



# Automotive Aerodynamics

HISTORY

FORCES AND MOMENTS ACTING ON A VEHICLE

DRAG

GENERAL DESIGN GUIDELINES

**WIND TUNNELS**

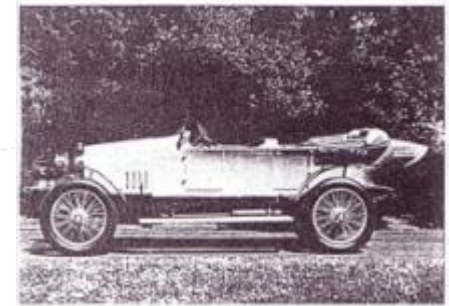
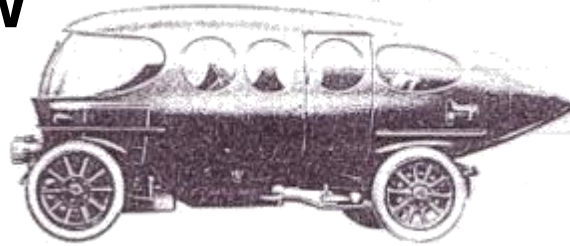
**APPLICATIONS**





# Review

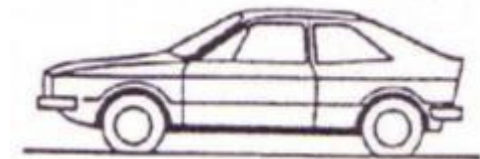
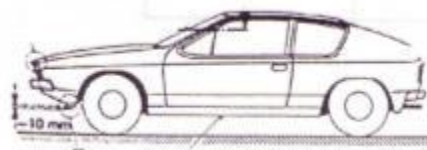
## Basic Shapes



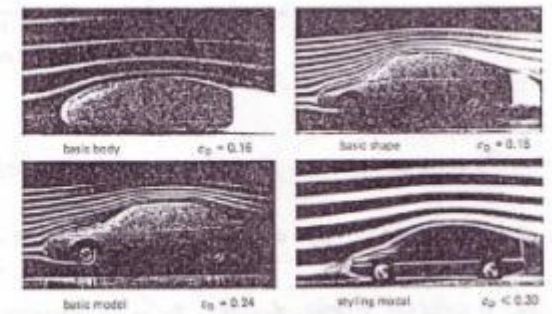
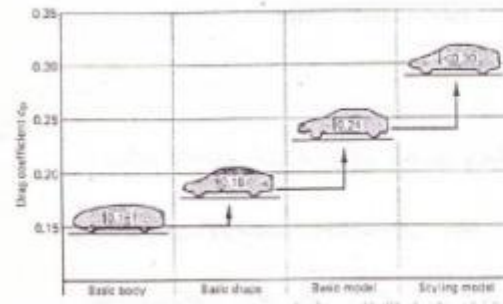
## Streamlined Shapes



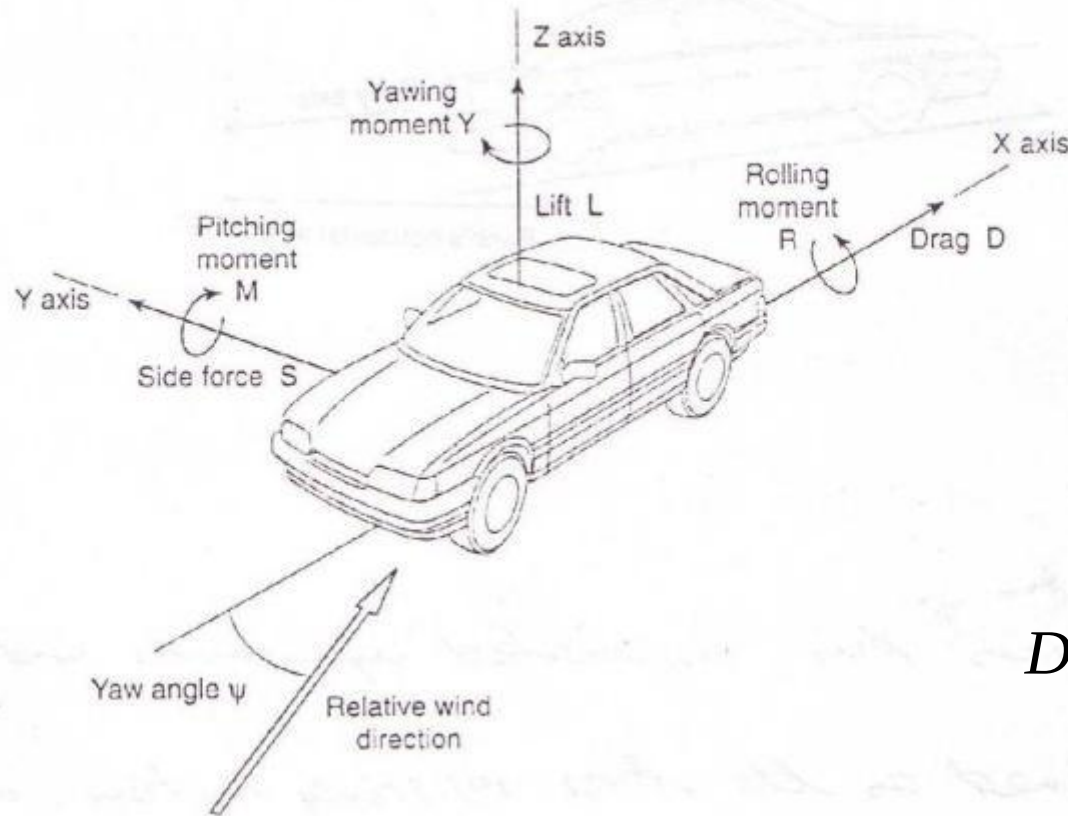
## Detail optimisation



## Shape Optimisation



# Forces and Moments acting on a vehicle



## Six Forces

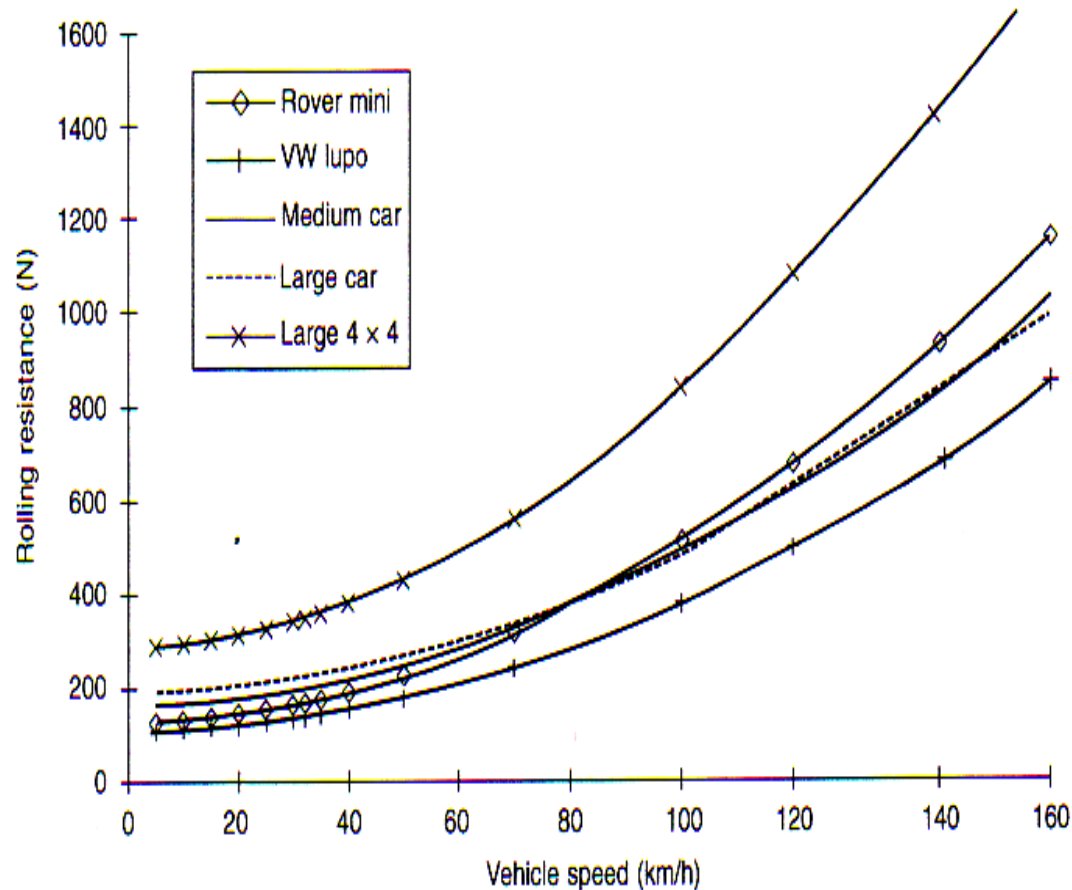
- **Drag**
- **Lift**
- Side Force
- Rolling Moment
- Yawing Moment
- Pitching Moment

$$DRAG = \frac{1}{2} \rho V_{\infty}^2 A \times C_D$$

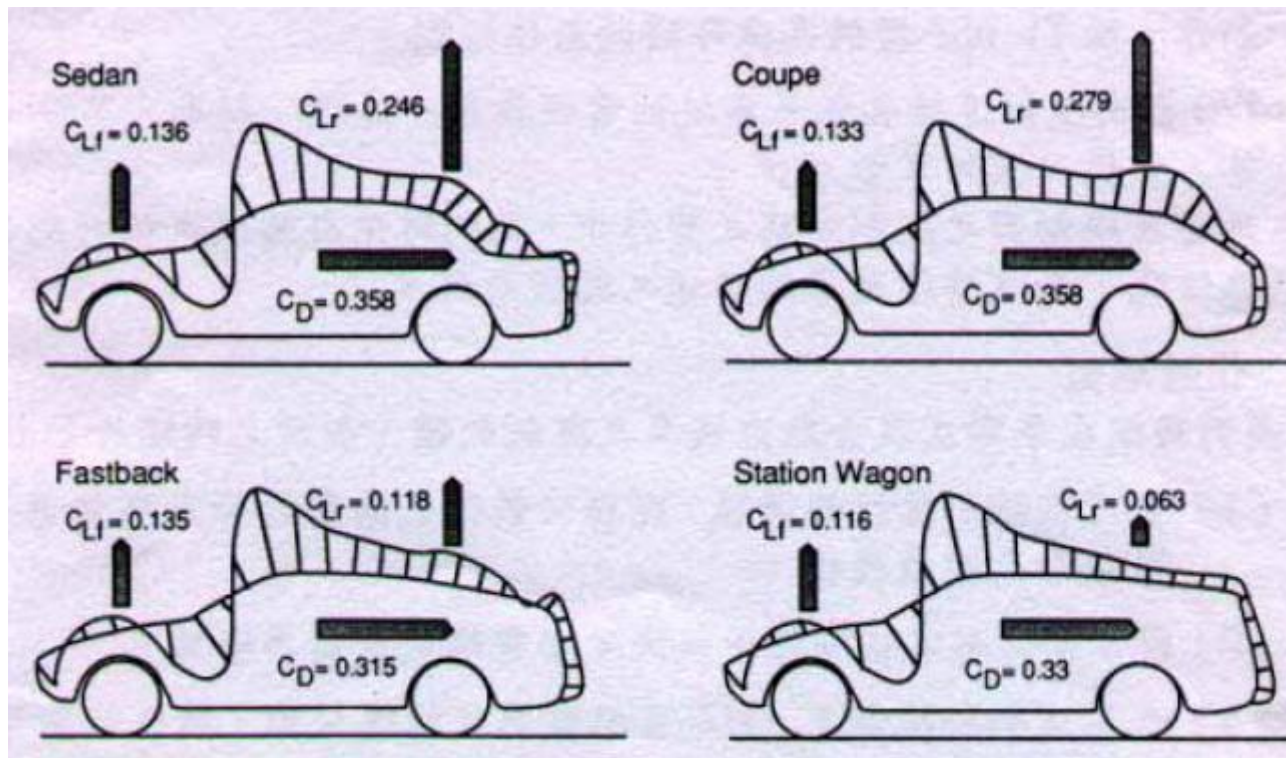
$$LIFT = \frac{1}{2} \rho V_{\infty}^2 A \times C_L$$



# Forces and Moments acting on a vehicle

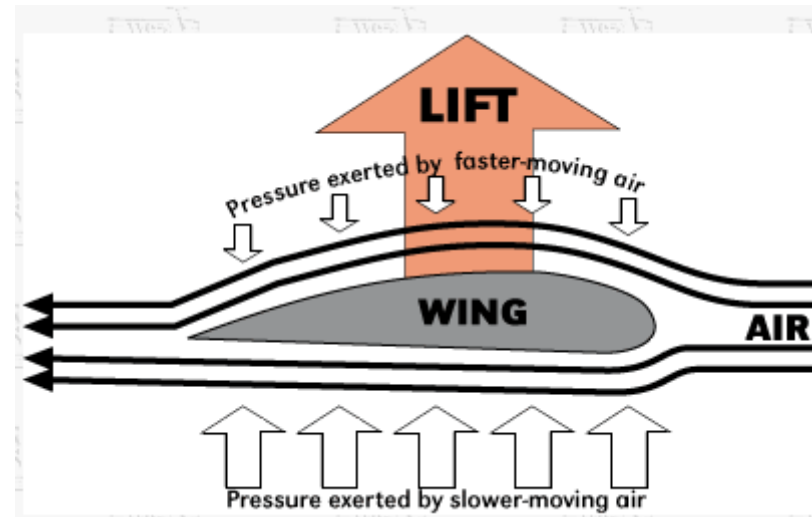
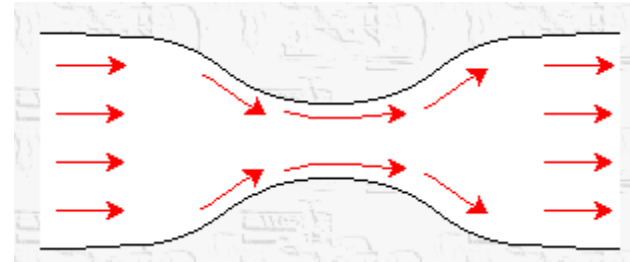


# Forces and Moments acting on a vehicle



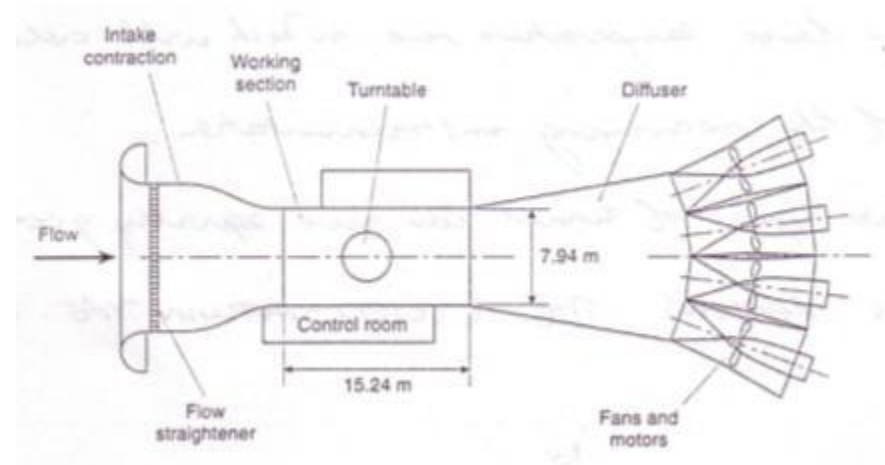
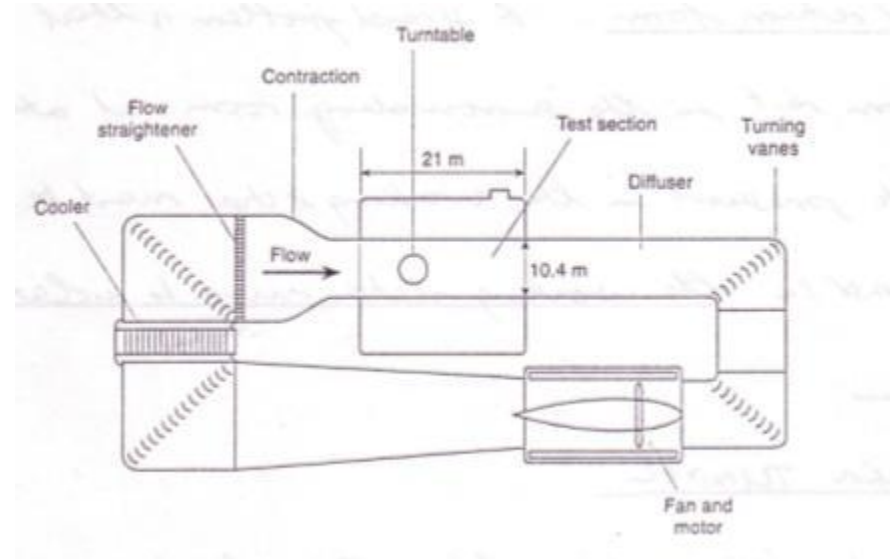
# Basic Theory

$$P_1 + \frac{1}{2} \rho u_1^2 + \rho g z_1 = P_2 + \frac{1}{2} \rho u_2^2 + \rho g z_2$$



# Wind tunnels

- Originally developed for aeronautical use
- Closed return Type (GM)
  - Air circulates around a closed circuit
  - 
  -
- Open return type (MIRA)
  - Air flow through the system
  - 
  - 
  - 
  - 
  - 
  - Can't be pressurised to raise reynolds number
  - Pressure is less than atmospheric (Bernoulli)





# Wind tunnels

Three primary sources of error in wind tunnel testing

- The scale or Reynolds number effects
- Errors due to the road moving but the floor of the tunnel is stationary
- Errors due to blockage

Reynolds number

If testing a scale model the Reynolds number plays a major role

$$\text{Reynolds number} = \frac{\rho V_{\infty} L}{\mu} \quad \mu = \text{viscosity}$$

# Wind tunnels

## Reynolds number effect

- Transition from laminar to turbulent flow happens at same distance from leading edge

- Hence scale model has greater proportion exposed to laminar flow > lower drag/unit area

- To get similar behaviour on model the Reynolds number must be the same

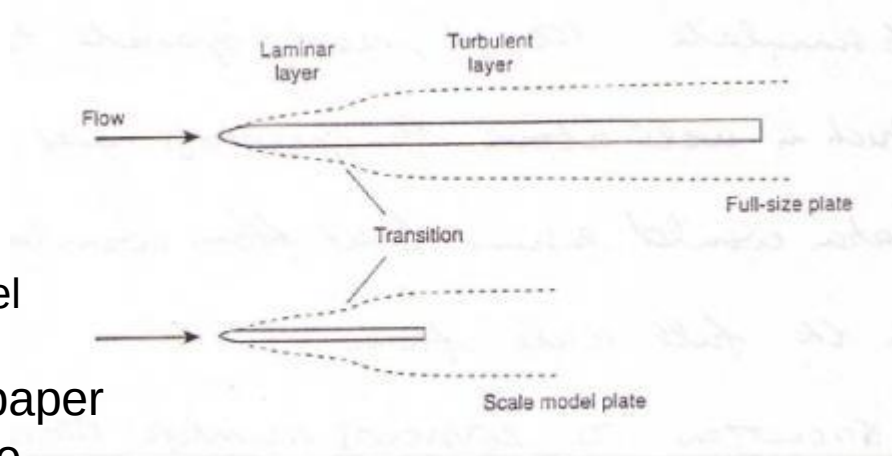
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- Generally cheaper to build full scale tunnel

- If scale models must be used then sand paper can be added to cause separation on scale model

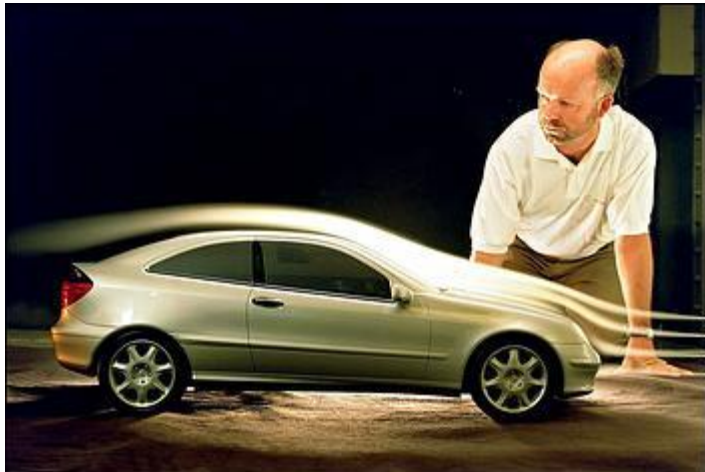
$$\text{Reynolds number} = \frac{\rho V_{\infty} L}{\mu}$$



Scale model and full size vehicle placed in the same airflow



# Wind tunnels



Model



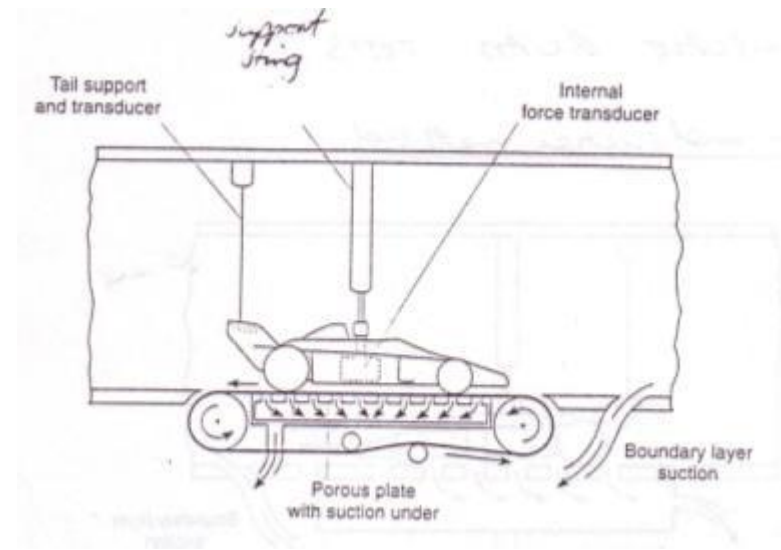
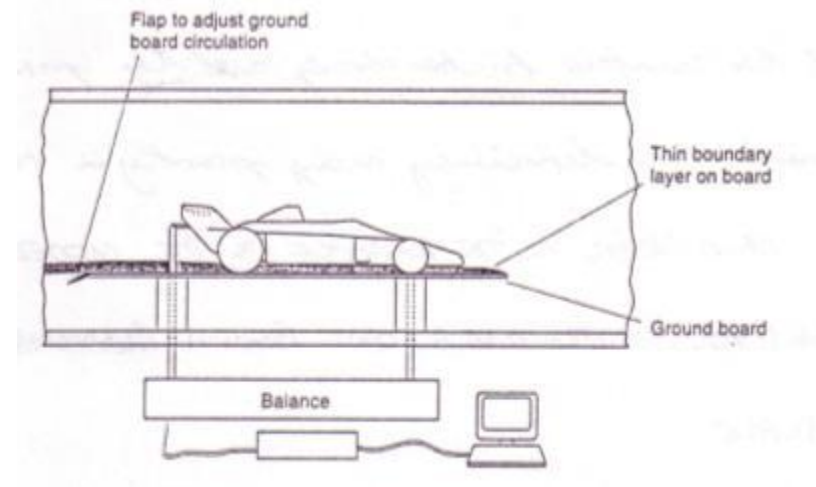
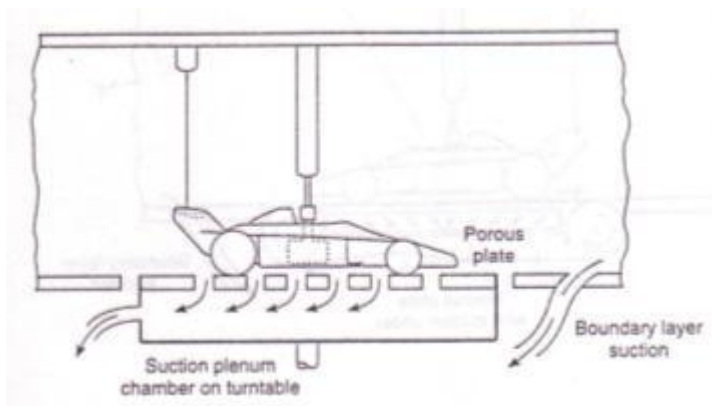
Full size



# Wind tunnels

## The Moving Road Problem

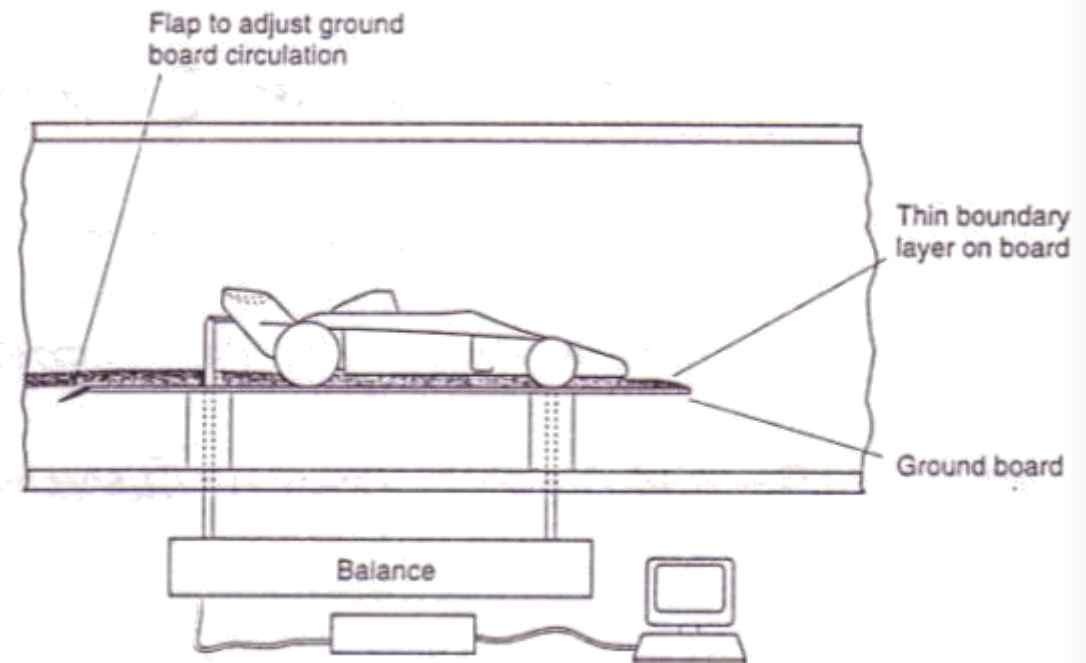
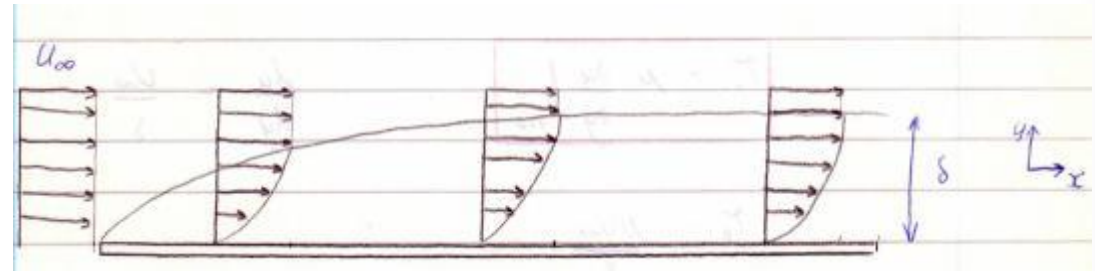
- Under real world, still conditions, there is no relative motion between the road and the air
  - No boundary layer is developed on the road
- In a wind tunnel the vehicle gets immersed in the boundary layer which significantly effects the results
  - Use of a ground board
  - Using a belt with same speed as the air
  - Use of a porous board with suction



# Wind tunnels

## The Moving Road Problem – Use of a ground board

- Car is raised on ground board above boundary layer on tunnel floor
- Small boundary layer still forms from the leading edge of the ground board
- Blockage at car level can cause circulation from higher pressure under board
- Acceptable solution for family cars and commercial vehicles



# Wind tunnels

## The Moving Road Problem – The moving belt method

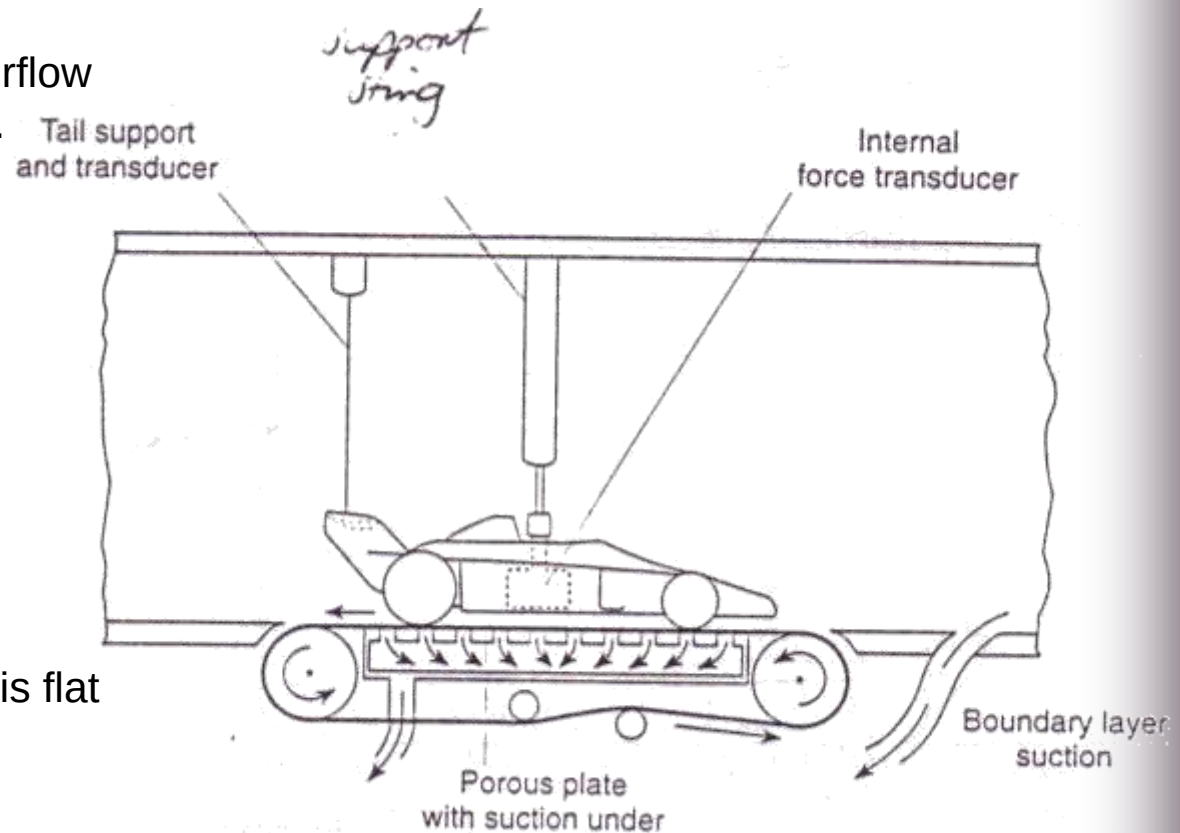
- Floor boundary layer is removed by suction just upstream of the belt
- The belt moves at the same speed as the airflow meaning that a boundary layer is not formed.

### •Problems

- 
- 
- 

### •Solutions

- Porous plate with suction ensures belt is flat
  - The car is suspended
- Preferable for race cars with low ground clearance





# Wind tunnels

Wheels separated from the car to separate forces.



*Fig. 8.3 Half-scale wind tunnel model mounted in wind tunnel.  
(Courtesy of Sutton Motorsport Images)*



*Fig. 8.4 Half-scale model without bodywork or wings fitted.*

## The Moving Road Problem – Porous floor and suction method

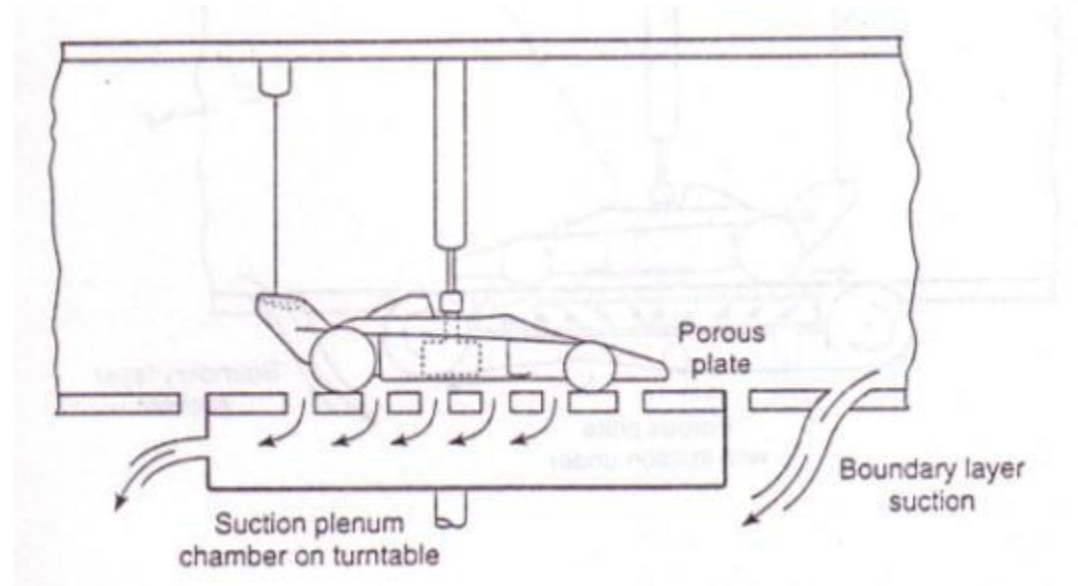
- Boundary layer is removed upstream of the car by suction
- A new layer is stopped from forming by suction in the test area

### • Problems

- 
- 

### • Advantage

- Mechanically simpler than belt method



## Blockage Effects

- Constraining effects of tunnel wall will distort streamlines
- Vehicle partially blocks flow leading to increased air speed in the vicinity
  - Forces become larger and if no correction is applied  $C_D$  and  $C_L$  will be overestimated

A crude blockage correction method...



# Wind tunnels

Used to show the size of the wake

- Where streamlines separate from the body
- Centreline smoke tracing
  - 3D flow not represented





# Wind tunnels

Yaw angle = 0 degs

(Note “boat-tail”)



Yaw angle

- Increased wake
- Three dimensional flow



Mean yaw in uk ~



# Wind tunnels

- A rear wing would need to be perhaps 250mm above the rear lip of the boot.

- Flow attached right to tail of car

- streamline leaves the car at the rear spoiler - which has been placed there to give clean separation to stop turbulent wake causing lift.





# Wind tunnels

Tapered rear end  
Attached laminar flow  
Small spoiler





# Wind tunnels

Filling the wake with smoke to see turbulent flow

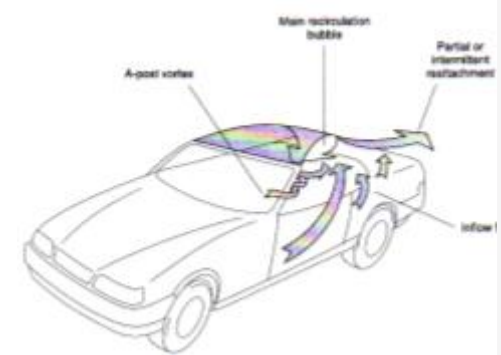




# Wind tunnels

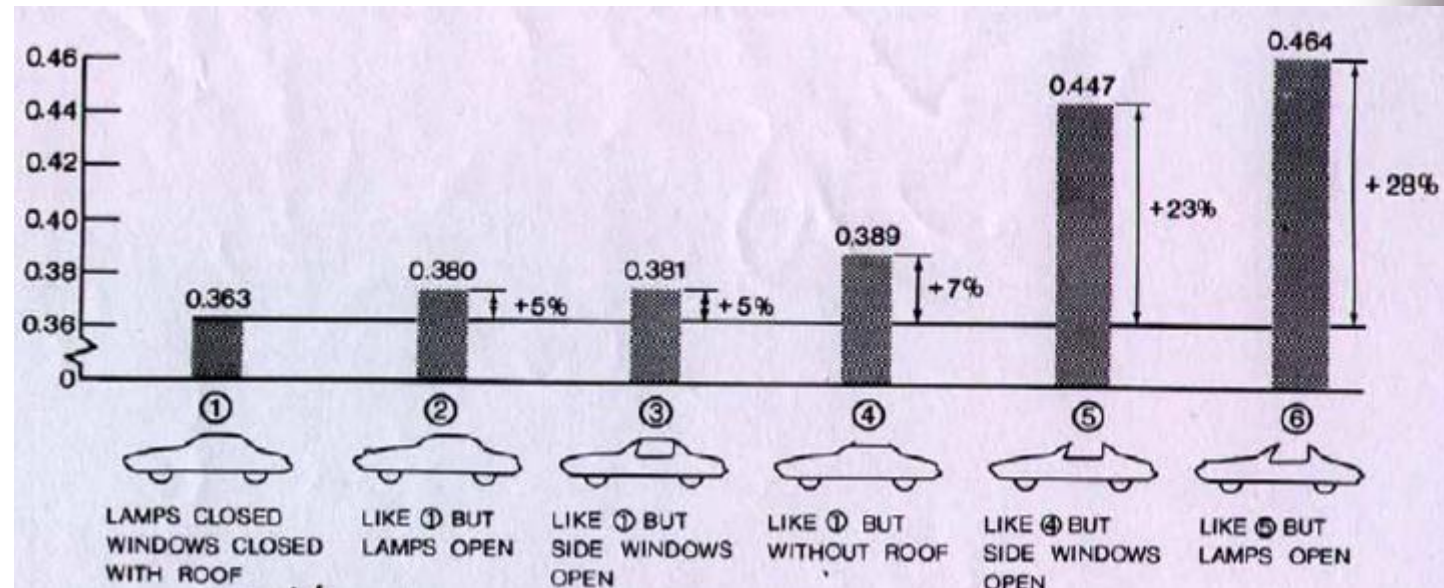
## Effect of a convertible

- Size of wake increased significantly
- $C_D$  figures usually quoted with roof up!
- Raised windows stop inflow
- Deflector stops forward flow from bubble



## Effect of protrusions

- Low pressure turbulent wake



# Wind tunnels

## Ground Effects

- Raised car to clear boundary layer as air is moving relative to the floor
- Ground effect of vehicle aerodynamics is not accounted for as no ground board
- Wheels not rotating
- Flat underbody





# Wind tunnels

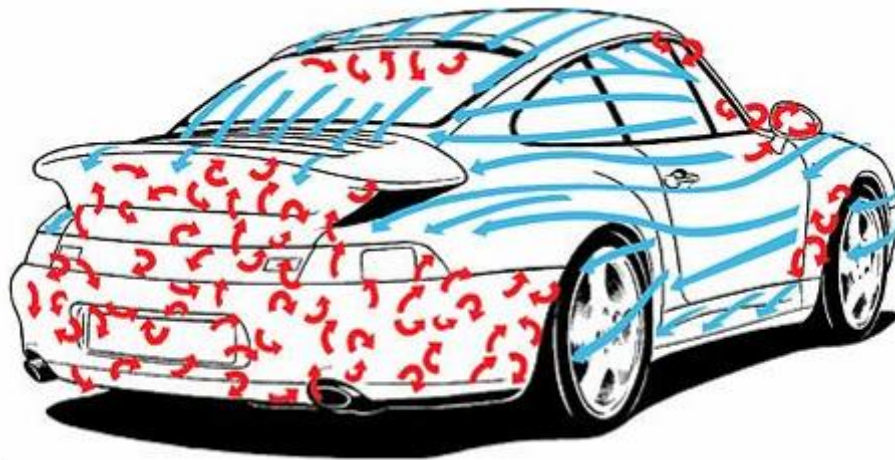
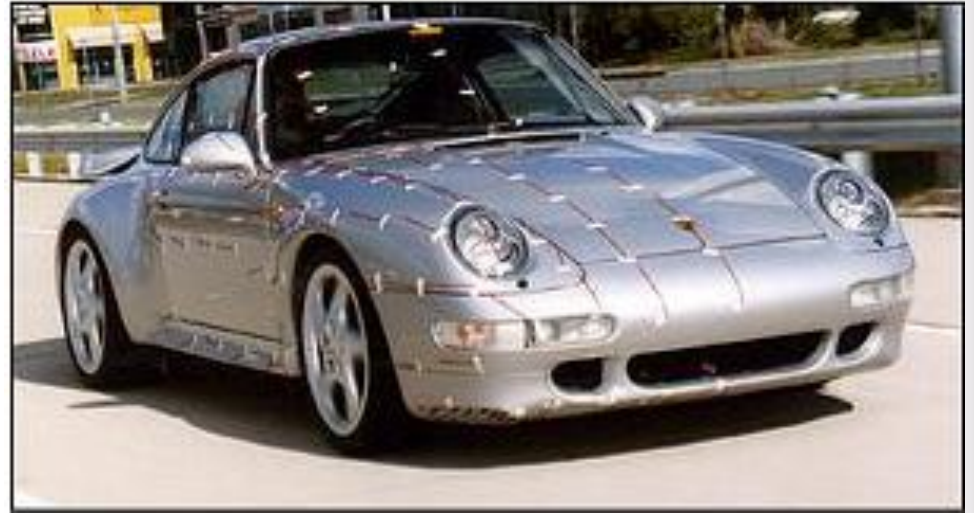
## Rain testing

- Used to monitor
  - Water flow
  - Effectiveness of wipers
  - Optimise dirt deposition
    - head- and tail-lights
    - driver vision through side windows.





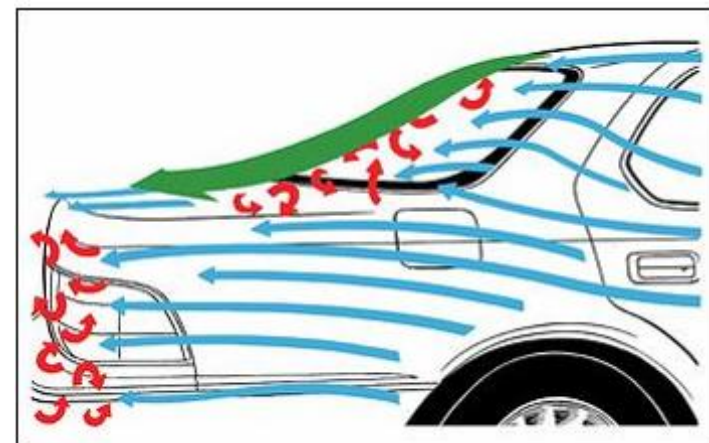
# Wool tufts...





# Wool tufts...

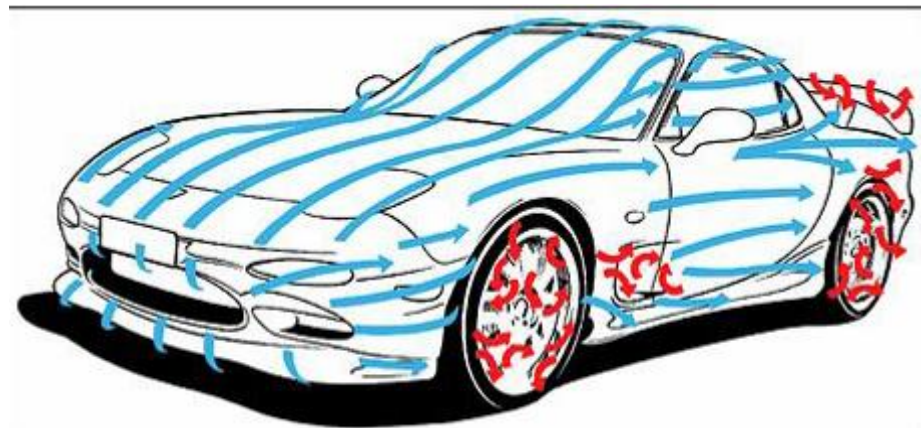
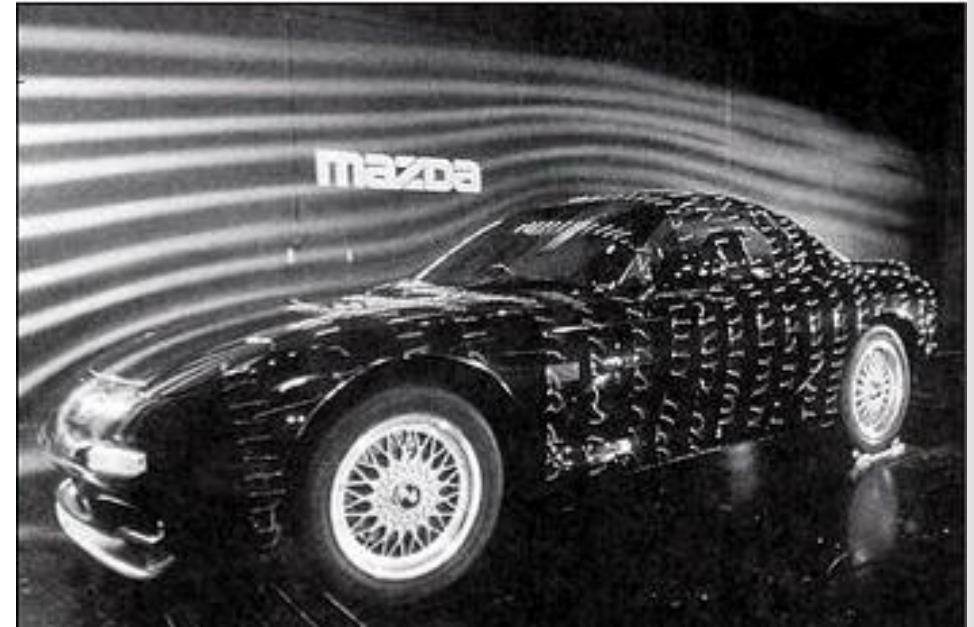
- Turbulence
  - Behind rear screen
  - Behind boot



1991 Lexus LS400



# Wool tufts v Wind tunnels





# Applications - Wings

First introduced to Formula One in late 1960s

- Mechanism for controlling the incidence angle
- Split wing surfaces with independently variable incidence.
  - Greater downforce on inside wheel to offset the effects of body roll
- Wing mounted directly on to wheel
- flimsy and vulnerable structure

Accidents at the Spanish Grand Prix in 1969

- The maximum height, width and locations are controlled
- Aerodynamic devices have to be of fixed geometry
- They have to be rigidly attached to the body work



1969\_barcelona\_crash.avi

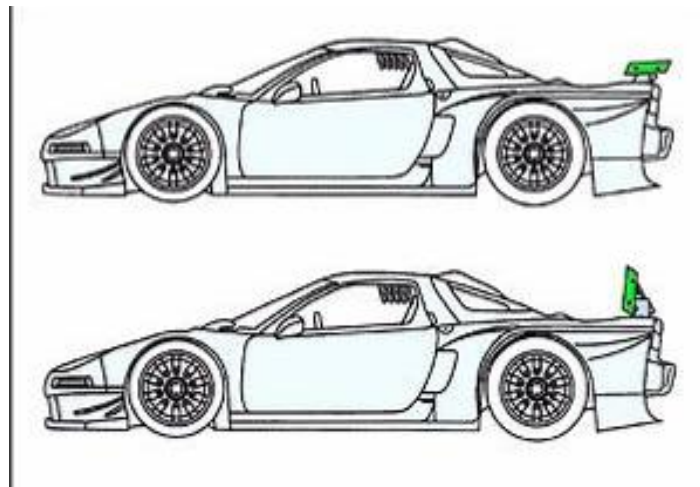


# Applications - Wings

Deployable spoilers



Spoilers as brakes





# Applications - Ground effect

## Ground effect

- 'zero' ground clearance
- Sculptured underbodies



1980 Alfa Romeo

## 1981

- 6cm ground clearance
- hard suspension
- Pitch control

## 1983

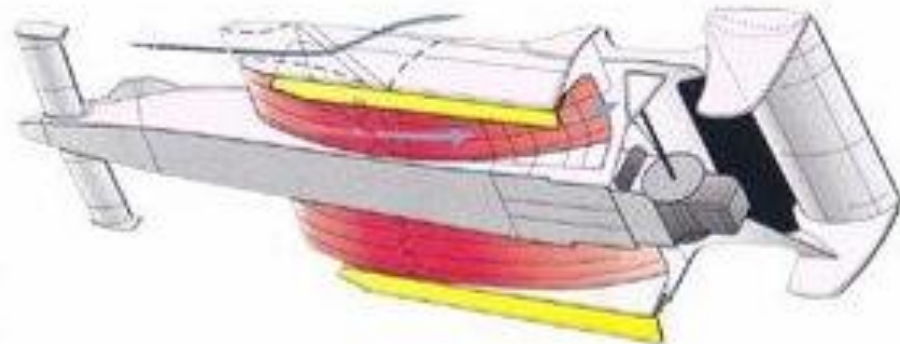
- Sculptured underbodies prohibited.
- Flat bottoms were required
  - trailing edge of the front wheels
  - leading edge of the rear wheels



The stepped floor of the 1997 Jordan 197.

## 1995

- Increase in the minimum permitted ground clearance over a large proportion of the underbody, creating a 'stepped floor'





# Applications - Ground effect

1979 – Indy car



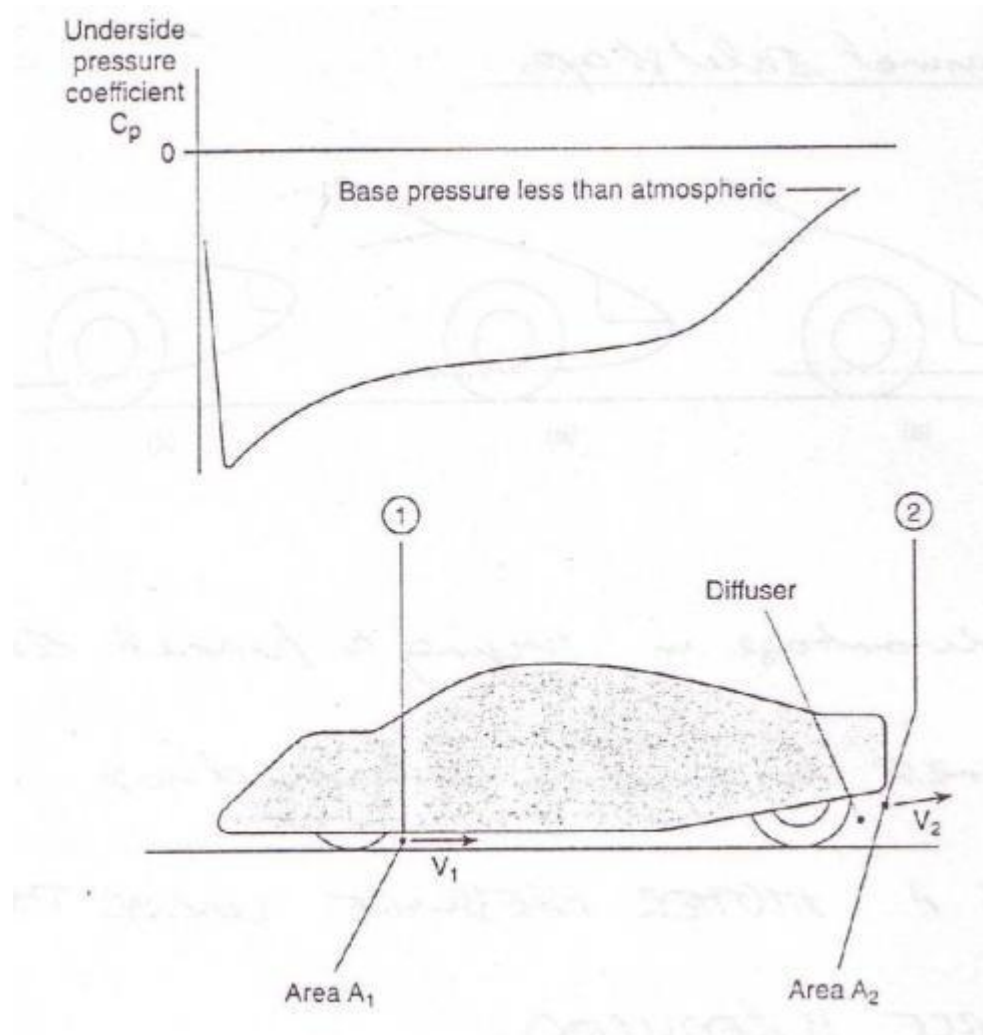


# Applications - Diffusers

diffusers before the rules limited their width and distance behind the rear axle line



1990 McLaren





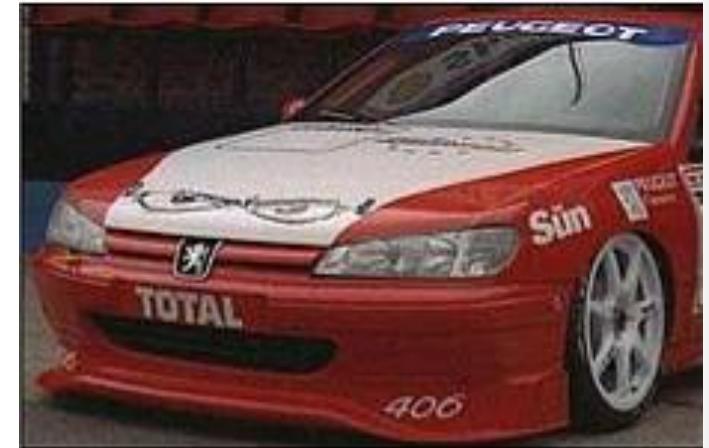
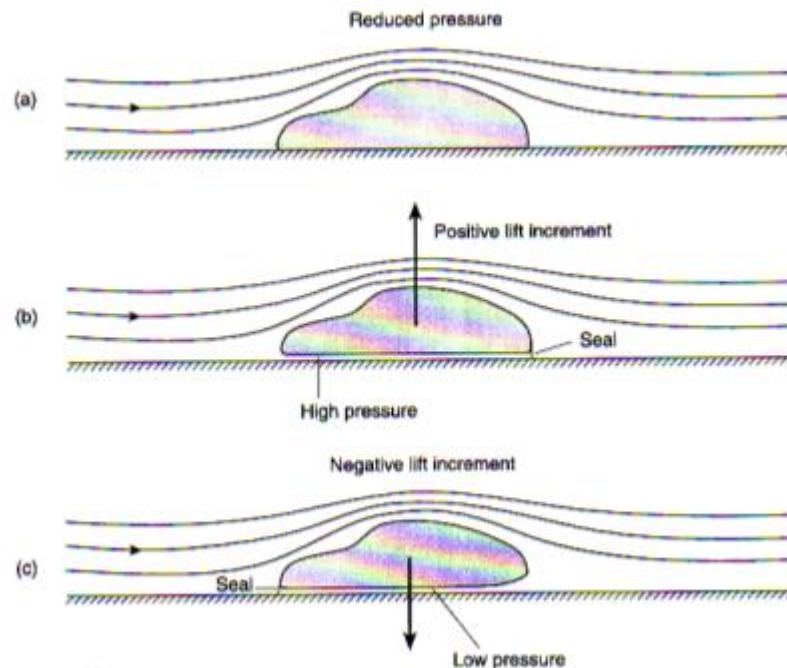
# Applications – Underbody flow

## Air dam

- Limits airflow under vehicle
- Air velocity increases resulting in low pressure

## Splitter

- Stops air 'spilling' under vehicle





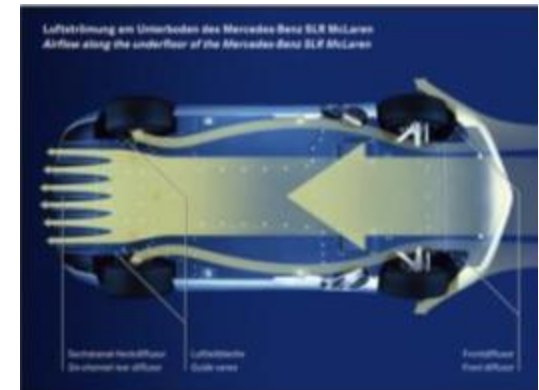
# Applications – Underbody flow

McLaren SLR

Flat under tray

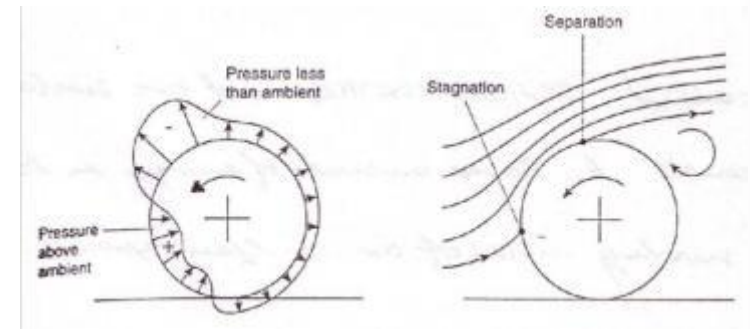
Rear diffuser

Wheel deflectors



Honda S2000

Wheel deflectors





# Applications – Frontal Area

| Vehicle          | $C_D$ | A    | $C_DA$ |
|------------------|-------|------|--------|
| Ford Sierra      | 0.34  | 1.97 | 0.67   |
| Vauxhall Calibra | 0.26  | 1.88 | 0.49   |



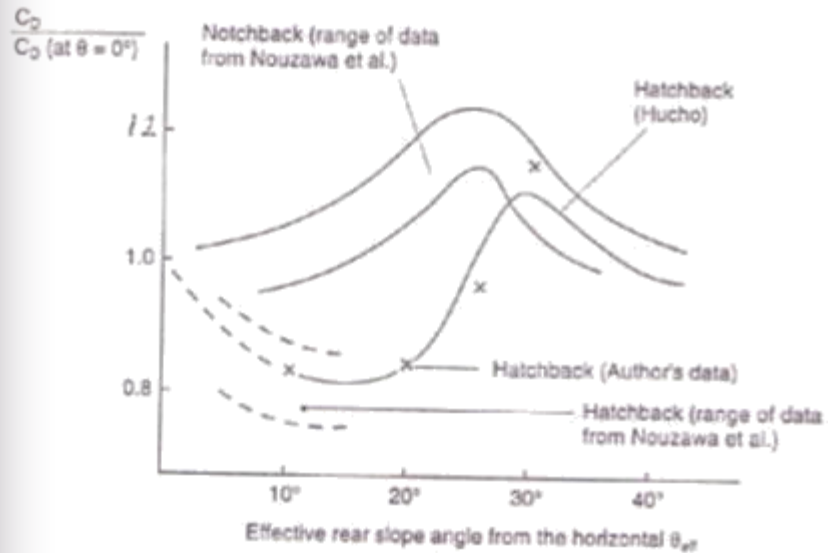
Tyrrell P34

Reducing the frontal area

- 10 inch wheels
- Won swedish GP in 1976
- Current FIA regs state car must only have 4 wheels

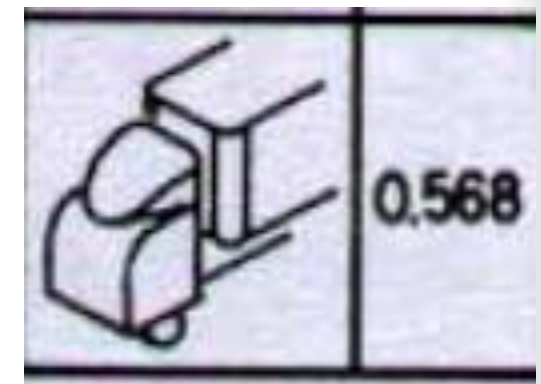


# Applications – The Notchback





# Applications – Trucks



$$C_D \ 0.86 > 0.57$$



# Rx-7

|                         | Baseline RX7 | RX7 - R-2 |
|-------------------------|--------------|-----------|
| Drag Coefficient        | 0.29         | 0.31      |
| Lift Coefficient, front | 0.16         | 0.10      |
| Lift coefficient, rear  | 0.08         | 0.08      |



Front Air Dam –

Rear Spoiler –



# Audi TT Recall

- Introduced in 1998
  - Unstable under high speed cornering
  - Several fatalities
- AUDI recalled 40,000 TT Coupes worldwide in Nov 1999
  - rear-wing spoilers were fitted to reduce lift
  - Suspension settings were altered to increase understeer
- Cost to Audi was reported as nearly £200m (<http://www.supercarworld.com/cgi-bin/showgeneral.cgi?133>)





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