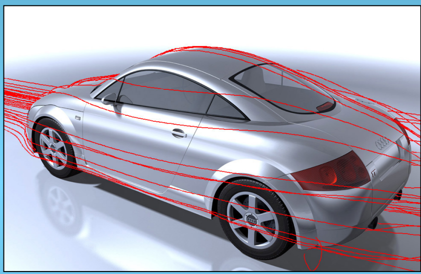
VEHICLE AERODYNAMICS

The drag



by Rossi 2002 (University of Bologna)

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1

KTH, May 2011

Cars are bluff bodies ?

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

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2

Flow around a car

- Car=relatively bluff body (c_D=0.25-0.45)
- Two types of separation
  1) Quasi 2D wakes
  2) Longitudinal vortices
- Underbody flow
- Wheels
- Interactions
- Ground effect

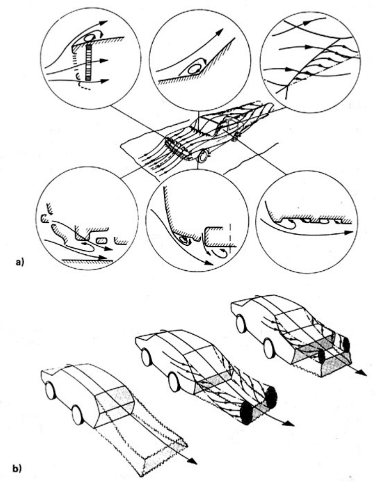


Fig. 4.3 Airflow around a car and the main flow separations: a) on the front-end structure, b) on the three types of car back.

Drag and Lift

- Drag and lift normally related (lift generates drag)
- Wing theory: Drag = profile drag (form drag + friction drag) + induced drag (induced drag from wingtip vortices)

$$c_{Di} = k\frac{c_L^2}{\Lambda} \qquad \Lambda = \frac{b^2}{A_{plan}}$$

- Cars: low aspect ratio ($\Lambda \approx 0.4$). Too low to allows the use o a wing theory
- Strong interaction between tip vortices and the central flow

Approaches to analyse drag I

Global Surface analysis

- Calculate or measure pressure and wall-shear stress everywhere
- Drag obtained from surface integral

$$D = \oint p \sin\varphi \, dS + \oint \tau_w \cos\varphi \, dS$$

- Both pressure and wall shear-stress contribute
- Lot of experimental data needed (unrealistic)
- It is possible to find the local origins of drag

Approaches to analyse lift

- Calculate or measure pressure and wall-shear stress everywhere
- Lift obtained from surface integral

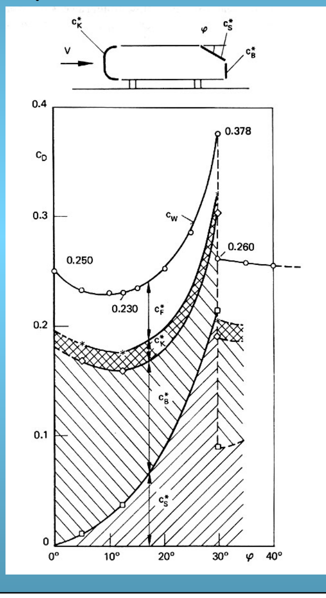
$$L = \oint p \cos\varphi dS + \oint \tau_w \sin\varphi dS$$

- In this case only pressure contributes !!!!!
- Lot of experimental data needed (unrealistic)
- It is possible to analyse the different contributions to lift

Approaches to analyse drag II

Contribution analysis

- Find the local contribution of each part of the car
- Usually possible for simple bodies (see figure)
- Problem: in real cars different components interact!



Approaches to analyse drag III

Wake analysis

- Control volume approach + momentum theorem
- Energy assessment

!! Stationary wall: must subtract contribution from wall boundary layer

$$c_D A = \int_S (1 - c_{ptot}) dS - \int_S \left(1 - \frac{u}{V}\right)^2 dS + \int_S \left[\left(\frac{v}{V}\right)^2 + \left(\frac{w}{V}\right)^2\right] dS$$

- Extensive measurements needed (costly)
- Need of traversing mechanism

Local origins of drag - Front end I

- Local separation less pronounced suction peak - increased drag
- Small edge radius enough to reduce local drag

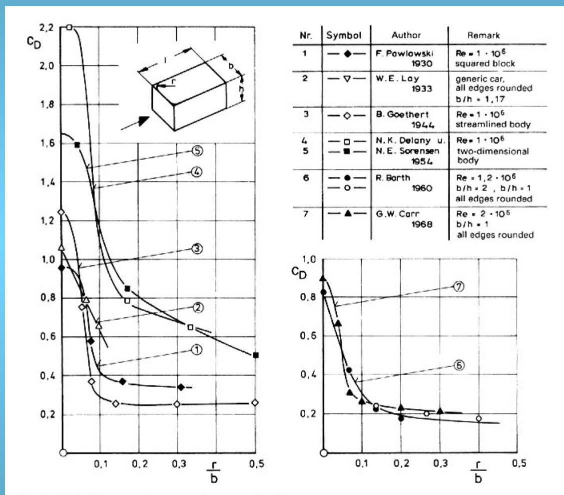
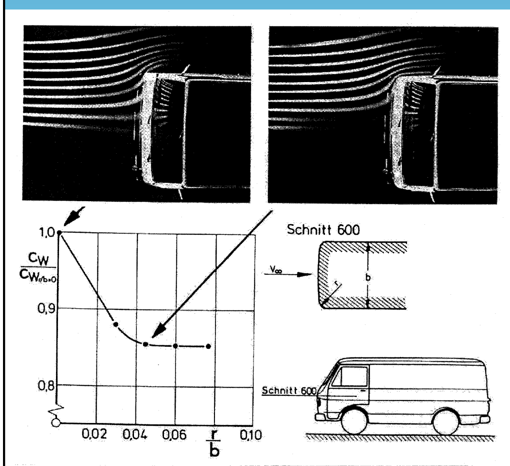
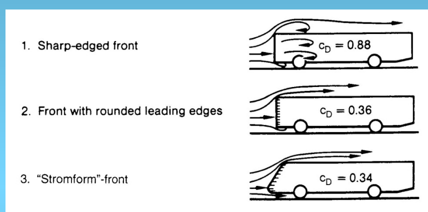


Fig. 4.26 Influence of edge radius on the drag of squared blocks, compiled from [4.29].

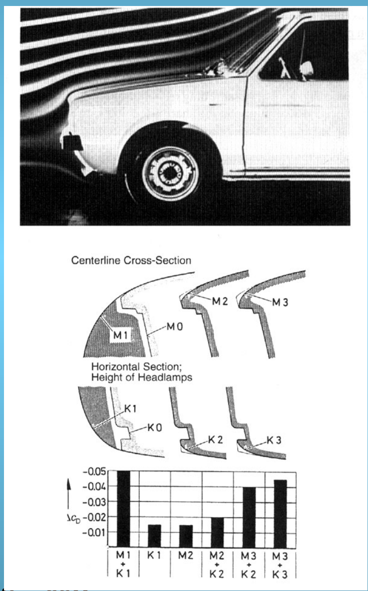
Local origins of drag - Front end II

A real case





Local origins of drag - Front end II



- Optimization of the front of Golf I
- Small radii can give significant drag reduction

Local origins of drag - Angle of hood and wind shield I

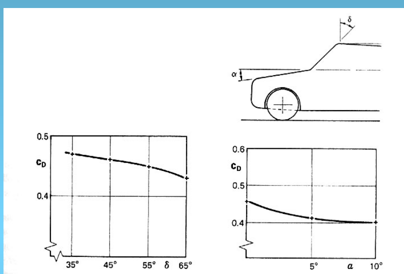


Fig. 4.27 Reduction of drag with hood inclination angle α and windshield inclination angle δ; after G.W. Carr [4.30].

- Drag reduction due to hood angle (α)saturates
  BUT: Combination effect of hood angle & front radius!
- Increased angle of wind shield (δ) can reduce drag
- $\delta \geq 60°$ => visibility and temperature problems
- indirect influence on drag:
  - Influence flow around A-pillar
  - Smaller suction peak at the junction to the roof

Local origins of drag - A-pillar

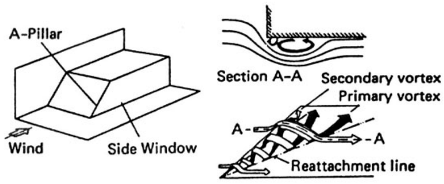
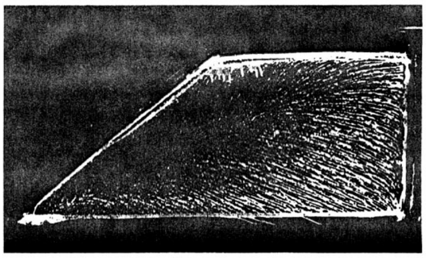
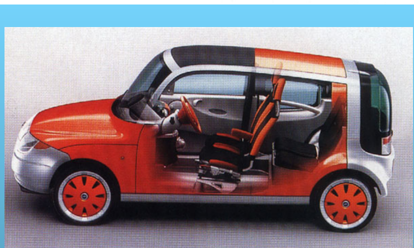


Figure 4.34 Vortex formation on the A-pillar, after ref. 4.33



- 3D-separation (vortex)
- Wind noise
- Water and dirt deposition

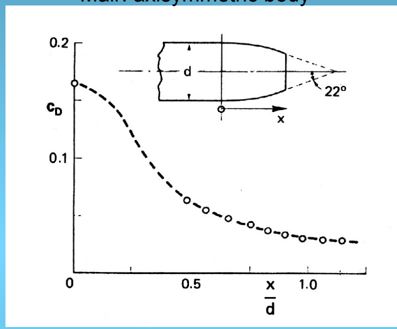
Local origins of drag – Roof and Sides



- *Mainly friction drag (flow is generally attached)*
- Increased camber give larger radii =>reduced suction peaks
- Negative angle of roof => reduced wake
- Problems: large front area and/or smaller internal space

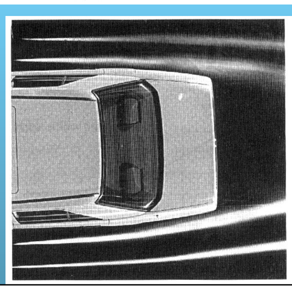
Local origins of drag - Rear End

Mair: axisymmetric body



Boat tailing

- Increase base pressure
- Reduce base area
- Minor improvements by further extension of the body (x/d > 5)
- Squareback vehicles: lower the roof
- Flow devices (Air intakes, wings)



Mercedes 190
Angle ca 10°

Local origins of drag - Rear End II

Boat-tailed underbody

- Requires smooth underbody
- Decreased drag for moderate diffuser angles
- Reduction in lift

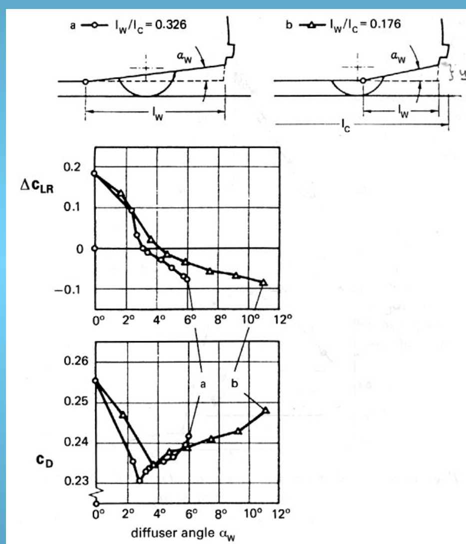


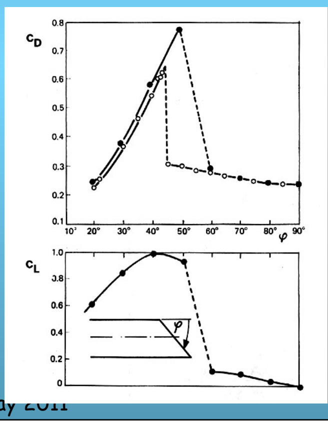
Fig. 4.48 Reducing drag and lift on the rear axle by means of a rear diffuser, after J. Potthoff [4.45].

Local origins of drag - Rear End III

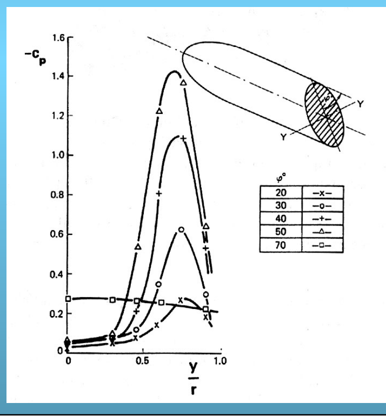
Fastback/squareback

- Basic experiments =>understanding of rear end flow
- Drag due to strong side vortices
- Vortex break-up above critical slant angle

Morel (1976)



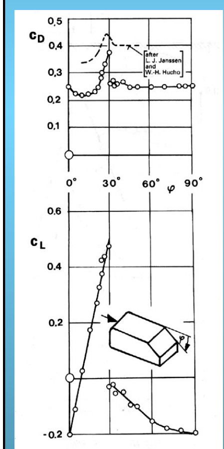
Bearman (1979)

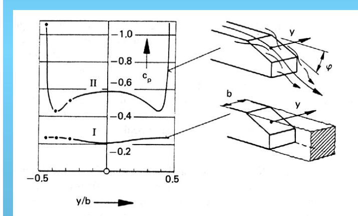


Local origins of drag - Rear End IV

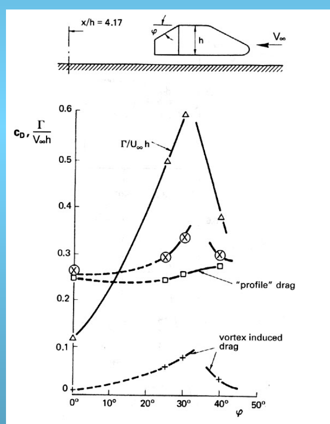
Fastback/squareback

- Prismatic body near ground (qualitatively similar results)
- Critical slant angle ca 30°
- Drag minimum at φ≈15° (coupé)





Morel (1976)



Bearman (1982)

Local origins of drag - Rear End V

A real case:
development of Golf I:
In-fluence of slant angle (φ)

- Bi-stable separation around critical angle ($\varphi \approx 30°$)
- $\varphi > 30°$: reduced drag and flow conditions similar to a square back
- $\varphi > 30°$: Vortices are weaker and with opposite rotational direction than $\varphi < 30°$:

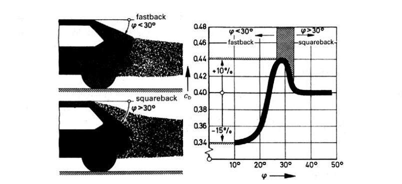


Fig. 4.55 Influence of slant angle φ on drag coefficient c_D and the flow regime in the rear of the car, measured during development of the Volkswagen Golf I (Rabbit), after L.J. JANSSEN and W.-H. HUCHO [4.33].

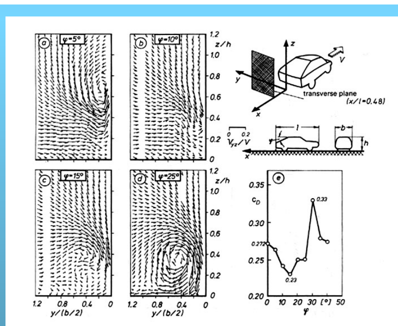


Fig. 4.8 Lateral-speed vectors and drag coefficient of a fastback, as a function of the slant angle φ, after S.R. AHMED [4.10].

Form vs. vortical drag

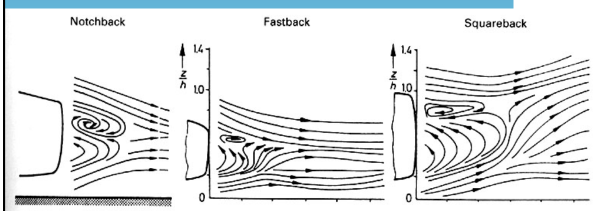


Fig. 4.4 Contrarotating vortices in the dead water behind cars of different rear-end shape, after S.R. AHMED and W. BAUMERT [4.6].

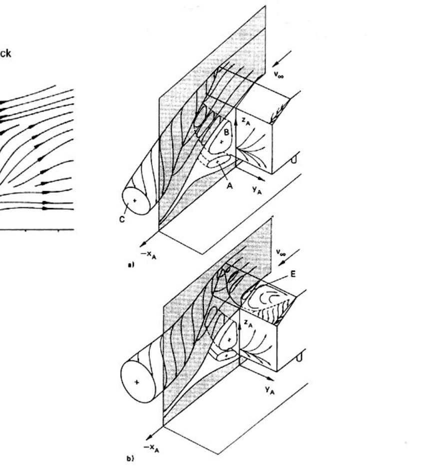
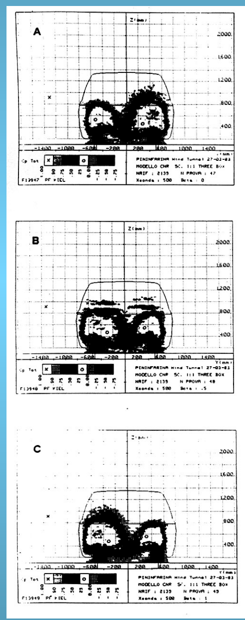
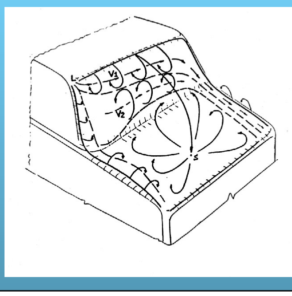


Fig. 4.10 Vortex system for a fastback with: a) low drag coefficient, b) high drag coefficient with $\varphi = 30°$, after S.R. AHMED, et al. [4.13].

Drag Sensitivity to side wind

- Wake-analysis behind a notchback (Cogotti 1986)
- Total-pressure distribution show strong influence of small yaw angles (β=0, 0.5° & 1°)
- Overall no strong changes on cars





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Local origins of drag
Underbody flows

- Complex flow
- Flow angles important
- Avoid obstacles (stagnation)
- Return of cooling air can influence

- Large improvement by rear panels
- Also effect on lift

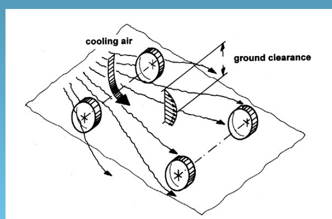
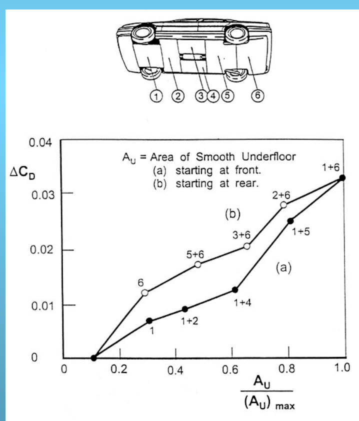


Fig. 4.12 Outward-spreading flow underneath a car.



Ahmed (1999)

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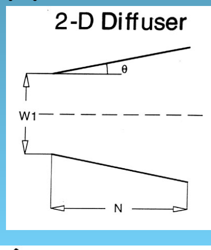
Aspects of underbody diffuser

- Rear end underbody diffuser brings up the velocity below the car (normally reduces lift)
- Higher velocity below the car changes flow angles around the wheels
  - Reduced drag due to the wheels
  - Requires a smooth underbody to avoid drag from obstacles
- Underbody diffuser reduces the base area of the vehicle (can reduce drag)

Underbody shaped for downforce I

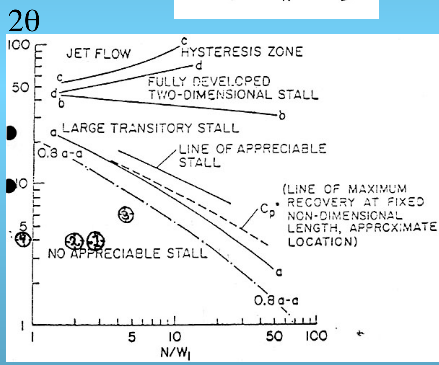
- ❑ Ferrari 360 Modena
  - "Venturi-tunnel" for max downforce
  - Smooth underbody
  - No spoilers
  - 5400 hours in wind-tunnel (source: Teknikens Värld 11/99)

Mechanism of a 2D-diffuser



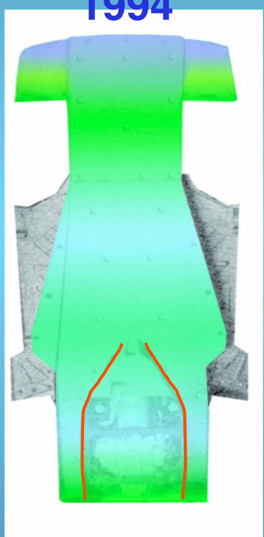
- Pressure increases as long as flow not separated
- Max diffuser length longer for small diffuser angles

- Is the analogy with a 2D diffuser really correct?
- (Can explain reduced drag, but not reduced lift)



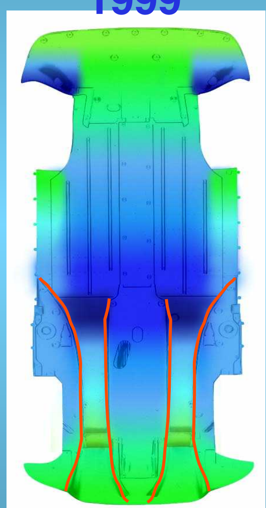
Underbody shaped for downforce I

1994



F355

1999



360 Modena

Underbody shaped for downforce II

Wheels

- Up to 50% of the drag of a streamlined car
- Wheels are not streamlined
  - 3 vortex pairs
  - Influenced by ground and rotation
- Local flow is yawed (≈15°)
  - Separation on the outer side
  - Water drops sucked out

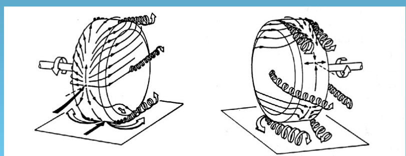
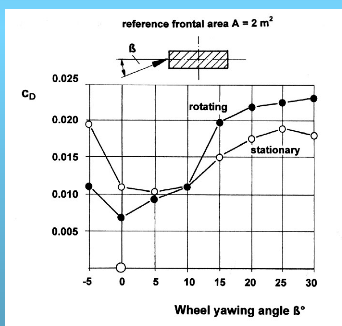


Fig. 4.72 Flow pattern of a wheel rolling on the ground, after E. MERCKER and H. BERNEBURG [4.61].



Wheels II

- Force on a rotating wheel changes sign when contact with ground
- Lift force due to wheel rotation for a free-standing wheel

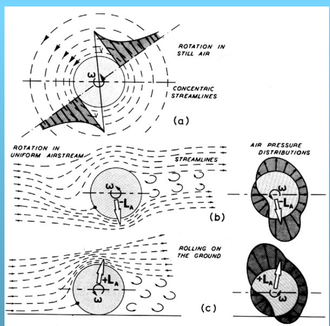
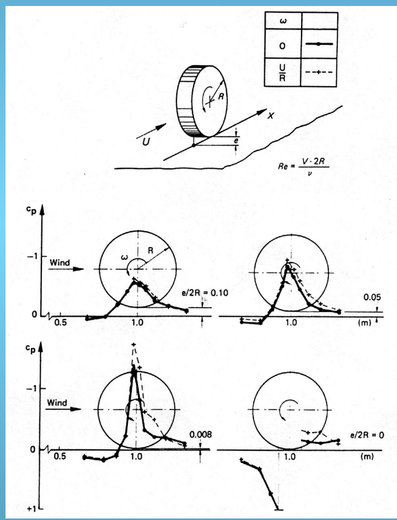
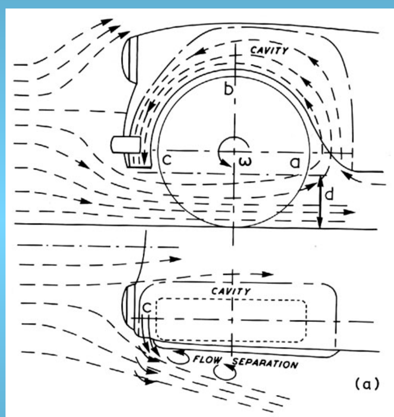


Fig. 3.11. Airflow pattern and pressure distribution around a rotating wheel in (a) still air (b) a uniform airstream, and (c) when rolling on the ground



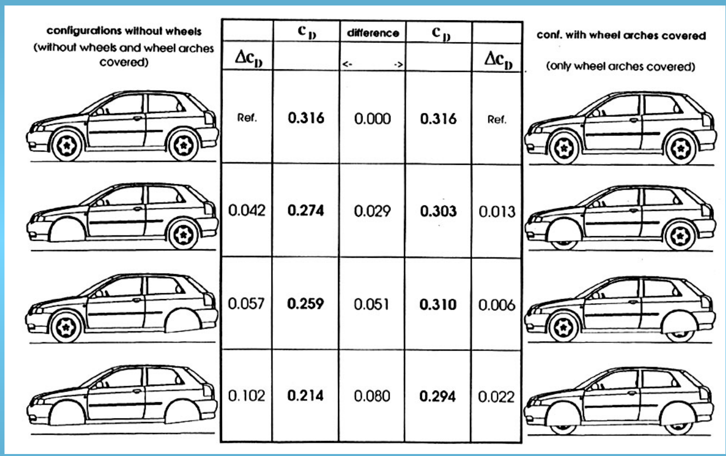
Wheels III

- How does the flow in the wheel-housings look like?
- Wheel-housings
  - Smaller=better
  - Both lift and drag reduced
  - Largest effect on lift (see e.g. Cogotti 1983)



Wheels IV

Audi A3



Δc_D	c_D	difference <- ->	c_D	Δc_D
Ref.	0.316	0.000	0.316	Ref.
0.042	0.274	0.029	0.303	0.013
0.057	0.259	0.051	0.310	0.006
0.102	0.214	0.080	0.294	0.022

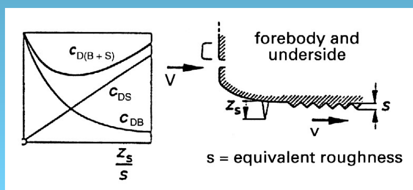
- 30-35% of drag due to wheels + wheel arches
- Ca 25% only due to wheels

From Pfadenhauer, Wickern & Zwicker (1996)

Spoilers

Front spoiler

- Reduced drag
- Reduced front axle lift
- Improved cooling air flow
- Reduced flow rate under the car
- Low pressure region behind the spoiler
- Optimization needed



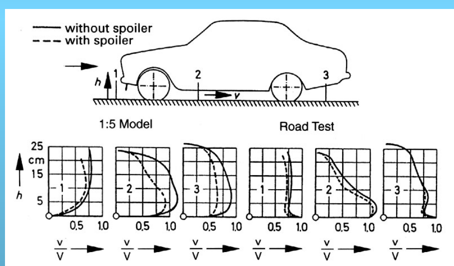


Fig. 4.78 Velocity distribution underneath a car with and without front spoiler, after C. Kramer, et al. [4.65].

Hucho (1998)

Spoilers

Rear spoiler

- Reduced drag (sometimes)
- Reduce rear axle lift
- Higher c_p in front of the spoiler
- Increased spoiler height increases the lift, but also drag

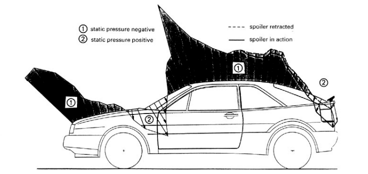
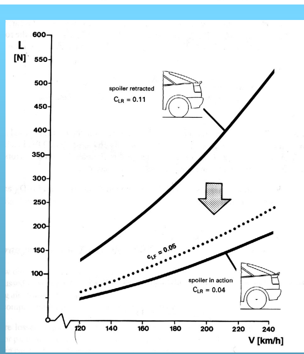


Fig. 4.91 Change in pressure distribution around the Volkswagen Corrado with the addition of a retractable rear spoiler, after H. Schuster and R. Horn [4.72].



Do not exagerate !!!

Miscellaneous

- Cooling air flow: $\Delta c_D \approx 0.02\text{-}0.06$
- Side mirrors: $\Delta c_D \approx 0.01$
- Antenna: $\Delta c_D \approx 0.001$
- Roof racks: up to 30-40% increase in c_D
- Ski box: Why are they shaped in this way??

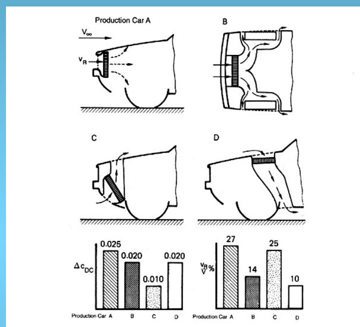
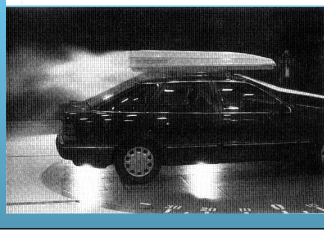


Fig. 4.97 Alternative radiator arrangements to reduce cooling air drag, after R. Buchheim, et al. [4.36].

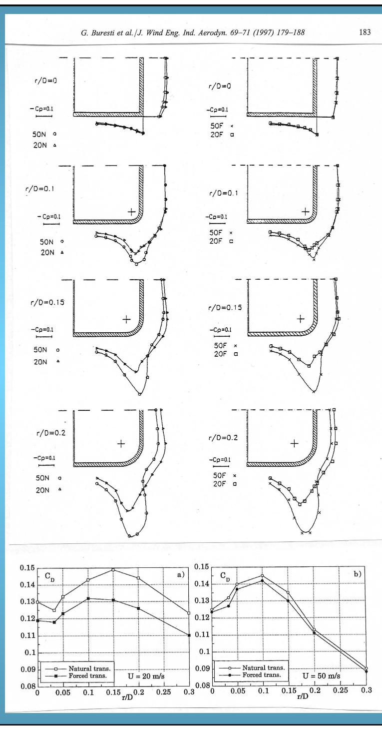


Potential fields for drag reduction

- More focus on underbody and wheels
- Active reduction of the dead-water region
  - Base bleed
- Separation control
  - Boundary layer suction?

Optimization

- NOT AN EASY TASK !!!



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Discrepancies in c_D

- Different c_D depending on equipment
  - Tire width
  - Engine type (cooling air flow)
  - Ground clearance (load dependent)
  - Angle of attack (load dependent)
  - Additional spoilers etc.

- Official c_D values "corrected"

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Interference effects

❑ Bluff bodies in tandem

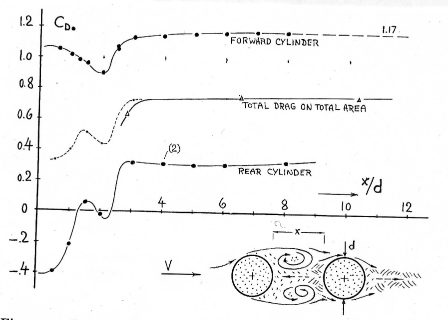

Figure 2. Drag coefficients of two circular cylinders, one placed behind the other.

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Interference effects

❑ Aerodynamic bodies in tandem

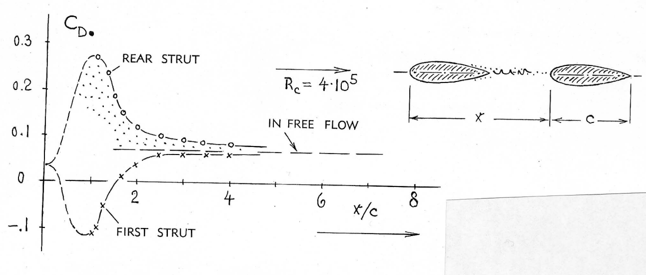

Figure 3. Drag of a pair of strut sections, one behind the other, in tandem (2,a).

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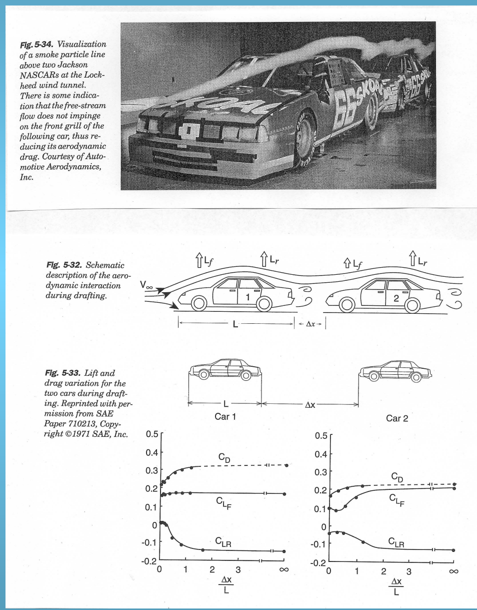
Interference effects

- Slip streaming



Interference effects

- Overtaking