Mach = v / a
    - Gravitational similitude: 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 (coupled with a BL suction system) 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

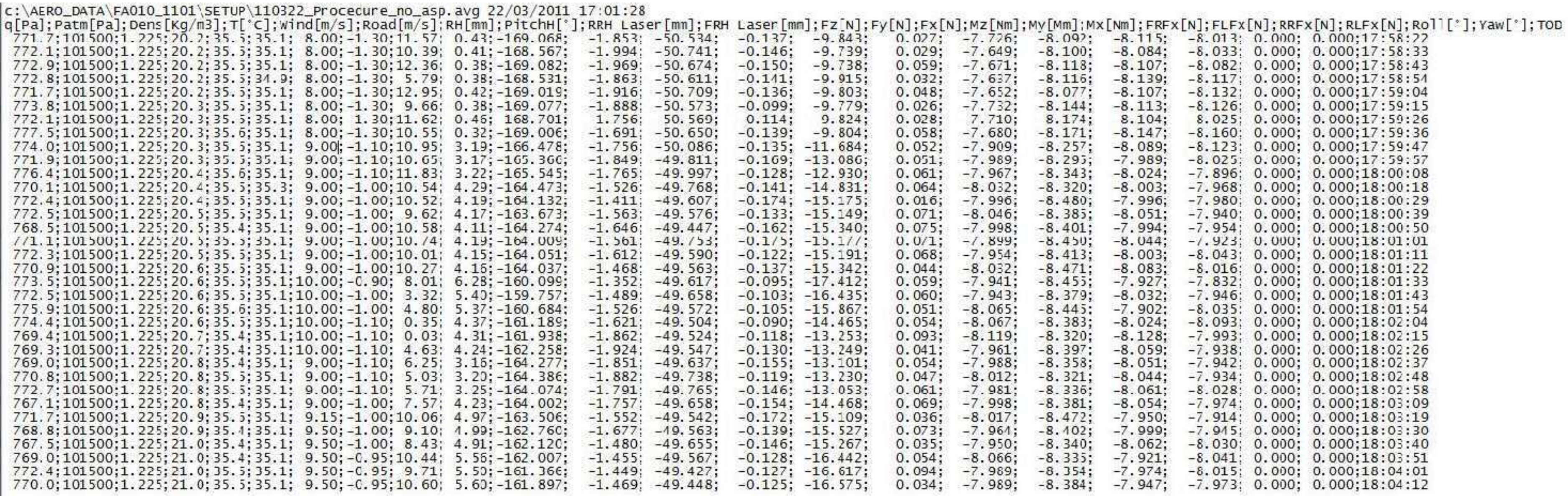
- Wind Tunnel: Model Installation
  - The rolling road causes some measurements problems:
    - The model have to be hold by the sting that interact with the body
    - Wheels are not connected to the chassis
    - Difficulties in measuring load on rotating wheels in contact with the belt

# Wind Tunnel Test Case

- Test program
  - Test procedure is planned to analyse the behaviour of the main aerodynamic devices:
    - Front Wing sensitivity
    - Rear wing sensitivity
    - Pitch attitude sensitivity
    - Cooling
    - Further investigation can be done on yaw and roll sensitivity, steered wheels, underfloor hysteresis...

# Wind Tunnel Test Case

- Data logging
  - Data are logged from balance system, positioning system and pressure sensors
  - Raw data are then processed to correct blockage, temperature and density variation, wheel friction...



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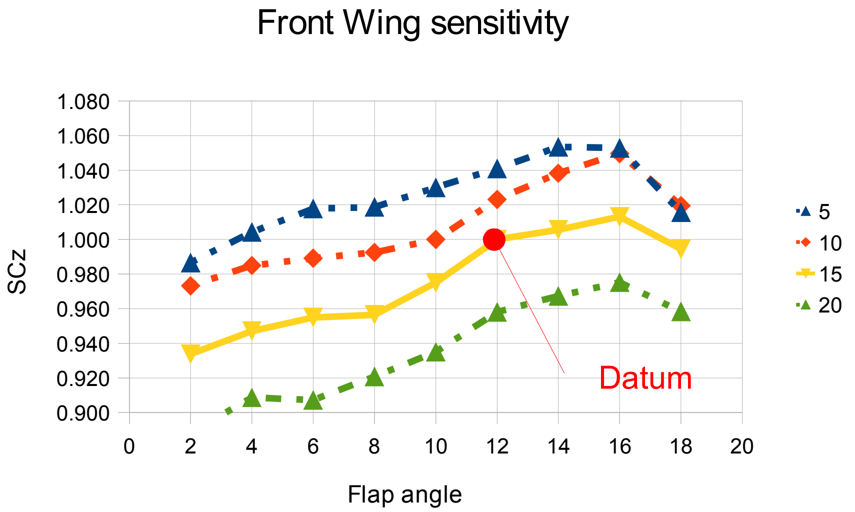
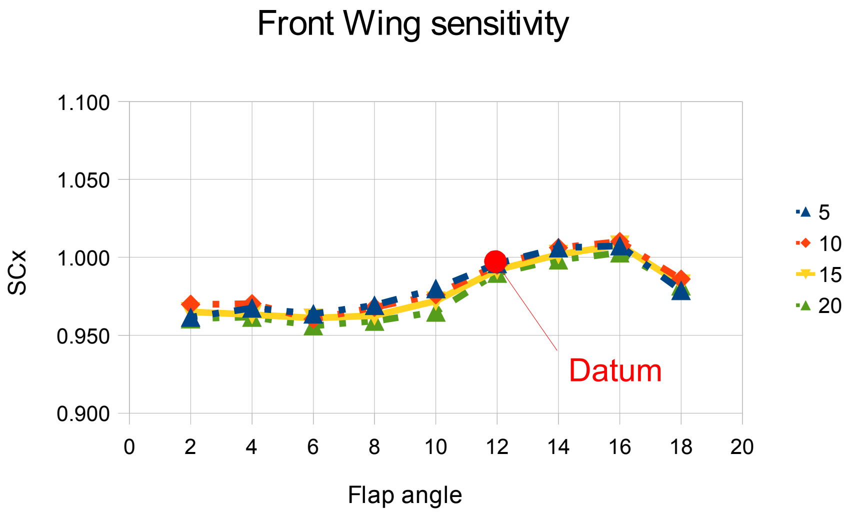
```

# Wind Tunnel Test Case

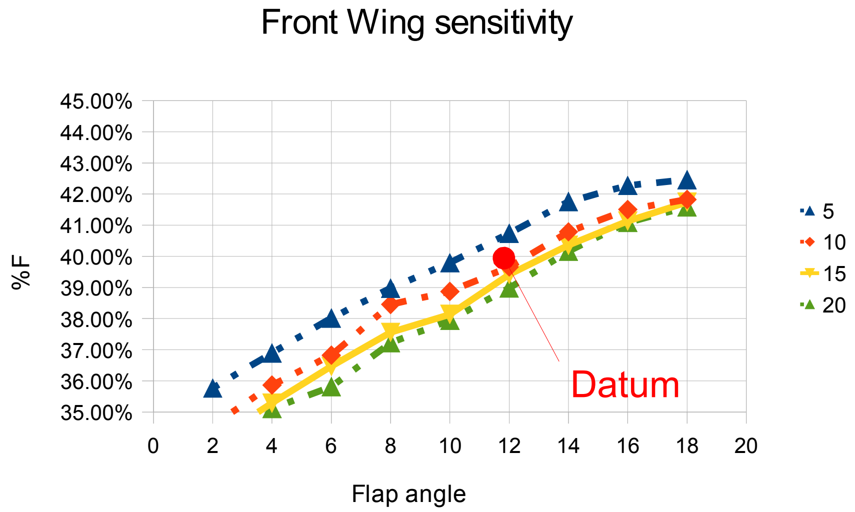
- Post Processing: Front wing
  - The following diagrams show the sensitivity of the front wing to the flap position and the main wing distance from the rolling road
  - Data are collected at the datum attitude (pitch, roll, yaw and ride heights) and scaled to the datum point reference values

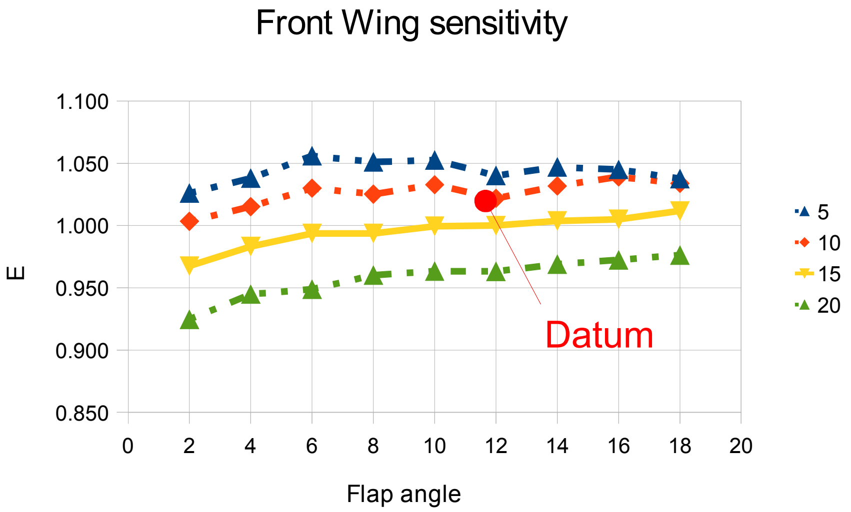




# Wind Tunnel Test Case

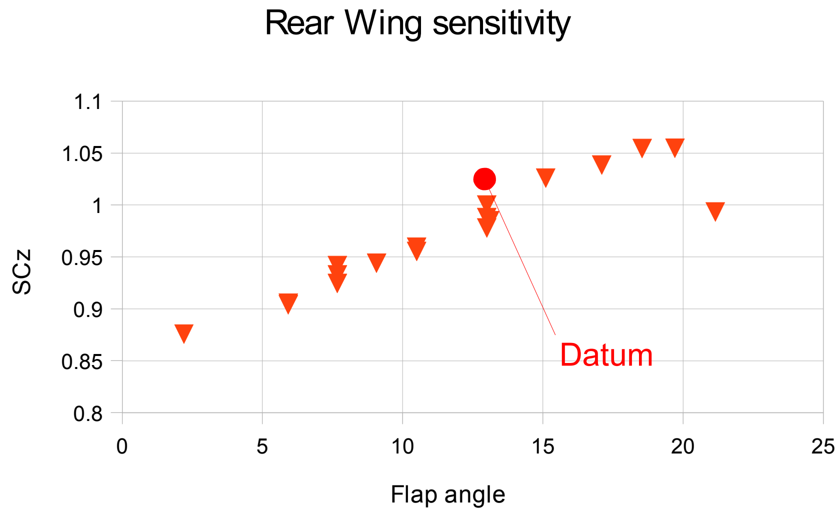
- Post Processing: Front wing

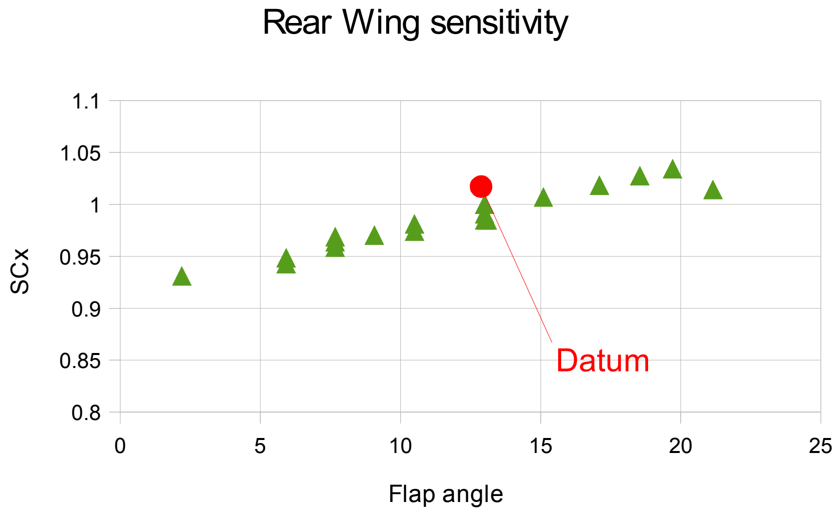




# Wind Tunnel Test Case

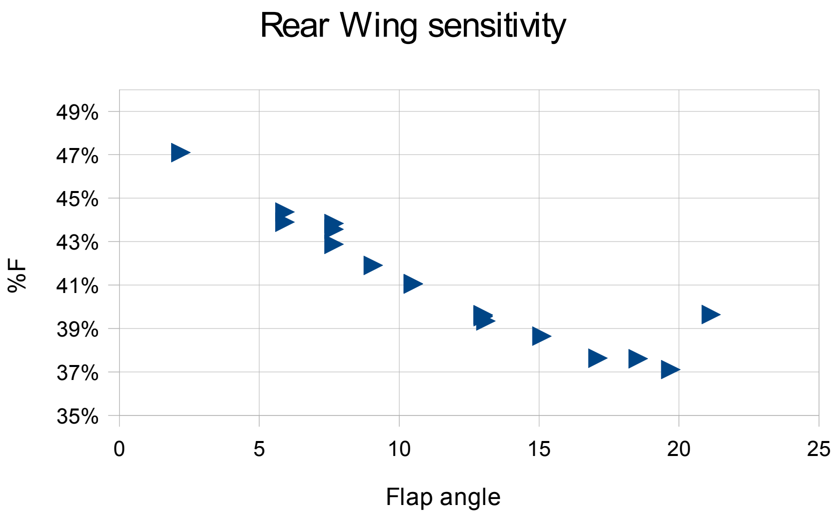
- Post Processing: Rear wing
  - The following diagrams show the sensitivity of the rear wing to the flap position
  - Data are collected at the datum attitude (pitch, roll, yaw and ride heights) and scaled to the datum point reference values

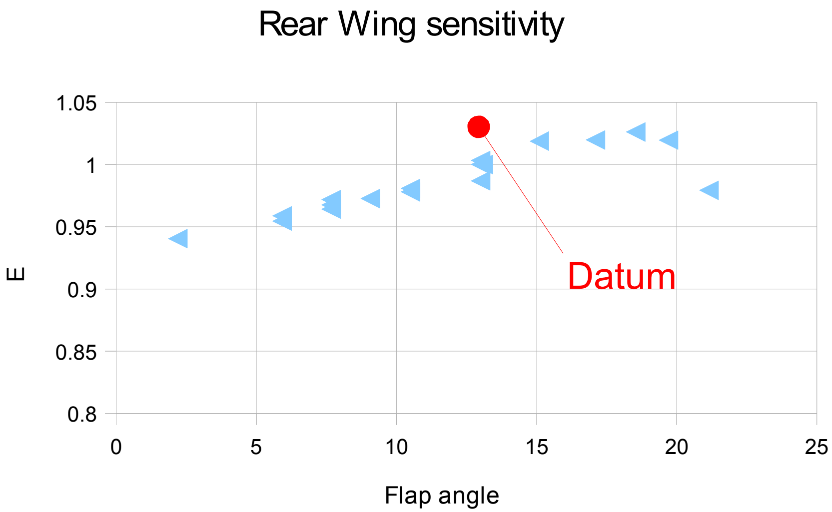




# Wind Tunnel Test Case

- Post Processing: Rear wing



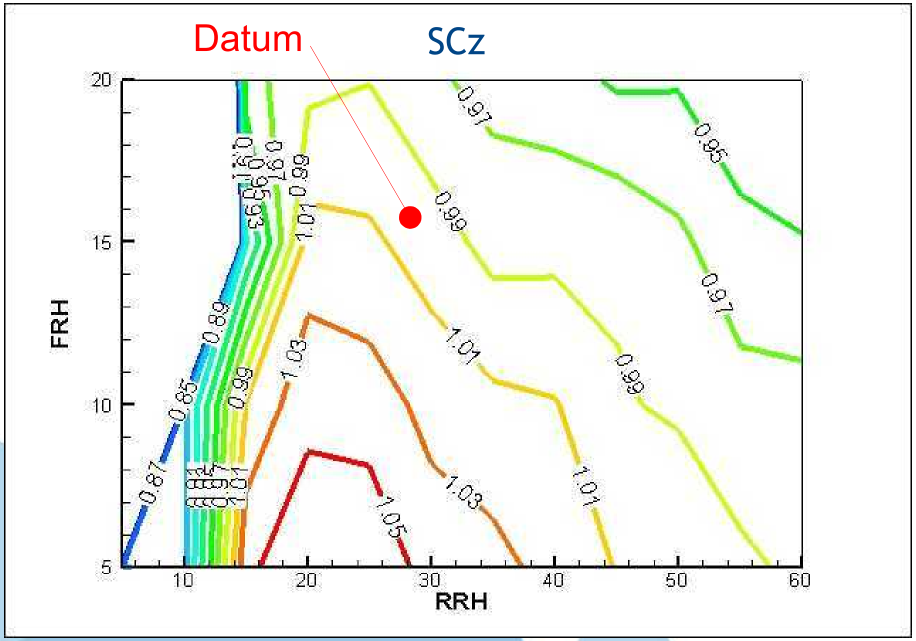


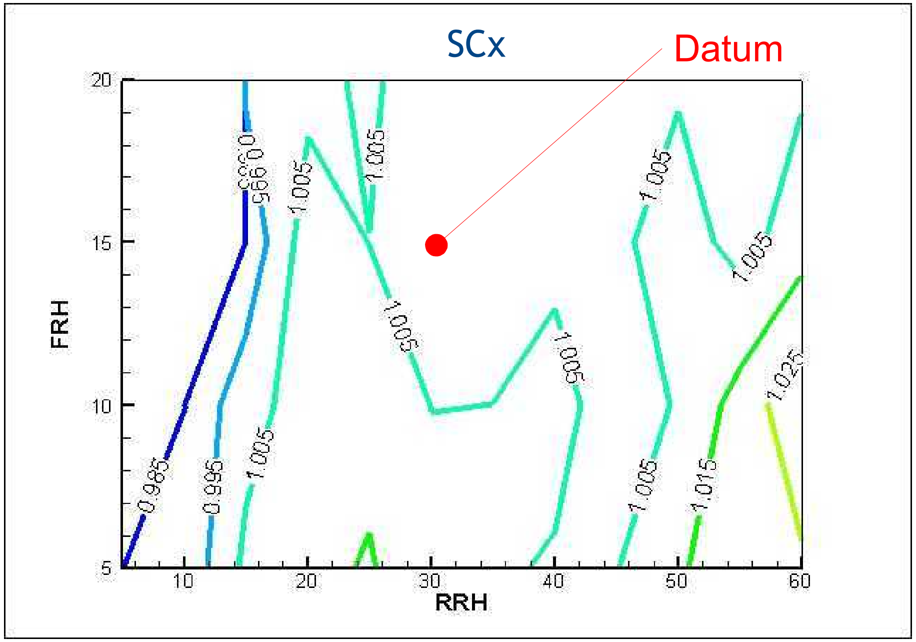
# Wind Tunnel Test Case

- Post Processing: Ride Height
  - The following diagrams show the sensitivity of the aerodynamic parameters the ride height (and pitch angle)
  - Data are collected at the datum wing set (front and rear flap) and scaled to the datum point reference values
  - Data are plotted as iso-lines of the relevant measure for Front Ride Height (FRH) and Rear Ride Height (RRH)

# Wind Tunnel Test Case

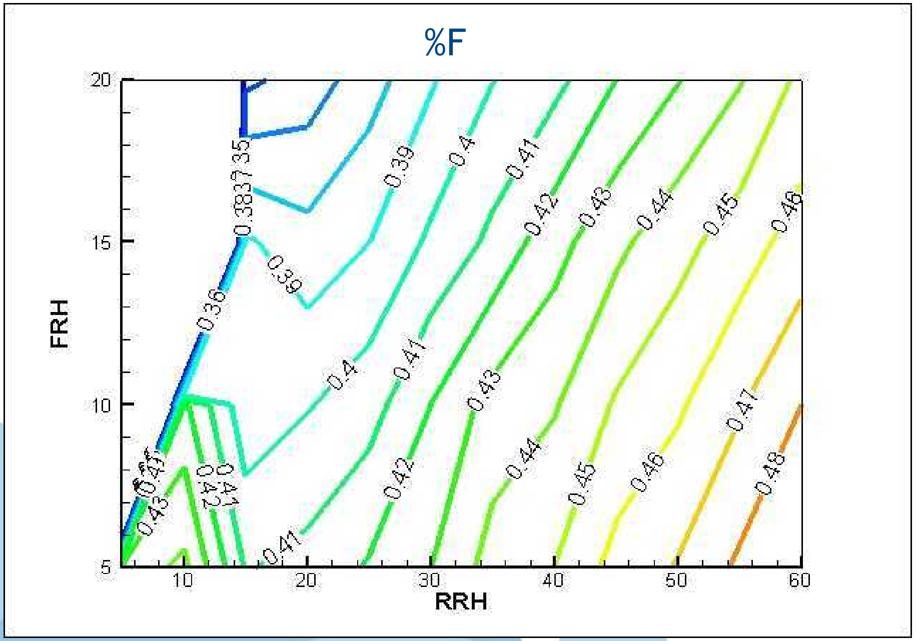
- Post Processing: Ride Height



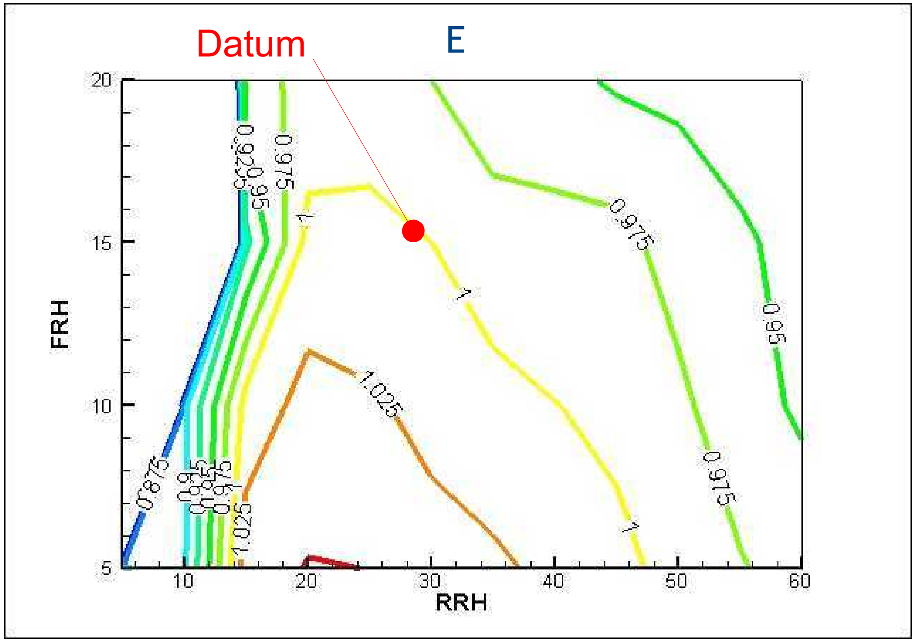


# Wind Tunnel Test Case

- Post Processing: Ride Height



%F



Datum

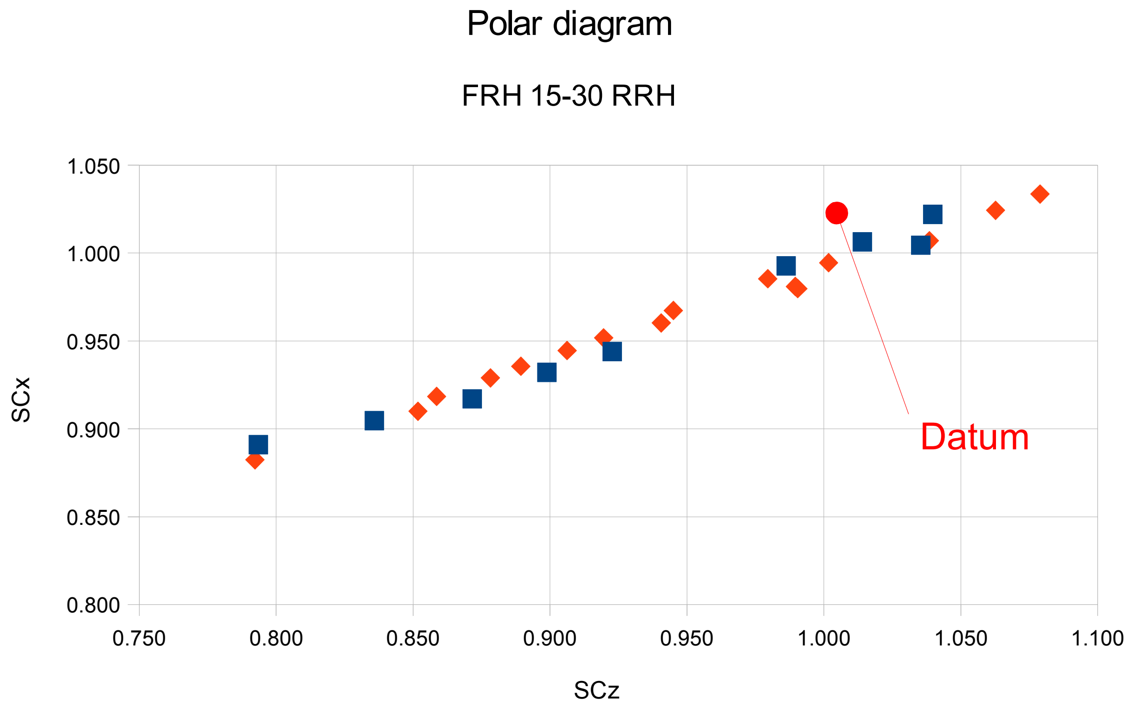
E

# Wind Tunnel Test Case

- Post Processing: “Re-balanced” data
  - The most critical parameter of the aerodynamic setup is the “Aero-balance” (%F)
  - Aero-balance is restored to the target value (40% Front in this case) acting on the Front wing, forces are then recalculated using the derivatives from the Front wing analysis

# Wind Tunnel Test Case

- Post Processing: Vehicle polar diagram
  - The following diagram resume a set of balanced setup plotted as function of Cz and Cx
  - Data are collected at the datum ride height and scaled to the datum point reference values

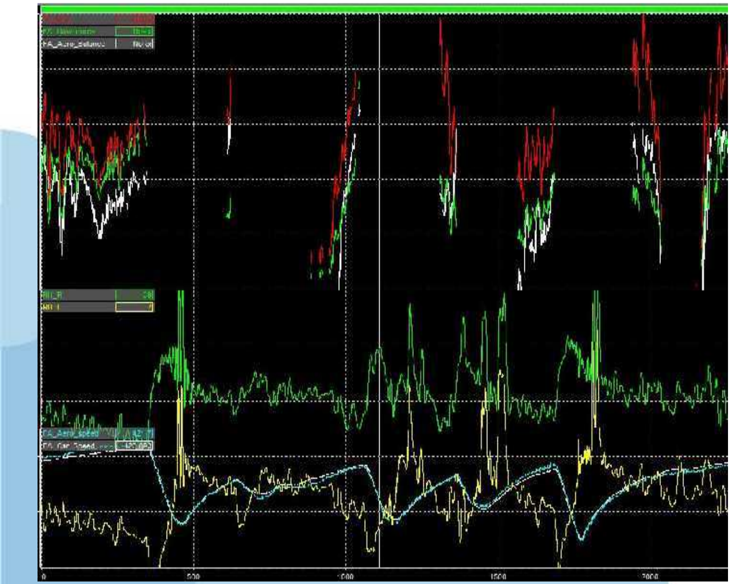


# Verification

- Track Test
  - Full scale aerodynamic test 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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| | | |
|---|---|---|
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# Acknowledgements

Thanks to Professor Alessandro Talamelli and KTH for inviting me

Thanks to Tatuus Racing for permission to show confidential information

Thanks to you for your interest