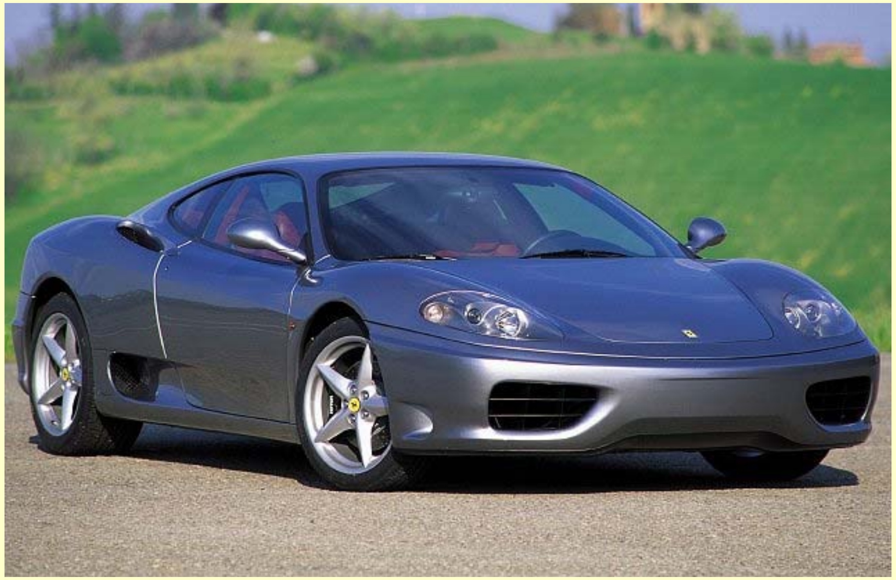
# The Influence of Aerodynamics on the Design of High-Performance Road Vehicles



**Guido Buresti**

*Department of Aerospace Engineering*

*University of Pisa (Italy)*

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# CONTENTS

# AERODYNAMIC FORCES

# THE AERODYNAMIC FORCES ACTING ON A BODY IN MOTION IN A FLUID DEPEND ON:

- GEOMETRY OF THE BODY → SHAPE, DIMENSIONS
- MOTION OF THE BODY → DIRECTION, VELOCITY
- CHARACTERISTICS OF THE FLUID
- INTERFERENCE WITH OTHER BODIES

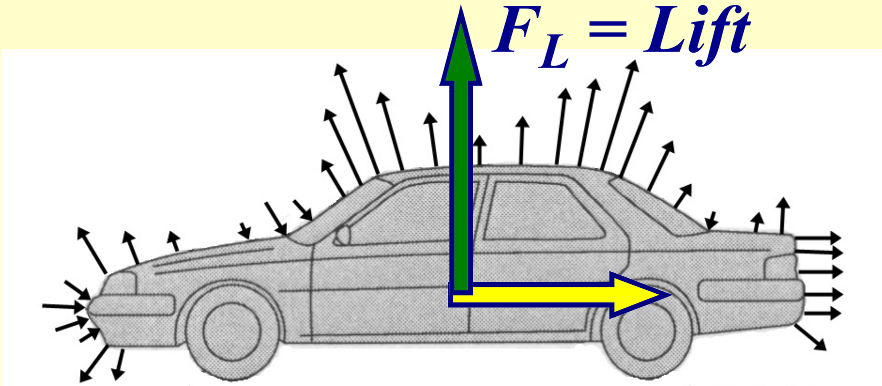
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

**Origin of the forces:**

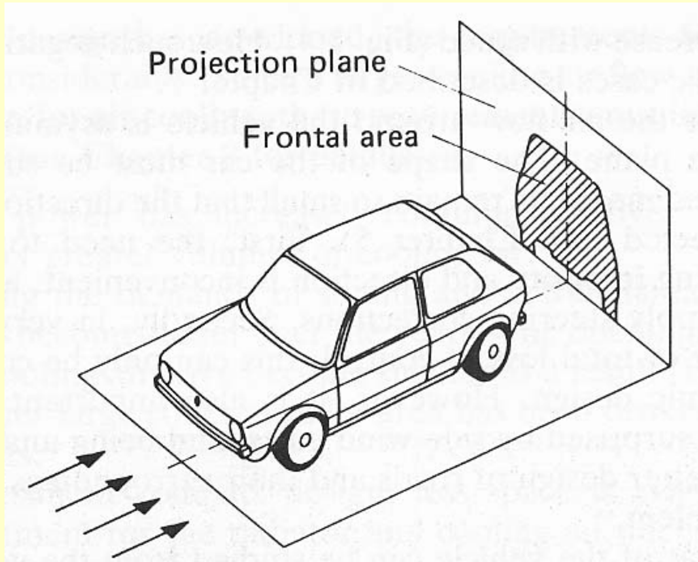
- **Friction over the body surface**
- **Pressures on the body surface**

$F_L = Lift$

**V**



$F_D = Drag$




$$F_D = \frac{1}{2}\rho V^2 \cdot S \cdot C_D \qquad F_L = \frac{1}{2}\rho V^2 \cdot S \cdot C_L$$

**Drag Coefficient**

$$C_D = \frac{F_D}{\frac{1}{2}\rho V^2 \cdot S}$$

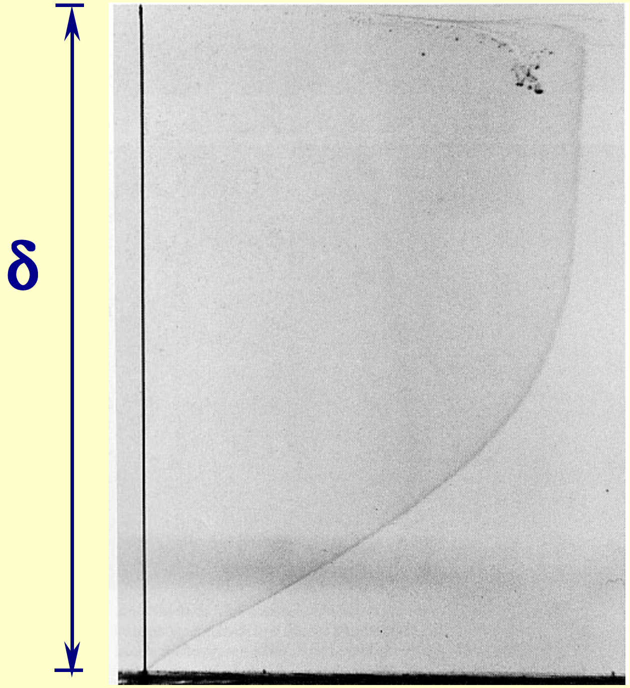
**Lift Coefficient**

$$C_L = \frac{F_L}{\frac{1}{2}\rho V^2 \cdot S}$$

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

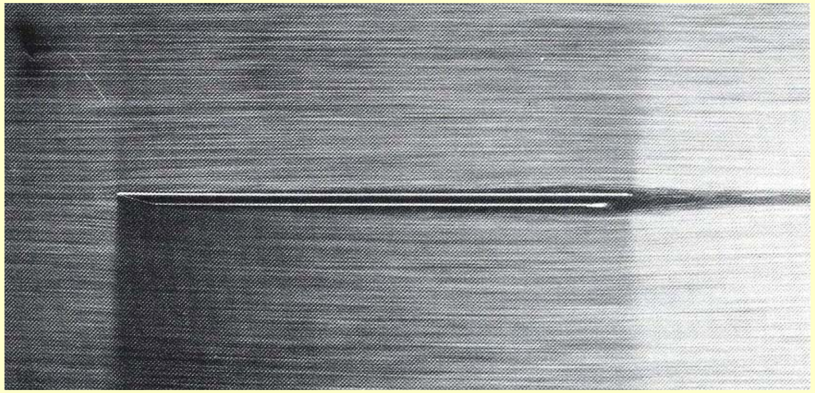
# Boundary layers

**At the wall the relative velocity between fluid and body is zero and a boundary layer develops**



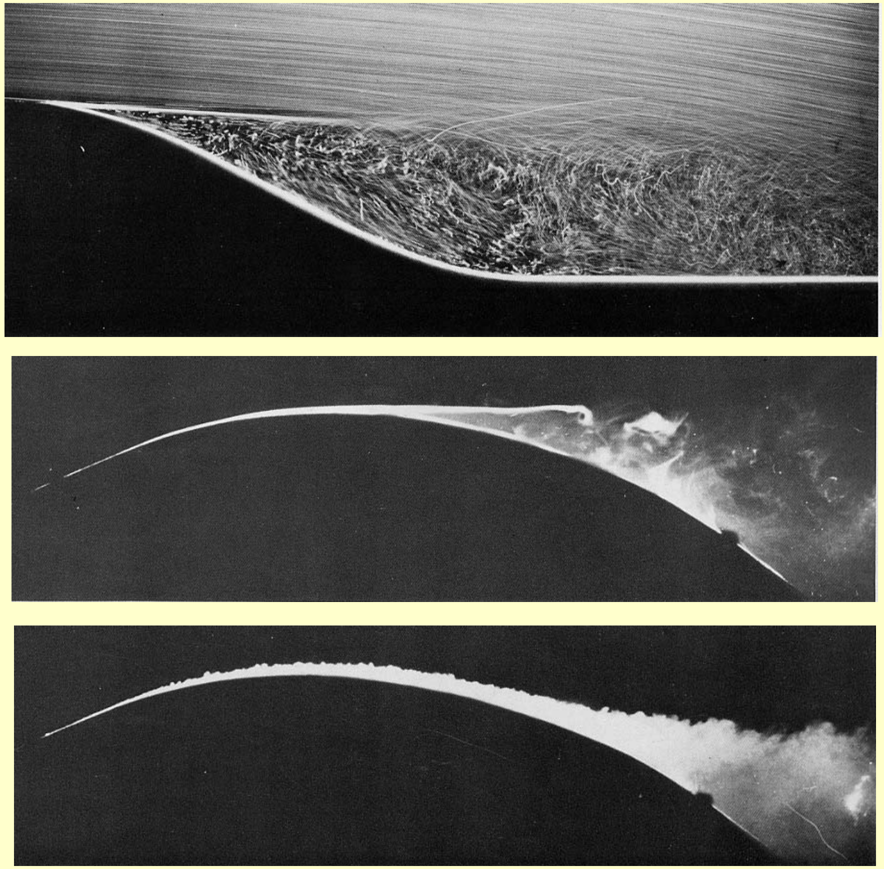

**But if the Reynolds number *Re* is high the thickness of the boundary layer may be very small**

$$Re = \frac{\rho V L}{\mu}$$



# Boundary layer separation

## If the curvature of the wall is excessive separation may occur



# Aerodynamic classification of bodies

## Aerodynamic bodies:

**Boundary layer attached over all their surface**
**Thin and generally steady wakes**

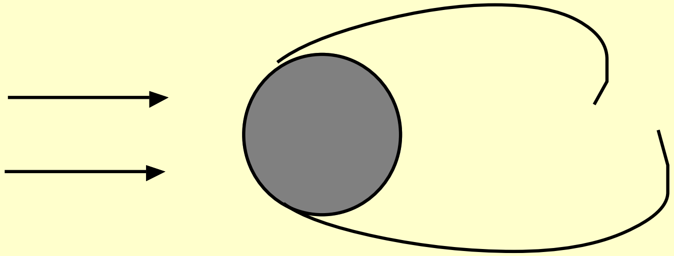
## Bluff bodies:

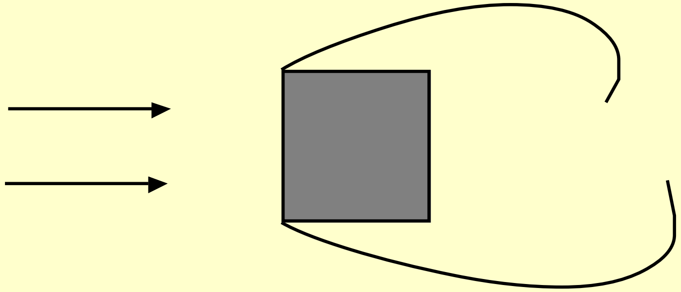
**Boundary layer separates from their surface**
**Wide and generally unsteady wakes**

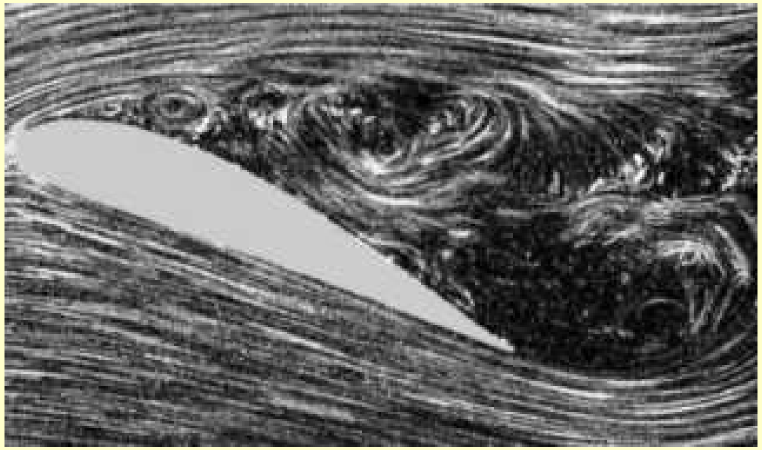
# Examples of Aerodynamic bodies

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Examples of Bluff bodies

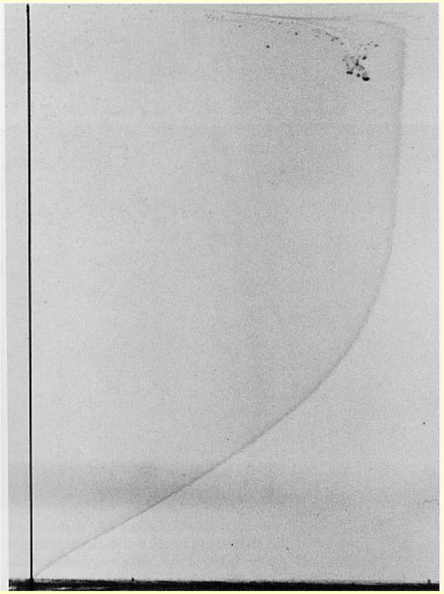






## The complete equations of motion (Navier-Stokes equations) are non-linear and very complex

$\delta$



**However, Prandtl showed that**

$$p(x,\delta) \cong p(x,0)$$

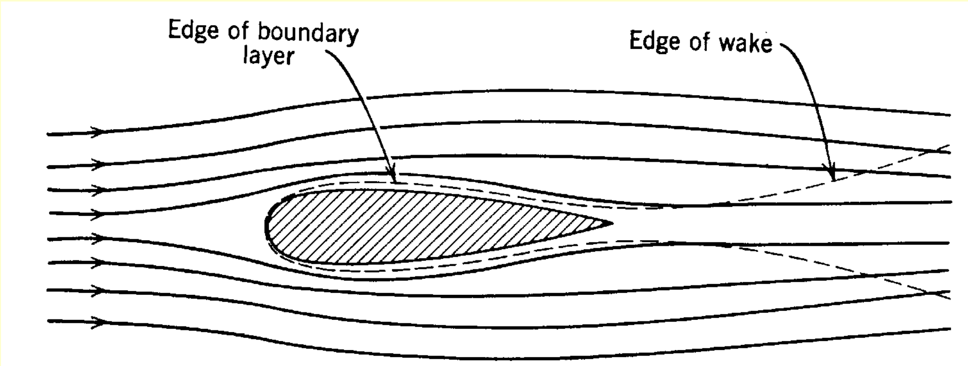
**and that outside the boundary layer a simple equation of motion applies ("potential flow" equation)**

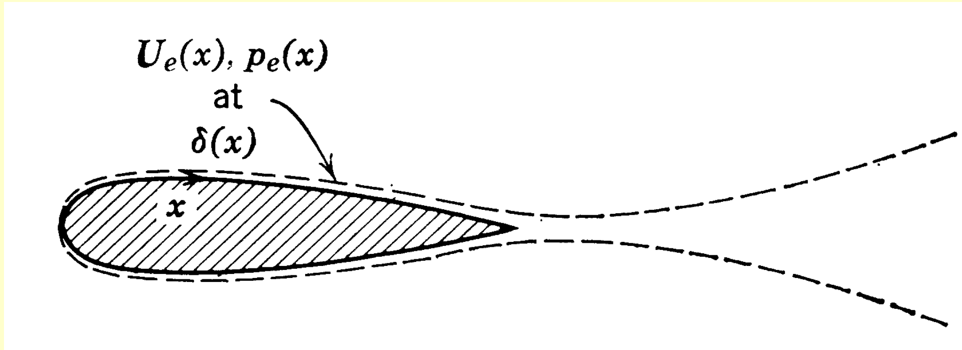
$$\nabla^2\phi = 0 \quad \text{with} \quad \vec{V} = \nabla\phi$$

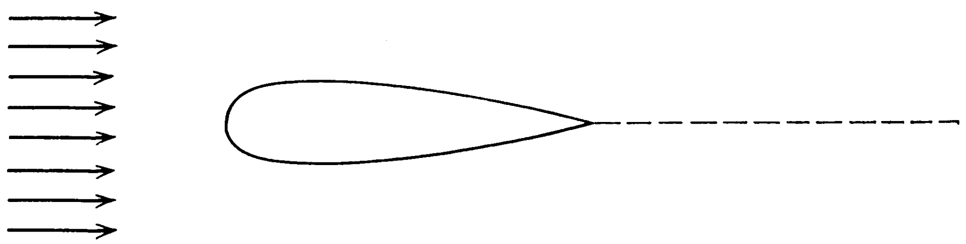
**Inside the boundary layer the equations of motion may be simplified, even if they remain non-linear**

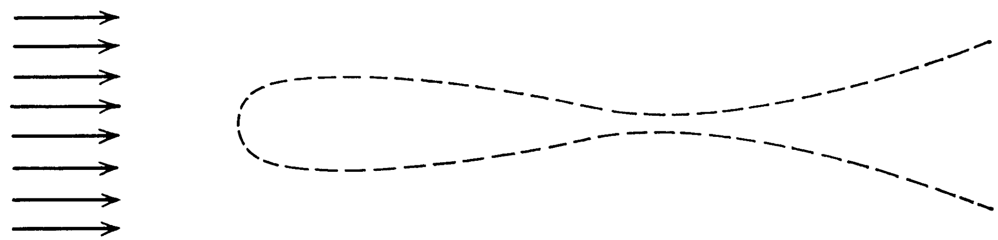
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## For aerodynamic bodies a simplified procedure may then be devised for the evaluation of the aerodynamic loads





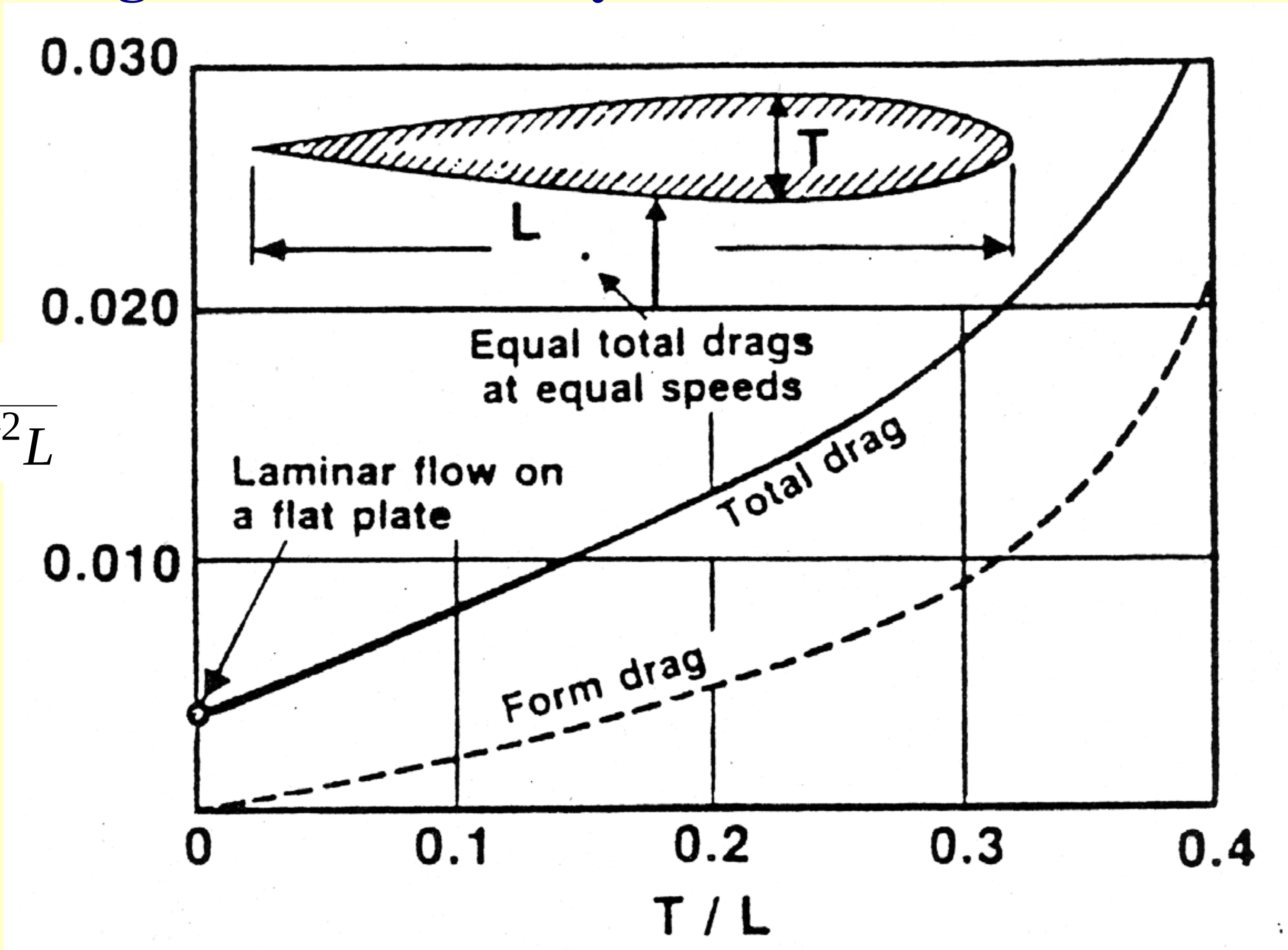
**<u>This is not possible for bluff bodies!</u>**

⇓

**Solution of Navier-Stokes equations or experimental data**

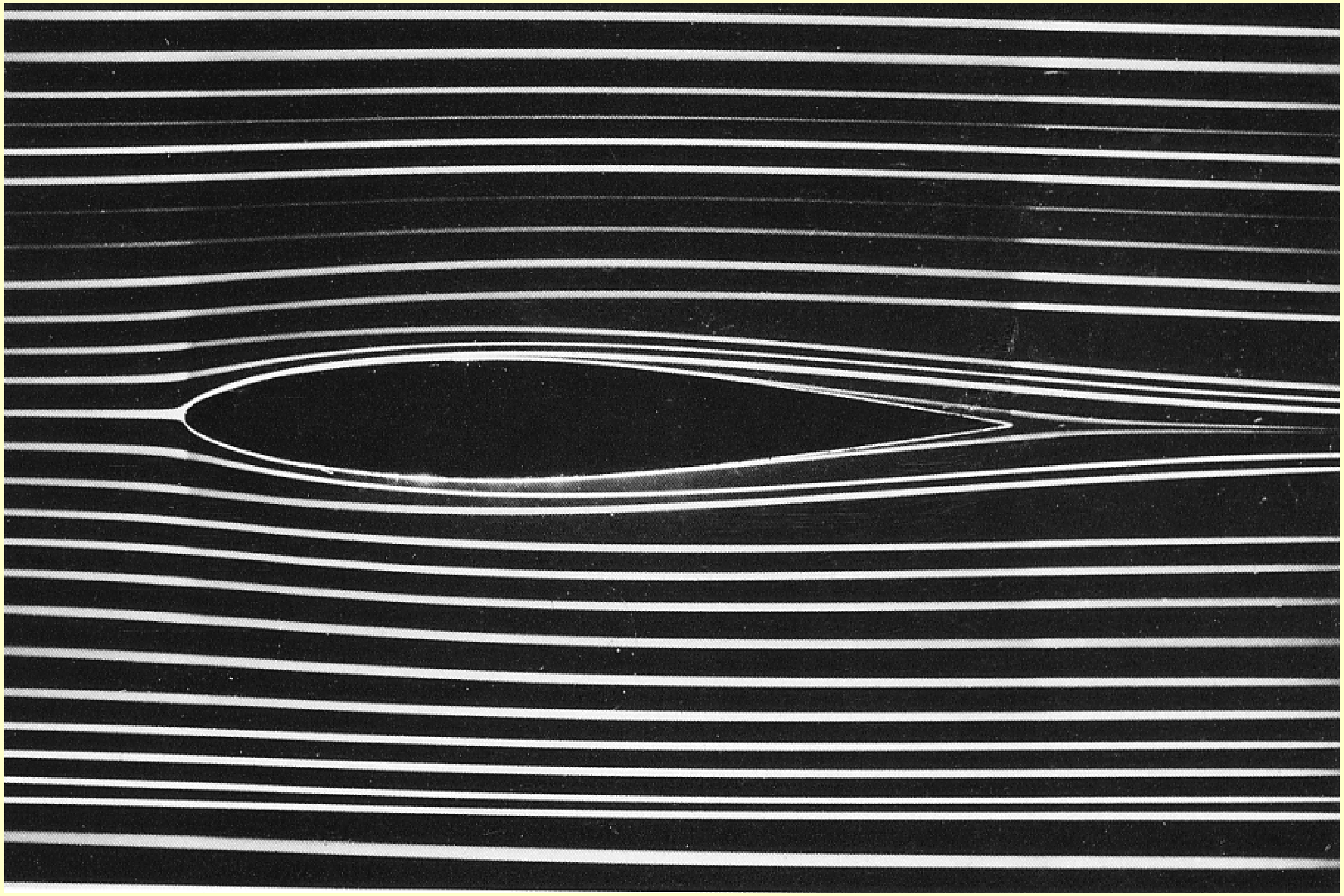
# Drag forces on aerodynamic and bluff bodies

$$\frac{F_D}{1/2\rho V^2 L}$$

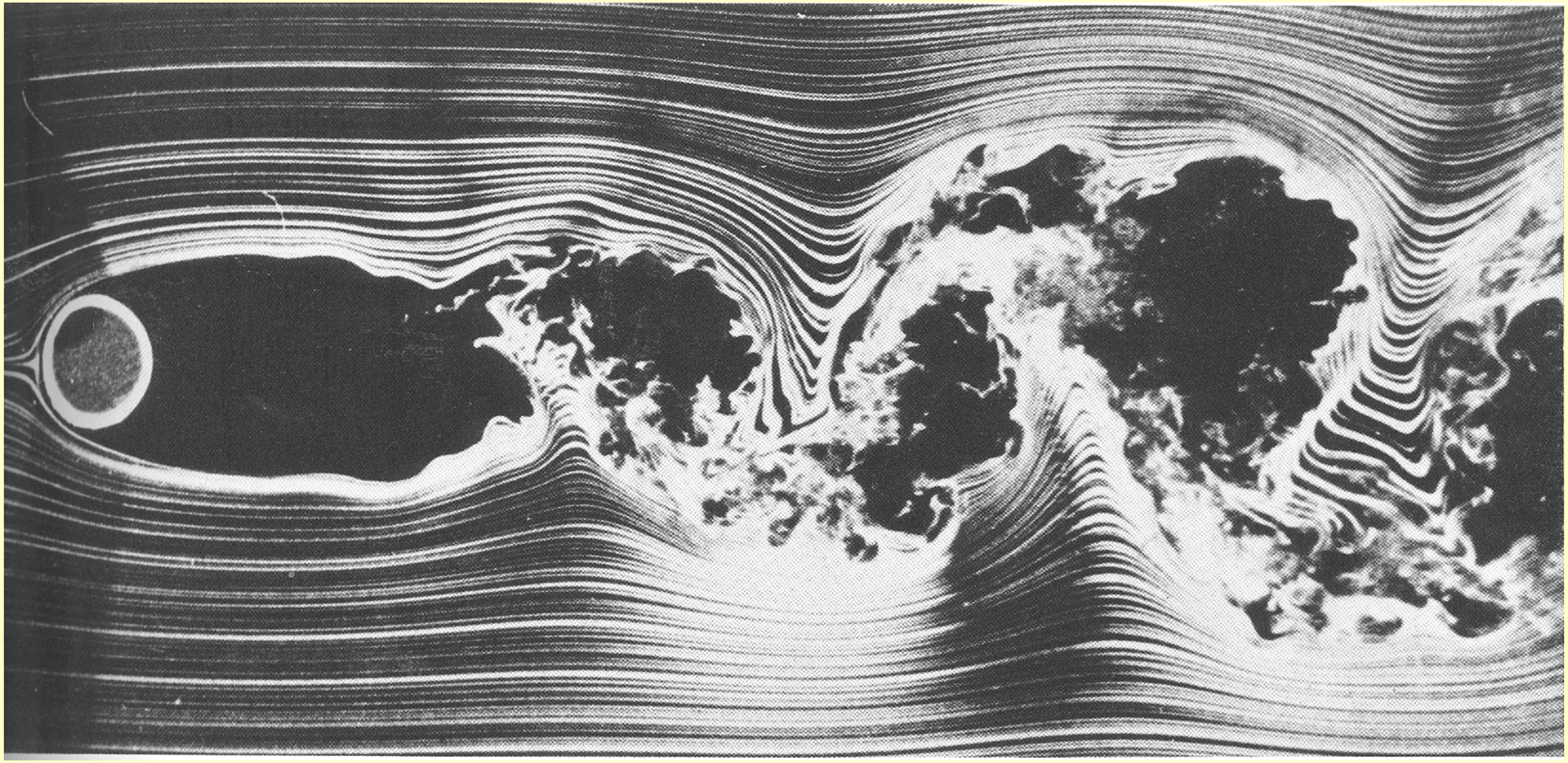


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Flow around an aerodynamic body



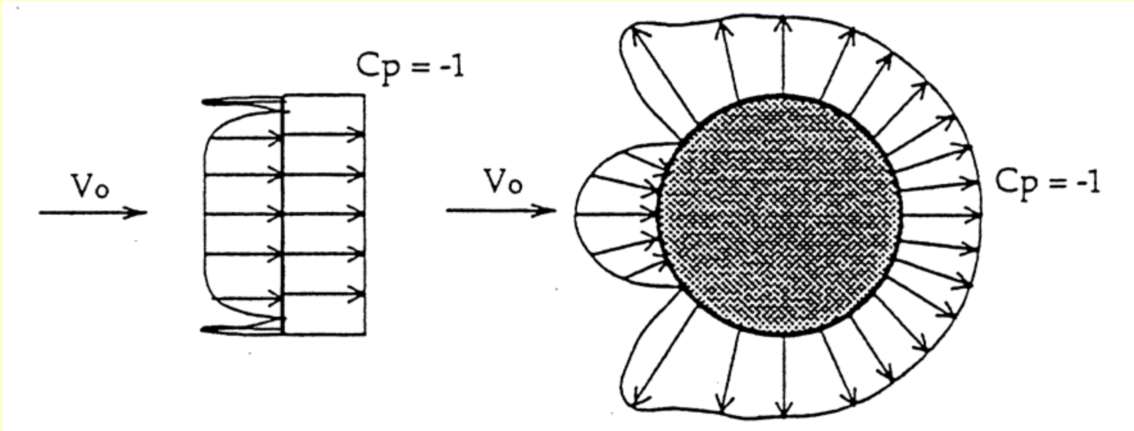
# Flow around a bluff body



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

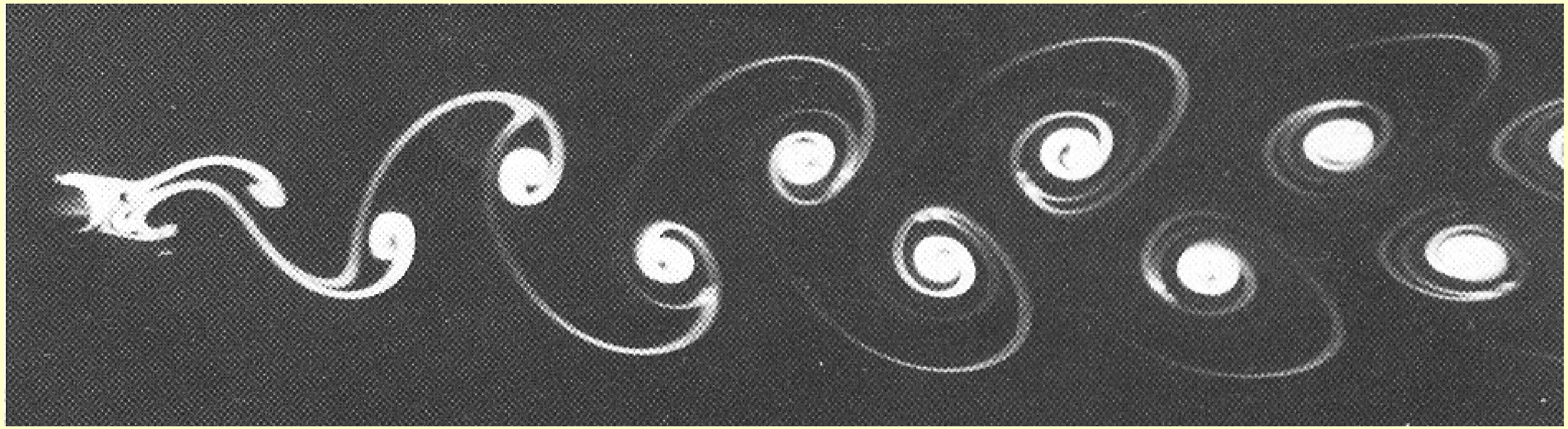
## Pressures on bluff bodies

$C_D = 2$



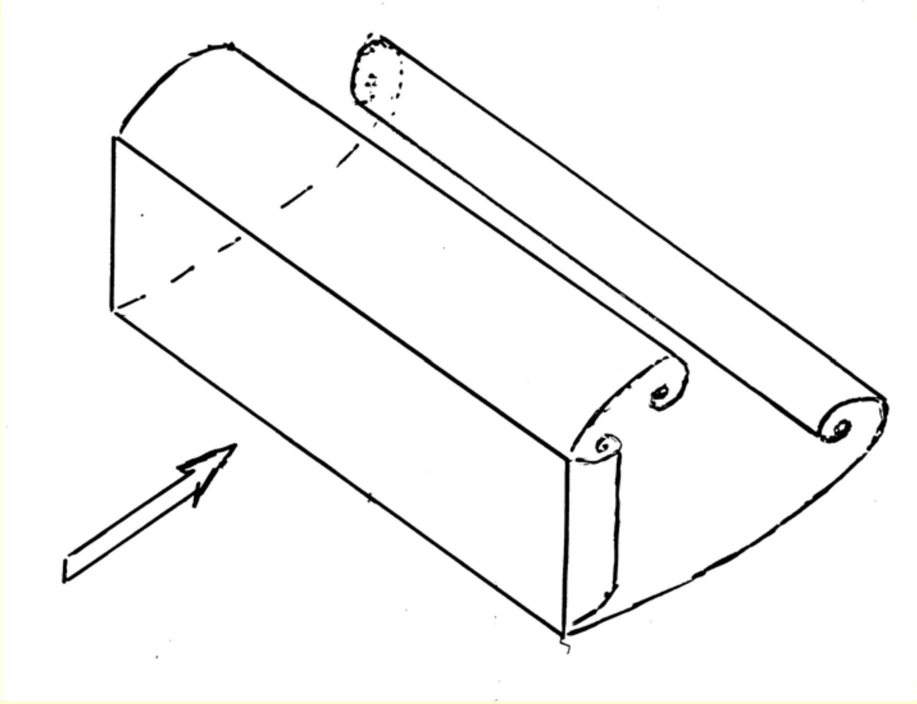

$C_D = 1.2$

## Wake flow of two-dimensional bluff body

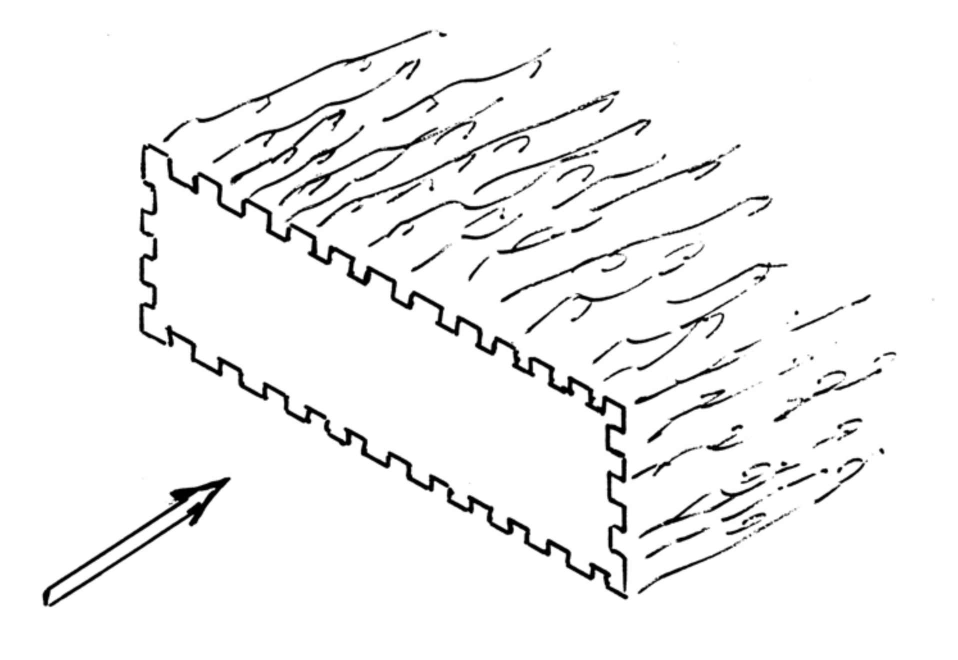


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## The aerodynamics of bluff bodies is often not obvious…



$C_D = 1.8$



$C_D = 0.9$

**It is important to understand physics in order to control it!**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# All cars are bluff bodies…but not all with the same bluffness!

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# For all road vehicles:

**The spent power is linked to the aerodynamic drag and depends on the cube of velocity**

$$P = F_D \cdot V = \frac{1}{2}\rho V^3 \cdot S \cdot C_D$$

⇓

**To decrease the aerodynamic drag implies**

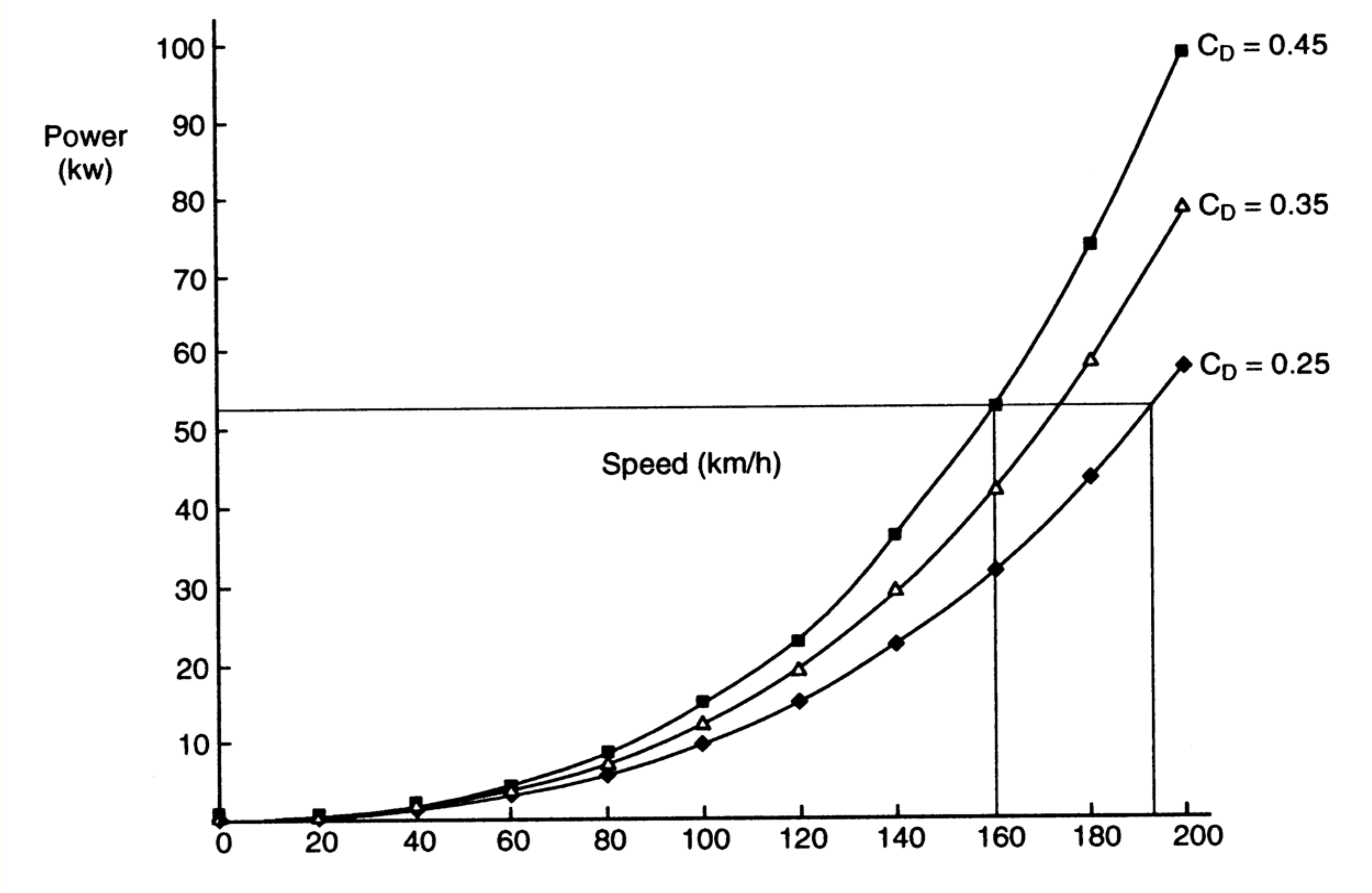
⇓

**Decreasing the frontal area**

**Decreasing the drag coefficient**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Influence of Drag Coefficient on velocity

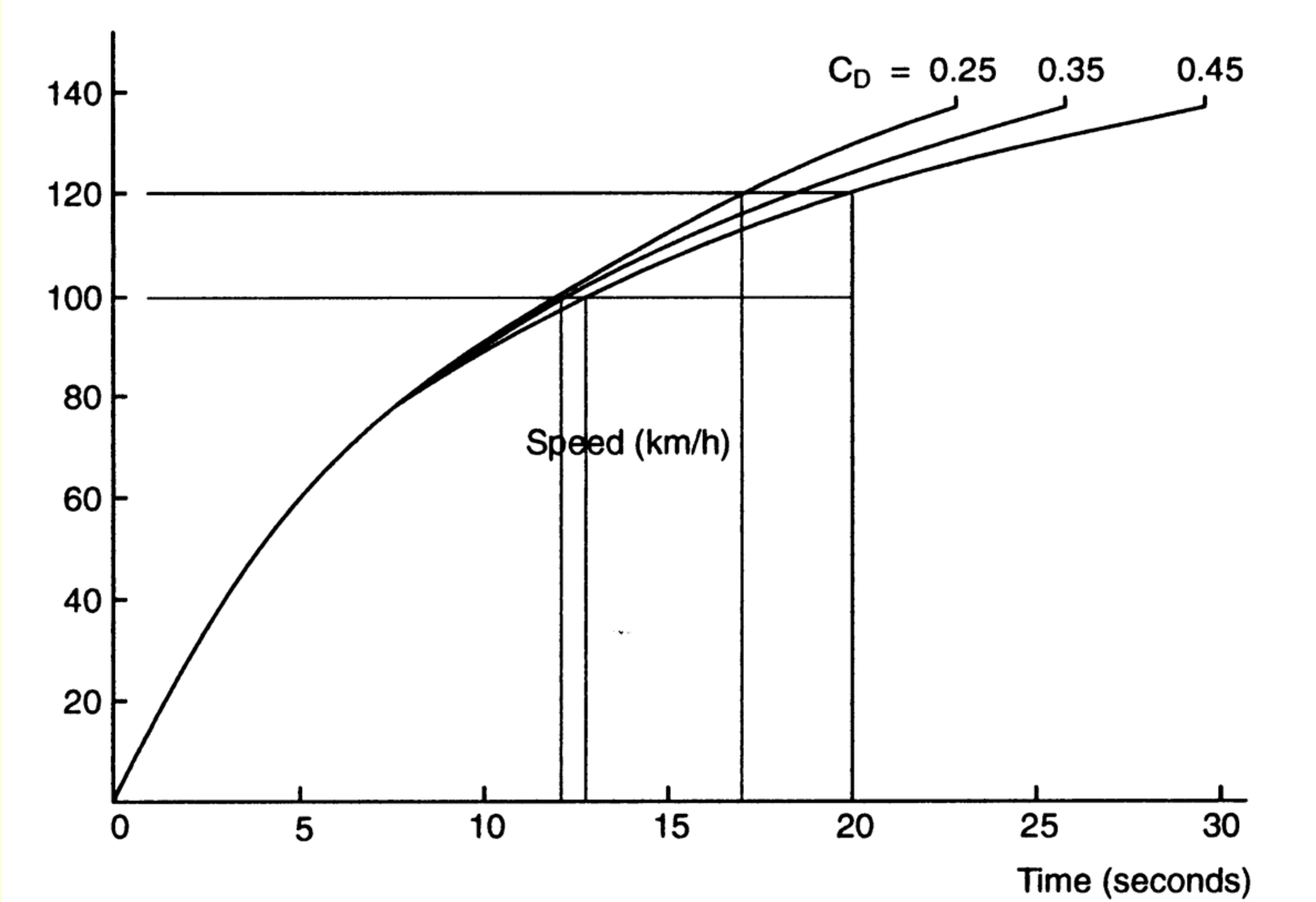


# Aerodynamic Drag Force and necessary power with increasing velocity

$S = 2.1\ m^2$ $C_D = 0.35$

| V (km/h) | $F_D$ (Kg) | P (HP) |
|---|---|---|
| 50 | 8.9 | 1.6 |
| 100 | 35.5 | 12.9 |
| 130 | 59.9 | 28.3 |
| 200 | 141.8 | 102.9 |
| 300 | 319.0 | 347.4 |
| 350 | 434.2 | 551.6 |

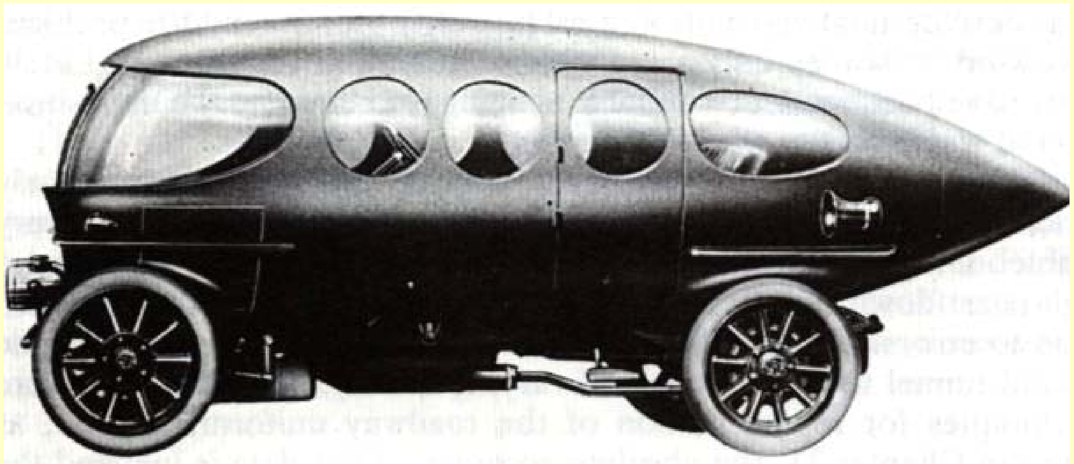
# Influence of Drag Coefficient on acceleration



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

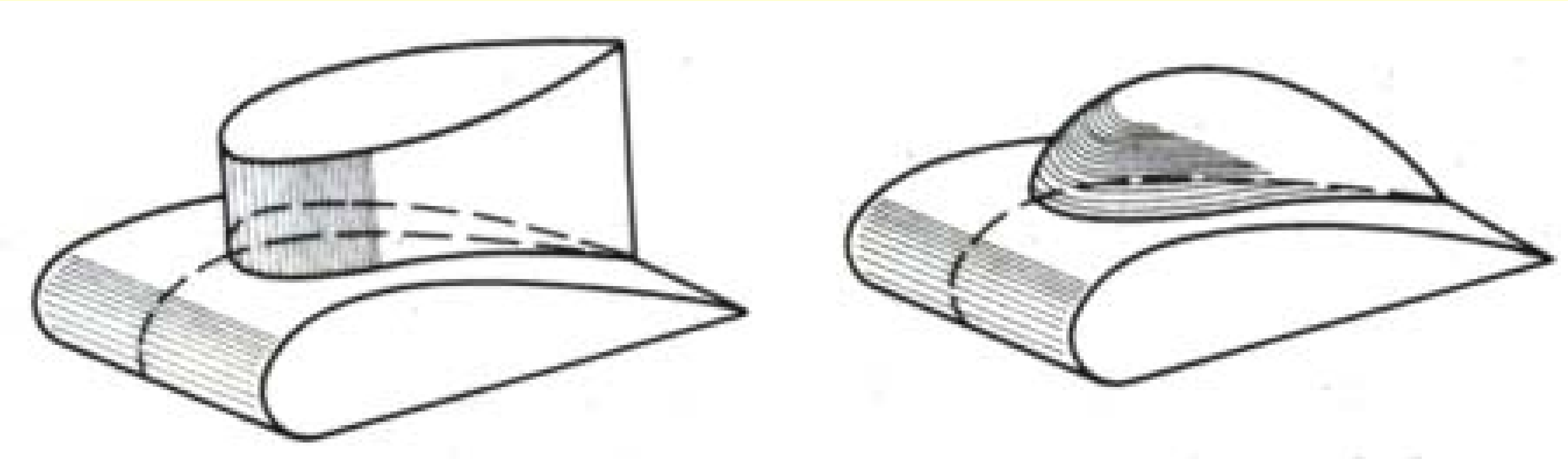
# Brief historical overview…

*Jamais Contente* of
Camille Jenatzy (1899)



*Alfa Romeo* of
Count Ricotti (1913)

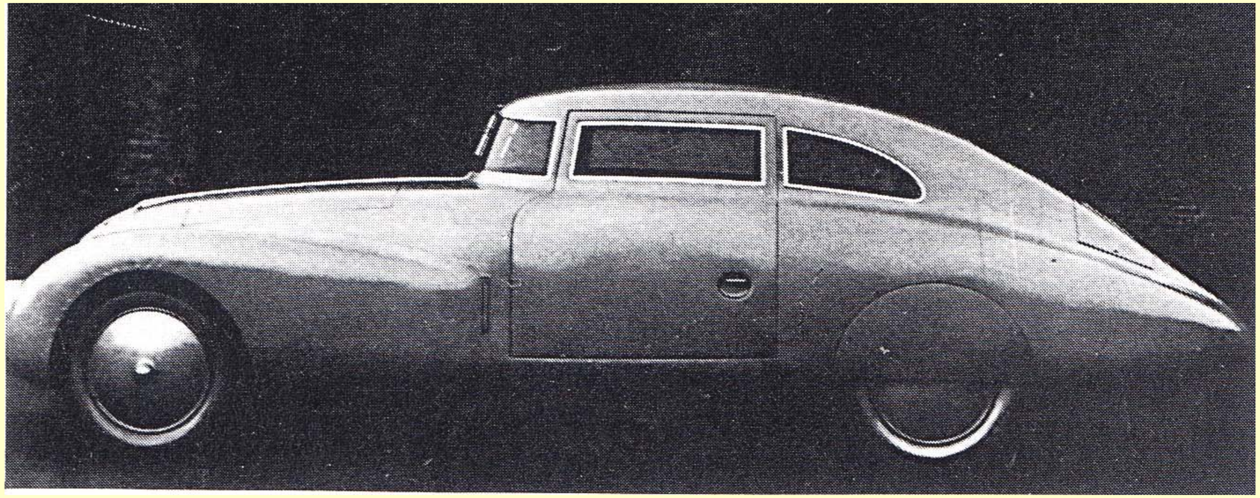
# Brief historical overview…

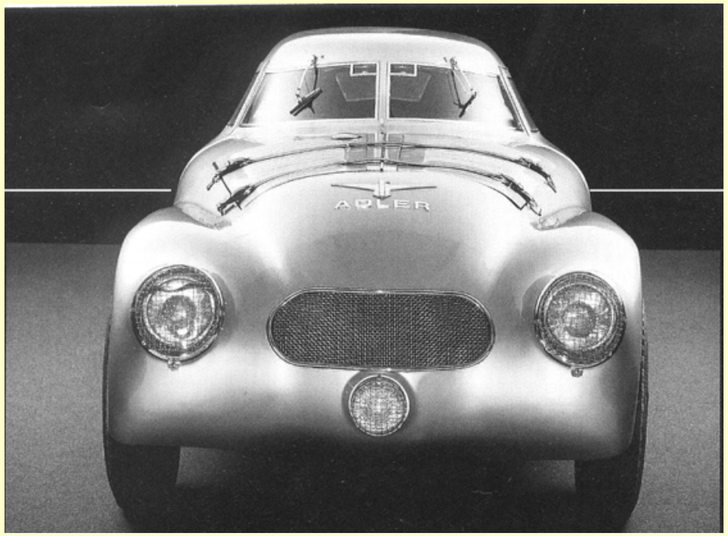


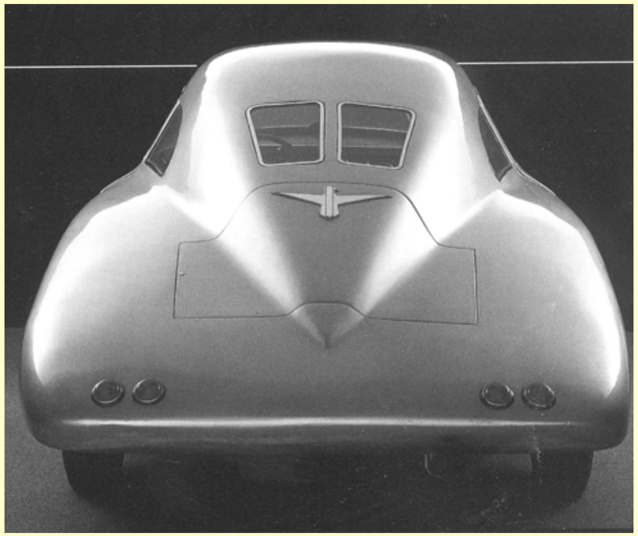
The combined aerodynamic shapes of Paul Jaray (1921)

# Brief historical overview…

*Adler-Trumpf*
**1.5 liter (1934)**

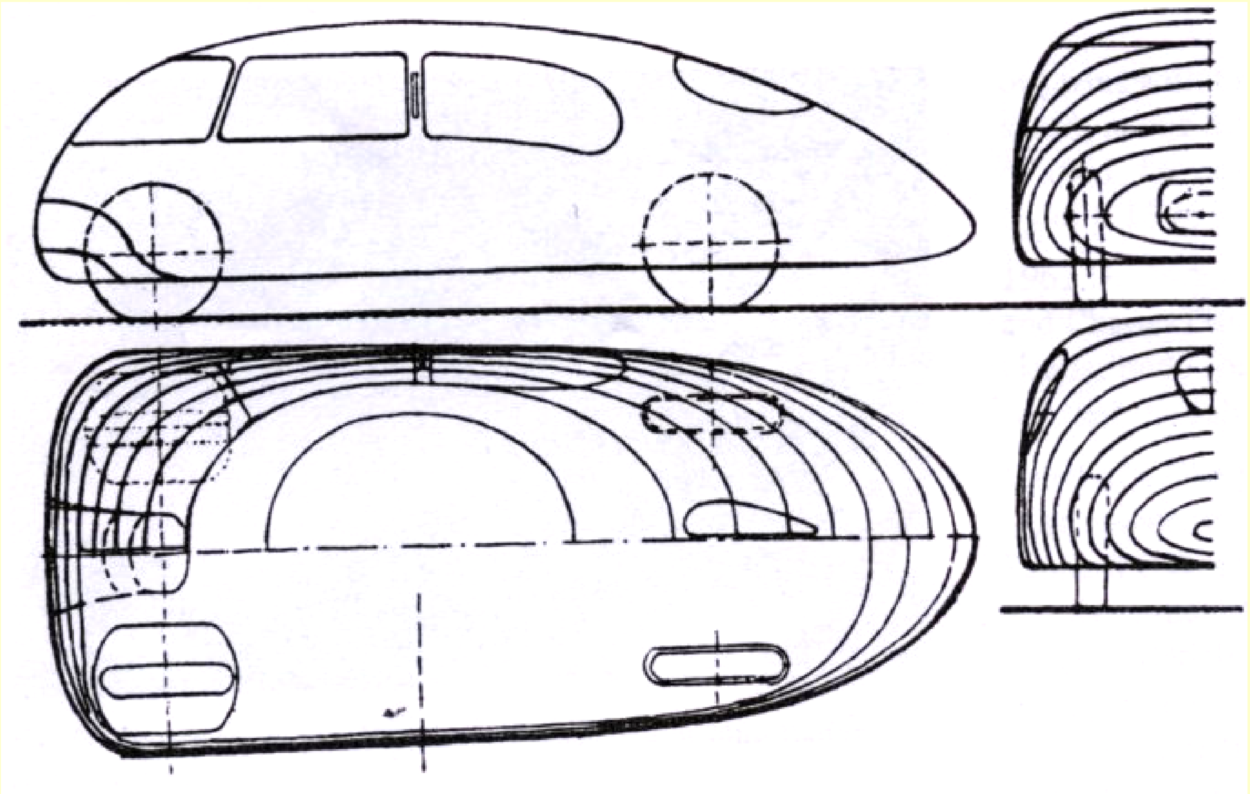




DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

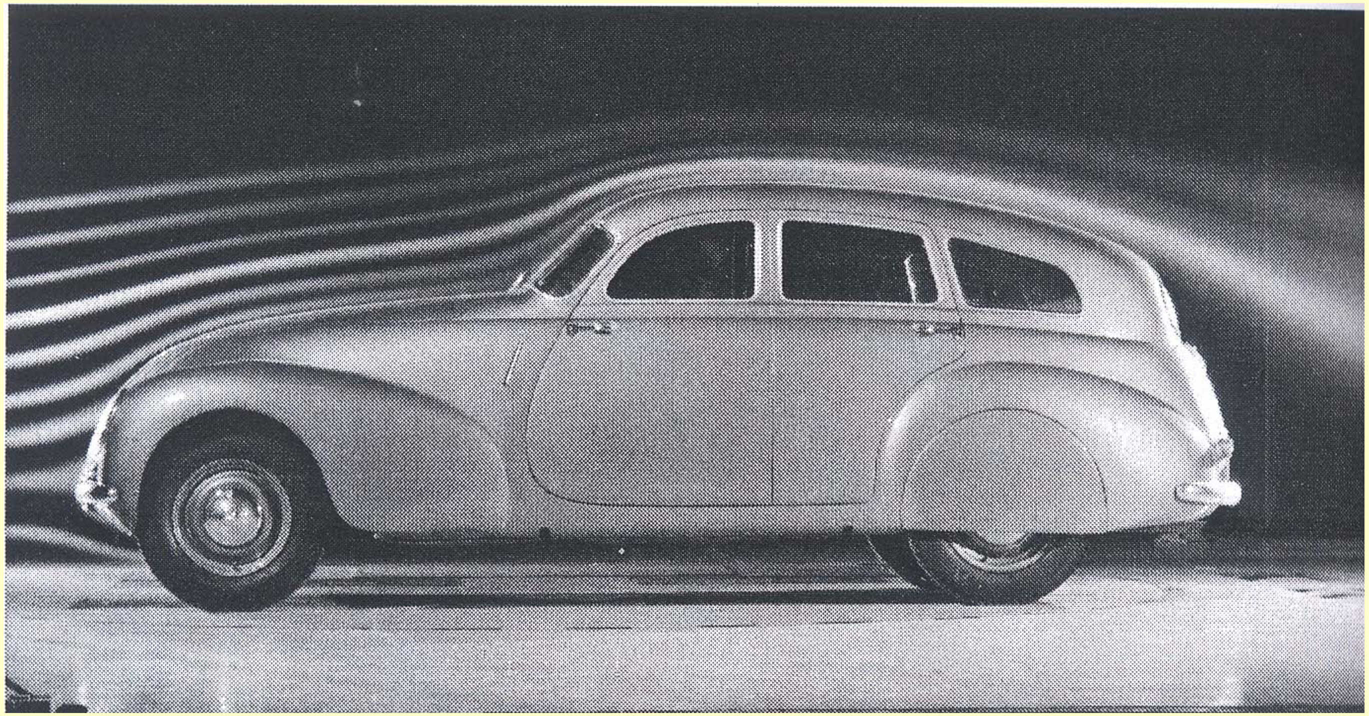
# Brief historical overview…



**The ideal automobile shape of Schlör (1938)**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

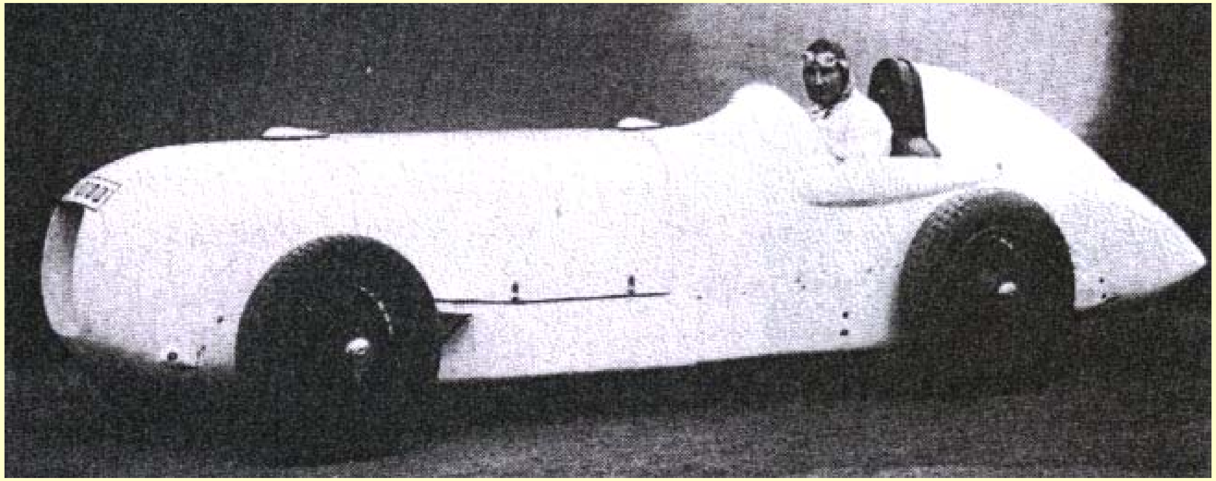
# Brief historical overview…



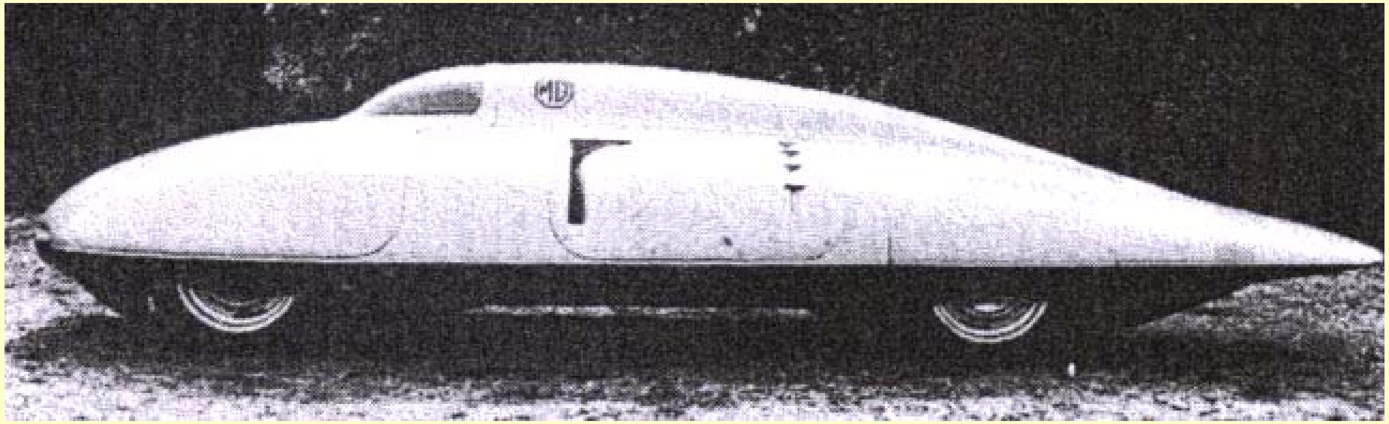
***K5* of Kamm (1938)**

$C_D = \underline{0.37}$

# Brief historical overview…

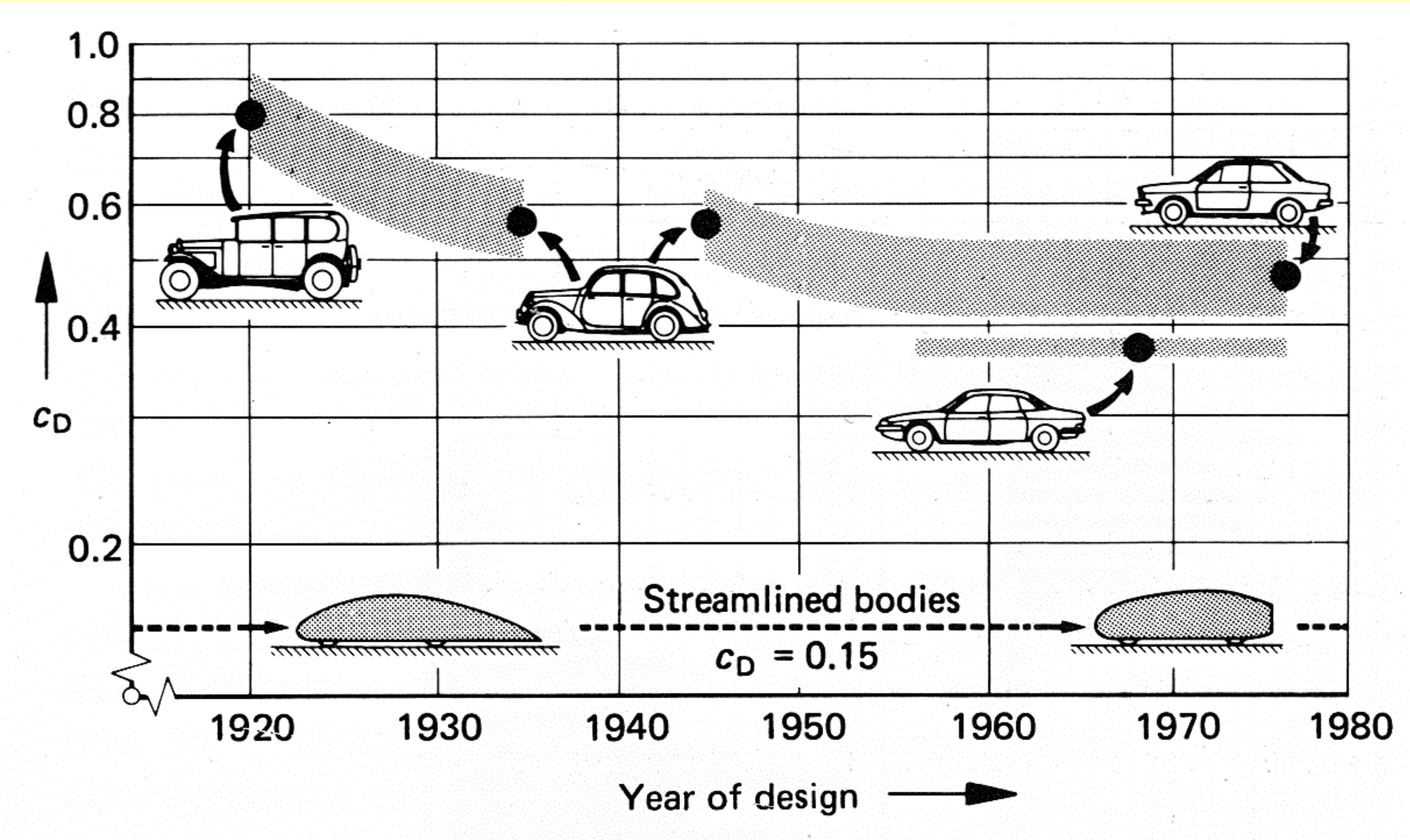


*Mercedes-Benz SSK*
**of Baron**
**König-Fachsenfeld (1932)**



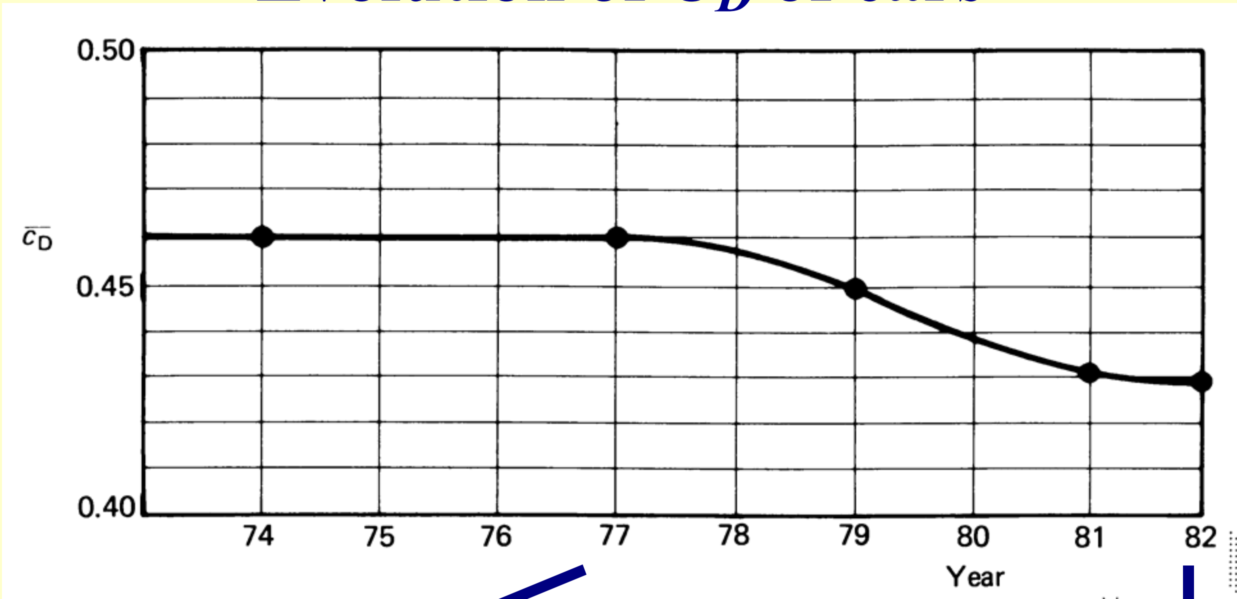
**The record car**
***MG/EX181* (1957)**

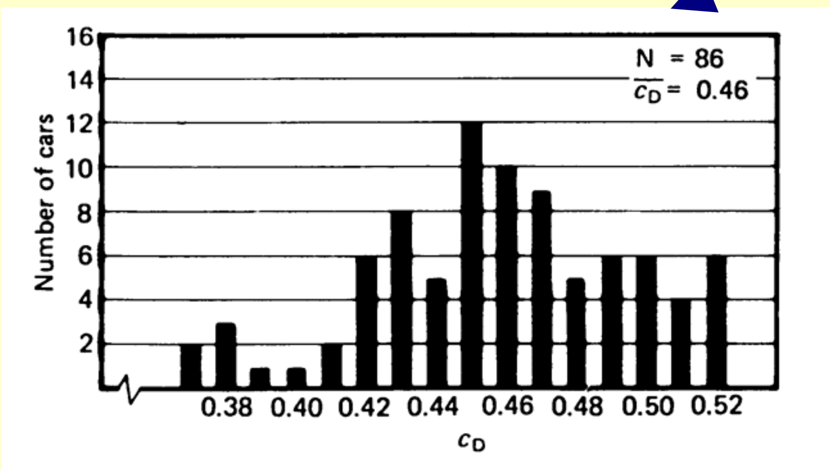
# Evolution of $C_D$ of cars

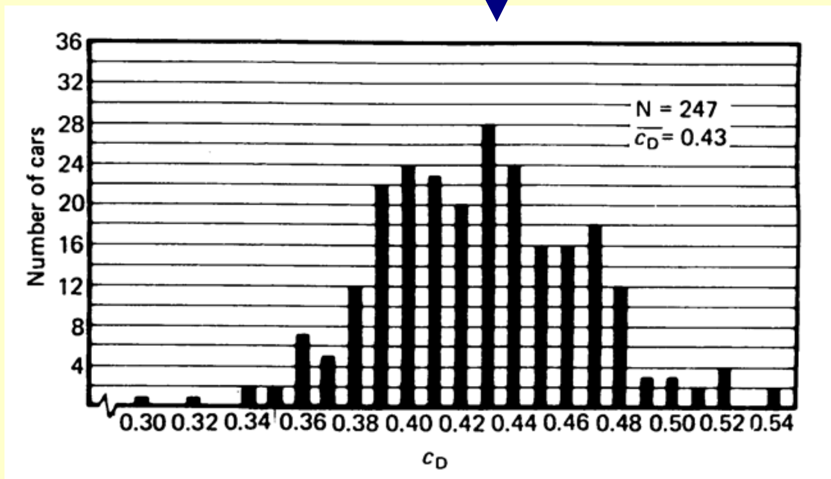


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Evolution of $C_D$ of cars

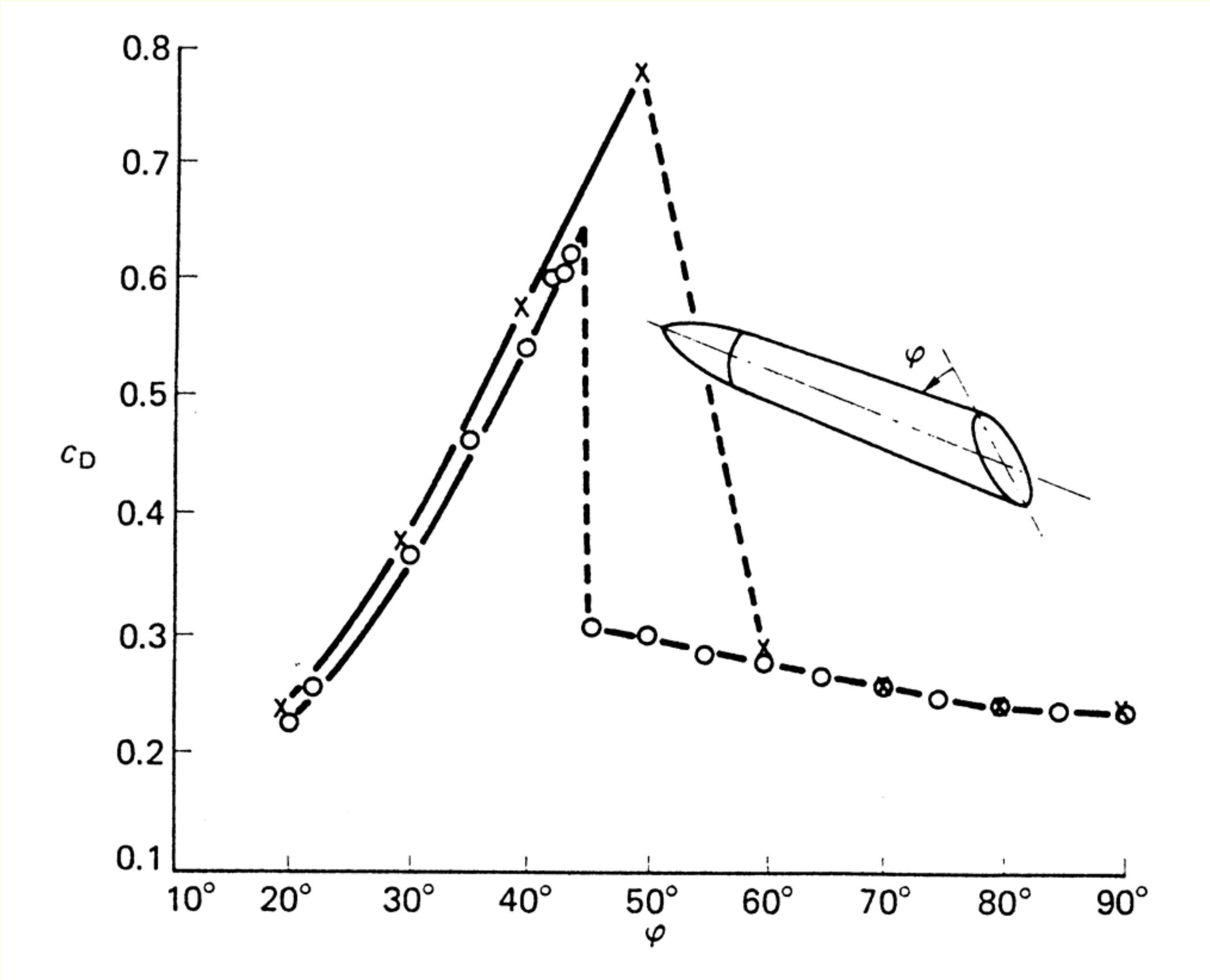


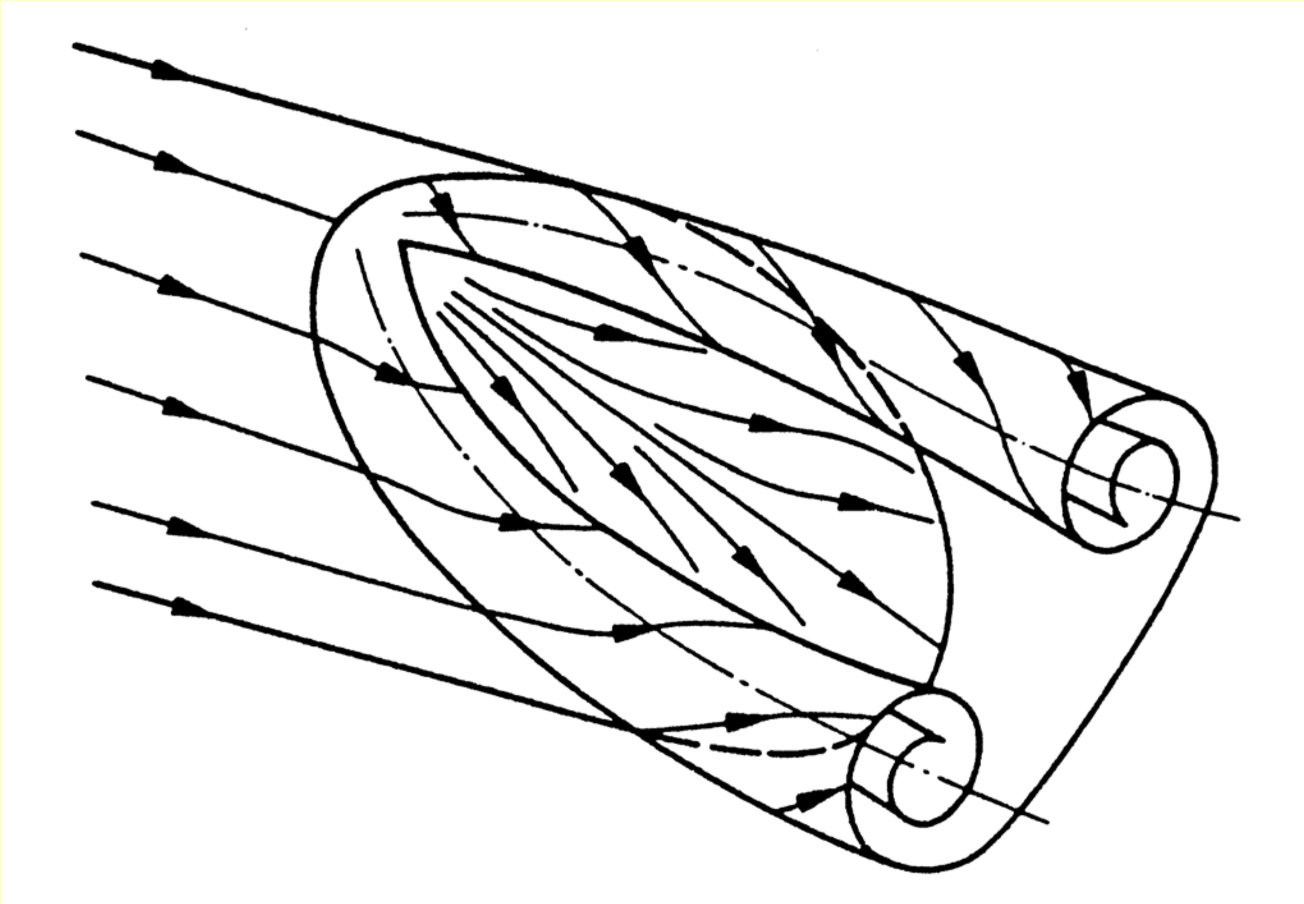
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# The Morel bodies

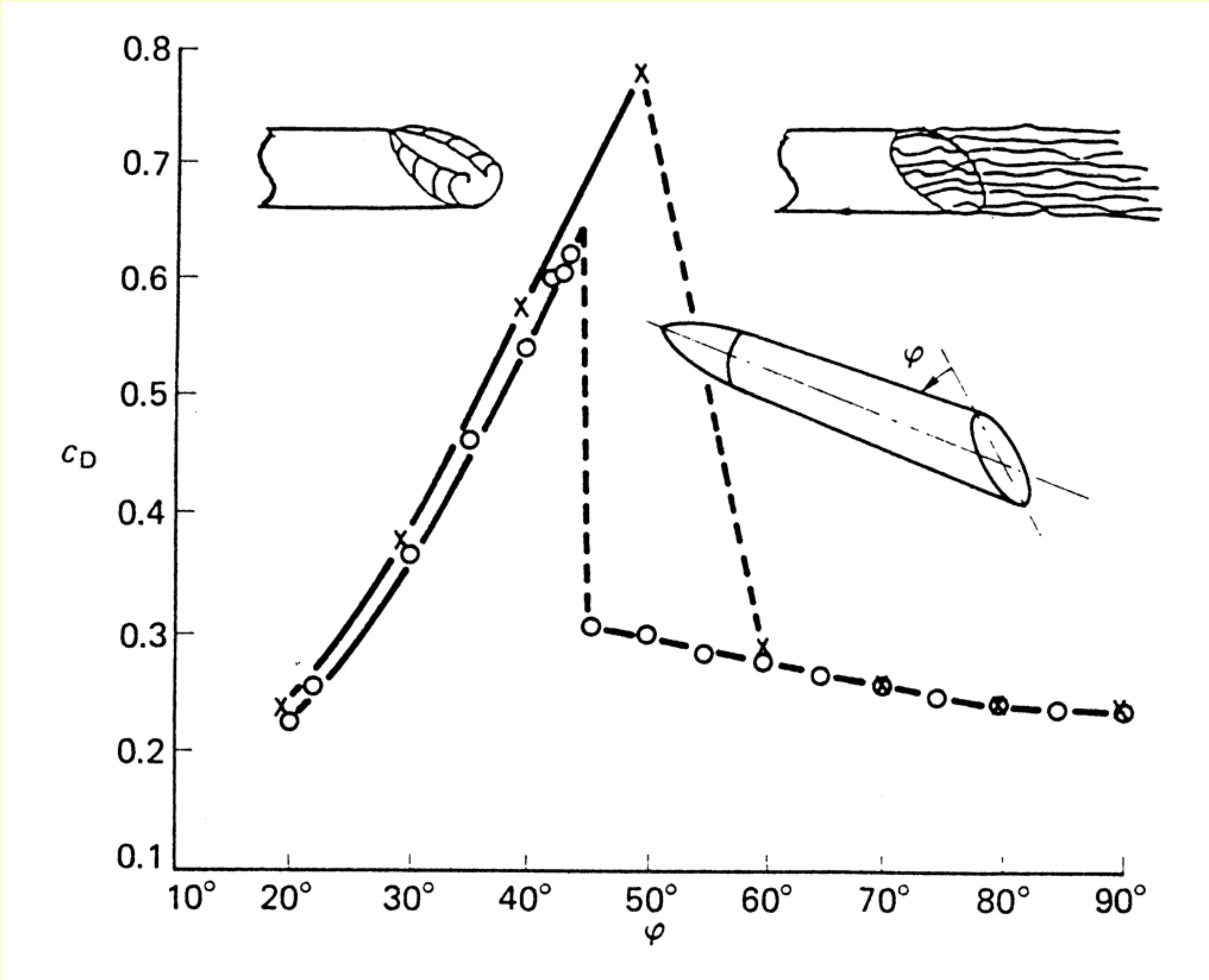


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

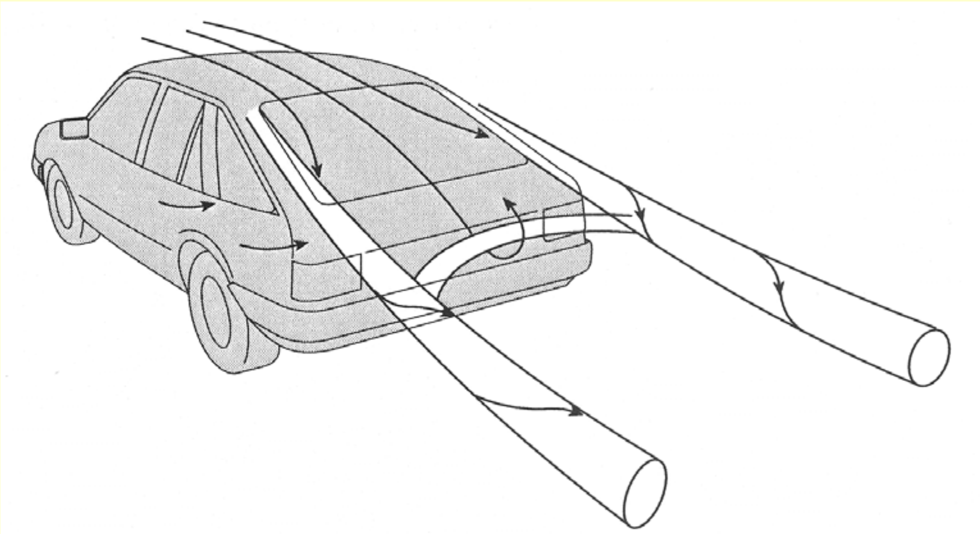
# Base flow with concentrated vortices



# The Morel bodies

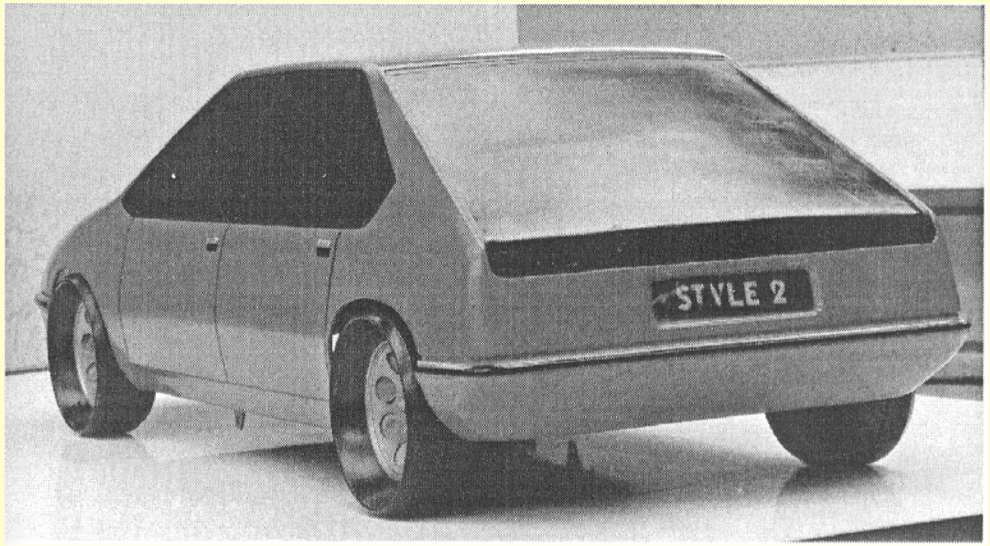


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE



**The same phenomenon may occur also for cars**

**$C_D = 0.55$!**



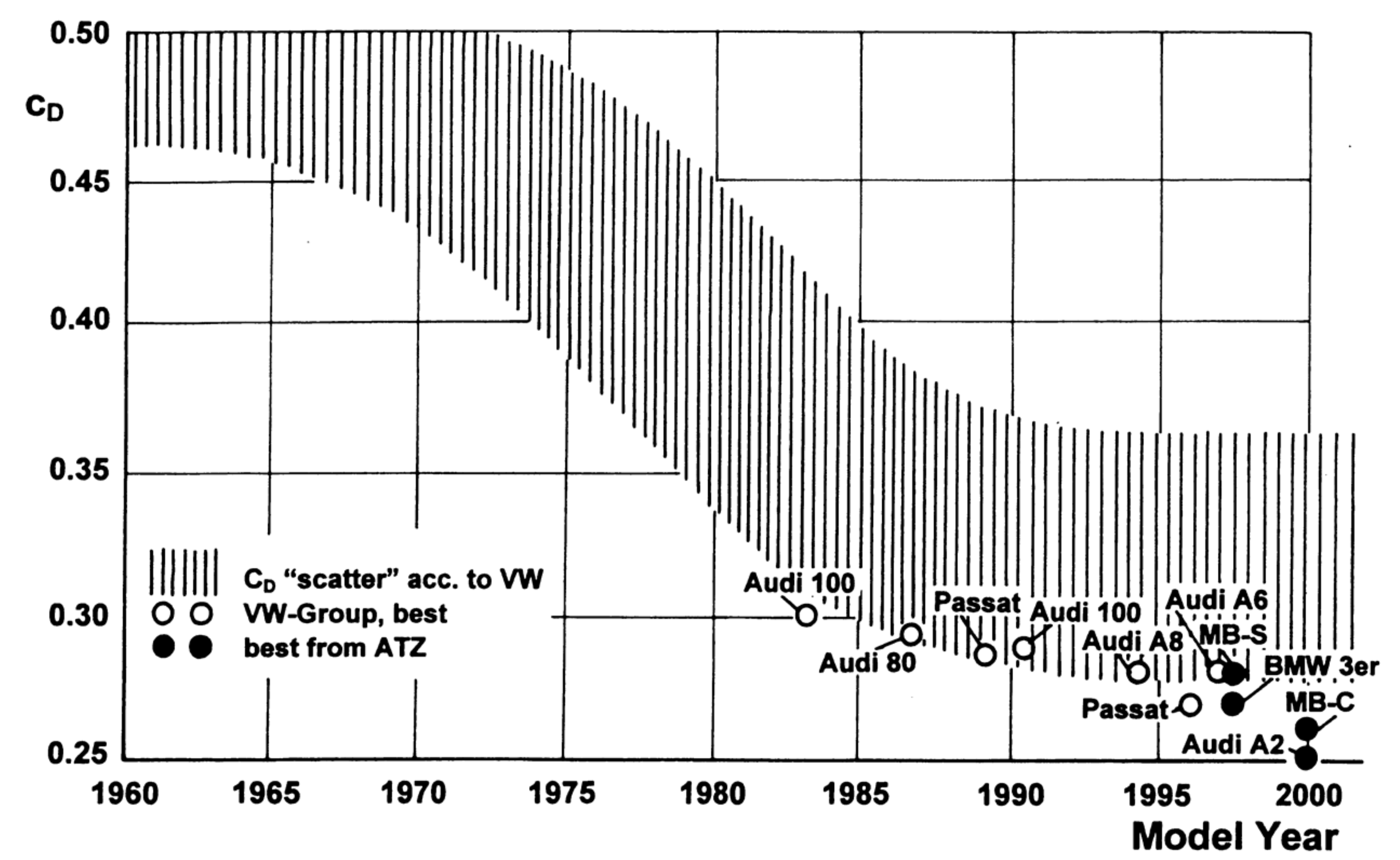
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# In the ‘70s several cars were Morel bodies…

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# But then the lesson was learned…


# Evolution of $C_D$ of cars



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

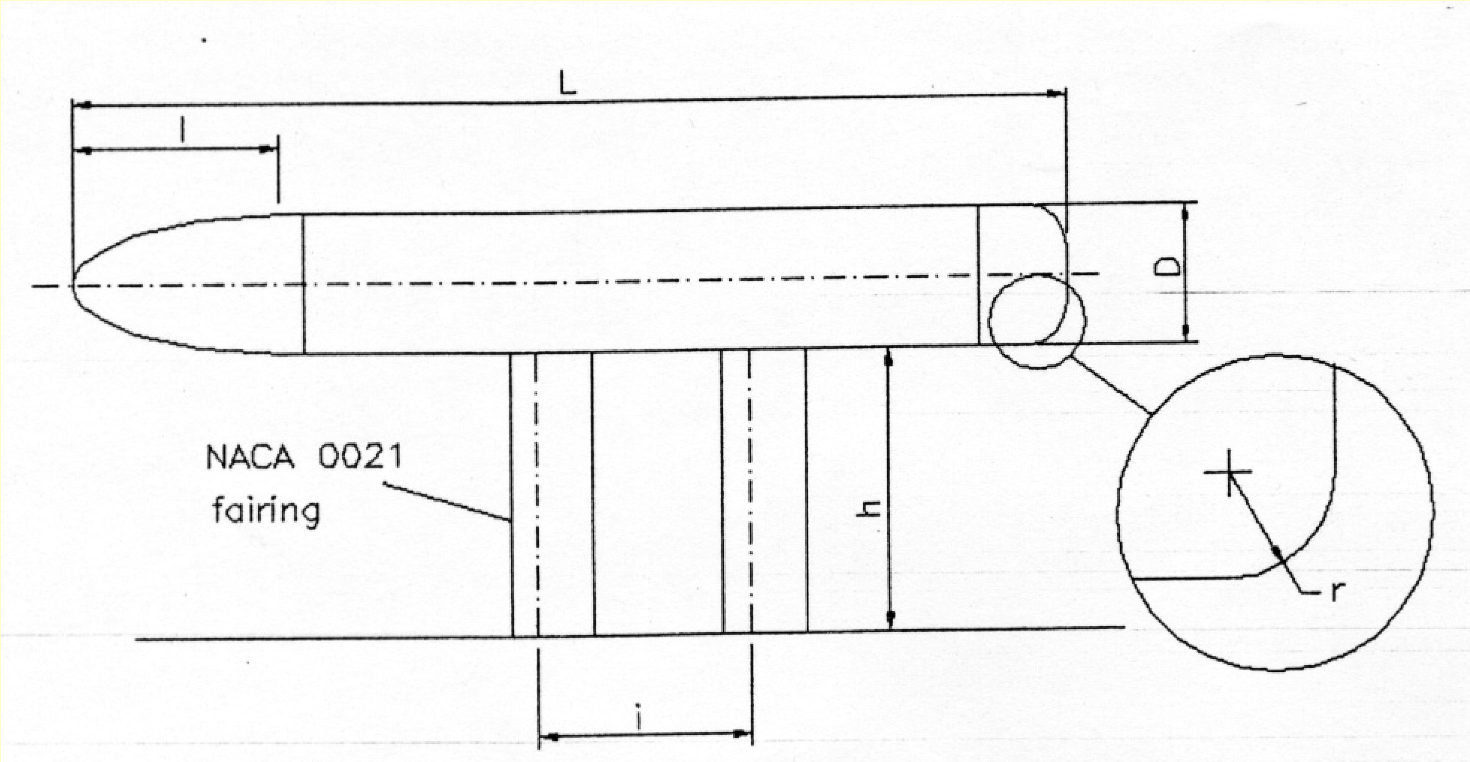
# Anyway…

## Certain cars were found to have a higher $C_D$ than expected


⇓

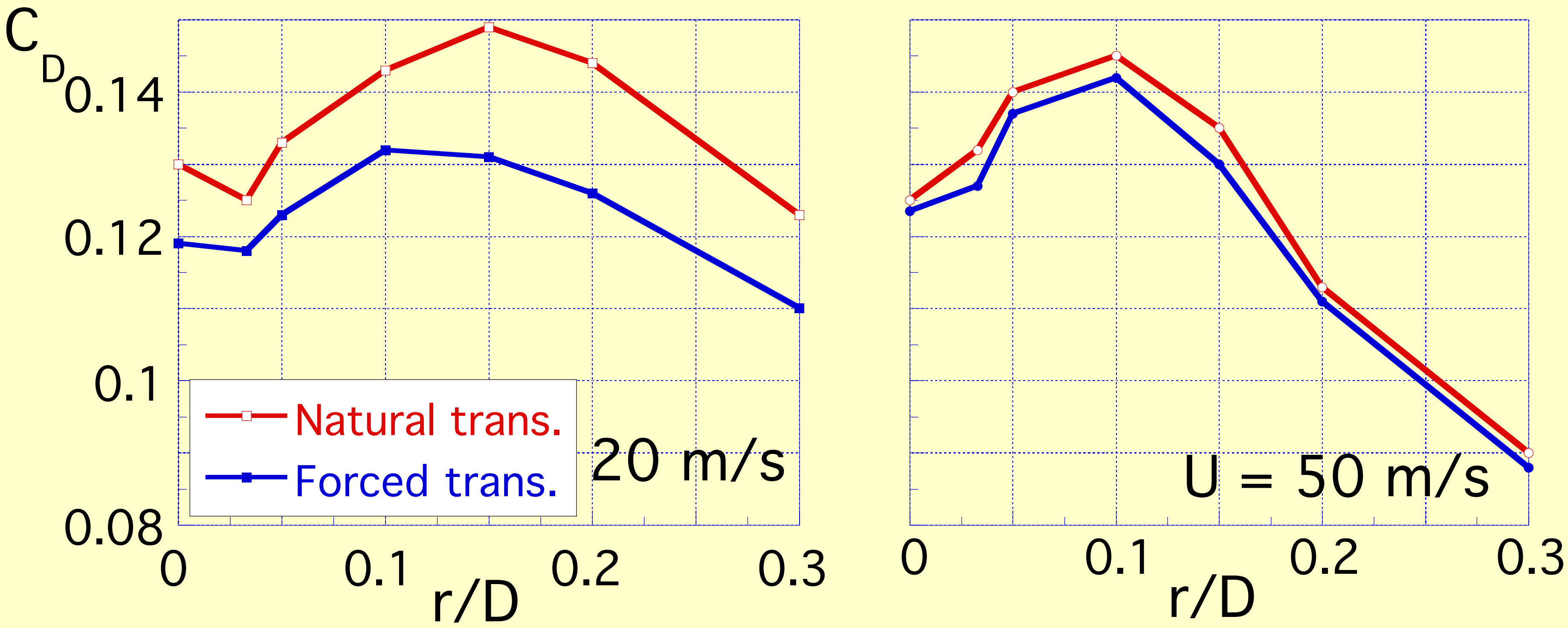
## Investigation to understand the reason

## Analysed problem: <u>Axisymmetrical body</u> ending with different radius of curvature, *r/D*




- **Measurement of forces and pressures**

# *Effect of afterbody rounding*




**A maximum of drag exists for a certain value of r/D**

**The phenomenon depends on geometrical and flow parameters**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Also in this case the lesson has been learned…



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## One of the present cars with lower $C_D$


$C_D = 0.25$

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Prototypes of cars with $C_D < 0.2$

***C.N.R.***
**Prototype**

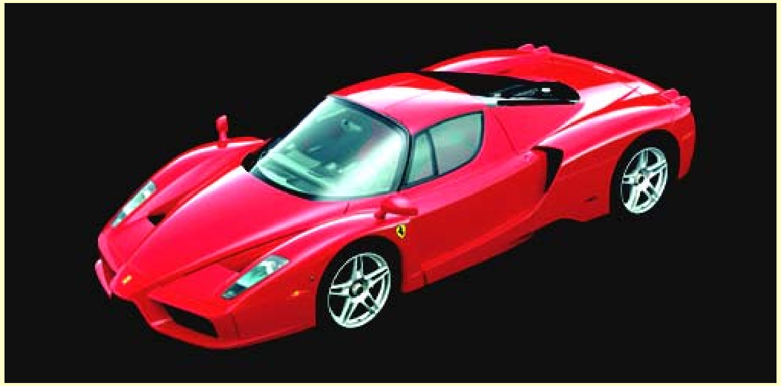
***Fioravanti Flair***
**Prototype**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Several present production cars have $C_D \leq 0.3$



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE




**High engine power**

↓

**$V_{max}$ > 300 km/h**

**Necessity of assuring high and safe global performance**

↓

**For high-performance cars it is essential that the vertical aerodynamic force be not directed upwards**

# Indeed:

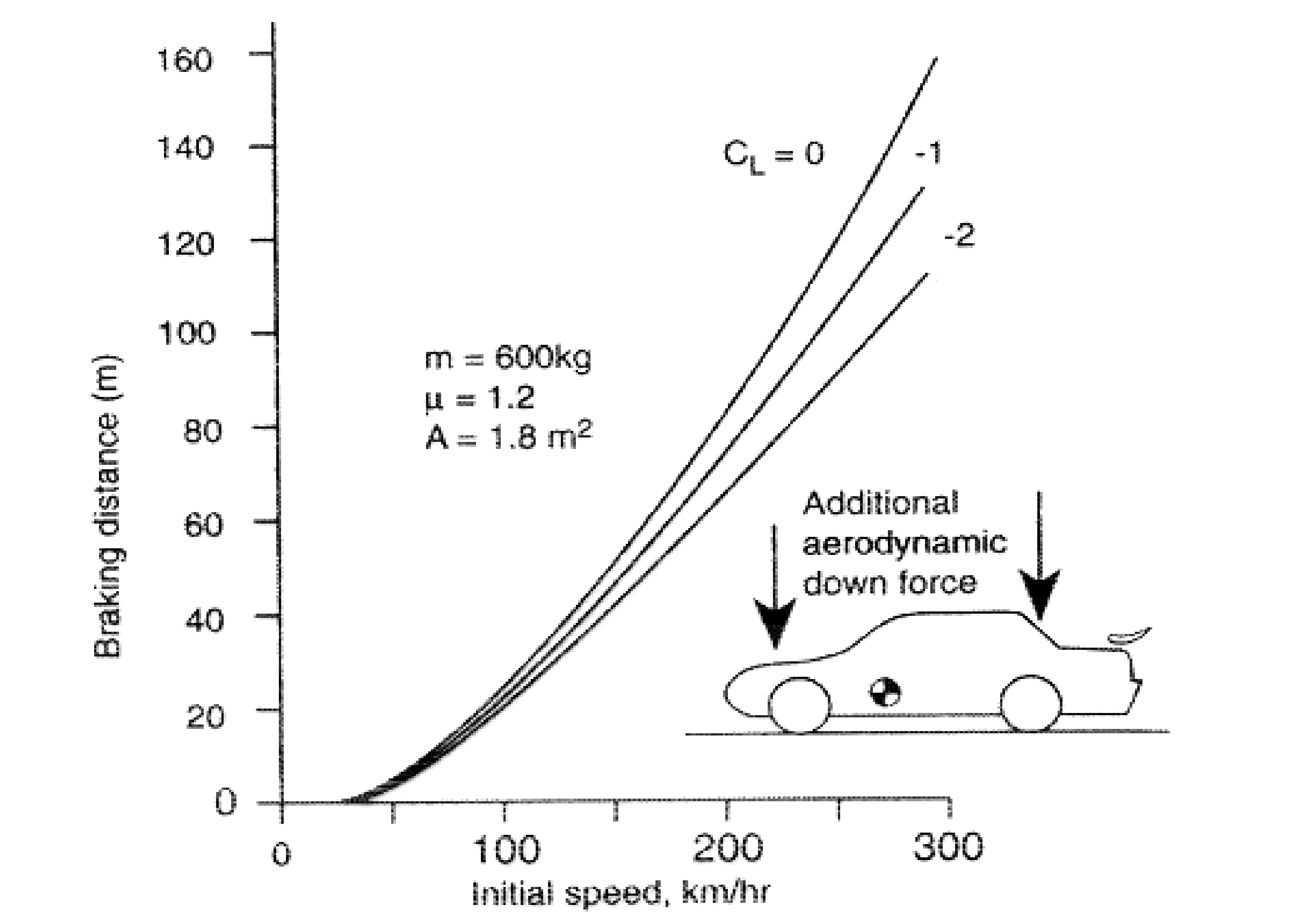
**The grip of the tyres is proportional to the downward force acting on them (weight ± aerodynamic force )**

**If the grip <u>decreases</u>:**

- **The breaking space increases**
- **The maximum admissible turning velocity decreases**

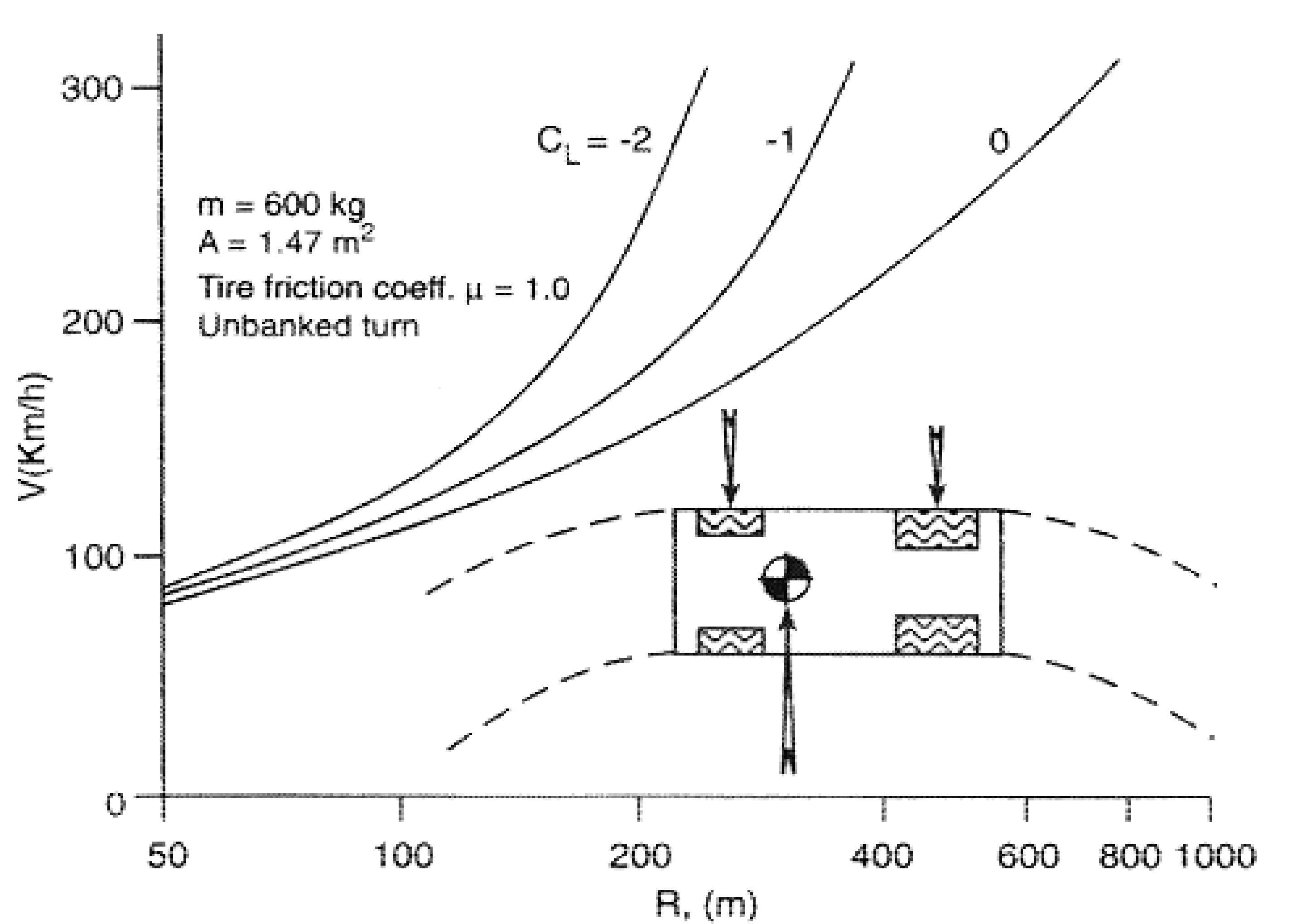
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Effect on breaking space



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Effect on maximum admissible turning velocity



**In general cars tend to be *lifting bodies***
**(upward vertical aerodynamic force)**

↓

**This may cause even beautiful cars**
**to become potentially dangerous**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Aerodynamic Design Goals:

**High downward aerodynamic forces (negative lift)**

**High efficiency (low drag)**

⇓

**Negative $C_z$**

**Balance between front and rear wheels**

**$C_x$ as small as possible**

**The increase of the vertical download generally causes an increase in drag**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Generation of Aerodynamic Download

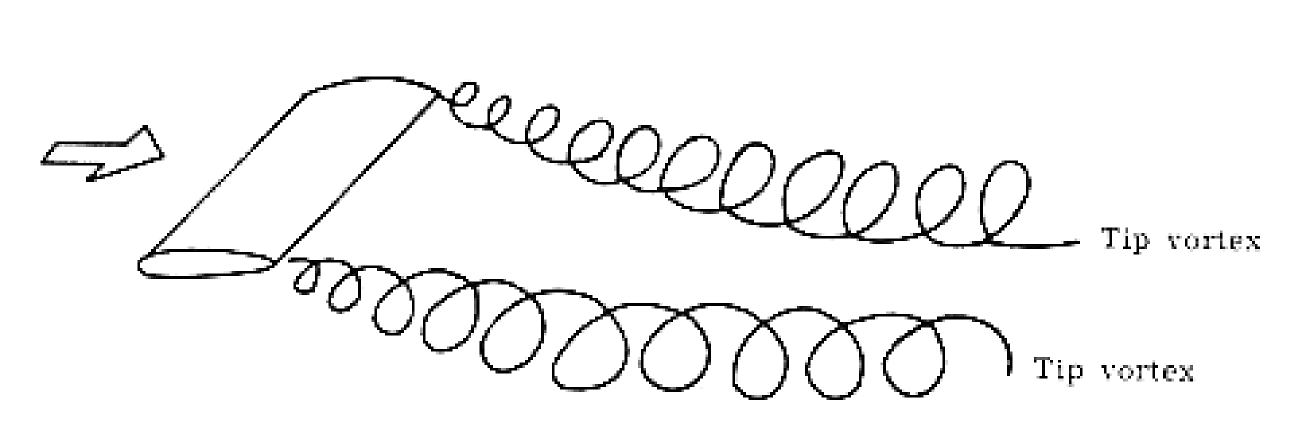
## Added devices: wings, spoilers, etc.


**High and concentrated load**

**Interference with the style and increased drag**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Wing wake drag




# Generation of Aerodynamic Download

**The whole car may be used to generate the download**

## Body

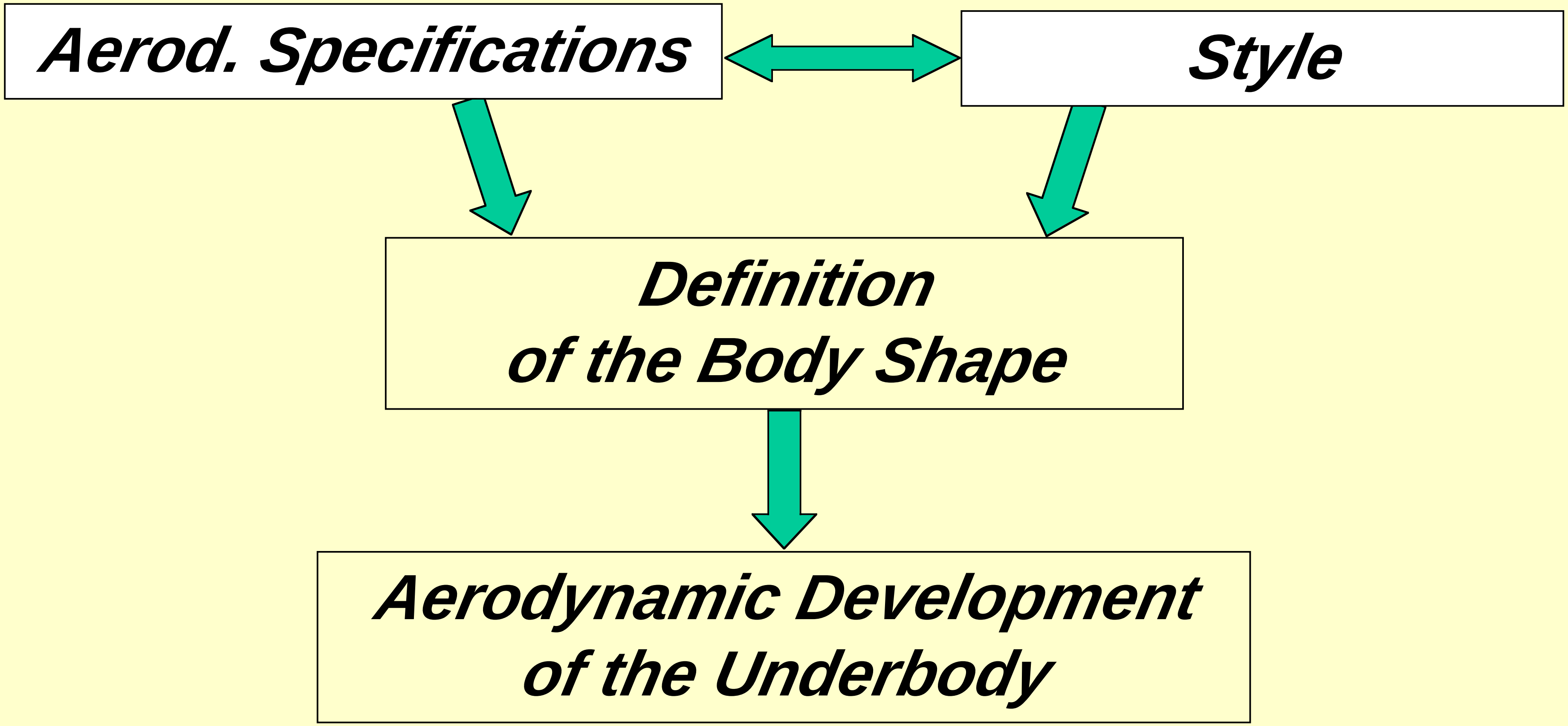
**The design of the upper part of the car may be used to generate the required download producing the minimum amount of drag**

## Underbody

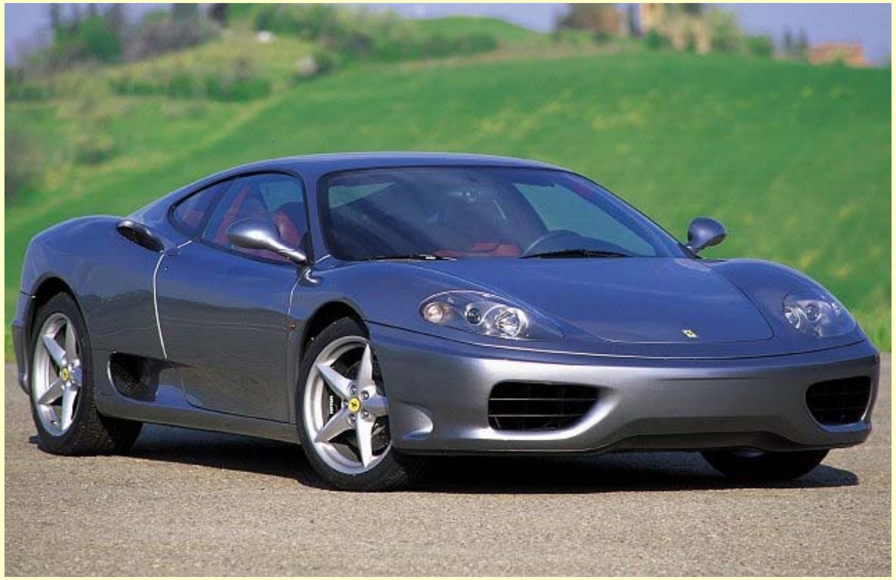
**An appropriate design of the underbody allows high aerodynamic performance to be obtained without interfering with the style**

- A "rough" uncovered underbody slows the airflow and does not allow the lower part of the car to be used to generate a download.
- A smooth faired underbody improves the airflow, increases the download and reduces the drag.
- A smooth faired underbody "modelled" with a diffuser accelerates the airflow below the vehicle and further improves the aerodynamic performance.

# SCHEME OF AERODYNAMIC DESIGN



# The Influence of Aerodynamics on the Design of High-Performance Road Vehicles - Part 2



**Guido Buresti**

*Department of Aerospace Engineering*

*University of Pisa (Italy)*

# CONTENTS

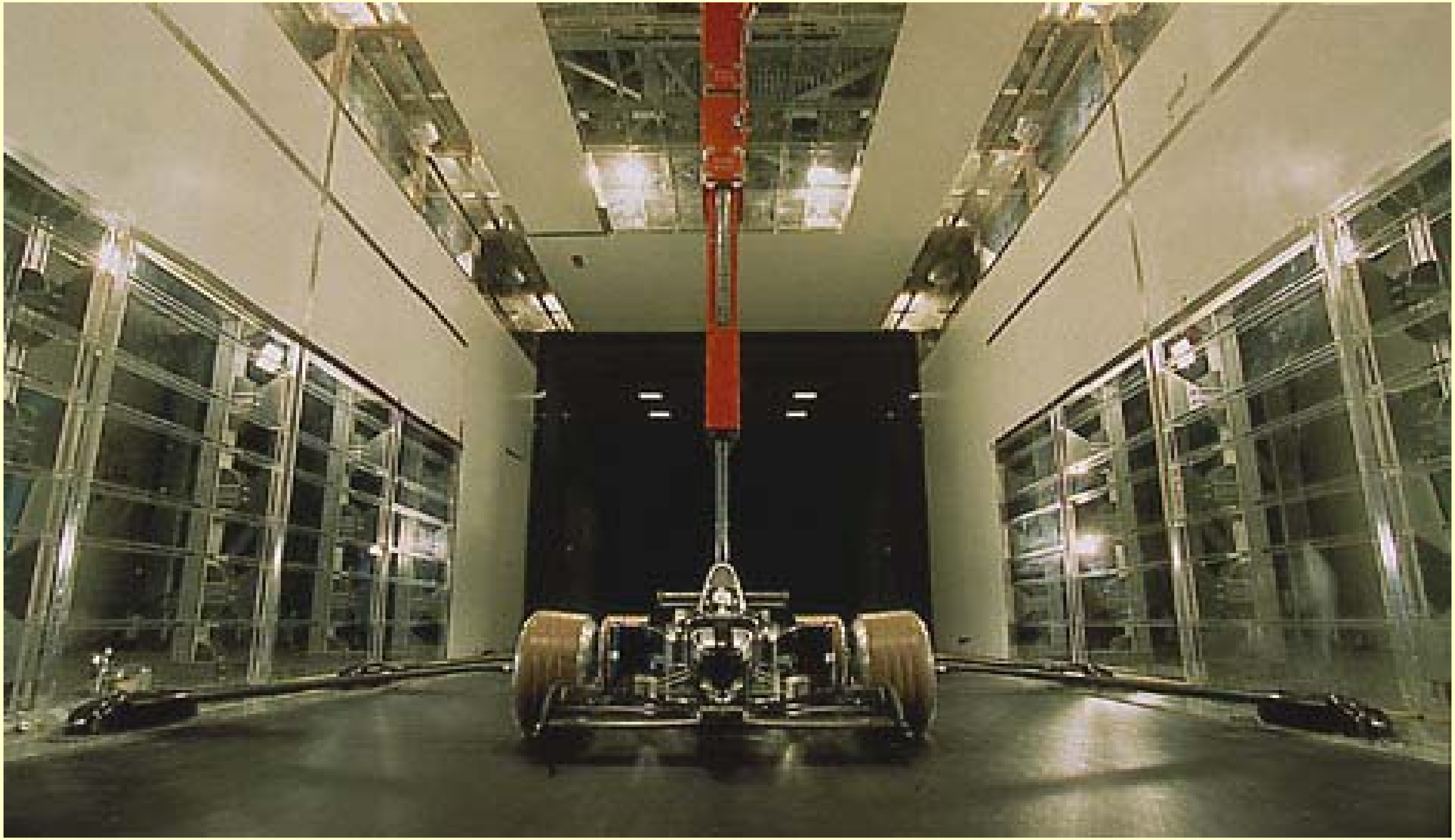
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Experimental techniques

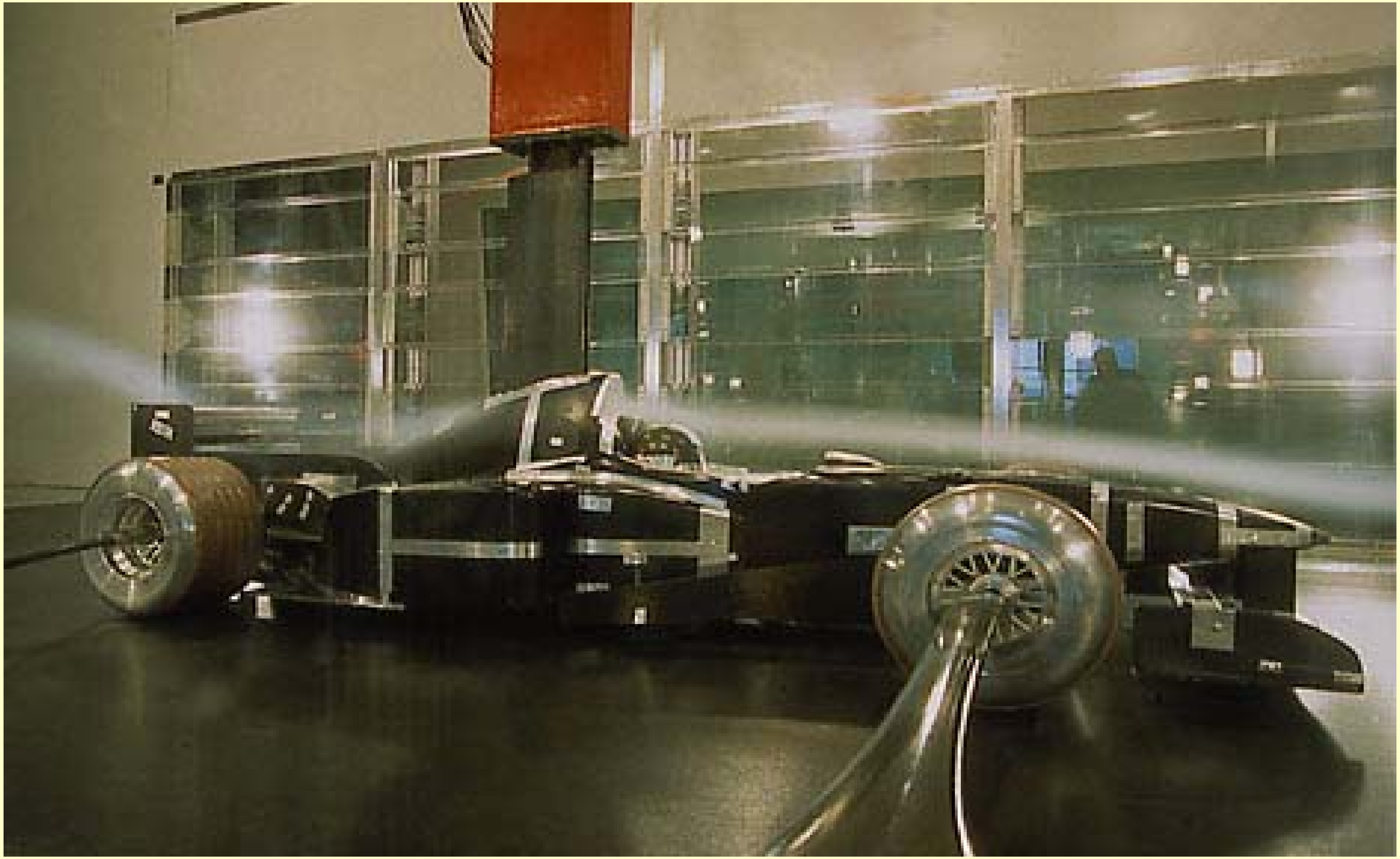
## Specific wind tunnels for automotive research

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# The Ferrari Gestione Sportiva wind tunnel



# The Ferrari Gestione Sportiva wind tunnel



# The Ferrari Gestione Sportiva "small" wind tunnel

# Numerical techniques

**Numerical solution of the equations of fluid dynamics (Navier-Stokes equations)**

**Basic method : Direct Numerical Simulation (DNS)**

⬇

**For typical application conditions DNS is not possible!**

⬇

**Reynolds-averaged Navier-Stokes equations (RANS)**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## Reynolds-averaged Navier-Stokes equations (RANS)

**"Commercial" codes are used (FLUENT, STAR-CD)**

**Computing times: from a few hours to several days according to complexity of configuration and available computational resources**

**Good qualitative results, and even quantitative, if codes are validated with experimental data for the analysed class of bodies**

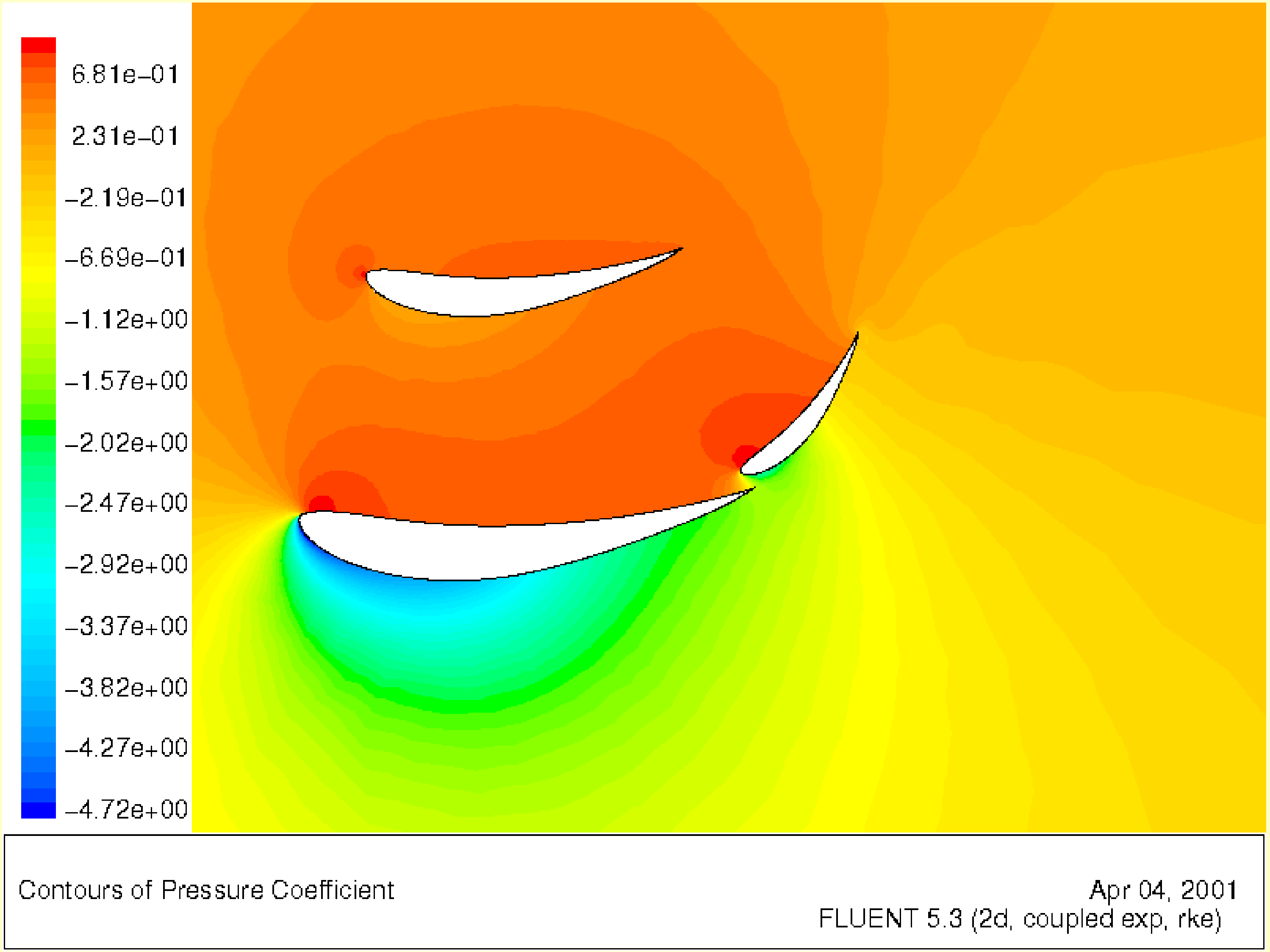
⇓

**A good aerodynamic competence is necessary**

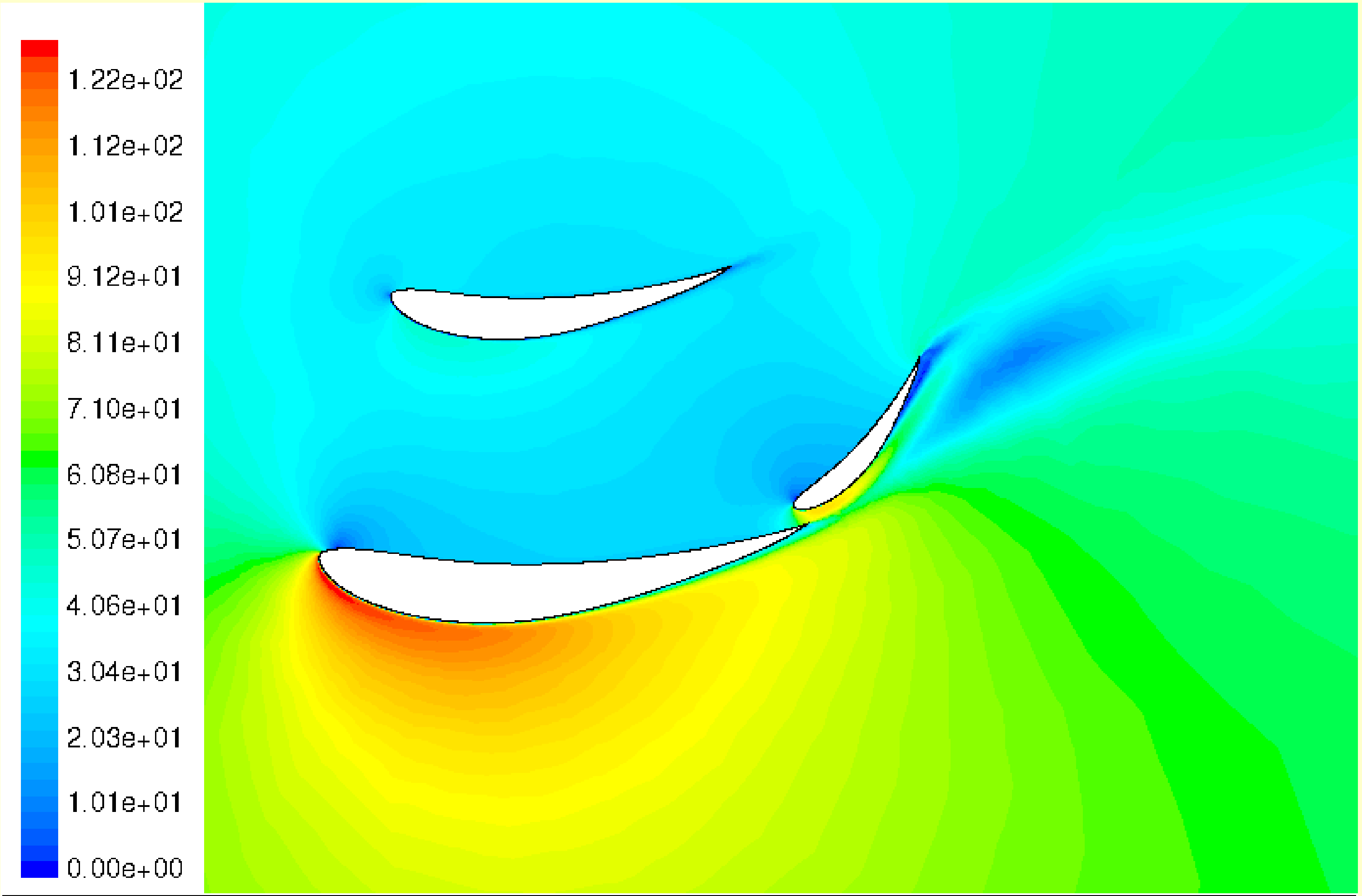
**Good for comparisons between different configurations**

**Good indications on physical phenomena**

# *Examples of RANS numerical results*



# *Examples of RANS numerical results*

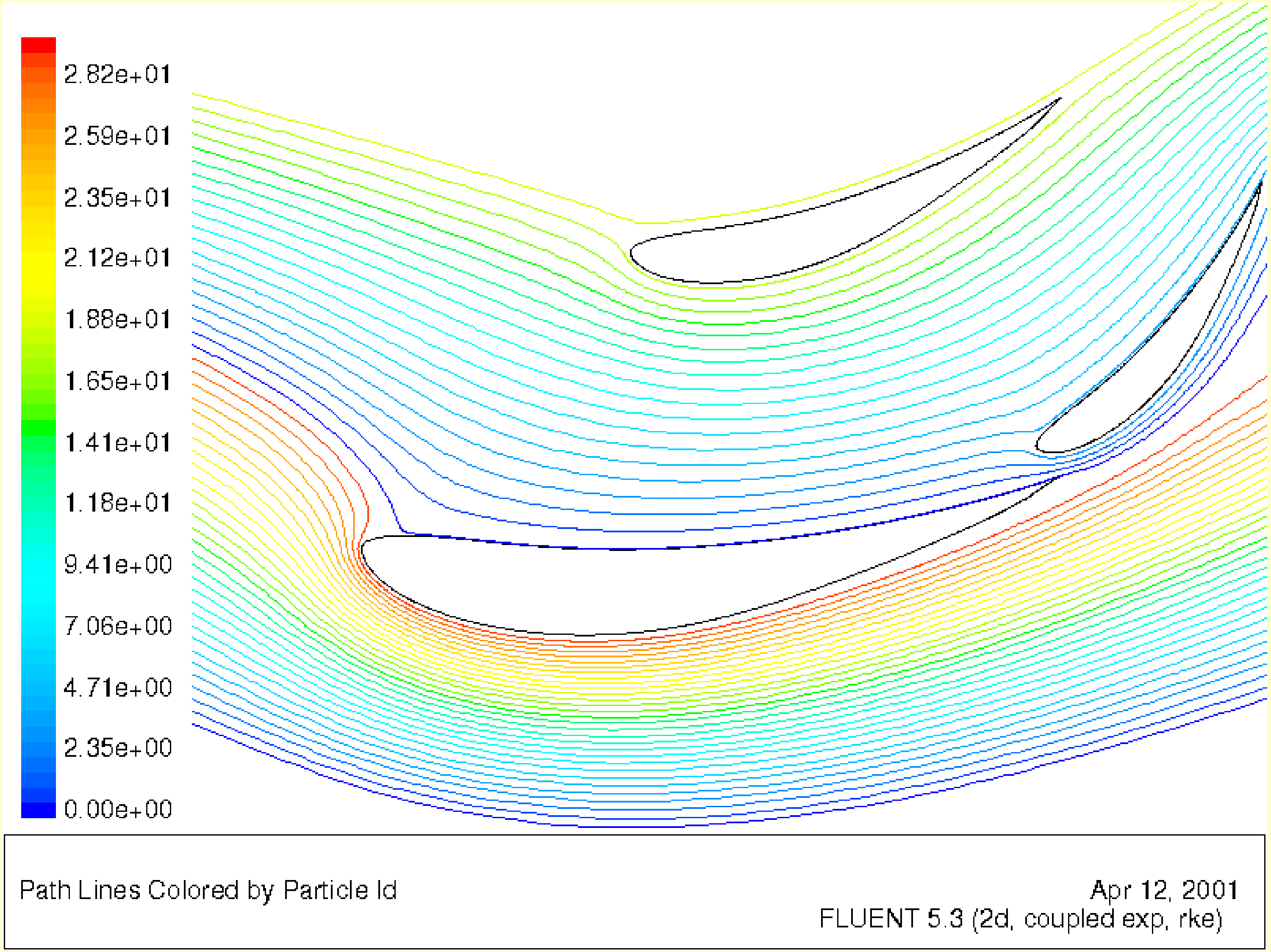



Contours of Velocity Magnitude (m/s)

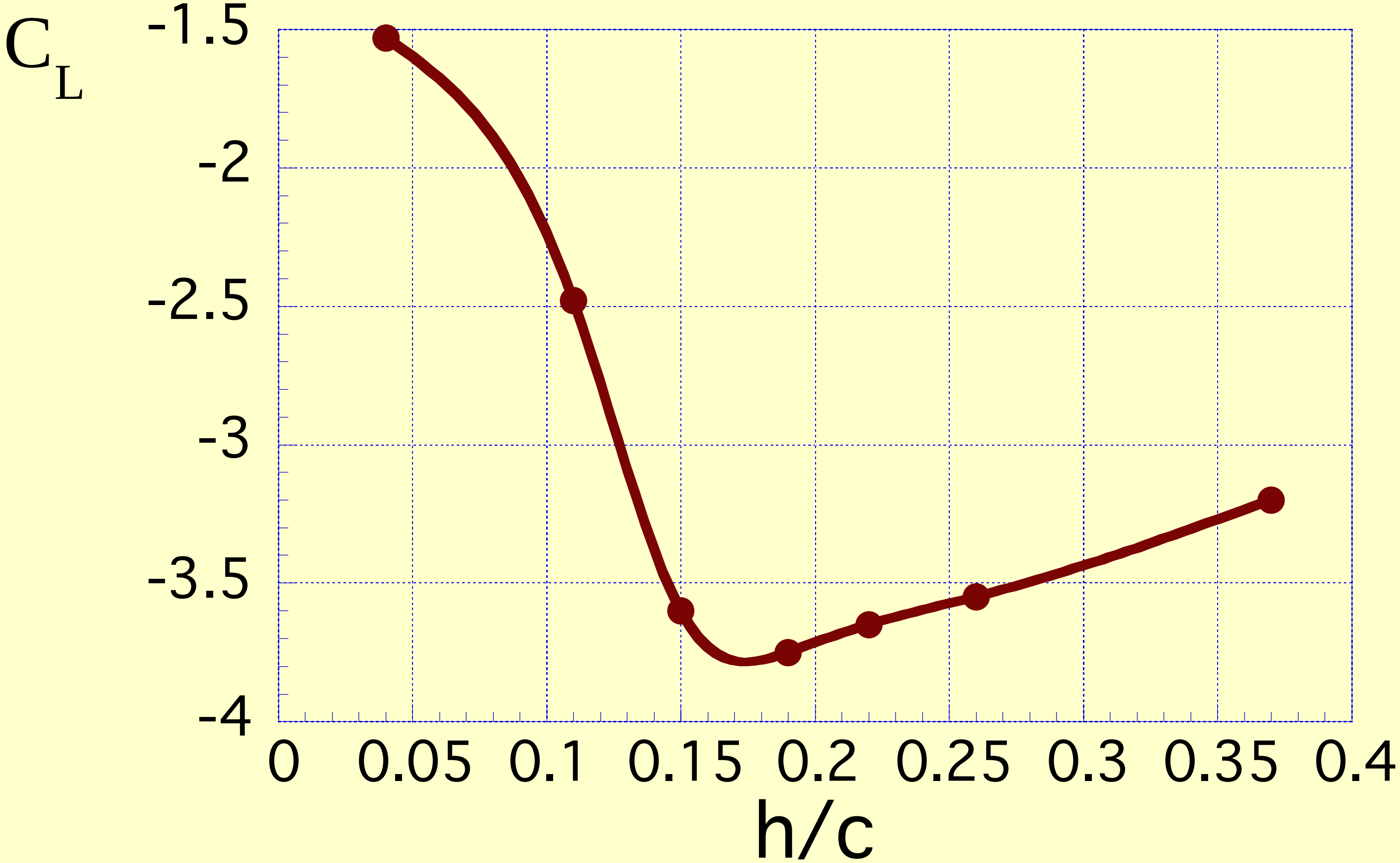
Apr 04, 2001
FLUENT 5.3 (2d, coupled exp, rke)

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# *Examples of RANS numerical results*

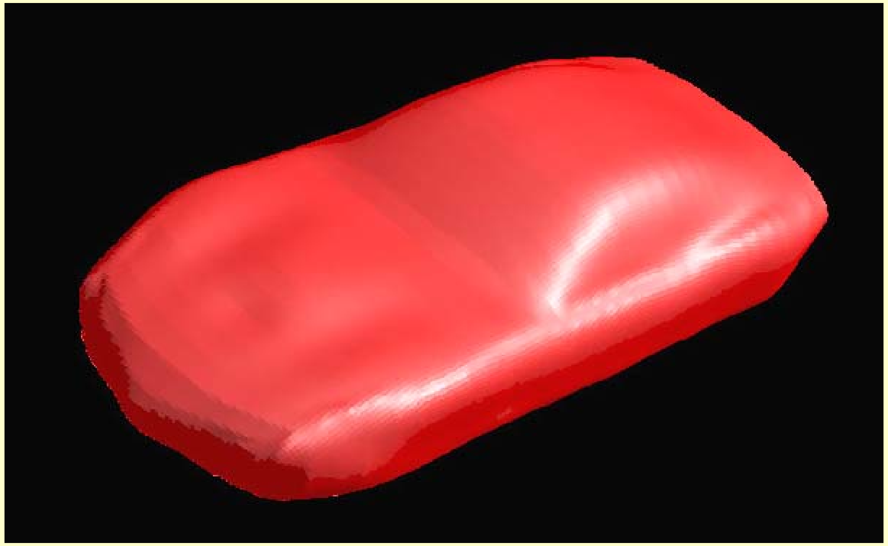


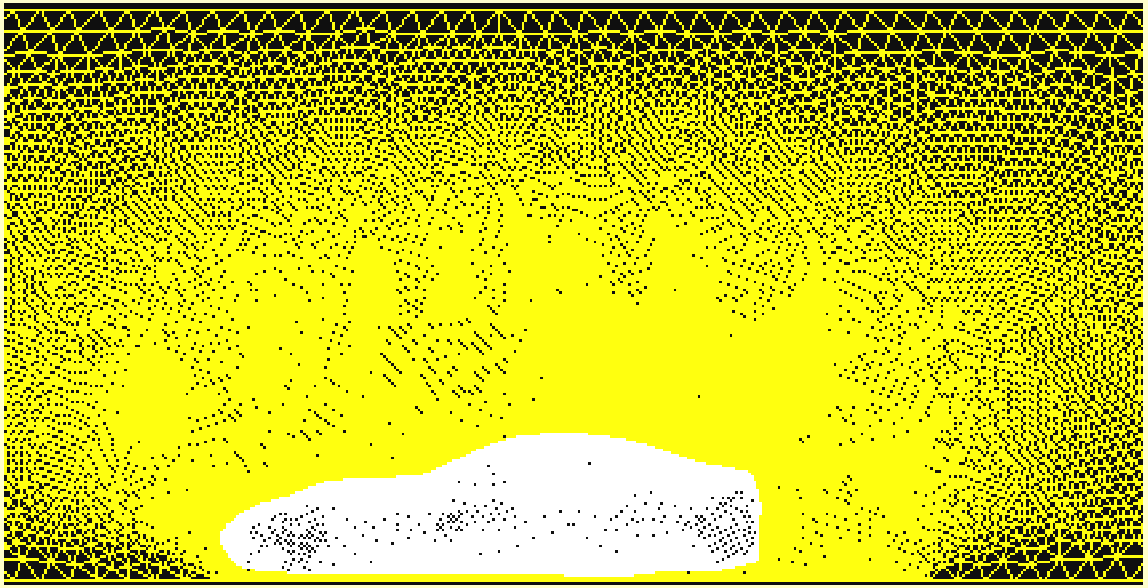
## Analysis of download of a front F1 airfoil with varying distance from the ground

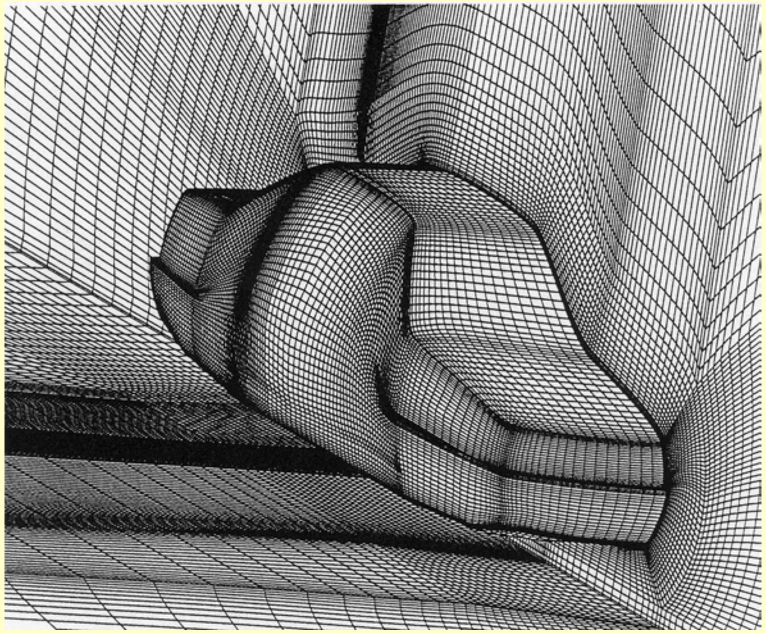


# *Examples of RANS numerical results*

**Discretization of vehicle and computational grid**

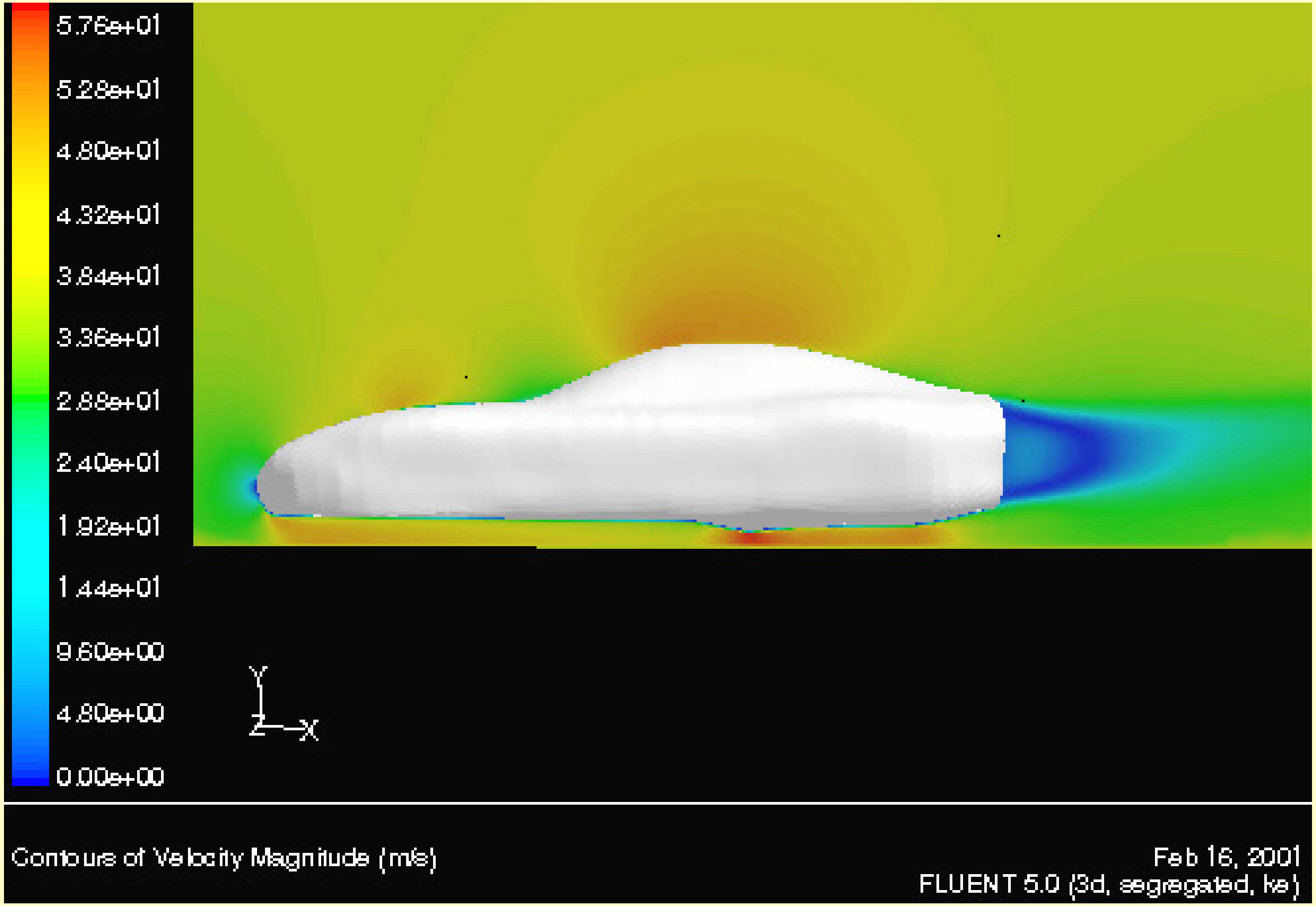




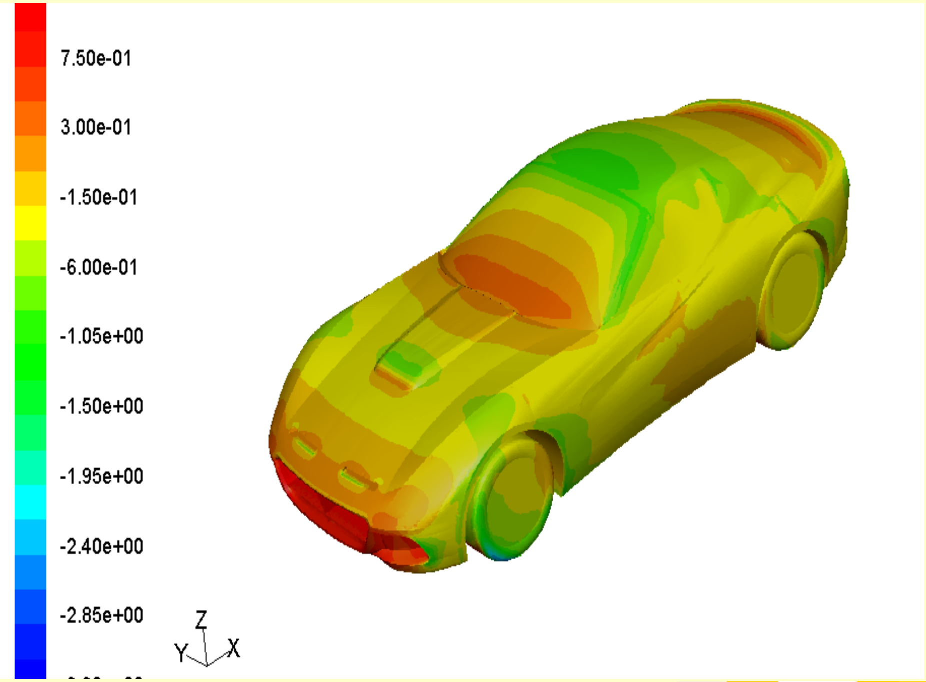


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Velocity magnitude

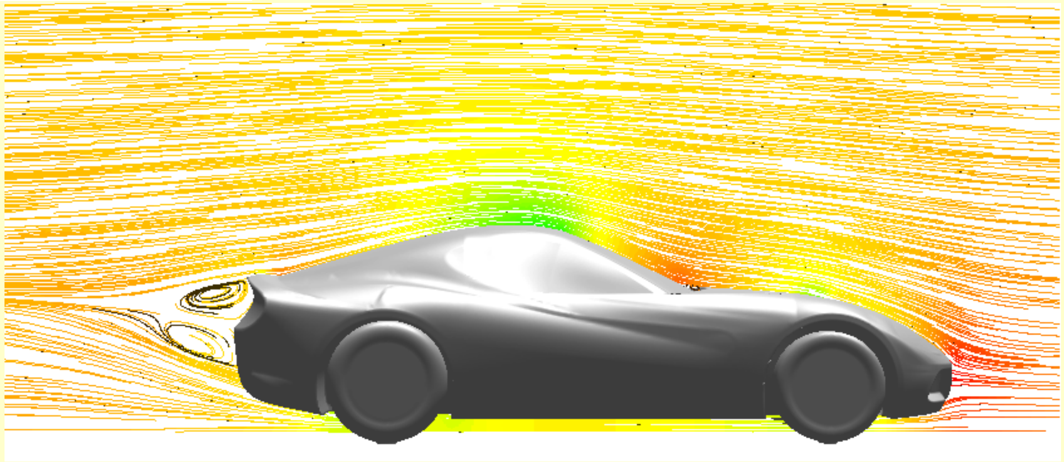


# *Examples of RANS numerical results*

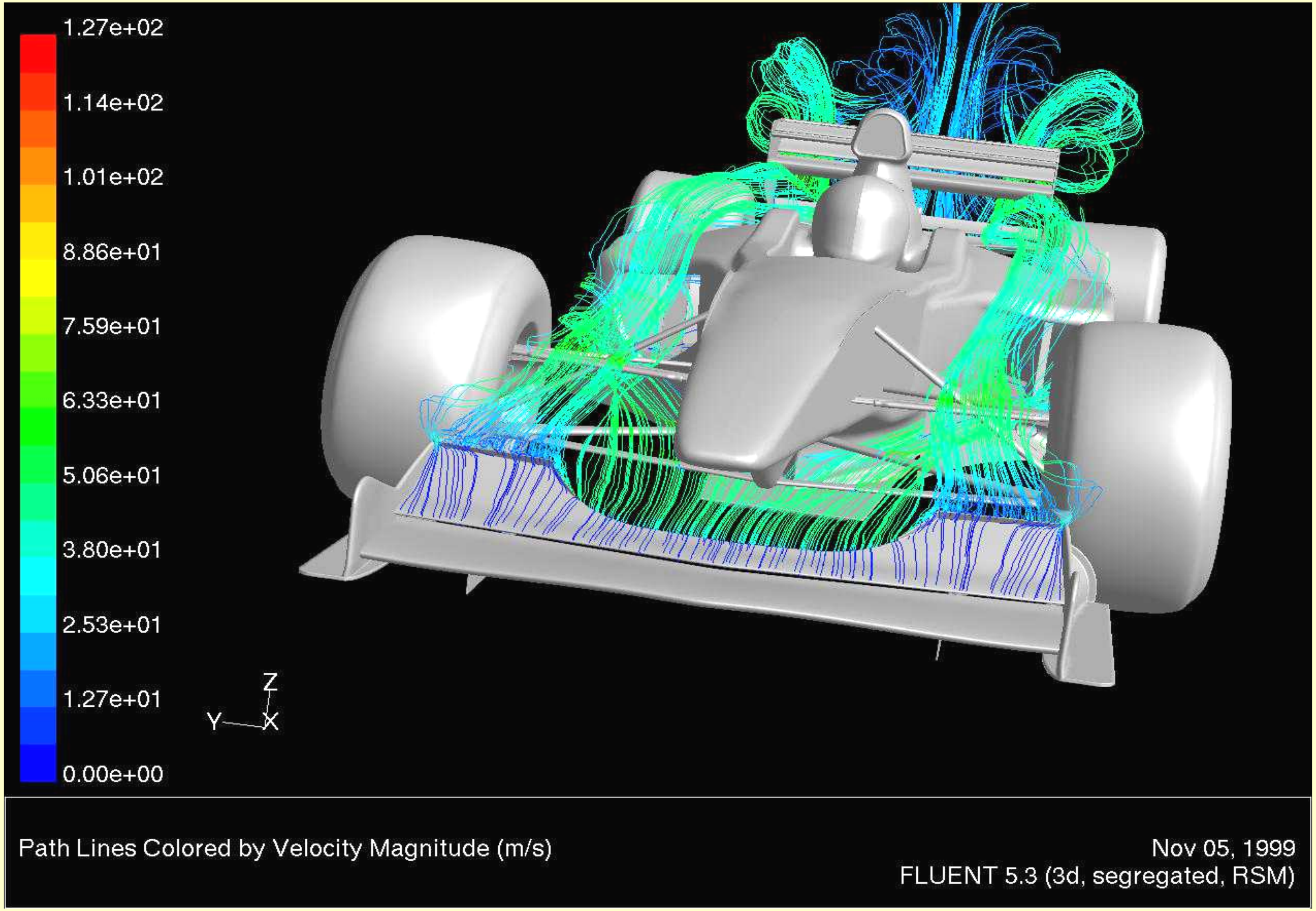



**Pressures**

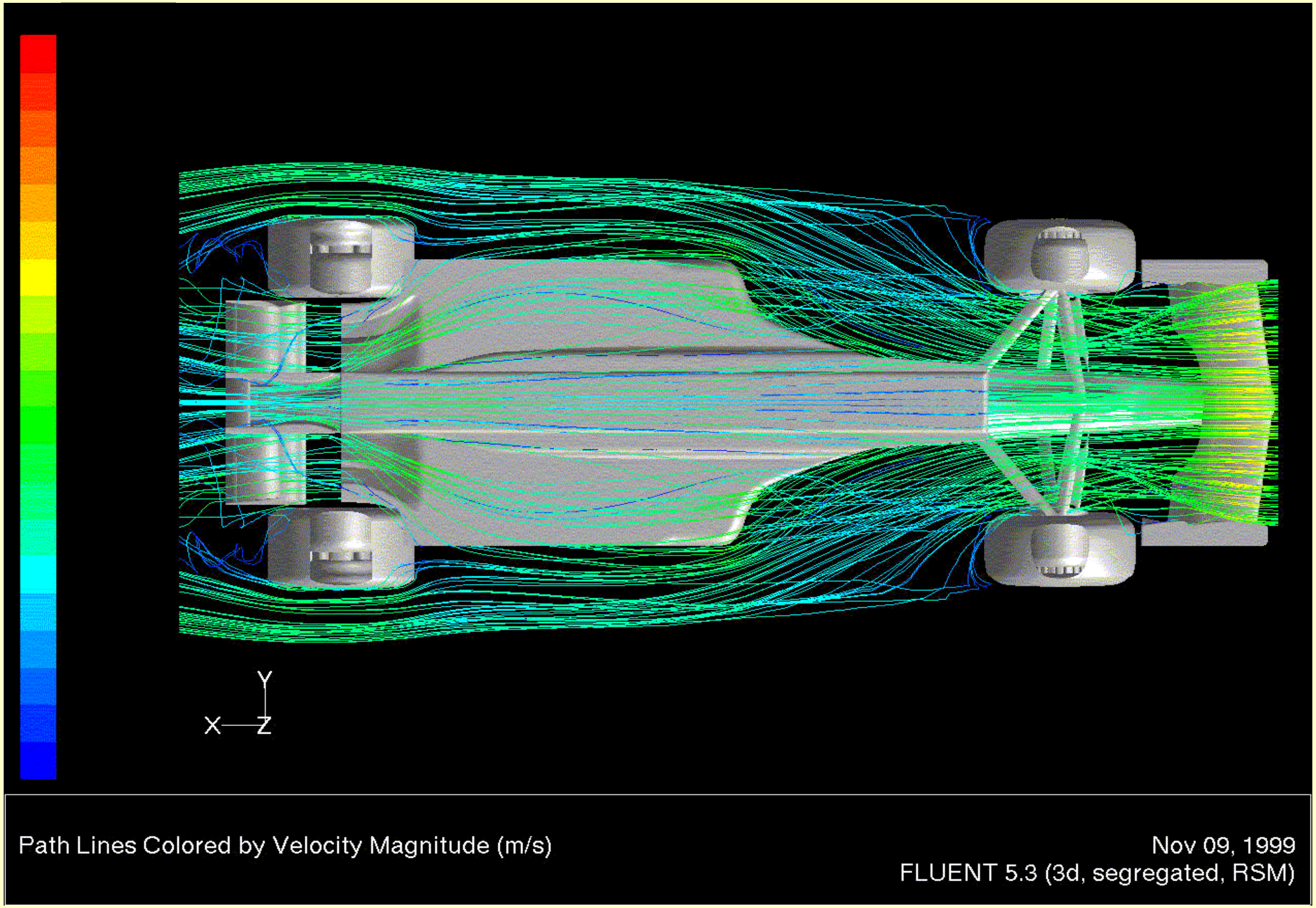
**Streamlines**



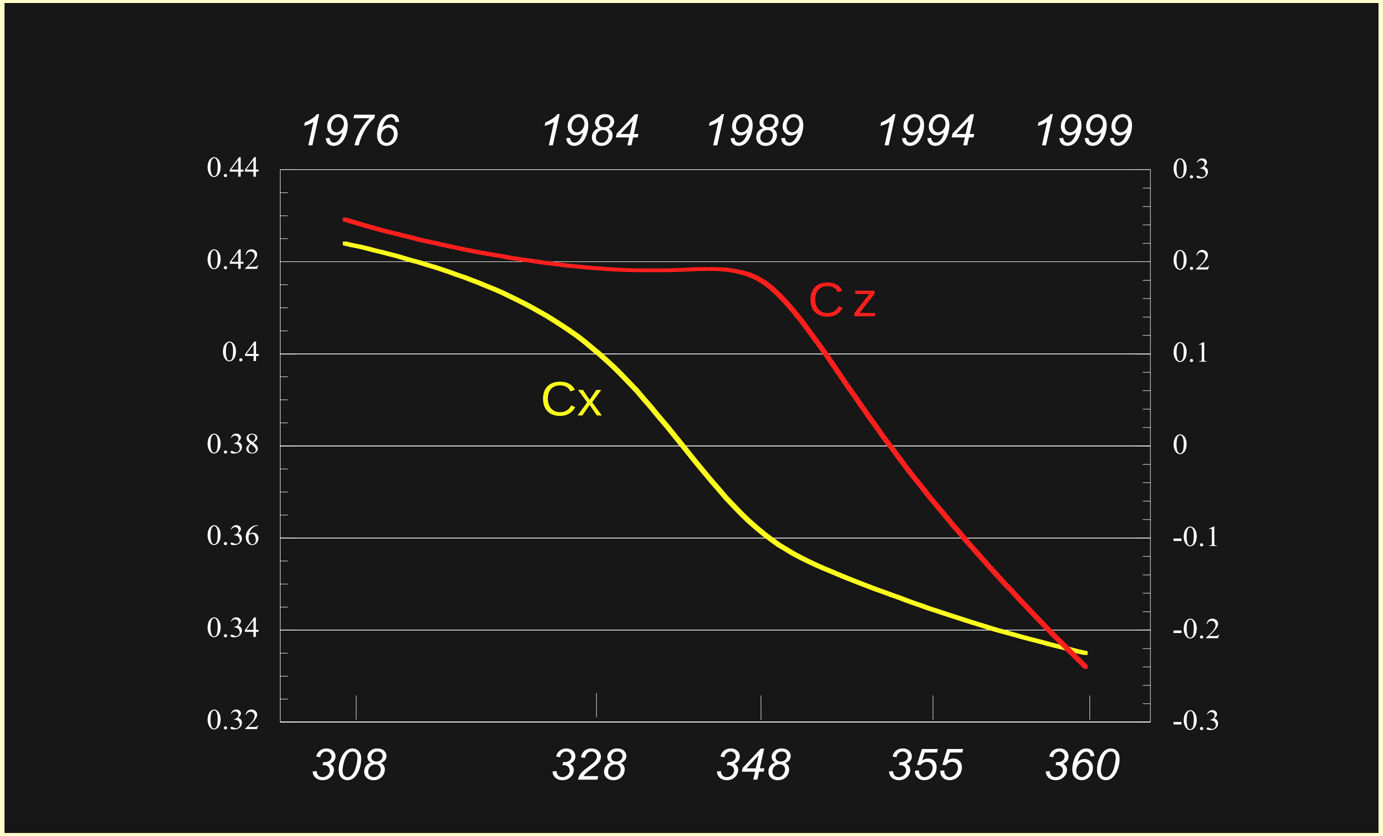
# Examples of RANS numerical results



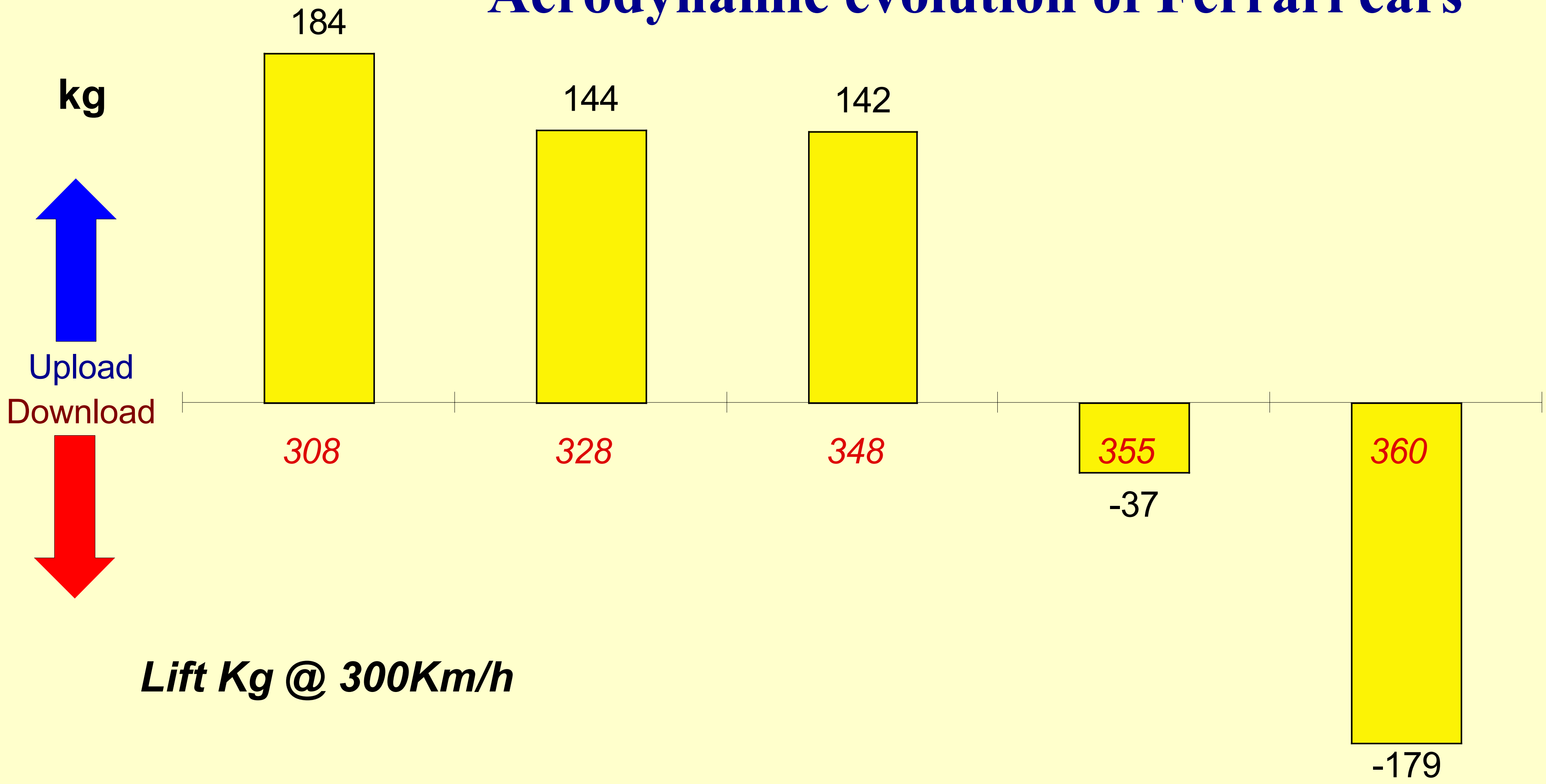
# *Examples of RANS numerical results*



# Aerodynamic evolution of Ferrari production cars



# Aerodynamic evolution of Ferrari cars

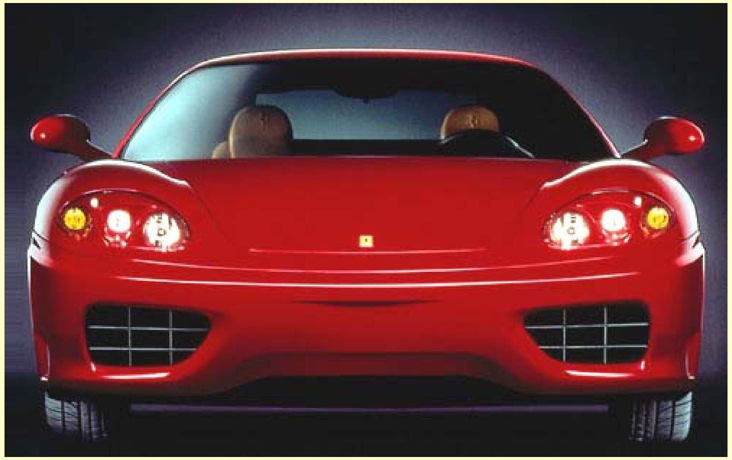


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Underbody and aerodynamic coefficients of F360 Modena

Ant: - 0.11

Post: - 0.13



$C_z$ = - 0.240

$C_x$ = 0.335

## Since 1989

- Characterization of new wind tunnel
- Solution of specific design problems
- Involvement of DIA in the development and utilization of new design tools

## Since 2000 - General agreement DIA - Ferrari:

- DIA is reference for research and innovation in aerodynamics
- DIA directly cooperates in the design of new cars

## Working tools:

- Graduation theses on research topics of interest for Ferrari
- Research contracts on specific problems

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## DIA cooperated in the aerodynamic design of:

550

360

Enzo

612

...

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Some topics:

## Particular measurement methods

**Direct measurement of vorticity**

**Surface visualization**

## Basic investigations of common interest

**Wall effects in wind tunnels**

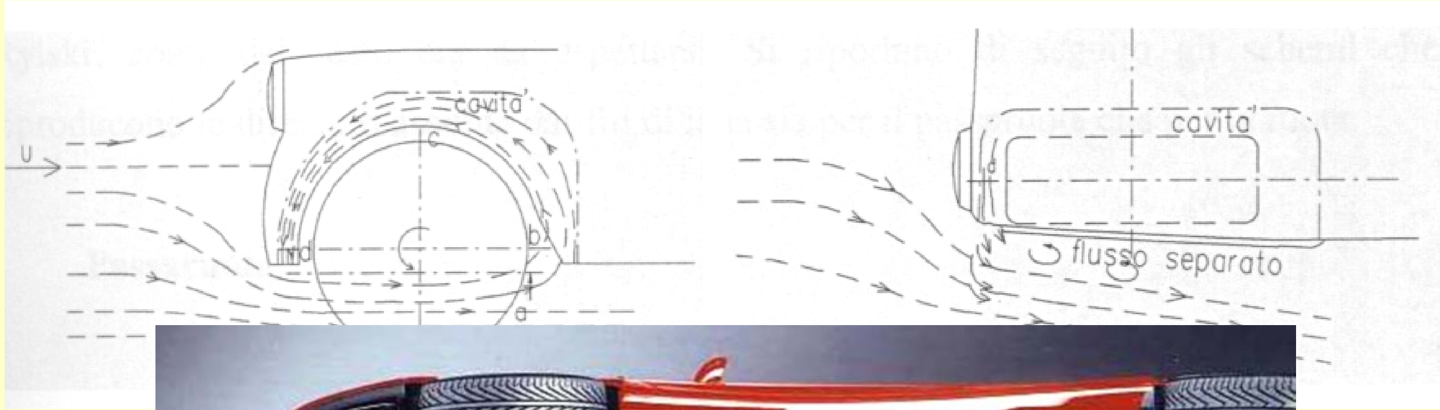
**Effects of afterbody rounding**

- **Aerodynamics of wheelhouses**

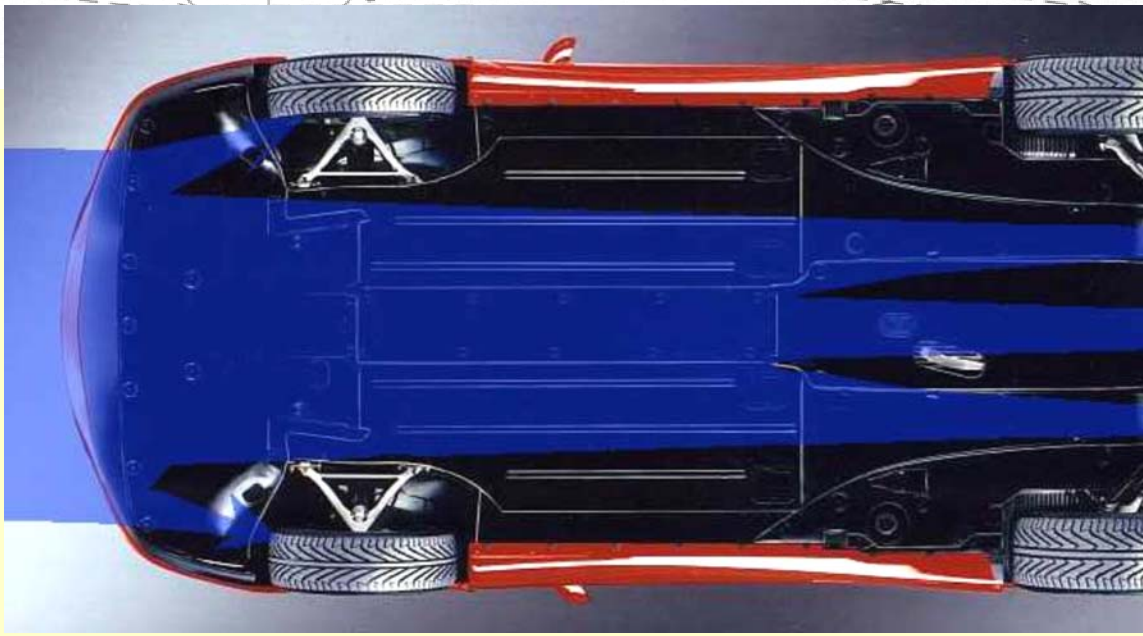
## Common research project

- **Development of a numerical procedure for the optimized preliminary aerodynamic design of new cars**

**Type of Flow**

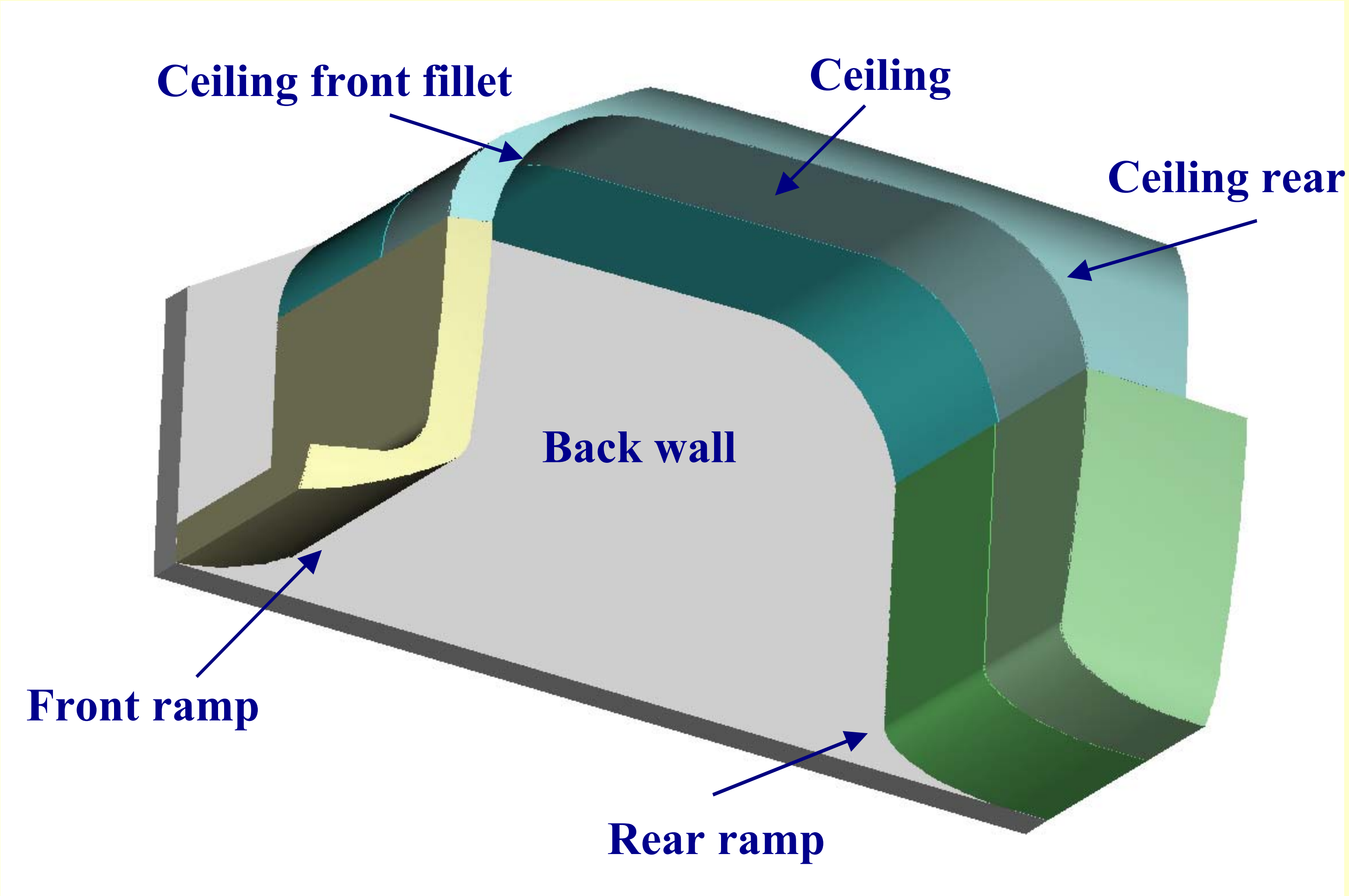



**Strong coupling with underbody**



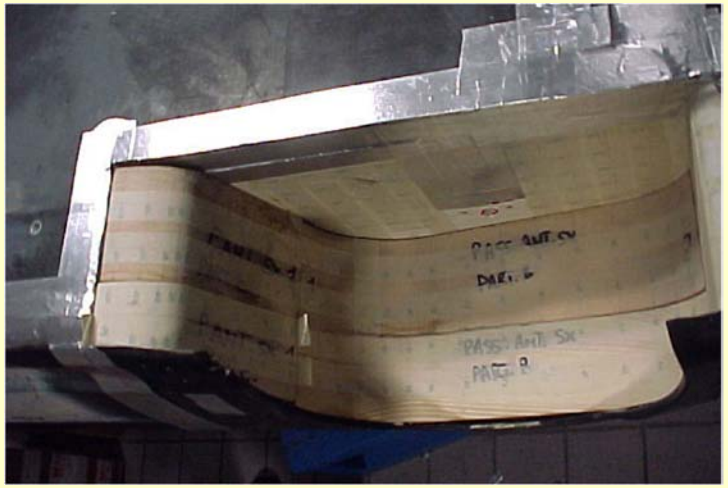
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Nomenclature

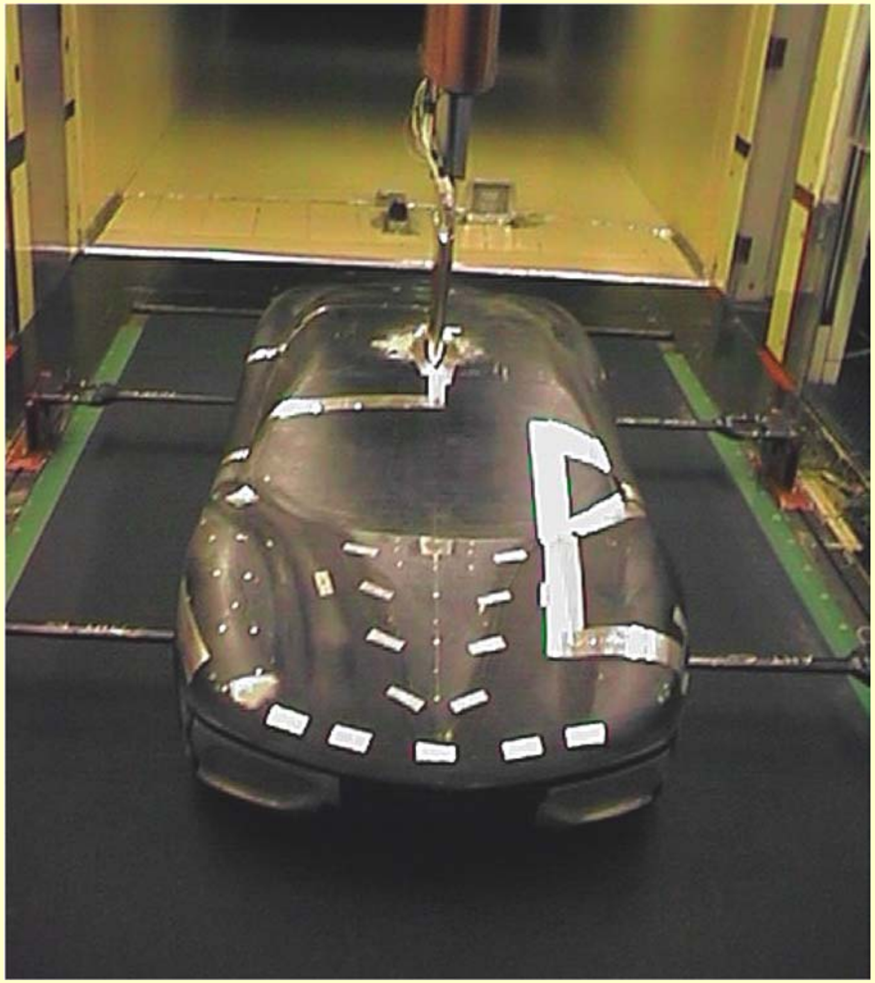


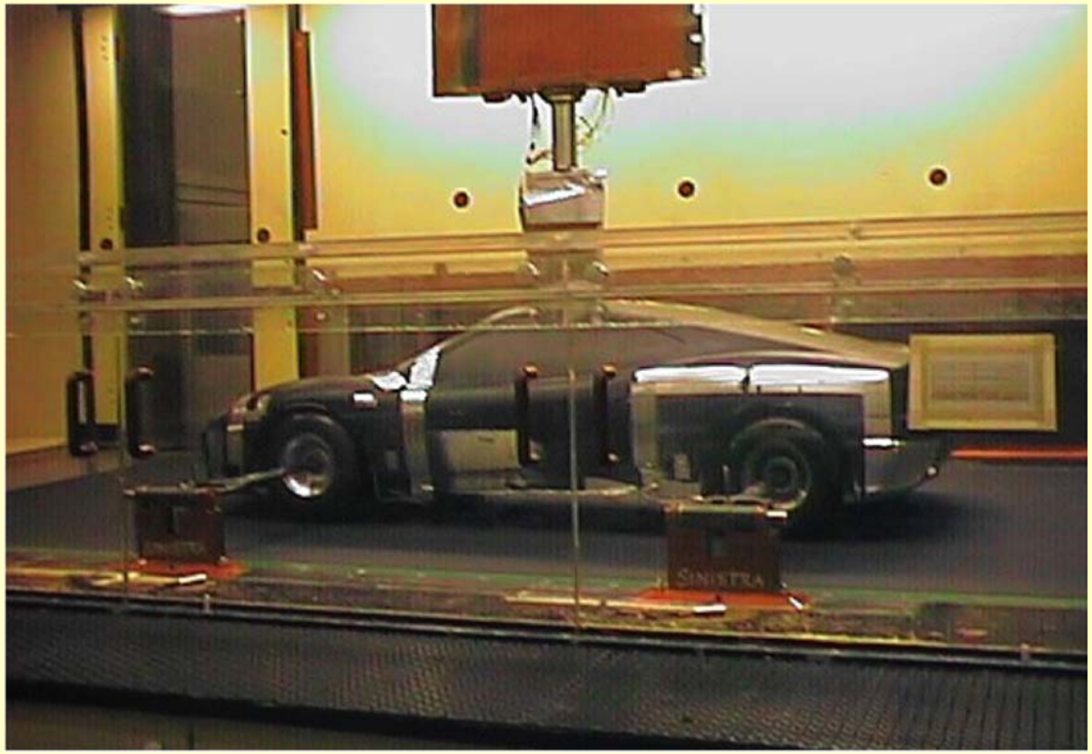
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## Different types of wheelhouse were analysed for different car attitudes relative to the ground



# Wind tunnel test campaign





# RESULTS

**Modifications to the geometry of wheelhouses were devised which provided significant improvements**

**A strong correlation exists between wheelhouse geometry and underbody aerodynamics**

**An improvement of the wheelhouses implies a careful analysis of the flow on the car underbody, specially of the outflow from the front wheelhouse**

## Objective of an aerodynamic optimization procedure:

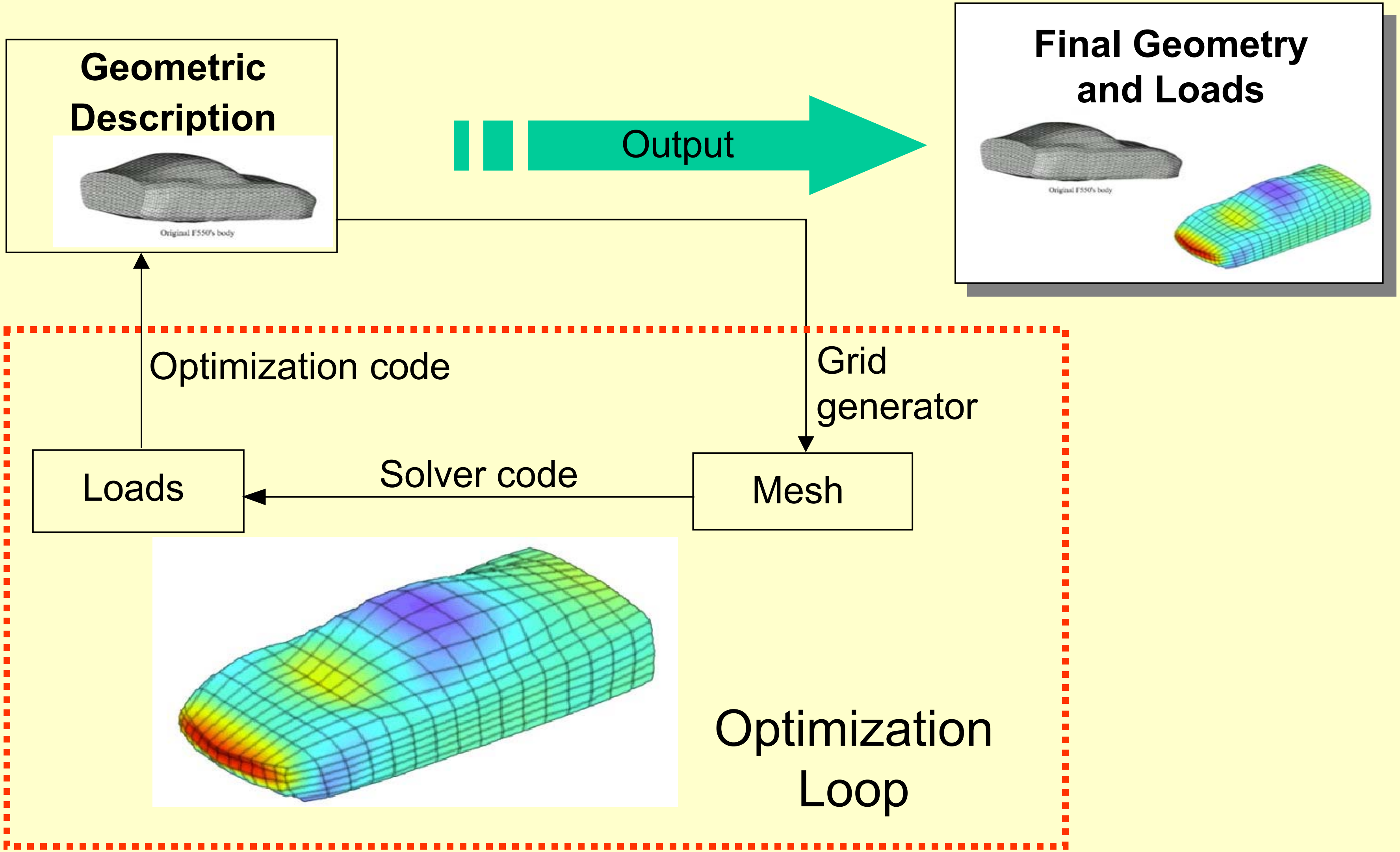
**To devise a**
**NEW GEOMETRY OF THE CAR**

**MINIMIZING AN OBJECTIVE FUNCTION**
**linked to the car aerodynamic performance**

**TAKING A SERIES OF "CONSTRAINTS" INTO ACCOUNT:**

- Geometrical (style)
- Aerodynamic
- Technological

# Scheme of an optimization procedure



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

**The evaluation of the aerodynamic loads must be repeated many times**

⇓

**The aerodynamic solver must be "unexpensive" as regards computational time, but sufficiently accurate**

⇓

**It is impossible (for the moment) to use codes for the solution of the Navier-Stokes equations (even RANS)**

⇓

**Modified "potential" methods**

## "Potential" methods

**Are much less expensive than RANS methods, but in principle may be applied only to "aerodynamic" bodies**

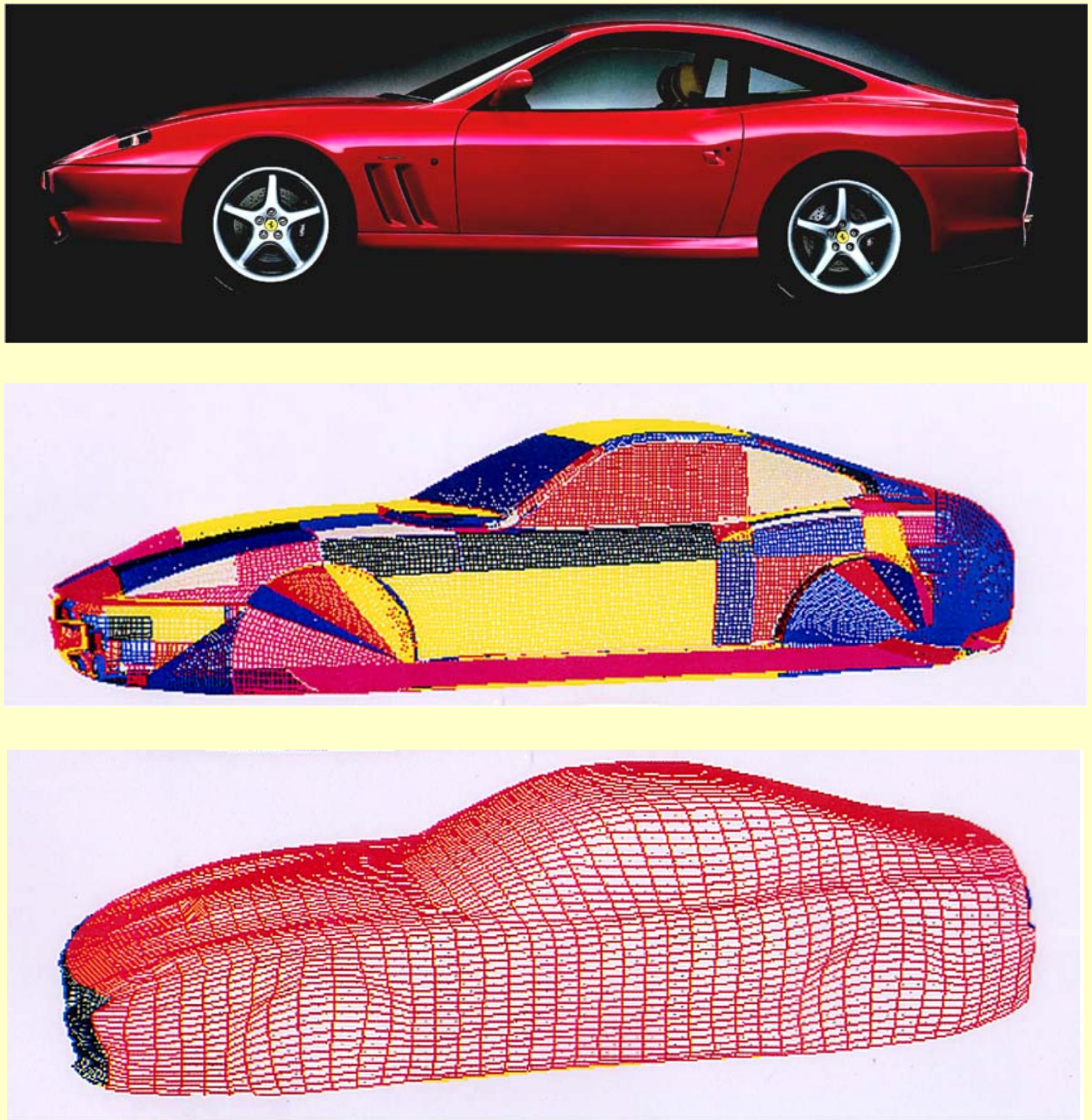
***However…***

**Investigations carried out by DIA showed that they may be used also for car shapes if the flow is attached until the body rear base and if the effect of the separated wake is adequately taken into account**

⇓

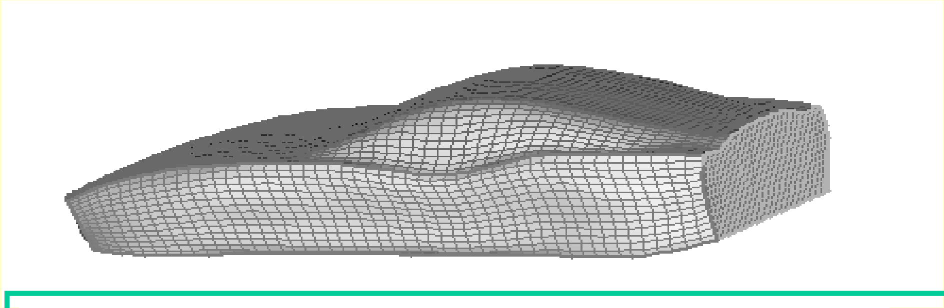
**The wake is modelled as a suitable continuation of the body *(wake model)***

# Optimized aerodynamic design

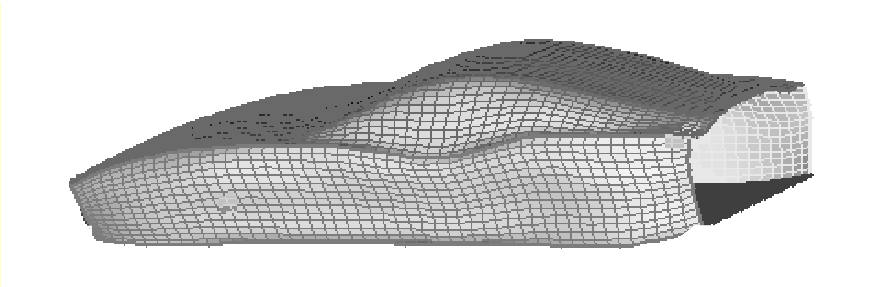


DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

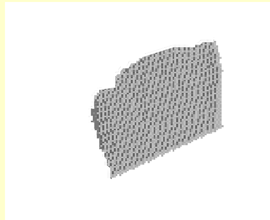
# Optimized aerodynamic design



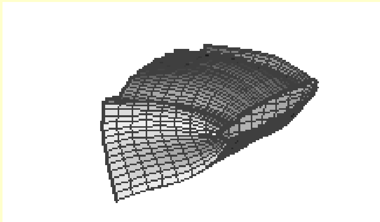
**The car surface is divided in two parts**



**forebody**

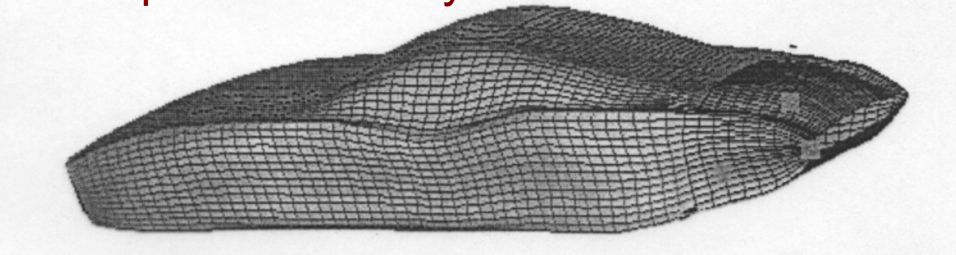


**base**



**A "fictitious afterbody" is evaluated, using the "wake model"**

Computational body

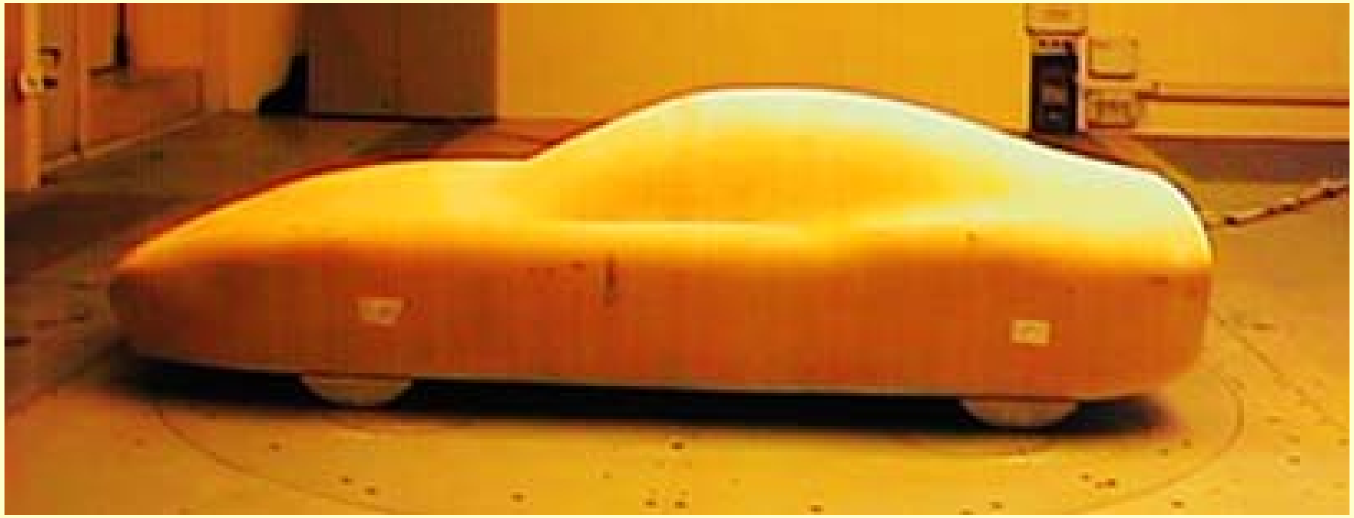


**The "computational body" is:**
**the forebody +**
**the "fictitious afterbody"**

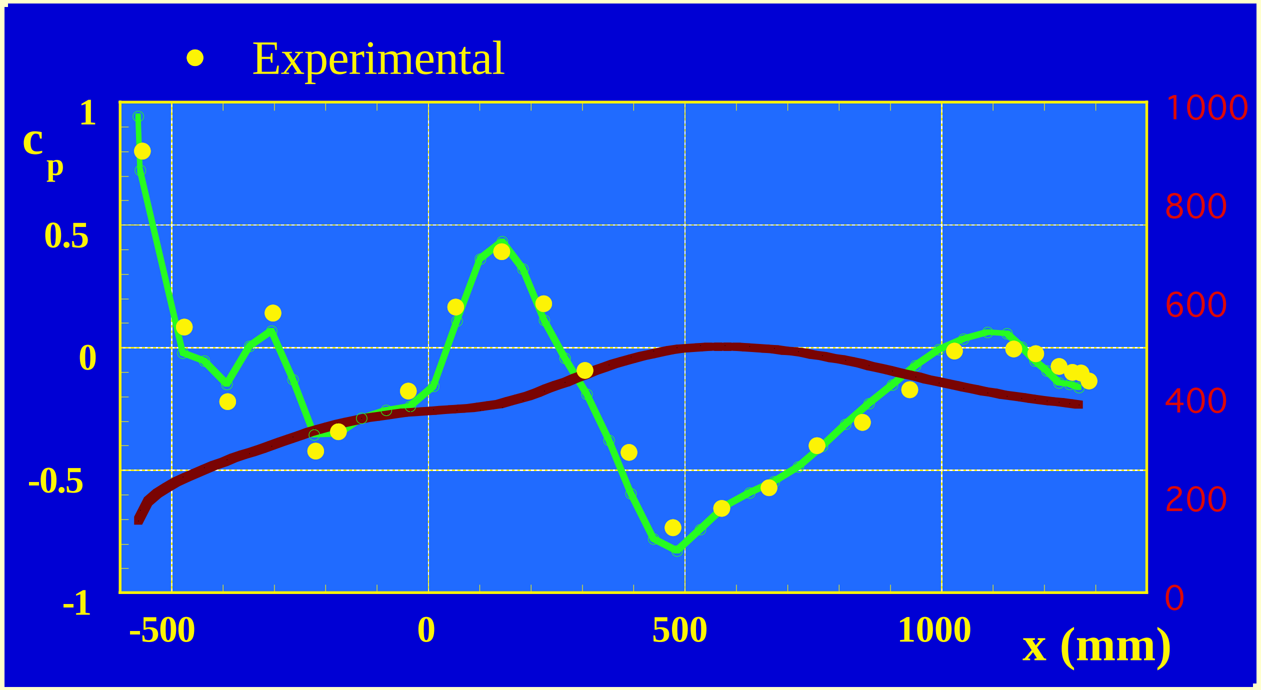
DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

**A WIND TUNNEL EXPERIMENTAL CAMPAIGN WAS CARRIED OUT TO VALIDATE THE PROPOSED SIMPLIFIED LOAD EVALUATION PROCEDURE**

**The shape and dimensions of the model were such that it could be considered a normal production car in 1:2.5 scale**



## Validation of the computational code




- **The comparison is very good**
- **The agreement extends to the end of the body, showing that the wake model works adequately**

# Validation of the optimization procedure

**OBJECTIVE FUNCTION : VERTICAL LOAD**

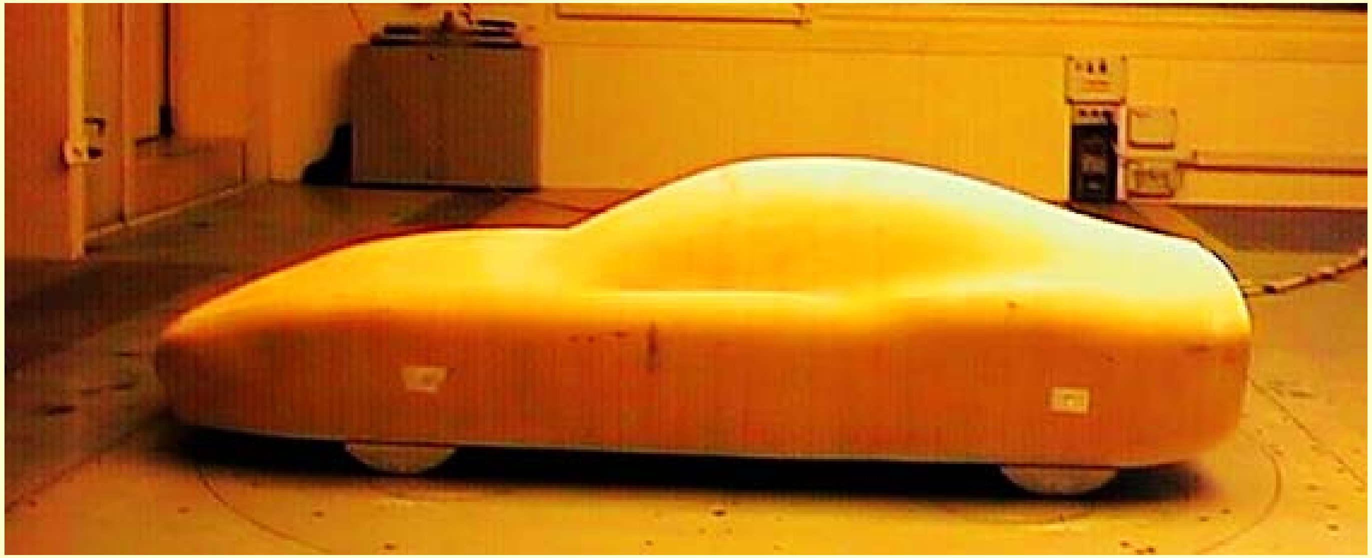
**CONSTRAINTS:**
- **Maximum aerodynamic drag**
- **Maximum displacement (3 cm in real scale)**

**The "potential" code with wake model was used**

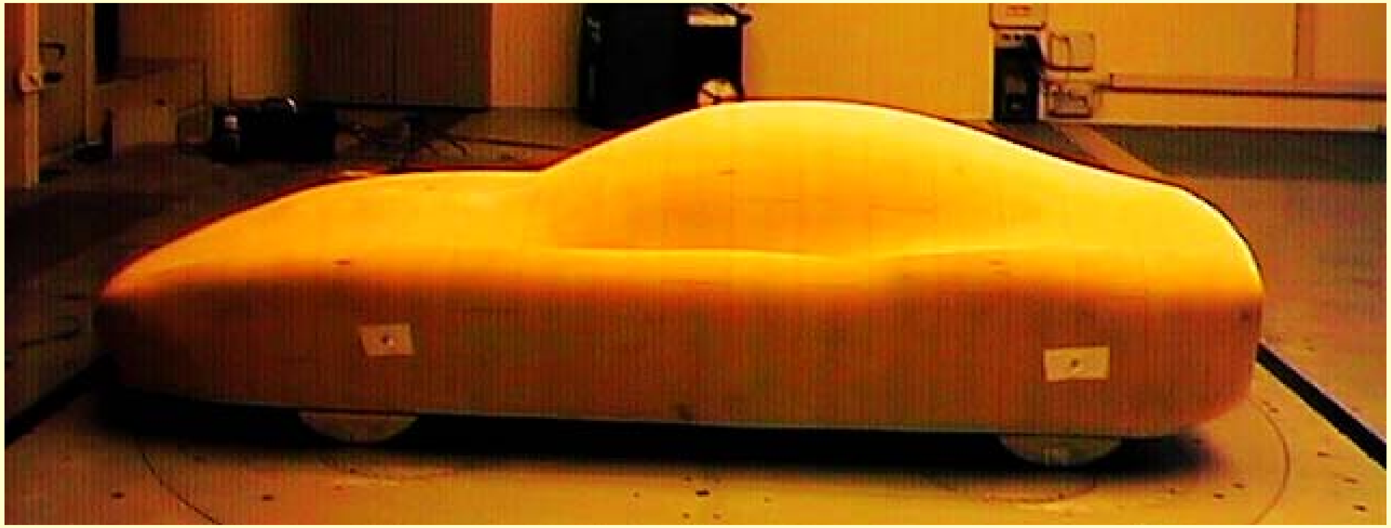
**THE WHOLE OPTIMIZATION PROCEDURE REQUIRED A ONE DAY WORK**

# Comparison between original and optimized models

**Original Model**



**Optimized Model**



DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# Validation results

## Wind tunnel experimental data

| | Basic Geometry | | Optimized Geometry |
|---|---|---|---|
| $C_z$ | 0.176 | → | 0.141 |
| $C_x$ | 0.185 | → | 0.181 |

## Load variations @ 280 Km/h

$F_z = - 28$ kg

16 cm x 1.5 m
Wing

$F_x = - 3.5$ kg

3 HP

**The aerodynamic optimization procedure has been introduced in the standard design process of the new Ferrari production cars**

**Style proposal (Pininfarina)**

↓

**Analysis with optimization procedure (Ferrari)**

↓

**Modification proposals**

↓

**New style proposal**

↓

**Model construction and wind tunnel tests**

↓

**Approval**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

# The synthesis of all the Ferrari aerodynamic know-how …

**Ferrari Enzo**

$C_z \cong -1.0$

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## The cooperation between DIA and Ferrari has produced:

- **Increase in the Ferrari internal know-how and consequent direct involvement of Ferrari in the styling process of the new production cars**
- **Introduction at DIA of new basic aerodynamic research activities with applications in the automotive industry**
- **Opening of new occupational perspectives for graduated students**

## The expected future:

- **Increased direct involvement of DIA in the design process of new production cars**
- **New interesting research topics**

## A good aerodynamic design requires:

- **High basic and specific aerodynamic competence**
- **Search for physical comprehension**
- **Capitalization of acquired know-how**
- **Integrated design (team work):**

**Clear and “realistic” definition of the aerodynamic specifications and of the technological and style constraints**

**Strong interaction between aerodynamic, style and production departments since the initial stages of the design process**

DIPARTIMENTO
DI INGEGNERIA
AEROSPAZIALE

## Some future research topics:

- **Increased know-how on the use of CFD (Navier-Stokes solvers) and their introduction in the optimization process**
- **Aerodynamics of cooling systems**
- **Increased understanding of and development of methods for the useful management of:**

**- base flows (base drag)**
**- locally-separated flows and vortical structures**
**- interference effects**

} **to produce know-how to be used when needed for new styles**

- **Study of "non-conventional configurations"**

# THANK YOU FOR YOUR ATTENTION!