

Race Car Aerodynamics

KTH - Royal Institute of Technology Stockholm - May 21st, 2010

Corrado CASIRAGHI Tatuus Racing







- Historic overview
- Race car categories
- Aerodynamic and performance
- Aerodynamic tools
- Validation: CFD, Wind Tunnel, Track Test





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



1915: Indianapolis 500



1916: Indianapolis 500



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



1965: Chaparral-2C



1966: Chaparral-2E

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



1968: Lotus - Type 49



1966: Chaparral-2J (Sucker car)



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



1977: Lotus type 78



1977: Lotus type 78



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



1983: McLaren MP4-1C



2004: Jordan "stepped" underfloor



- Sports Car
 - Apex of efficiency



1999: Mercedes CLR



1999: BMW-LMR



1999: Toyota GT-One



1999: Audi R8R

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





- 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)





- 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)





• 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:







- Braking performance
 - Increased downforce reduces braking space





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 $^\circ$ corner) versus track curvature R with and without downforce





c.p. forward of c.g.





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.





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_r) 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).

• 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



Regulations

FIA Sport / Départament Toohnique FIA Sport / Technical Department 28/51

7M	Annexe J / Appendix J – Art. 275
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TIA Sport / Département Technique 9. FIA Sport / Technical Department	01 22.44.2009

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

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





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









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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







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





- 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









• 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









- 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







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.









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.







• 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











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







- CFD
- Wind Tunnel
- Track Test







- **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



- 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









- 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





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









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





- 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





- 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 = ρvl/μ
 - 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)







• 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



- 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



- 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



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• Wind Tunnel: Data processing

• Data are resumed in some significant diagrams: Polar diagram of the vehicle (download vs drag)





Polar diagram NT07/09



• Wind Tunnel: Data processing

• Aero-map: a diagram that shows the magnitude of aero loads as a function of the ride height









• 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



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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)



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Track Test

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

 $SC_z = F_z$ (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

$$ma_{x} = -(SC_{x} p_{dyn} + R)$$



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





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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