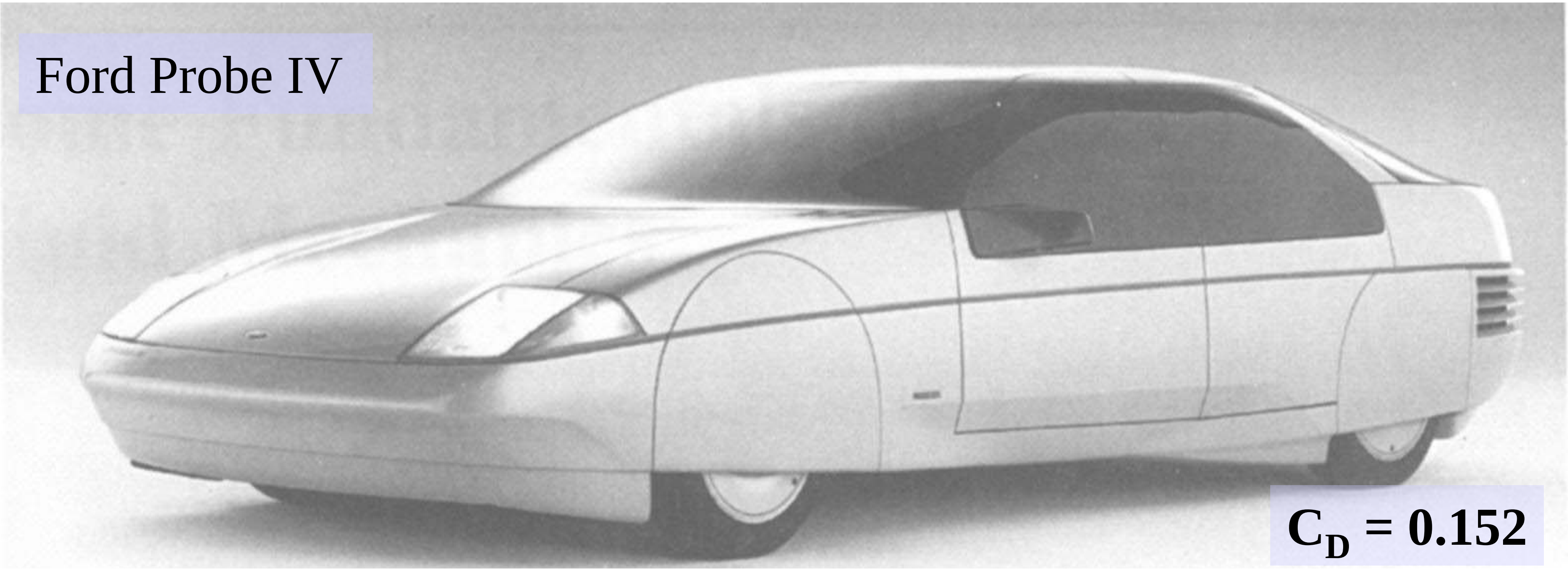
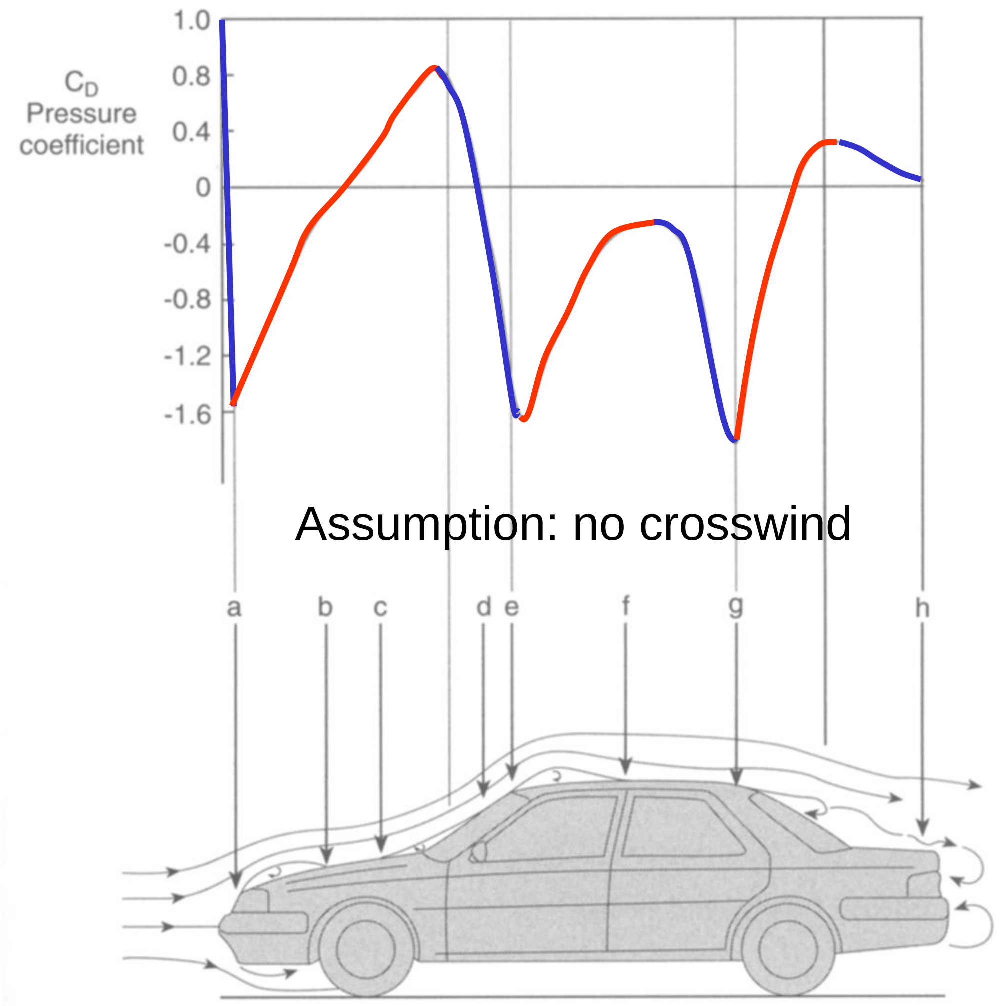
Flow Field Features and Aerodynamic Drag of Passenger Cars



Centerline Flow Field of a Typical "3-Box" Design

- The centerline flow field around a passenger car is characterized by separations and reattachments
- The flow character can be directly related to the pressure gradients, favorable in blue and adverse in red



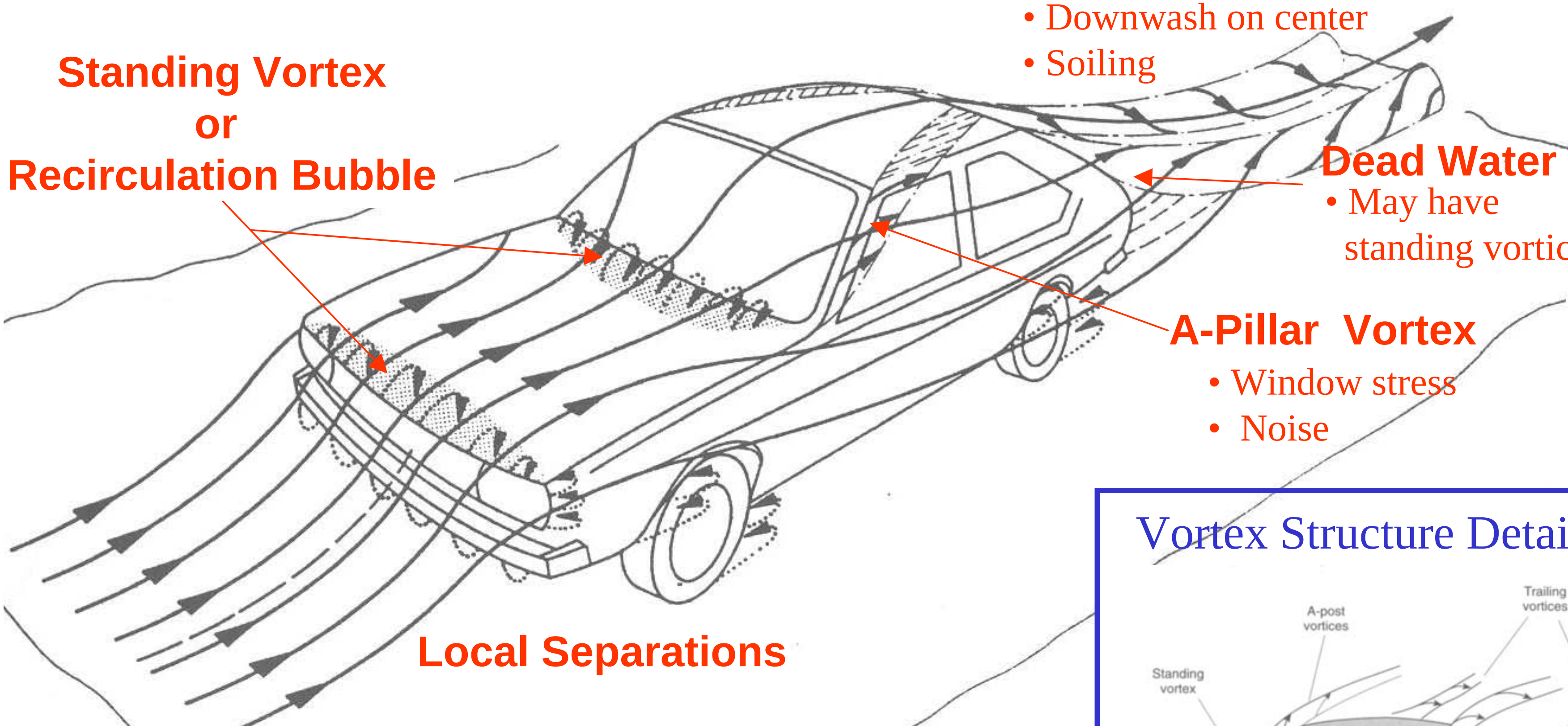
Adapted from: Barnard

a) Separation above grille
b) Reattachment on hood
c) Separation in front of windshield
d) Reattachment to top of windshield
e) Separation at roof corner
f) Reattachment downstream on roof
g) Separation at end of roof line
h) Unsteady attachment/separation over trunk

The 3-D Flow Structure

C-Pillar (Trailing) Vortices
- Induced drag
- Downwash on center
- Soiling

Standing Vortex or Recirculation Bubble



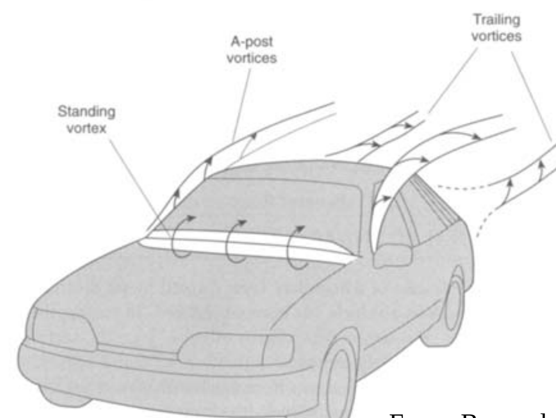
Dead Water
- May have standing vortices

A-Pillar Vortex
- Window stress
- Noise

Local Separations

From: Hucho

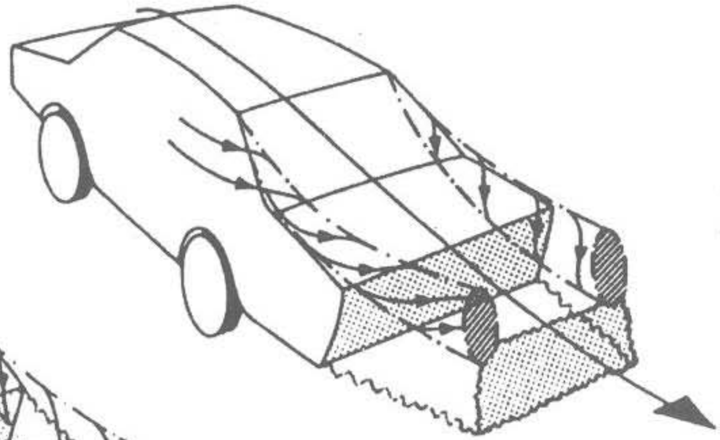
Vortex Structure Detail



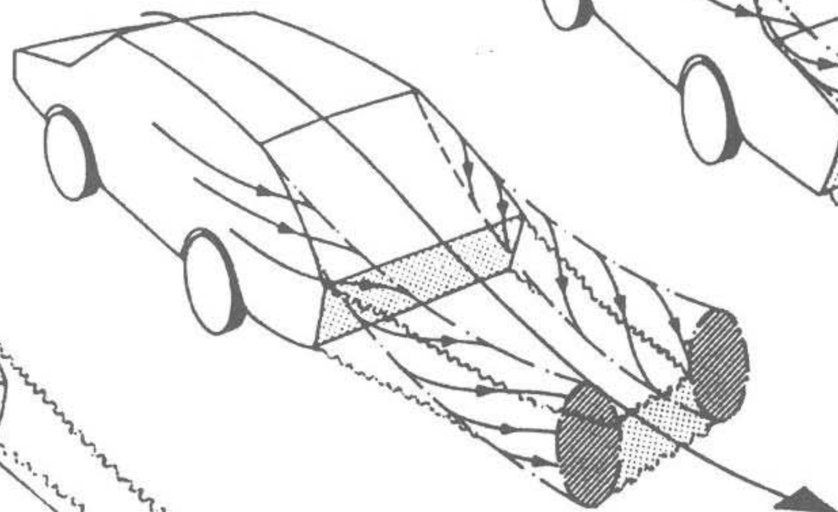
From: Barnard

Trailing Vortices

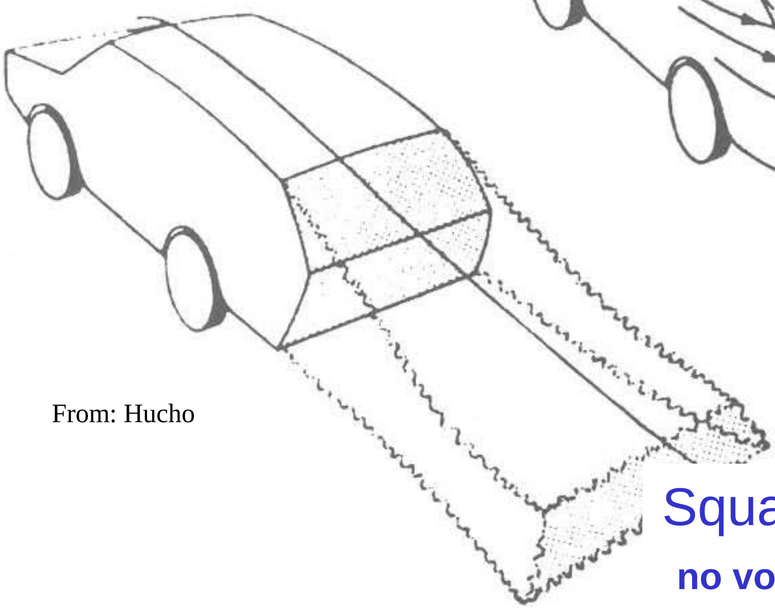
- The nature of the counter rotating vortex structure is controlled primarily by the rear end geometry while the upstream flow condition plays a secondary role
- Vortices expend energy => Drag



Notchback
weaker vortices, dead water below



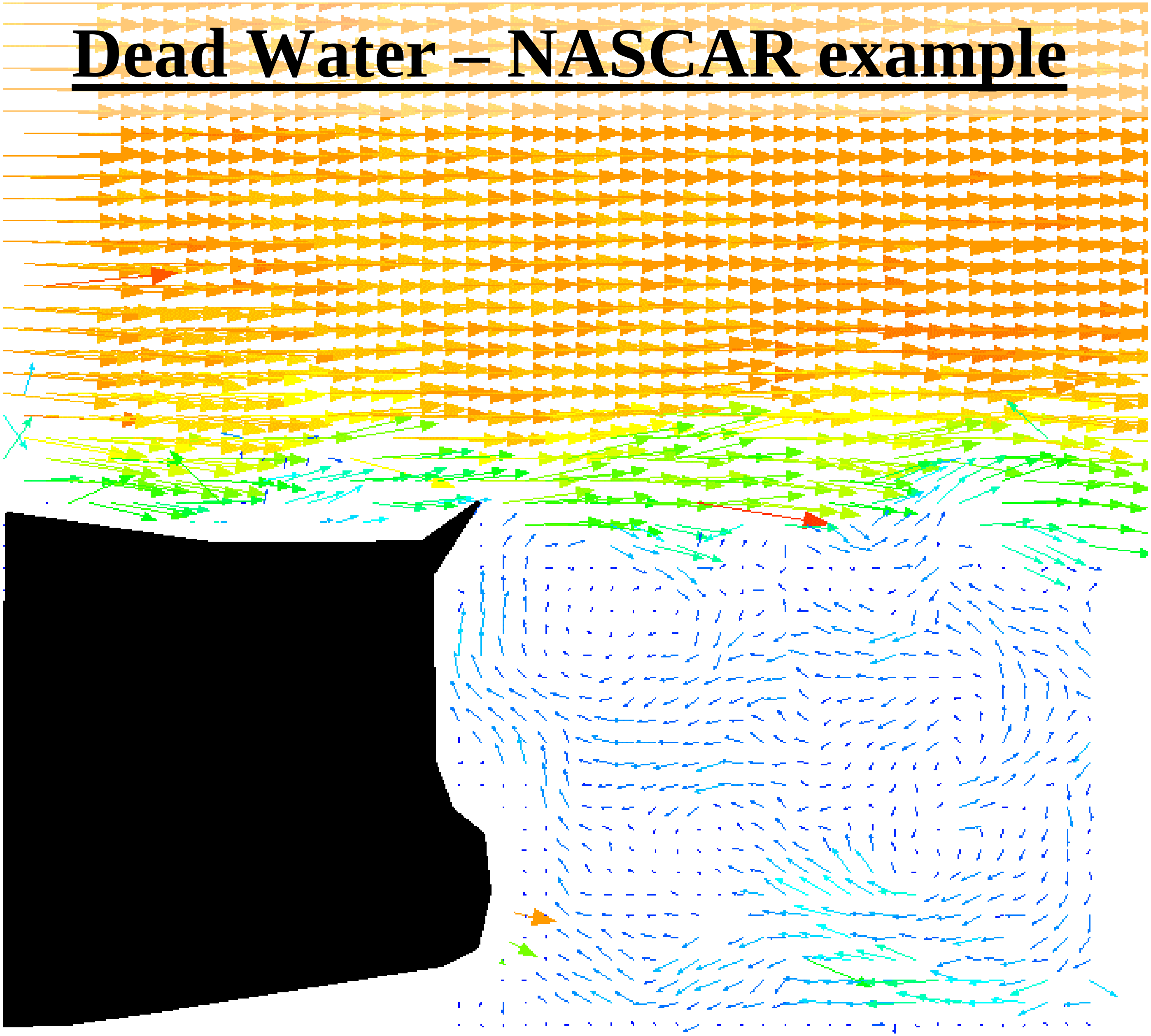
Fastback
strong vortices, dead water between



From: Hucho

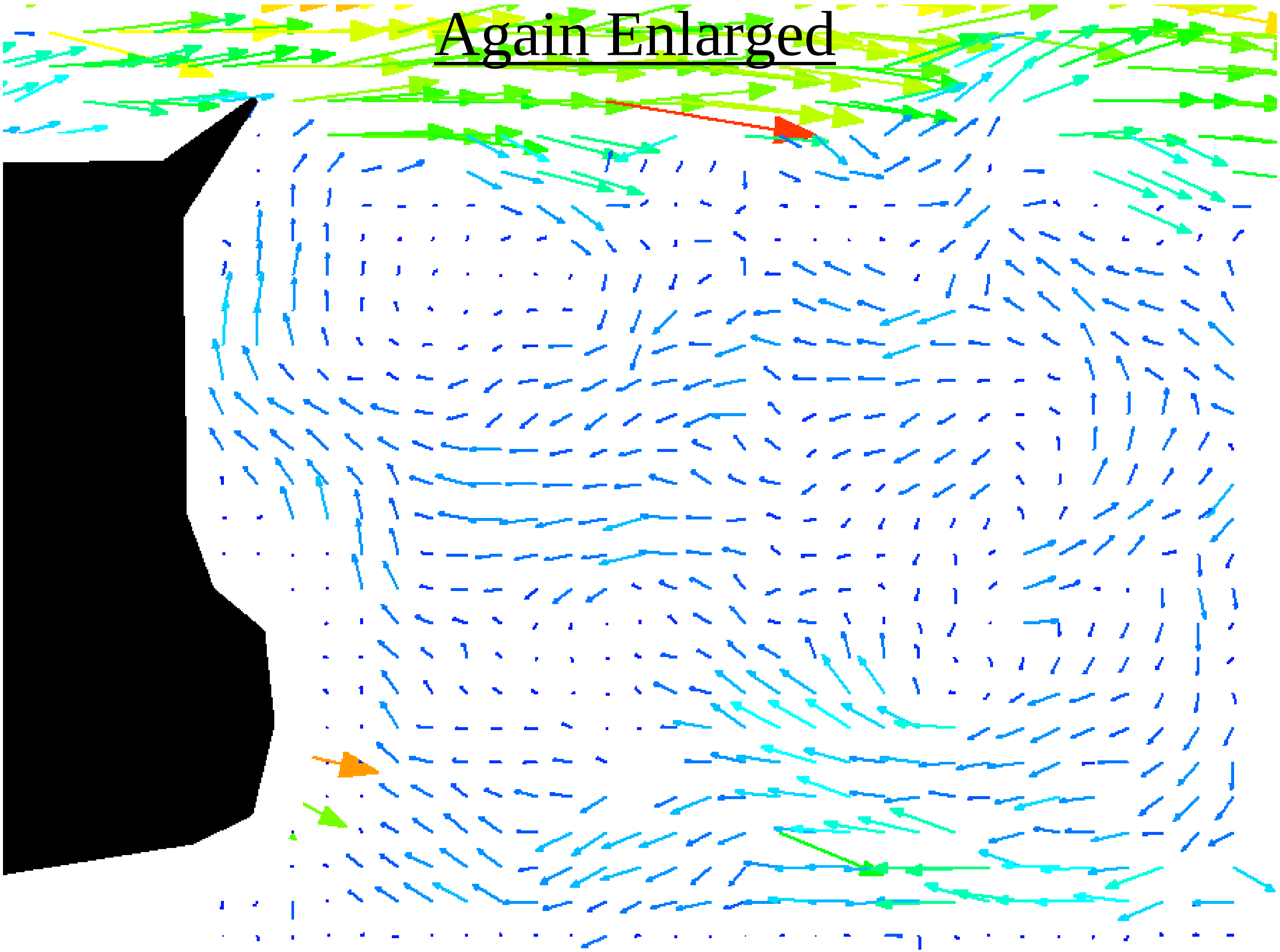
Squareback
no vortices, large dead water

Dead Water – NASCAR example



1/18th Scale Model PIV measurements by Landman et al.

Again Enlarged

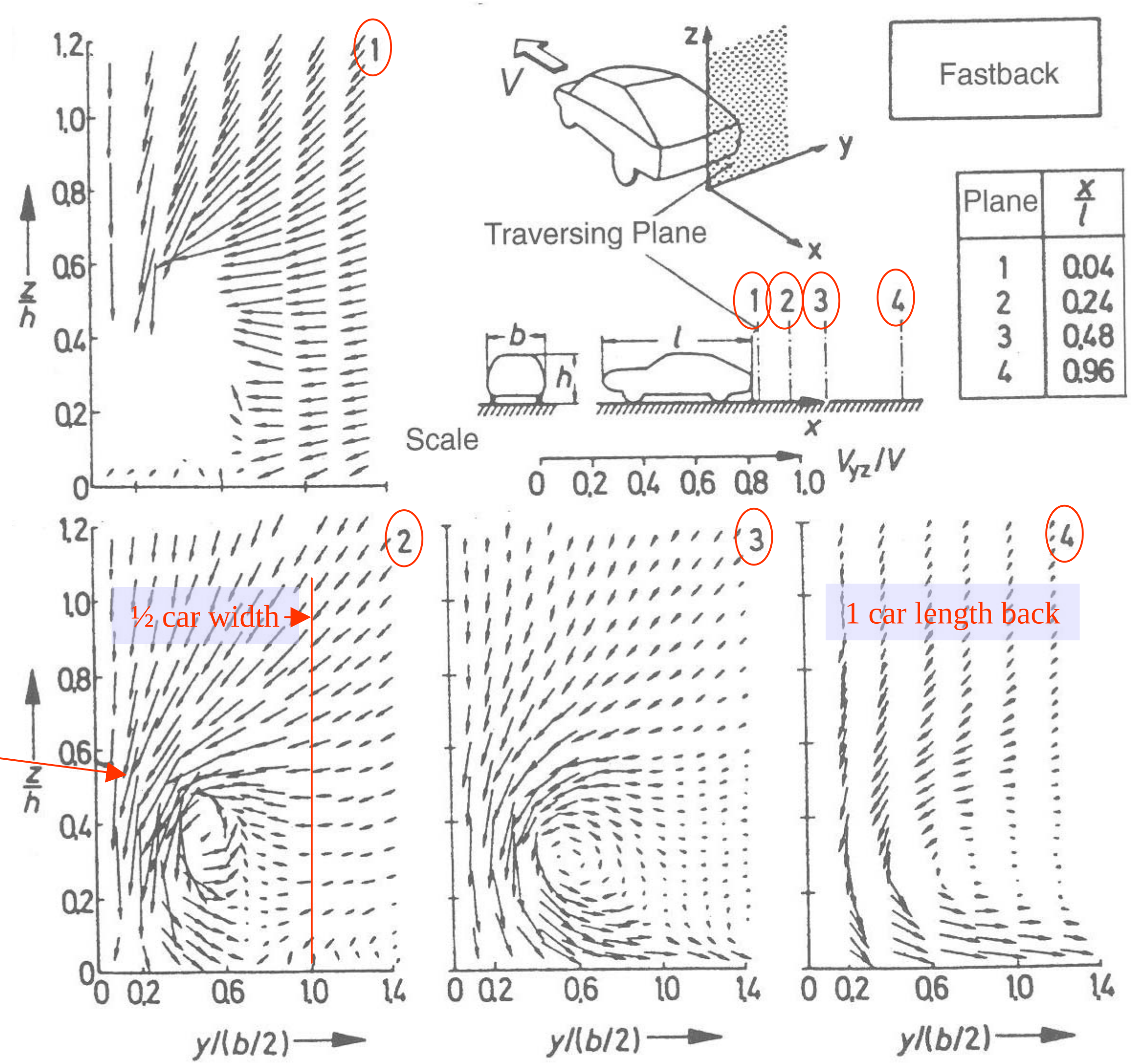


1/18th Scale Model PIV measurements by Landman et al.

Fastback Wake

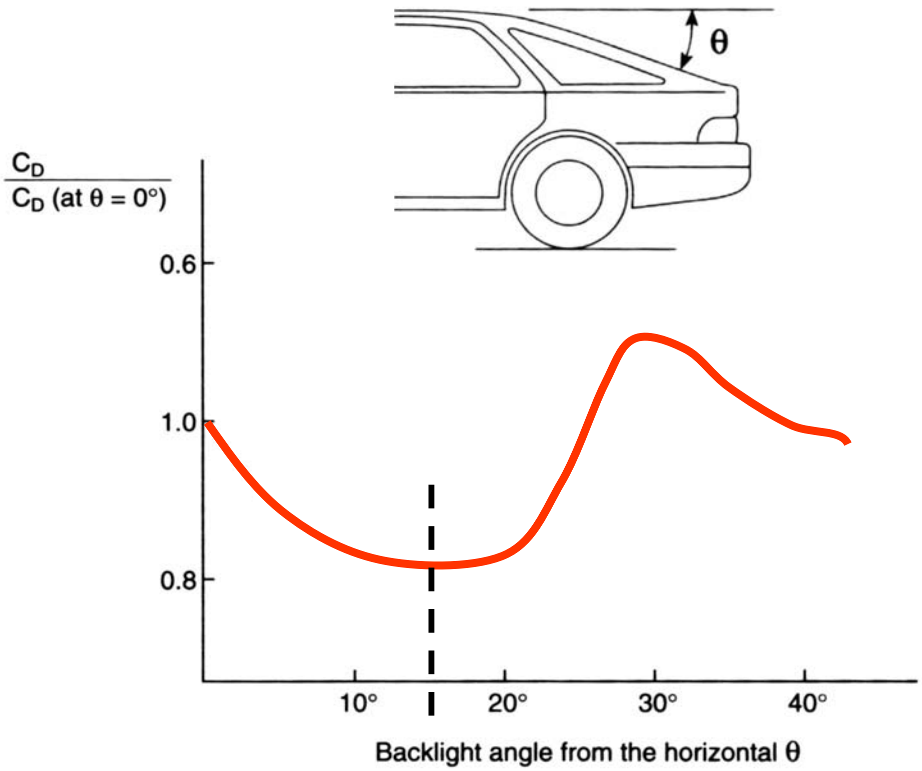
From: Hucho

- Velocity vectors in a transverse plane show the strong vortex developing and moving towards the ground with increased distance
- The slant angle of the backlight region determines the vortex strength
- Downwash is induced between vortex pair pulling flow off roof and down rear window



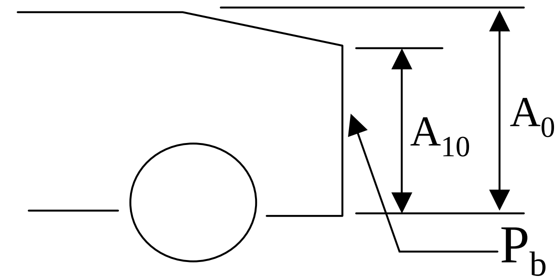
Sources of Drag: Backlight Angle

- The rear window angle with the horizontal is called the backlight angle
  - The angle of inclination affects the trailing vortex location and strength One Example:
  - Note how drag is shown. It is a ratio to drag at the current backlight angle (θ) to drag at $\theta = 0^o$
  - Dashed line at approximately $\theta = 15^o$ is nearly ideal for this car, 20% lower C_D than the value at $\theta = 0^o$

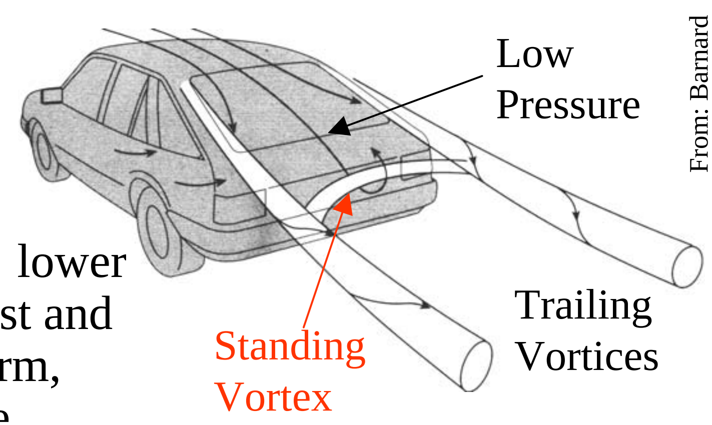


Exploring Backlight Angle and Drag

- Why the change in C_D for different angles ?
  - Lowering angles from 0=>10^o lowers the pressure drag since the area on the rear of the car is getting smaller and flow remains attached providing a constant base pressure (P_b) (squareback has same wake structure)
  - Just before reaching the minimum (~15^o) the flow will start to separate. The low pressure on the back will tend to cause the flow to form trailing vortices – trailing vortex drag similar in nature to the low aspect ratio delta wing
  - As the backlight angle is increased further, the vortices become stronger causing increasingly lower pressure on the back until at ~30^o the vortices burst and the whole rear end is separated, vortices cannot form, drag will now decrease with further increase of the backlight angle

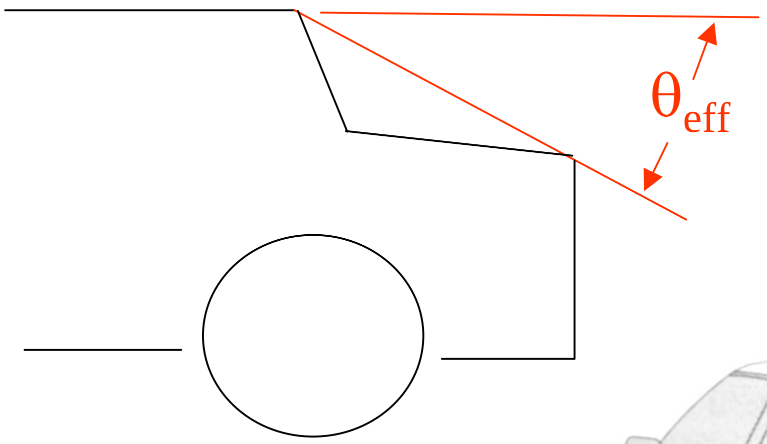


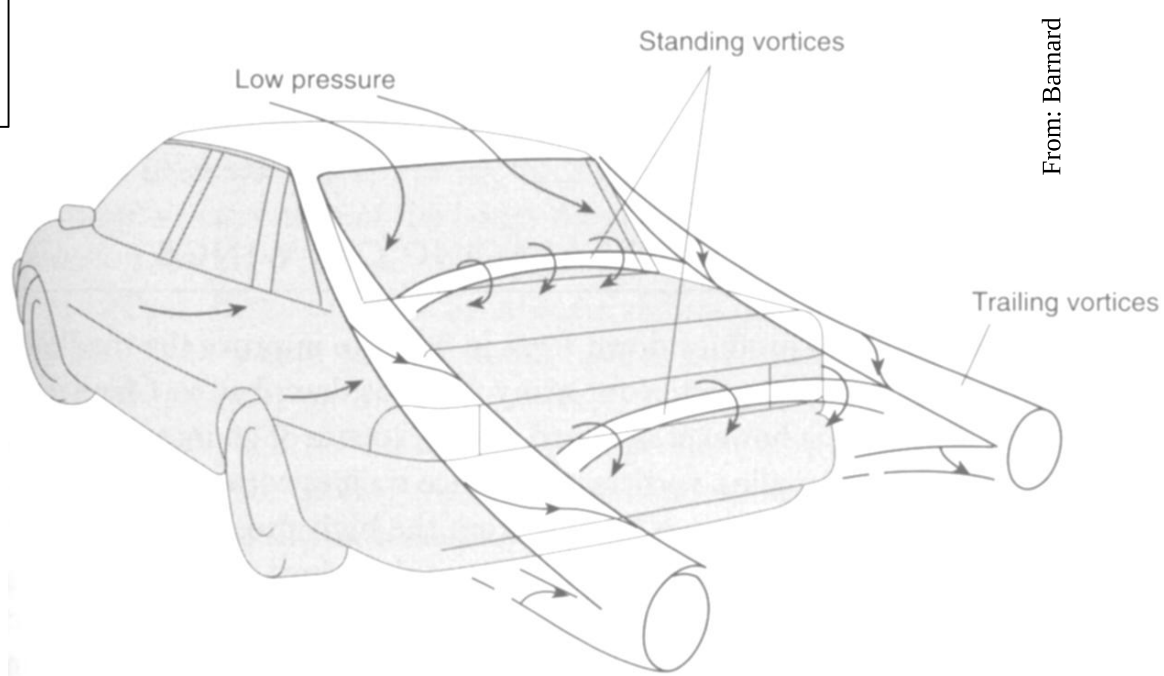
A_{10} is the base area at $\theta = 10^o$
A_0 is the base area at $\theta = 0^o$



The Notchback

- Follows the same basic flow structure arrangement as was shown for the fastback but using θ_{eff} as the ”backlight” angle





From: Barnard

A Wag at Drag Breakdown

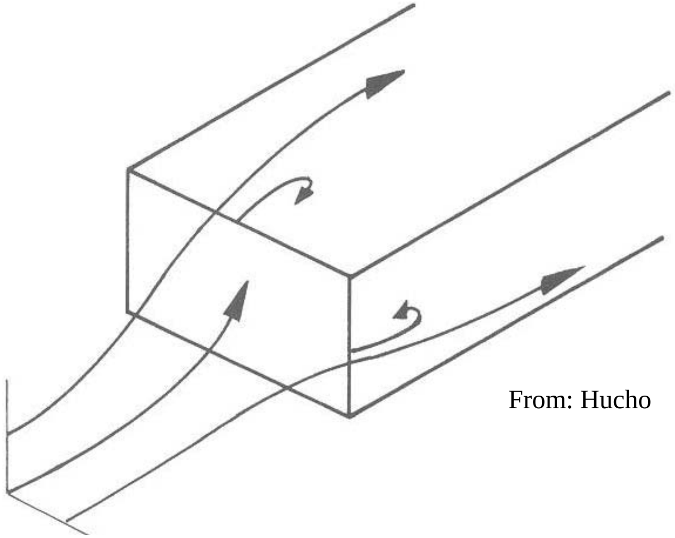
- Sources
  - **Pressure Drag: primarily the result of separation**
  - **Skin Friction: shear stress acting over the entire body**
  - **Induced or Vortex drag: due to the formation of trailing vortices**
    - **Relations such as those for wings where $C_{Di} = f(C_L)$ are poorly correlated**
- Estimates of contributions to drag on a well designed sedan

Contribution	ΔC_D
(Body) Shear Stress	0.08
(Body) Pressure Drag	0.10
Effects of Wheel Rotation	0.08
Cooling Drag	0.03
Trailing Vortex	0.01
Total	0.30

From: Barnard

Sources of Drag

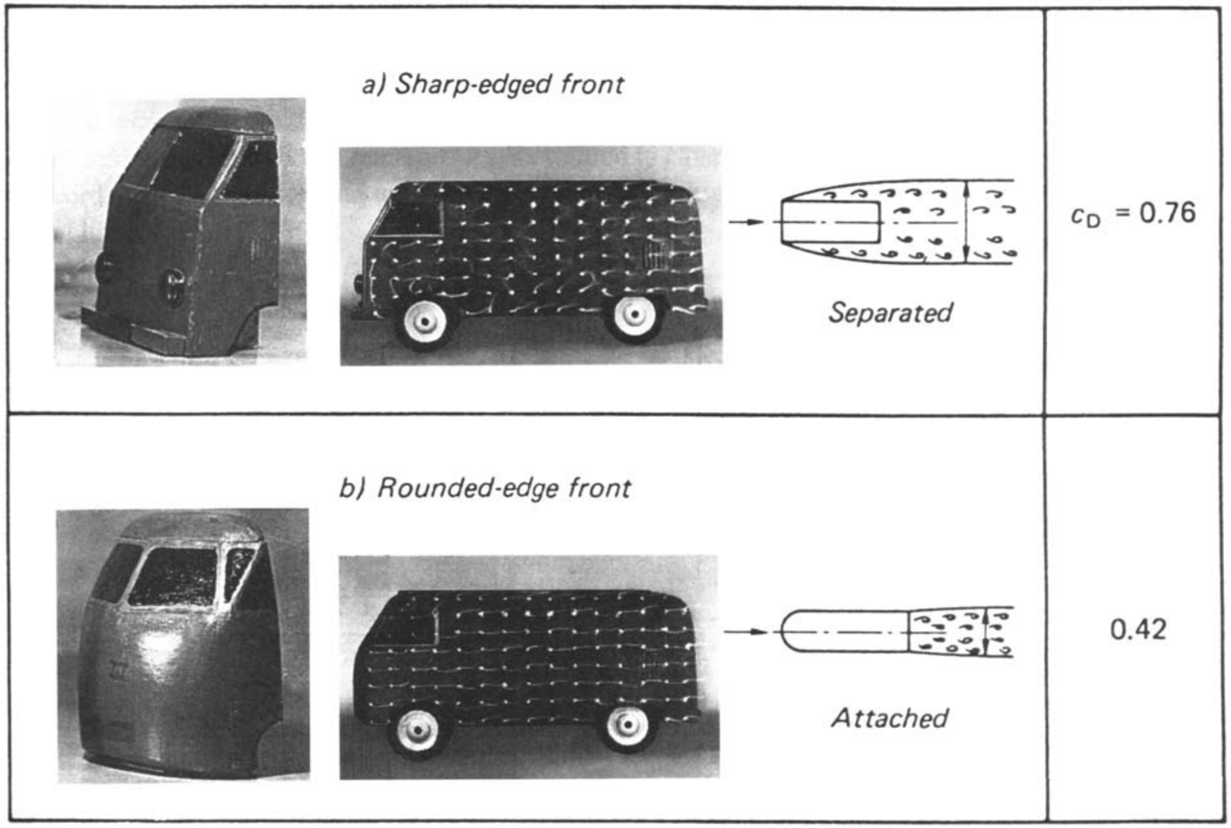
- Most automotive development projects will require the aerodynamicist to evaluate the drag by means of a force balance in a wind tunnel
- The first task is to eliminate separations wherever possible
- Since separations on the vehicle front end may effect flow development on the sides, roof, or rear, the front end is the place to start
- Note that the front end most closely resembles a rectangular solid
- It must be rounded to avoid separation
- Radius required is a function of Reynolds Number



From: Hucho

Corner Radii

- We saw the VW minibus development in the history section and it stands out as one of the more dramatic examples
  - By adding smooth radii to the corners of the front surface, drag was reduced drastically
  - Recent research has shown that the radii may be smaller and still effective
  - The wake and hence pressure drag were reduced
  - Flow now separates at the rear surface

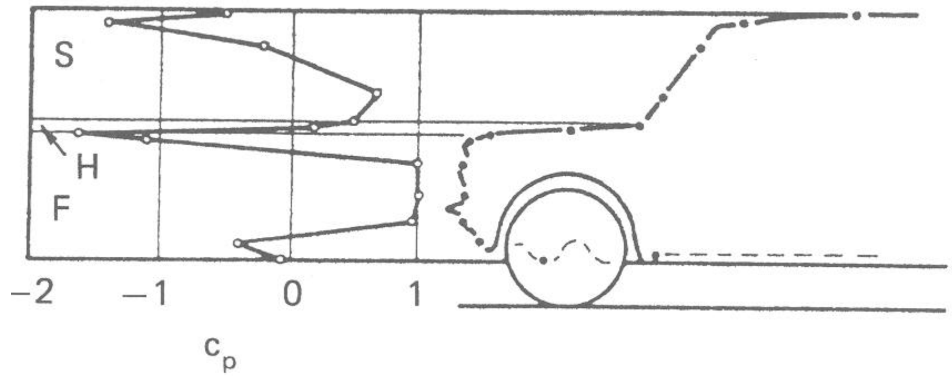


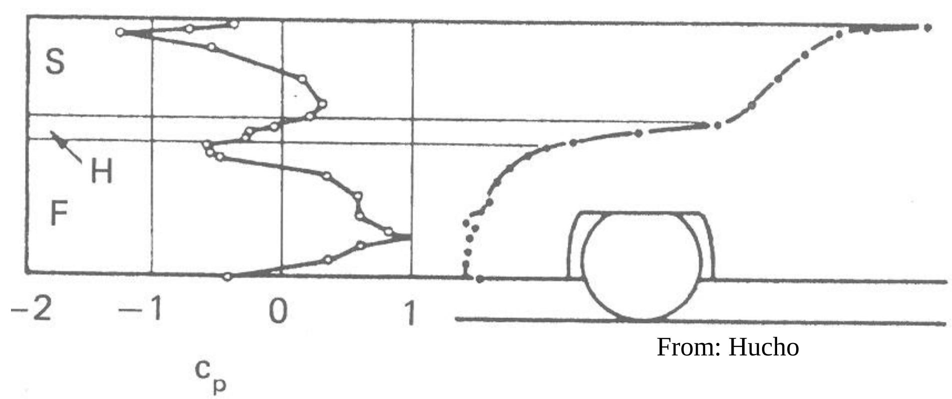
From: Hucho

Front End Pressure Measurements

- If the model can be pressure instrumented the aerodynamicist can then evaluate the pressure gradients

- As always, adverse pressure gradients should be avoided

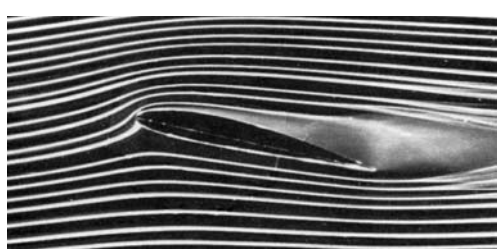


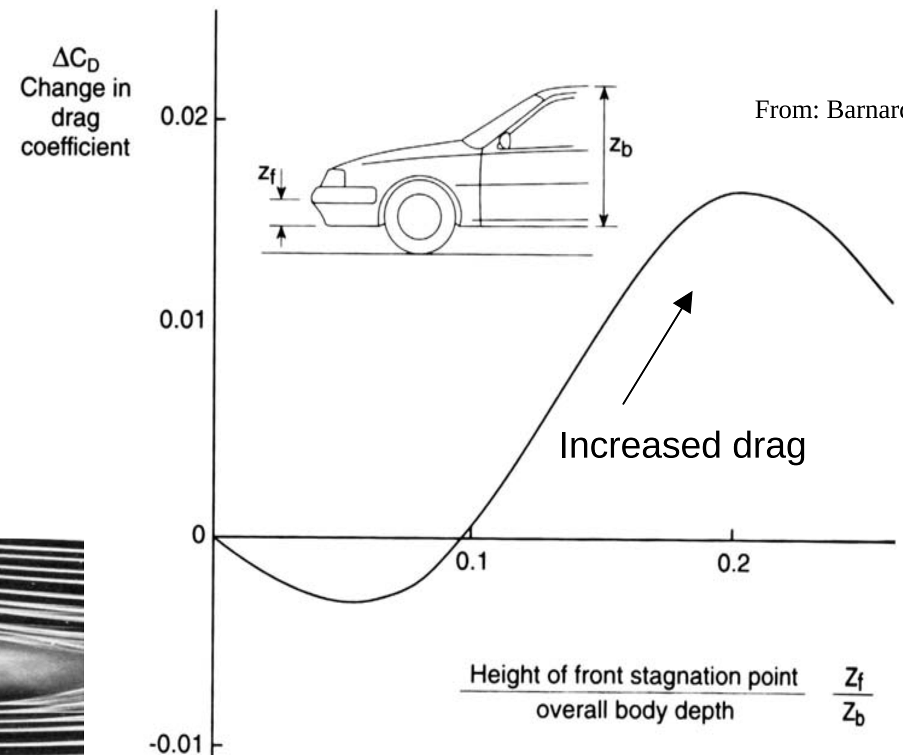


From: Hucho

Stagnation Point Location

- Example
  - Recall the stagnation point is the point where a streamline reaches zero velocity
  - The figure shows the relationship between C_D and the ratio of stagnation point height to passenger compartment height
  - A negative ΔC_D value indicates a lower drag than the original configuration
  - In general we want to lower the stagnation point to lower C_D
  - How do we find the stagnation point:

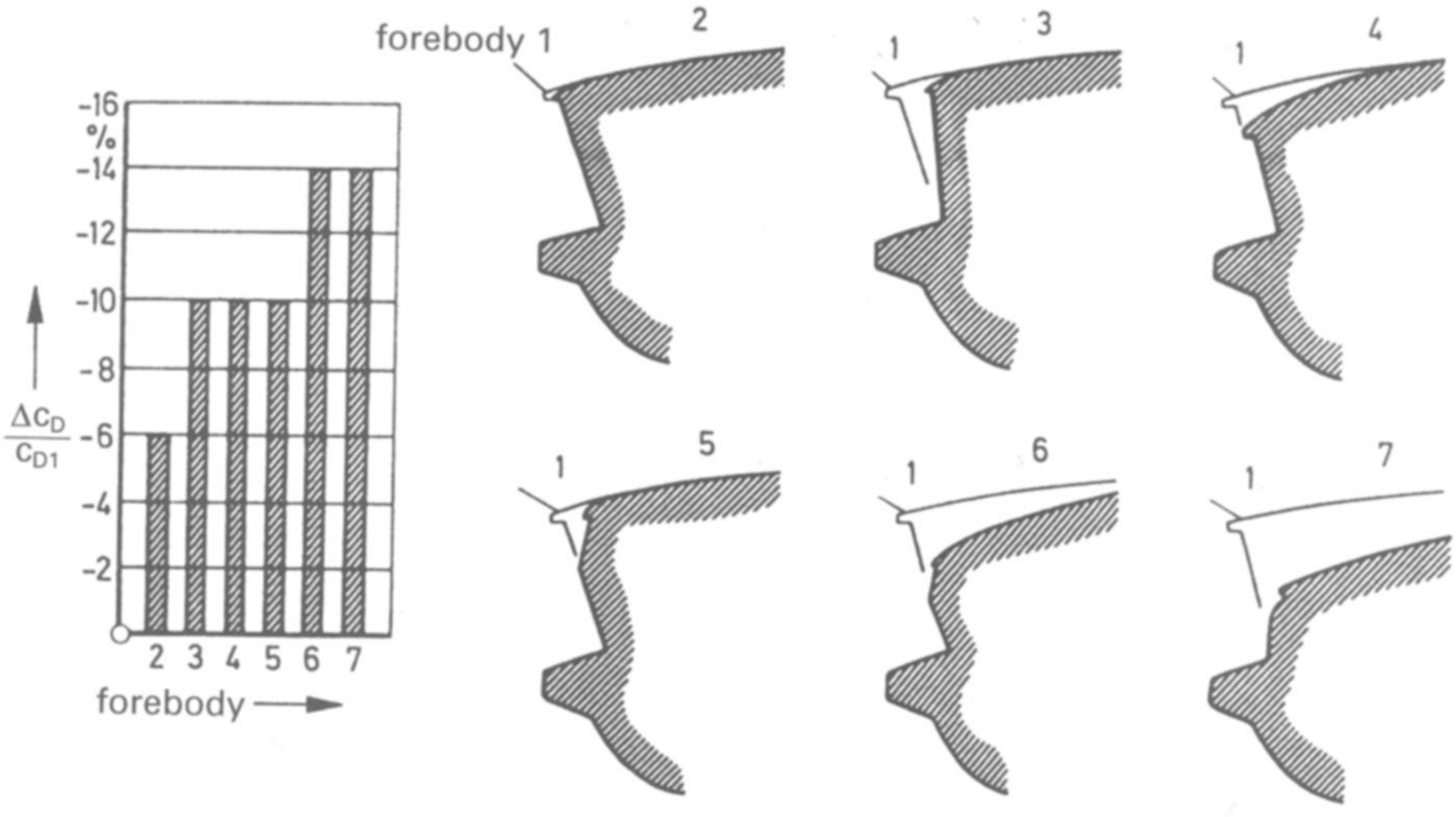




From: Barnard

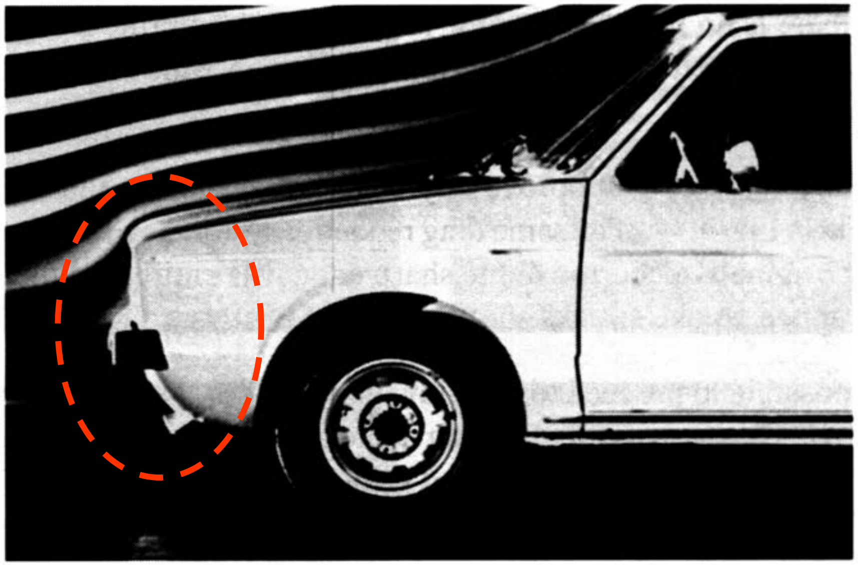
Front End Design Example I

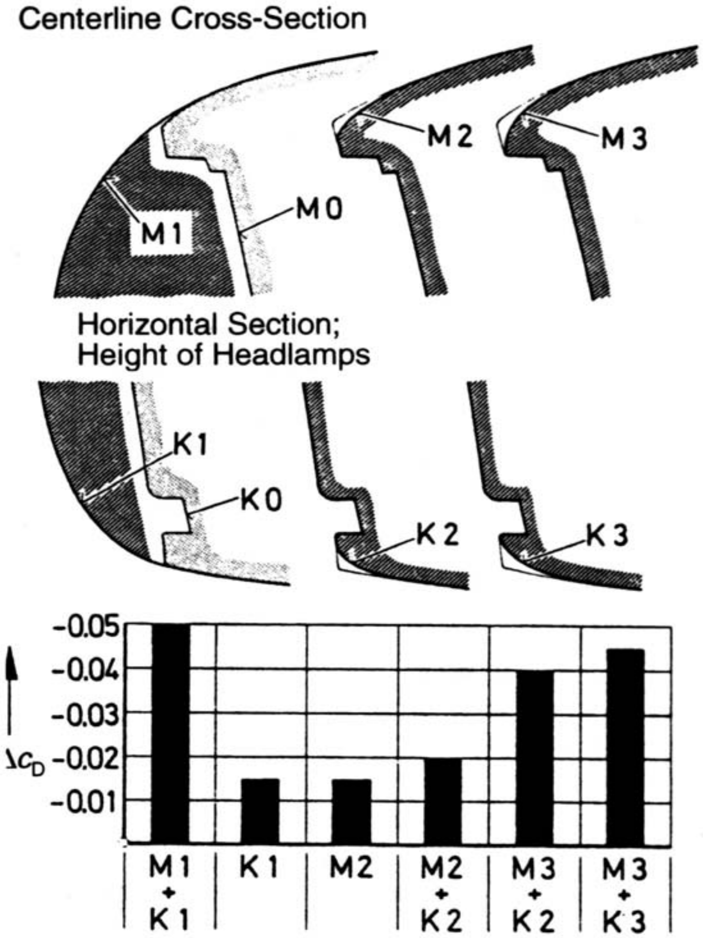
- Example by Hucho showing drag reduction



Front End Design Example II

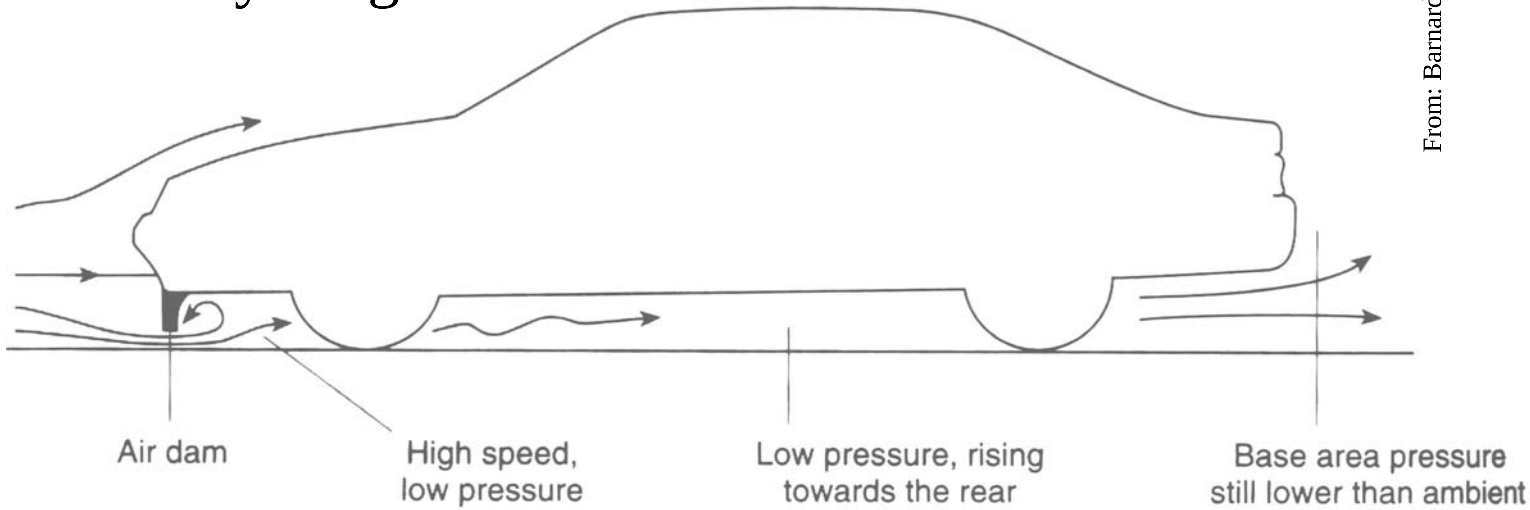
- Example by Hucho and Janssen
  - VW Rabbit (called Golf I in Europe)





Airdams

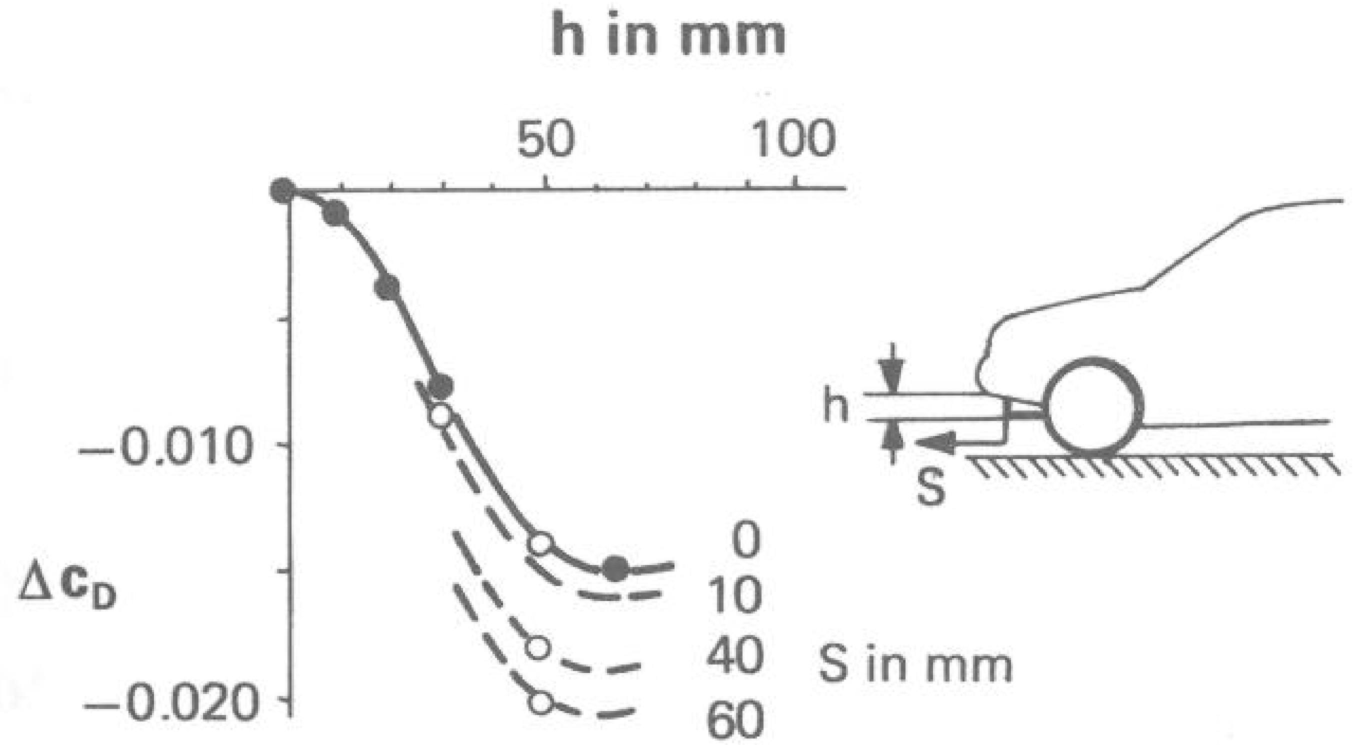
- An airdam is a panel that reduces ground clearance at the front of the car below the bumper
- The smaller gap forces flow to locally accelerate under the airdam reducing pressure under the car and creating downforce
- Lower air volume flow to underbody reduces drag due to underbody roughness



From: Barnard

Airdam Example

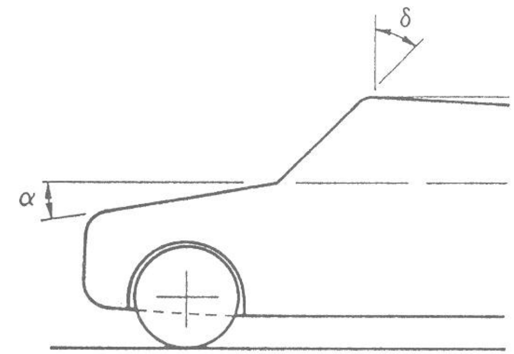
- Height and rearward position of airdam (also called front spoiler) are normally adjusted during wind tunnel testing
- Example by A. Costelli on Fiat Uno



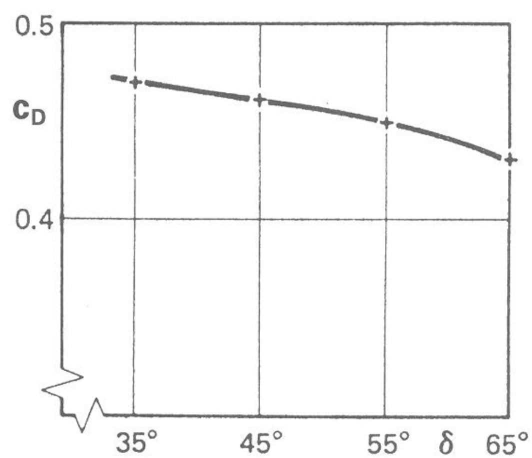
Hood and Windshield Angle of Inclination

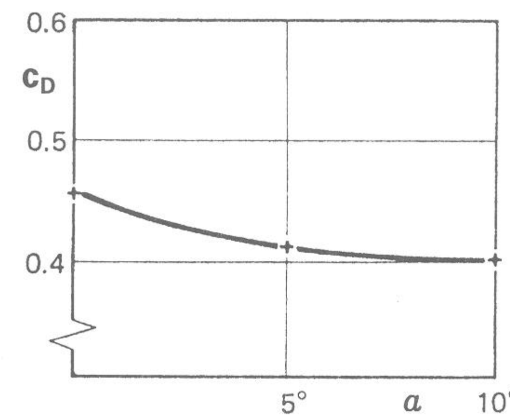
- The hood angle (α) determines the pressure gradient and plays a role in maintaining attached flow
  - Note that only a small angle is necessary, C_D asymptotes
  - Beneficial to delay downstream flow separation such as at windshield/hood junction

From: Hucho



- The windshield angle, δ (rake) plays a stronger role by controlling point of attachment of flow to roof
  - researchers here found no minimum in drag over a 30 degree range

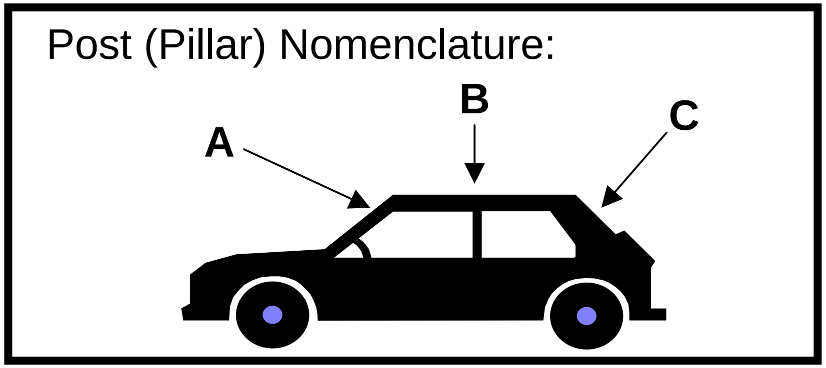


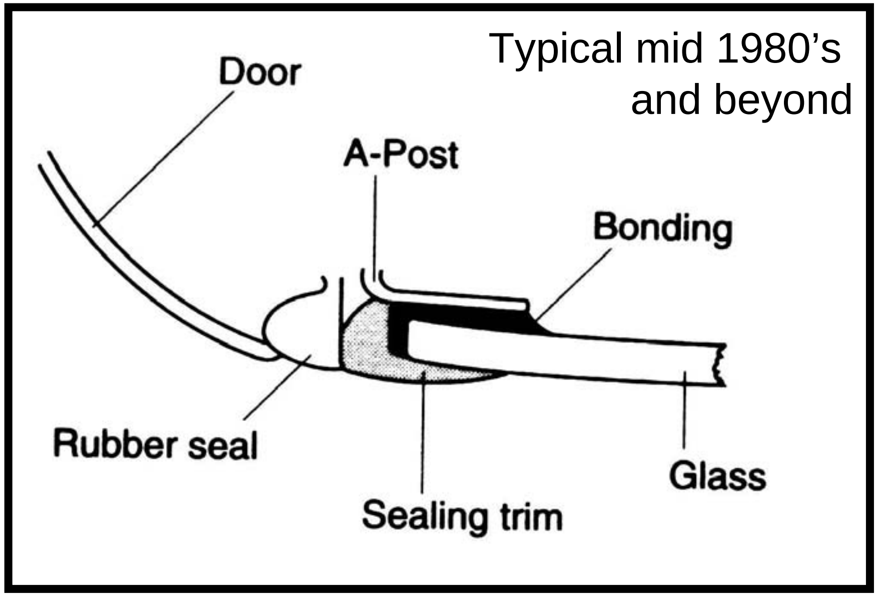


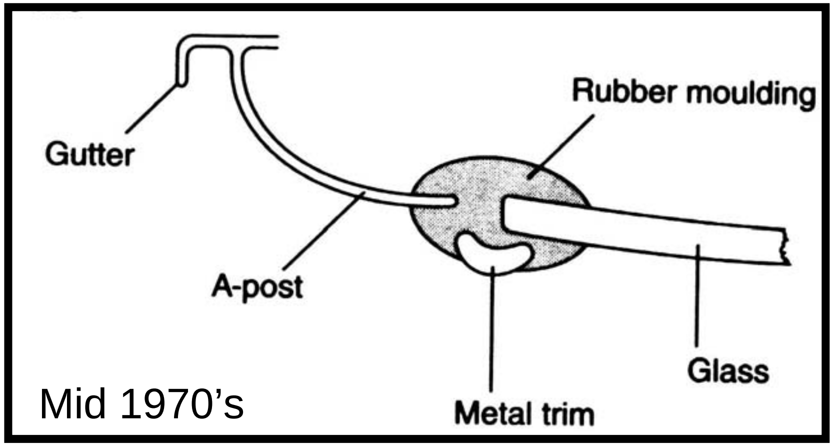
Door and Roof Seams

- Example: door seals and rain gutters
  - Typical designs for front doors on cars from eras noted
  - Flush panels can avoid premature separation, can lower skin friction

From: Barnard

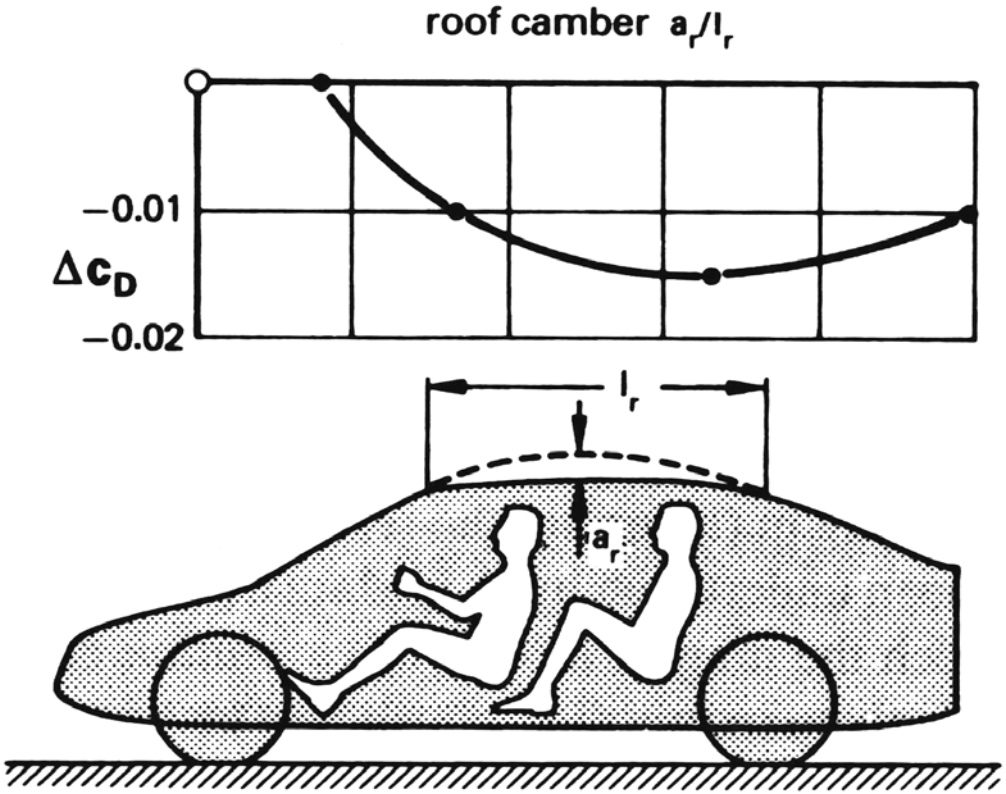






Roofline Shape

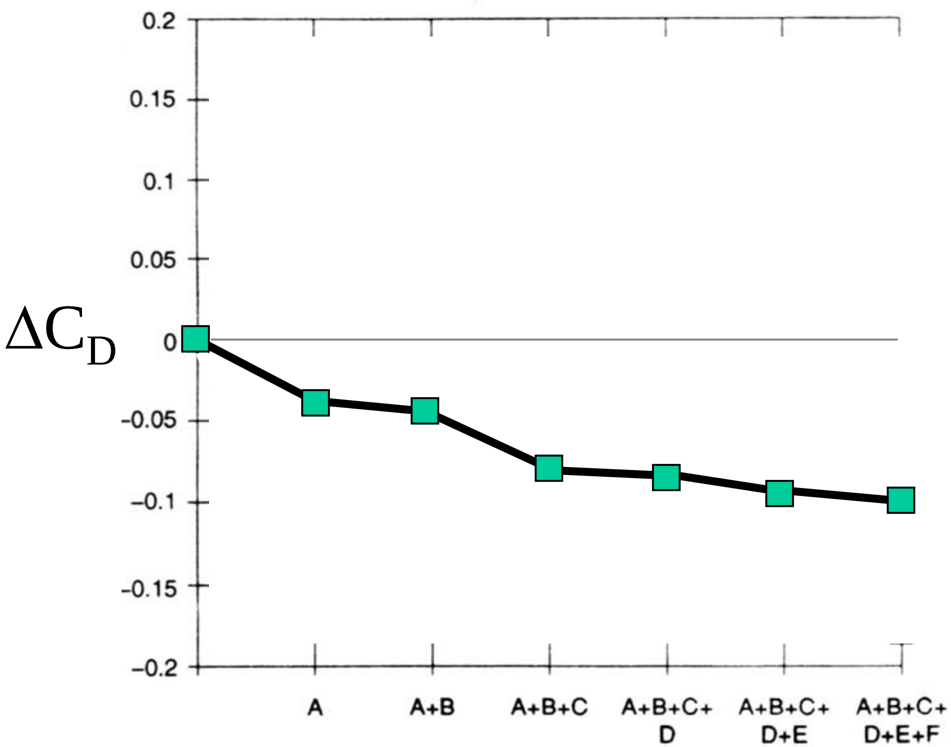
- Example: roofline camber
  - Curved (cambered) roofline helps maintain attached flow over the rear of the car

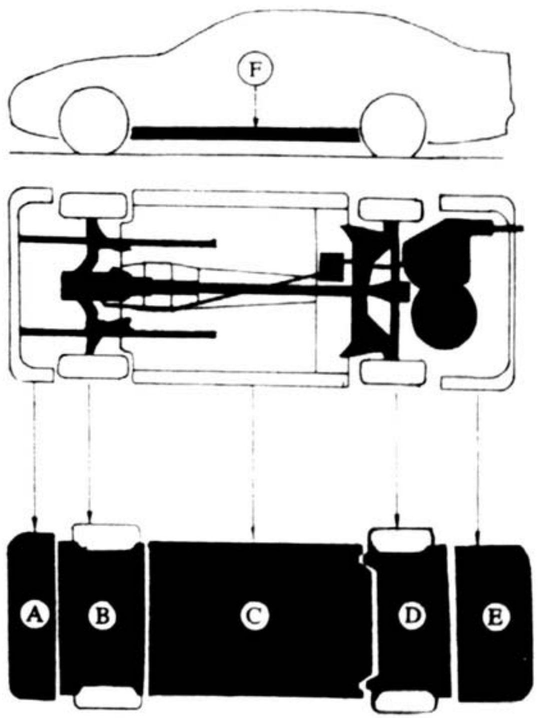


From: Hucho

Underbody Roughness: The Ugly Underneath

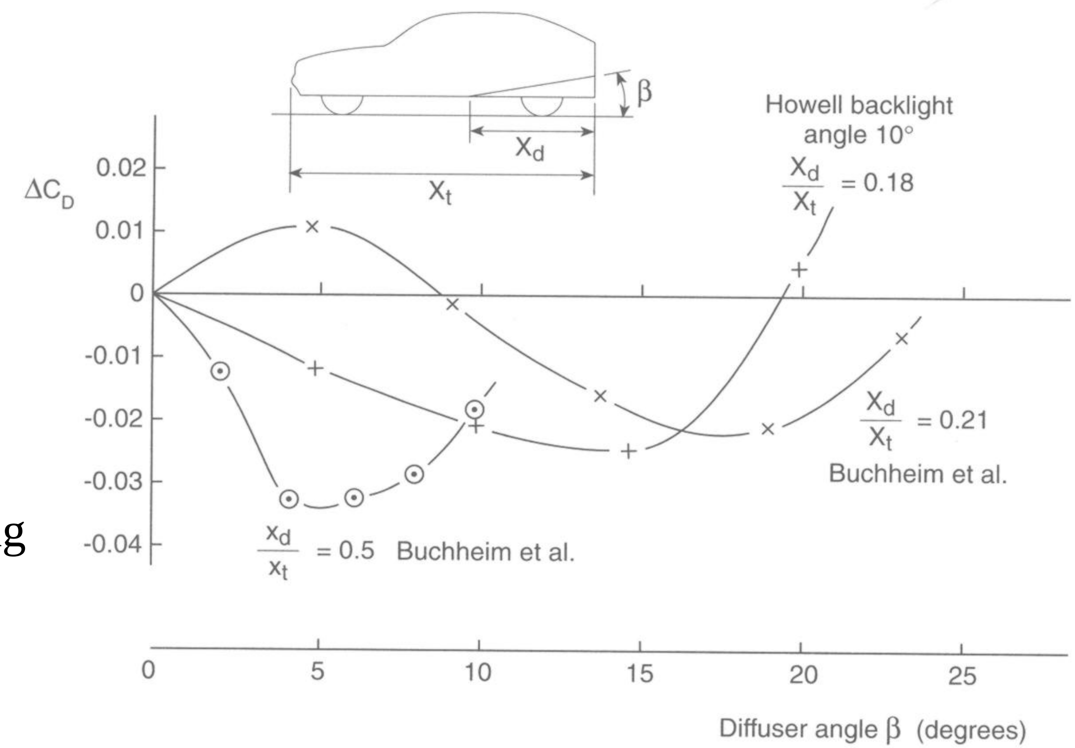
- Example: adding underbody cover panels to a sedan
  - A through E are smooth covers, F is a side modification (rocker panel)
  - Often production cars use underbody to reject heat – a consideration when enclosing





Underbody: Rear Diffuser

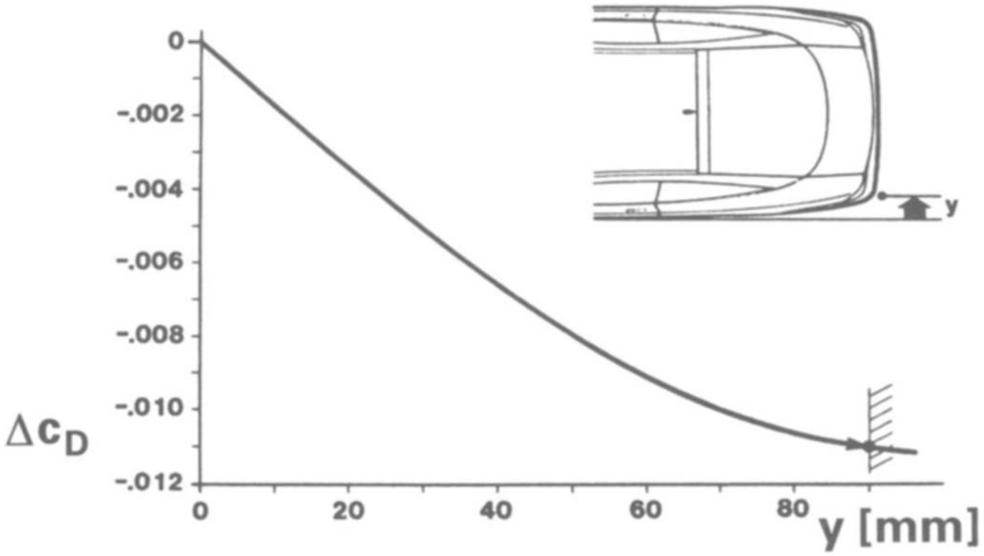
- Usually thought of as a downforce producing detail for race cars
- Has beneficial effect on passenger car drag too
  - Reduces the pressure drag
  - Tends to reduce trailing vortex strength
  - Reduces underbody surface friction

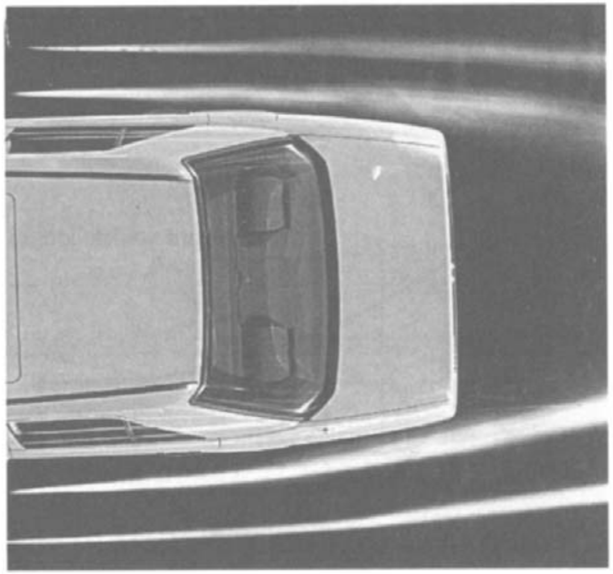


From: Barnard

Boat-Tailing

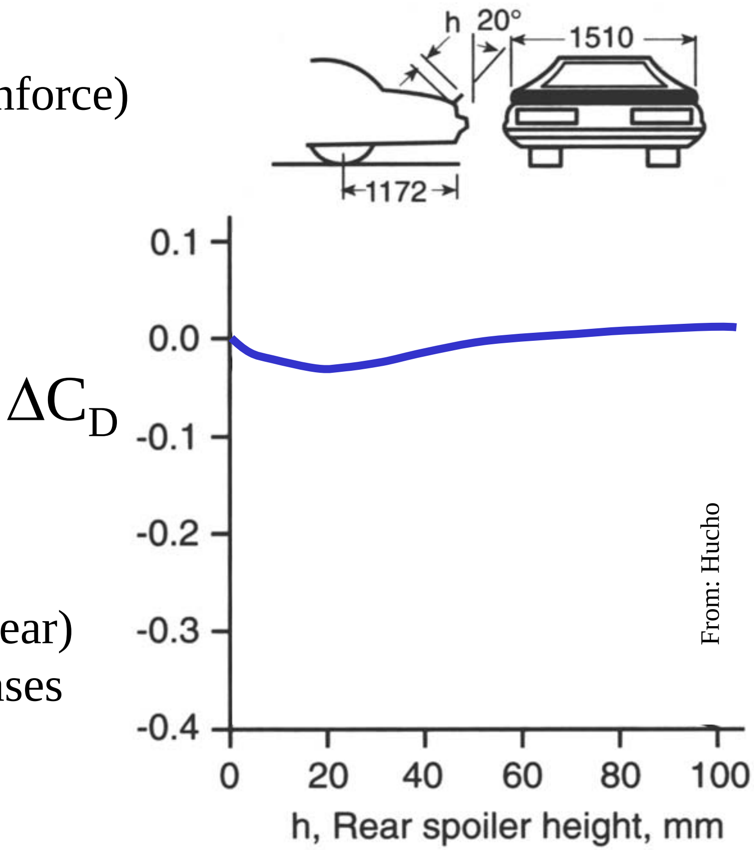
- To provide the highest possible static base pressure and to minimize the area over which it acts: Boat-tail
- Impractical at extremes but effective even if truncated as shown historically by Kamm
- Mid-Size sedan examples of boat-tailing (from Hucho)





Rear Spoilers

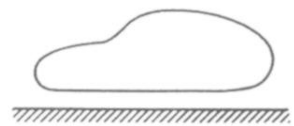
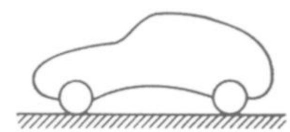
- For passenger cars the rear spoiler (if not just cosmetic) can have 3 effects
  - Reduce drag
  - Reduce rear axle lift (by creating downforce)
  - Reduce dirt on the rear surface
- Can be free standing device or "deck strip"
- Causes increase in pressure just forward of the spoiler
  - This increase helps combat pressure drag (which is due to low pressure at rear) up to a critical height, drag then increases again as region behind spoiler is separated



Wheels A Major Drag Contributor

- Can account for as much as 50% of drag of a streamlined car
- Why ?
  - Wheels are not streamlined
  - Underbody flow spreads out towards the sides, puts wheels in yaw, raising drag versus straight ahead by as much as 3X due to resulting separation
  - They rotate in close proximity to housings, pumping action raises stagnation pressure at windward side
- More details to come when we discuss lift

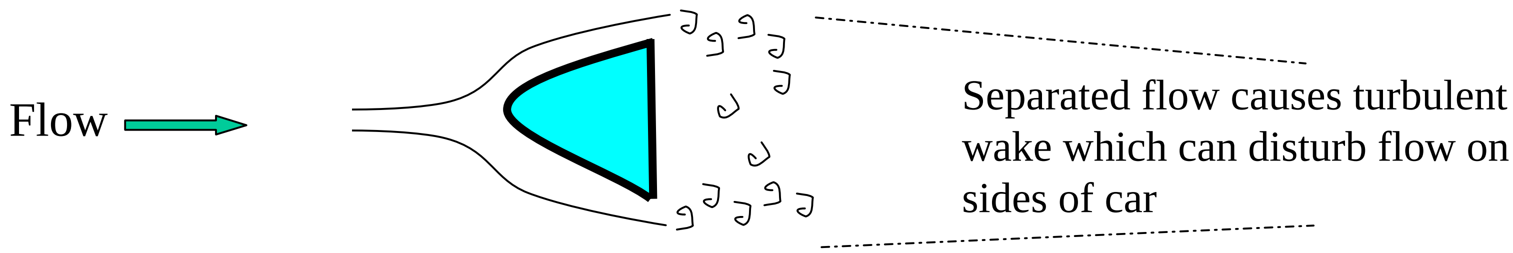
From: Hucho

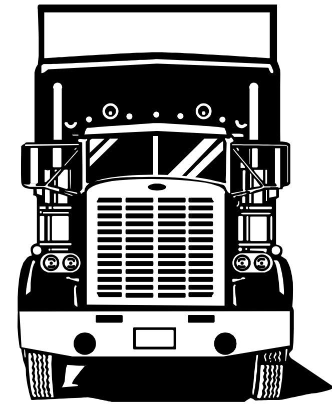
	c_D	c_L	A in m^2 M 1:2
	0.073	−0.044	0.407
	0.157	−0.009	0.462

Example above by Cogotti on low drag concept body

External Mirrors

- Two well designed mirrors on a passenger car will add ~0.01 to the overall $C_{D,}$
  - This is an additional 2.5% drag for a typical sedan
  - Additional detrimental effects can be experienced due to the flow interference effects caused by a mirror:





  - Poorly designed mirrors on large trucks can cause as much as a 10% increase in drag due to their size, shape, and interference effects
  - Drag caused by protuberances is called ***excrescence*** drag

Antennas and Roof Racks

- Radio Antenna: a typical well designed radio antenna on a passenger car will add ~0.001 to the overall C_D
  - This is only 0.25% of the total drag on a typical sedan and is therefore negligible
- Roof Racks: roof racks vary in size and shape, some examples:
  - Ski racks can add from 10% to 38% more drag to the car!
  - A bicycle on the top of a car can add 40% to the overall drag

From: Hucho