Vehicle Performance

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Lesson 4:
Vehicle road loads

Outline

- POWER AND TRACTIVE FORCE AT WHEELS
  - Transmission efficiency
  - Gear ratio
  - Expression of power and forces at wheels
  - Power and forces diagram

- VEHICLE RESISTANCE
  - Aerodynamic
  - Rolling resistance
  - Grading resistance
  - General expression of vehicle resistance forces

References

- T. Gillespie. « Fundamentals of vehicle Dynamics », 1992, Society of Automotive Engineers (SAE)
- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)
- J.Y. Wong. « Theory of Ground Vehicles ». John Wiley & sons. 1993 (2nd edition) 2001 (3rd edition).
- W.H. Hucho. « Aerodynamics of Road Vehicles ». 4th edition. SAE International. 1998.
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Vehicle road resistance

Vehicle road resistance

- The vehicle resistance forces include 3 types of forces
  - Aerodynamic forces (drag force)
  - Rolling resistance due to energy dissipation in tires, suspensions, shock absorbers, etc.
  - Grading resistance due to the slope of the road

Aerodynamic forces and moments

- The air flow around the vehicle during its motion creates aerodynamic forces that can become important especially at high speed

- The vehicle is a so-called bluff body which generates a lot of vortices and turbulent flows, especially at the level of back of the roof.

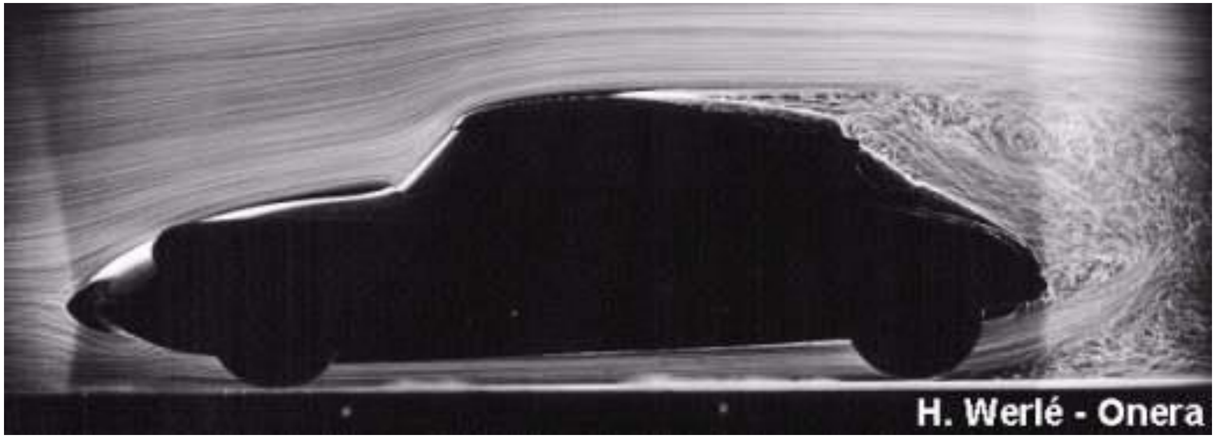
- The air flow is very complex because of
  - The ground effect that deeply affects the flow
  - The spinning wheels that strongly interact with the vehicle air flow.
  - The internal aerodynamic flow is necessary for engine cooling and for the air conditioning of the cabin, but it introduces a drag penalty

Aerodynamic forces and moments

- The aerodynamic forces have two major components:
  - Shape drag: the shape of the vehicle modifies the air flow creating a pressure distribution giving rise to a net force pointing backward

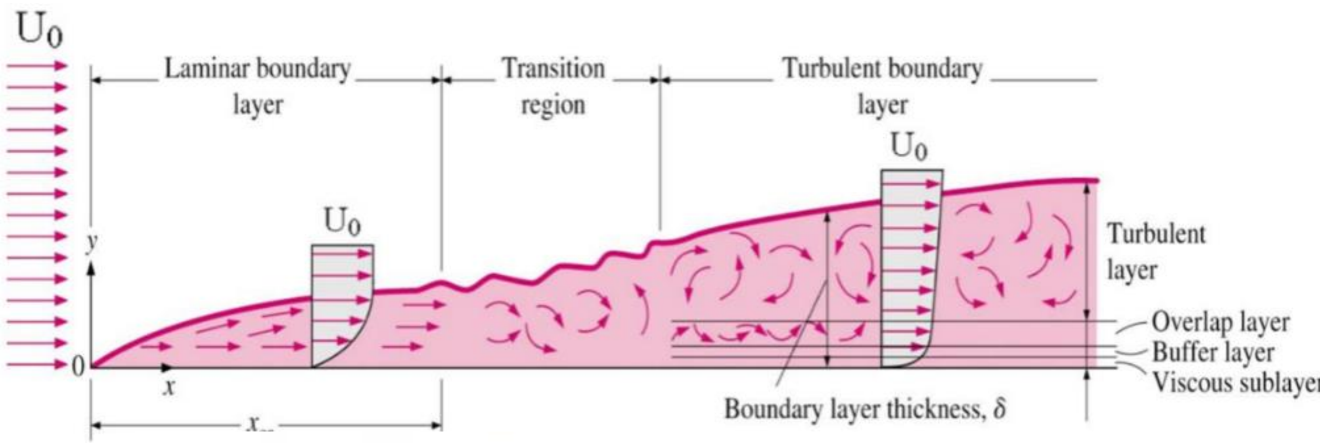
    Because of Mach and Reynolds numbers, the fluid flow is considered as incompressible and non viscous (except in the boundary layers)

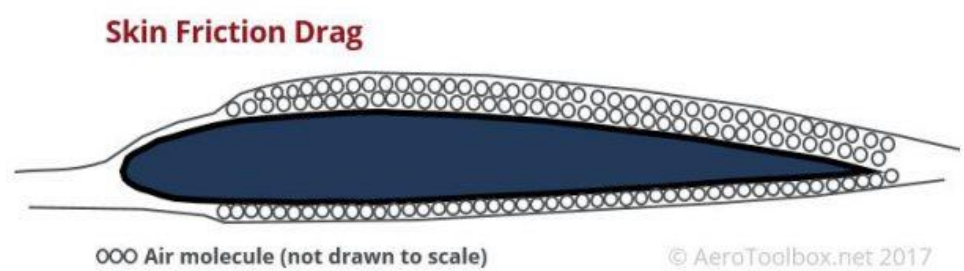
    Large vortices are present because of the bluff body geometry and the boundary layers are not attached



Aerodynamic forces and moments

- The aerodynamic forces have two major components:
  - <u>Skin friction</u>: the viscosity effects, which take place in the boundary layers around the vehicle skin

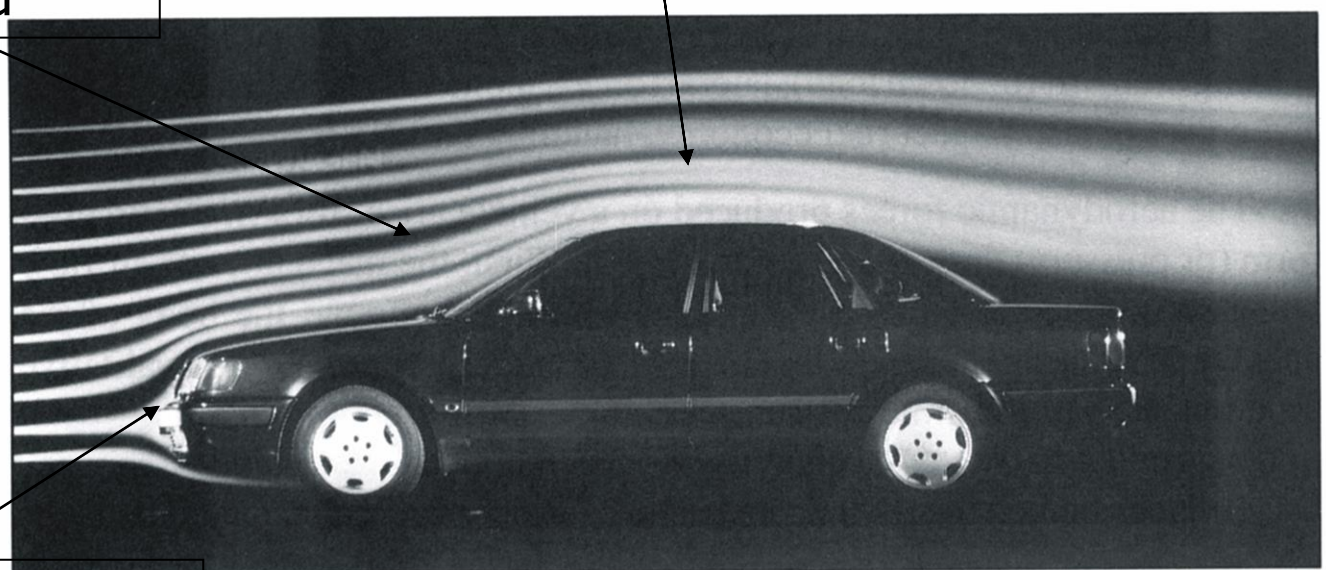




Aerodynamic forces and moments

High pressure / low speed

Low pressure / high speed



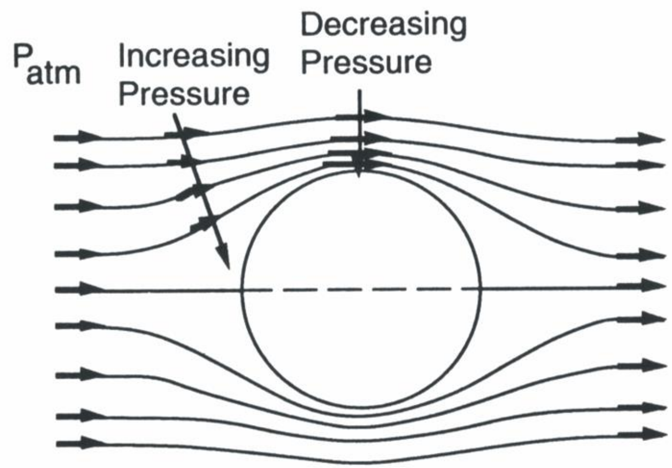
Stagnation point
$p = p_t$

Air flow around a car
(Gillespie, Fig4.1)

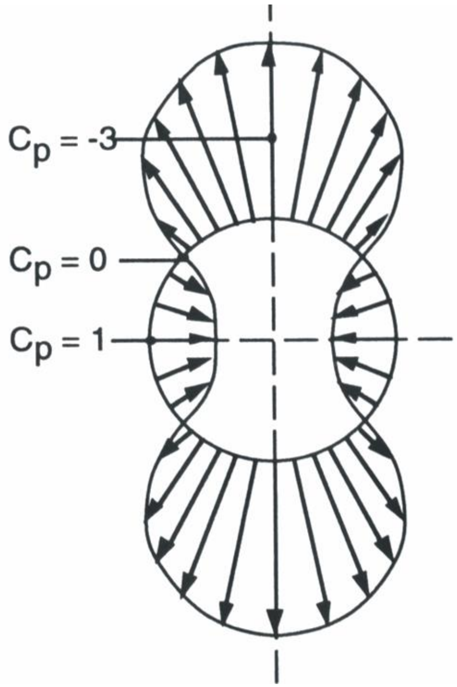
$$p_t = p_s + \frac{1}{2}\rho V^2 = \mathrm{Cst}$$

Aerodynamic forces and moments

Non viscous flow



Symmetric body



Net force= 0 ?

$$p_t = p_s + \frac{1}{2}\rho V^2 = \mathrm{Cst}$$

Aerodynamic forces and moments

- The viscosity is dominant in the boundary layer around the body

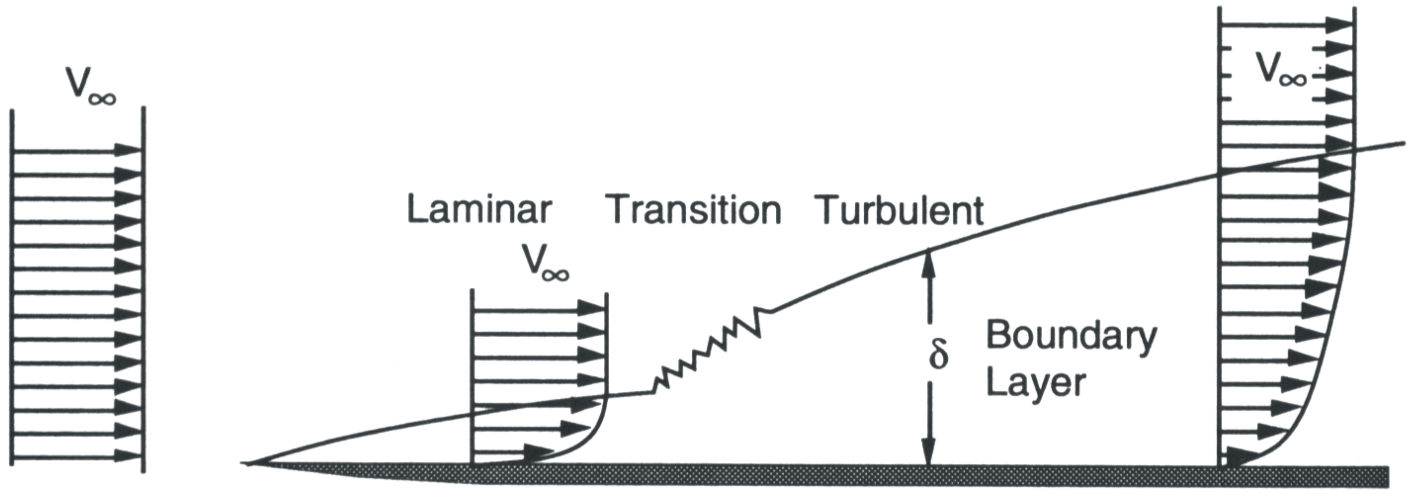
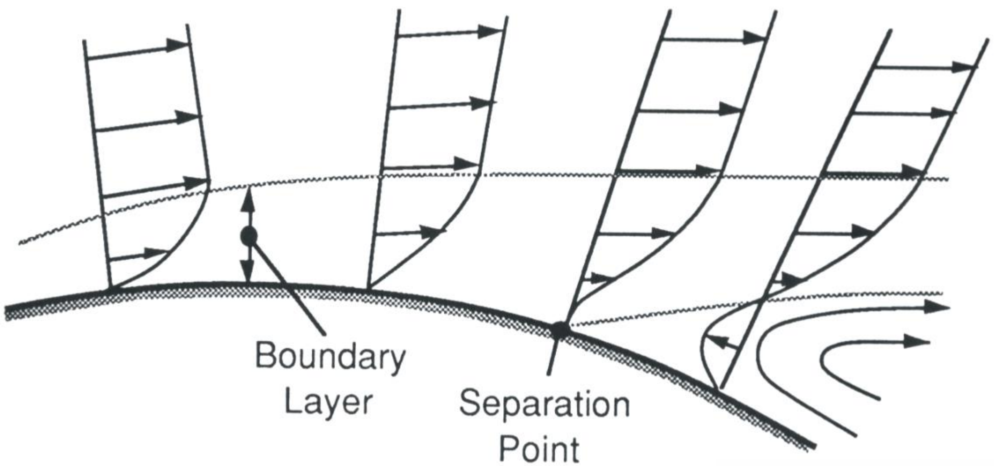


Fig 4.3 : Gillespie Boundary layer development

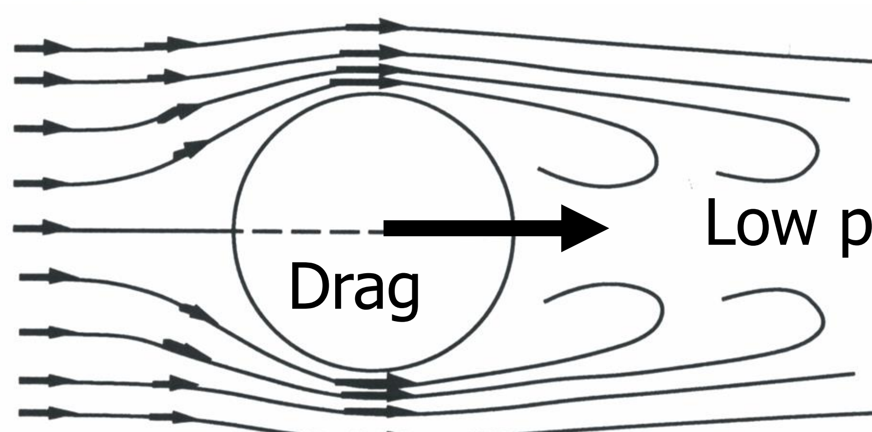
Aerodynamic forces and moments

- Flow separation in presence of large adverse pressure gradient



Gillespie Fig 4.4

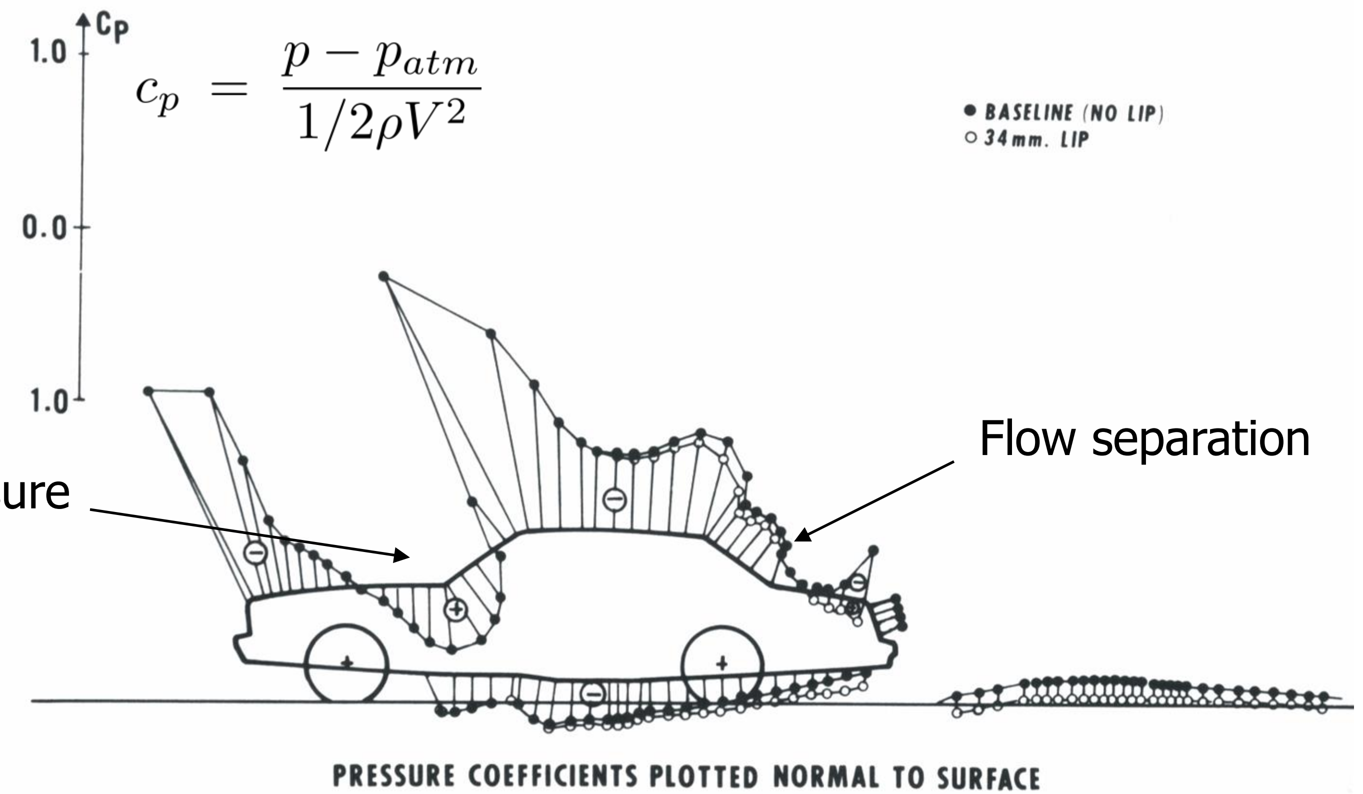
High pressure



Low pressure

Gillespie Fig 4.5

Aerodynamic forces and moments



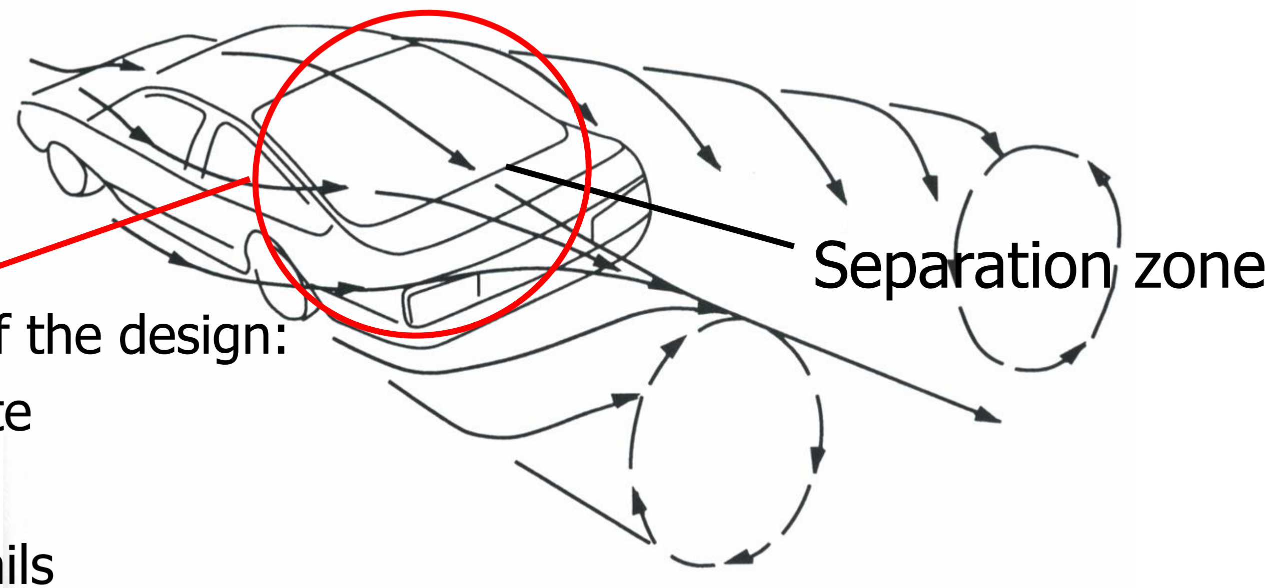
High pressure

Flow separation

Gillespie Fig 4.6 : Pressure distribution along the central line of the car

Aerodynamic forces and moments

<u>3D effects:</u> Air flow is intrinsically 3D which increases the air flow separation at the end of the car

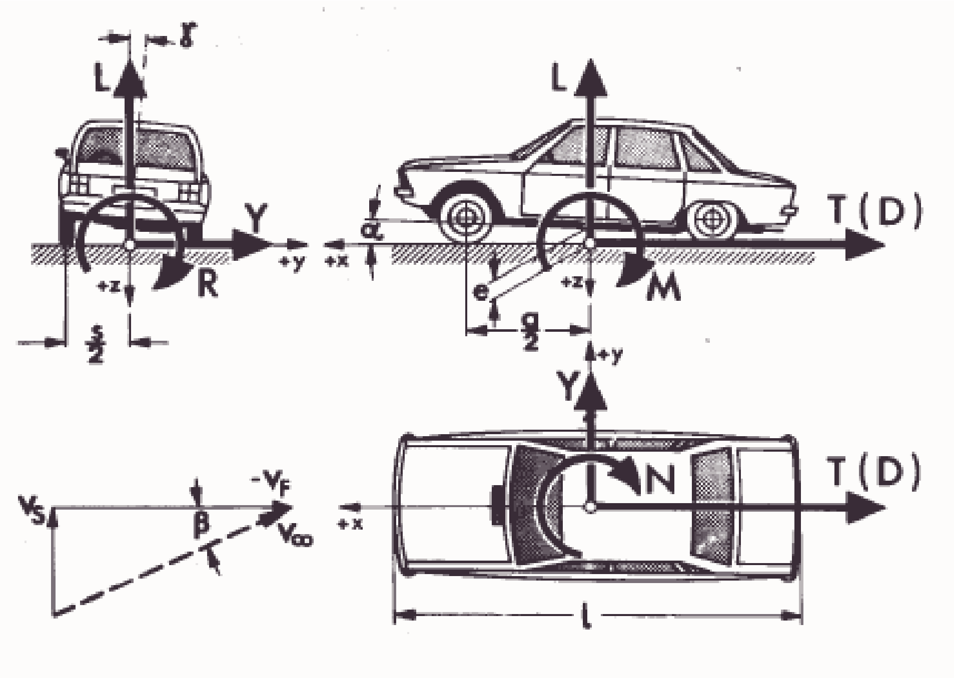


Importance of the design:

- bakelite
- trunk
- side rails

Gillespie Fig 4.7 : Wake systems at the back of the car

Aerodynamic forces and moments



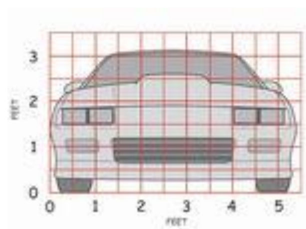
- Longitudinal (+ backward):
  - Drag force
  - Roll moment
- Side (+ to the right) :
  - Side force
  - Pitch moment
- Vertical (+ upward)
  - Lift force
  - Yaw moment

Centre of aerodynamic frame at mid wheel distance on the ground

Aerodynamic forces and moments

- Aerodynamic forces and moments are expressed classically using non dimensional coefficients : drag coefficient (C_x), side force (C_y), lift (C_z), rolling (C_l), pitch (C_m) and yaw (C_n)

$$
\begin{aligned}
F_x &= \frac{1}{2}\rho\, V^2\, S\, C_x \\
F_y &= \frac{1}{2}\rho\, V^2\, S\, C_y \\
F_z &= \frac{1}{2}\rho\, V^2\, S\, C_z
\end{aligned}
$$



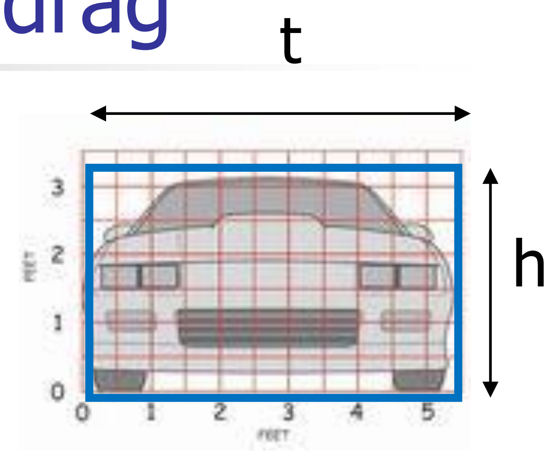
$$
\begin{aligned}
M_x &= \frac{1}{2}\rho\, V^2\, S\, t\, C_l \\
M_y &= \frac{1}{2}\rho\, V^2\, S\, L\, C_m \\
N_z &= \frac{1}{2}\rho\, V^2\, S\, L\, C_n
\end{aligned}
$$

- With S the frontal area (wet surface), L the wheelbase, t the track and ρ the air density, V the relative speed of the vehicle w.r.t. the fluid

Estimating the aerodynamic drag

- Drag force

$$\boxed{F_{AERO} = \frac{1}{2}\rho V^2 S C_x}$$



- Estimating the frontal area
  - Using CAD system
  - Using pixel counting
  - Approximation: Paul Frere formula

$$S \simeq \psi\, h\, t \qquad\qquad \psi \simeq 0.83$$

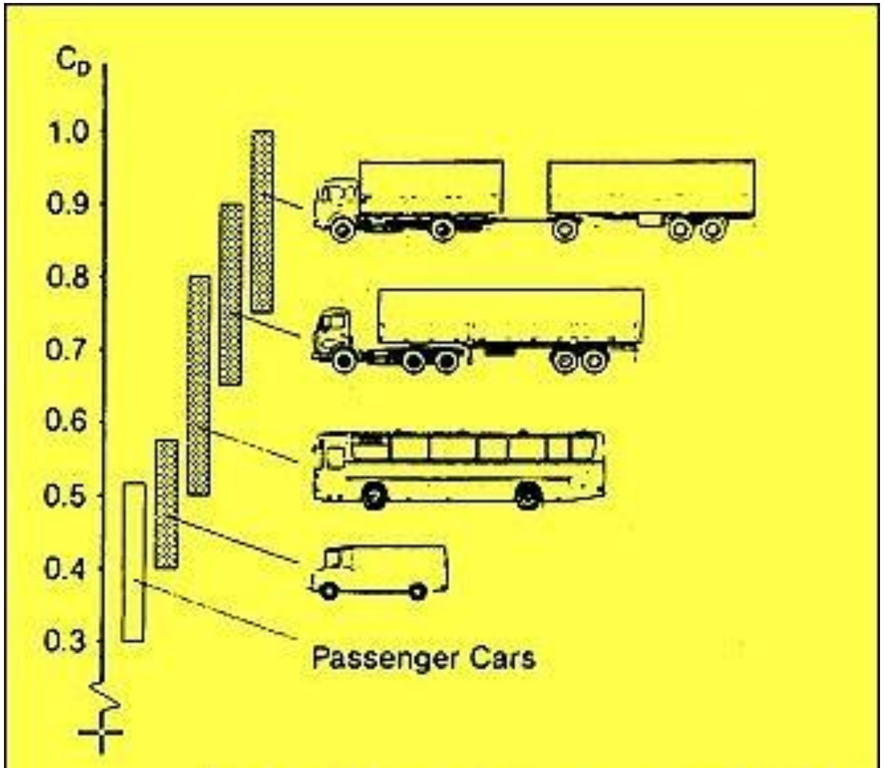
Typical drag coefficient of automobiles

TABLE 3.3 Values of Aerodynamic Resistance Coefficient for Various Types of Vehicle

Vehicle Type	Aerodynamic Resistance Coefficient C_D
Passenger cars	0.3–0.52
Vans	0.4–0.58
Buses	0.5–0.8
Tractor–semitrailers	0.64–1.1
Truck–trailers	0.74–1.0

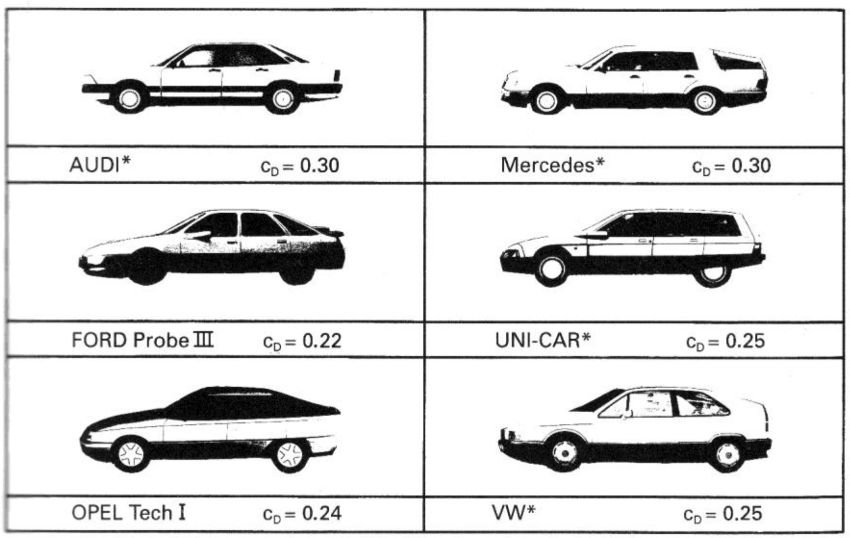
Source: Reference 3.12,

(Wong Table 3.1)



Drag coefficients of different commercial vehicles

Typical drag coefficient of automobiles



(Hucho Fig 4.131)

Coefficients et puissances de pénétration dans l'air de véhicules de différentes formes

	Coefficient de pénétration dans l'air c_x	Puissance de pénétration dans l'air en kW, valeurs moyennes pour $A = 2$ m² et différentes vitesses¹) 40 km/h	80 km/h	120 km/h	160 m/h
Cabriolet décapoté	0,5 ... 0,7	1	7,9	27	63
Limousine	0,5 ... 0,6	0,91	7,2	24	58
Berline	0,4 ... 0,55	0,78	6,3	21	50
Coupé: phares et pare-chocs intégrés dans la coque, roues recouvertes, plancher caréné, circulation optimisée de l'air de refroidissement.	0,3 ... 0,4	0,58	4,6	16	37
Phares et toutes les roues intégrés dans la coque: plancher recouvert	0,2 ... 0,25	0,37	3,0	10	24
Forme K (faible maître-couple)	0,23	0,38	3,0	10	24
Forme profilée	0,15 ... 0,20	0,29	2,3	7,8	18
Camions, trains routiers	0,8 ... 1,5	–	–	–	–
Motocycles	0,6 ... 0,7	–	–	–	–
Autobus	0,6 ... 0,7	–	–	–	–
Autobus de forme aérodynamique	0,3 ... 0,4	–	–	–	–

¹) sans vent contraire ($v_0 = 0$)

Main sources of the drag of passenger car

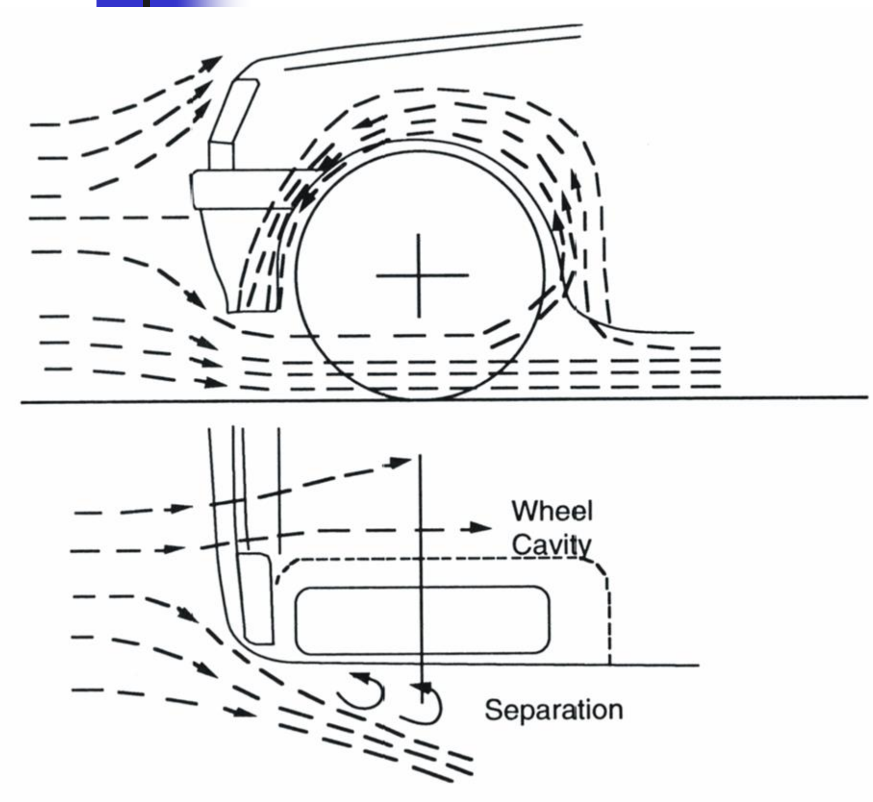
DRAG COEFFICIENT COMPONENT	TYPICAL VALUE	
Forebody	0.05	
Afterbody	0.14	
Underbody	0.06	
Skin Friction	0.025	
Total Body Drag	0.275	65%
Wheels and wheel wells	0.09	
Drip rails	0.01	
Window recesses	0.01	
External mirrors	0.01	
Total Protuberance Drag	0.12	28%
Cooling system	0.025	
Total Internal Drag	0.025	6%
Overall Total Drag	0.42[1]	
VEHICLE OF THE 1980s		
Cars	0.30 - 0.35	
Vans	0.33 - 0.35	
Pickup trucks	0.42 - 0.46	

[1] Based on cars of 1970s vintage.

Gillespie Fig 4.11

- 65% of drag comes from the body shape (front, back, floor, skin)
  - Large potential of reduction, especially for the back of the car to control the separation flows
- Influence as well of
  - Wheels (21%)
  - Details (7%)
  - Internal aerodynamics (6%)

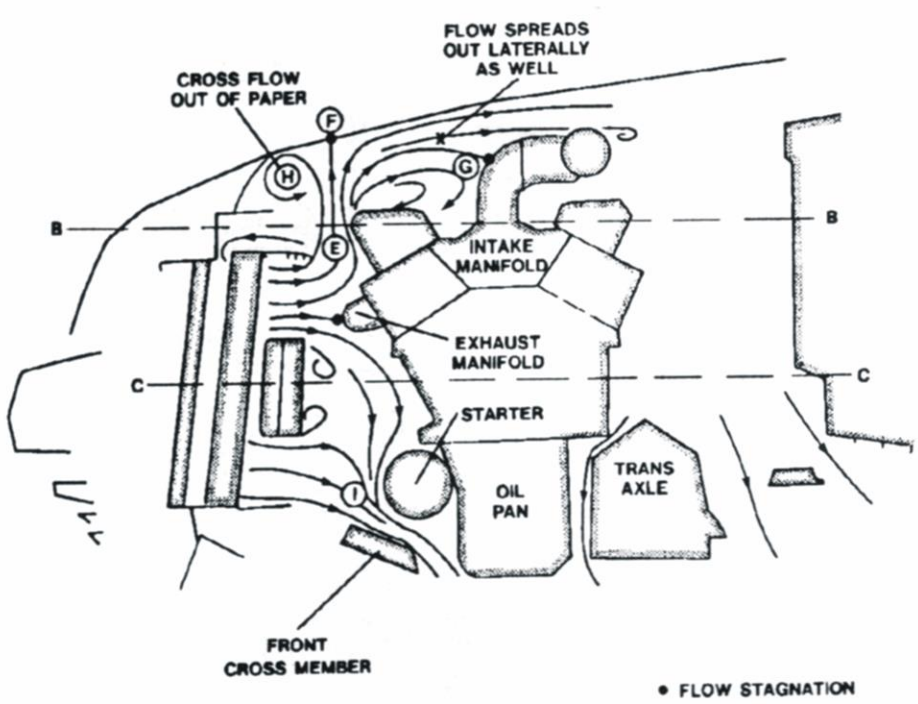
Influence of the wheels and wheel covers



Gillespie: Fig 4.15 Recirculation flow around the wheels

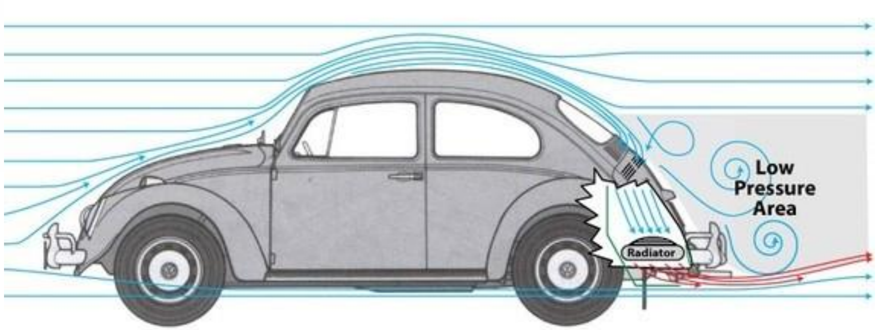
- Important contribution because of the spinning wheel is a source of turbulence and flow recirculation
- First improvement: wheel cover.
- Research has shown that it is interesting to reduce the gap between the wheel cover and the wheels

Influence of air in engine compartment



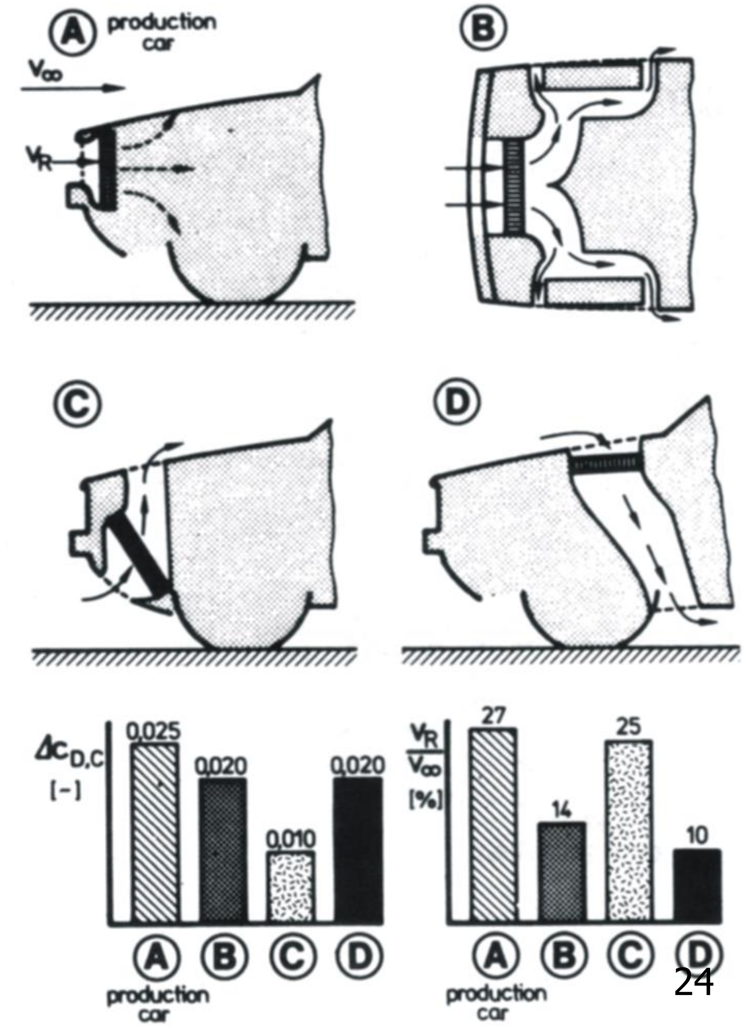
Gillespie: Fig 4.16 influence of engine cooling air flow

- The design of the air flow in the engine compartment has a major impact on the drag
- The introduced air loses its momentum giving rise to a net drag force
- The flow is very complex



Influence of air in engine compartment

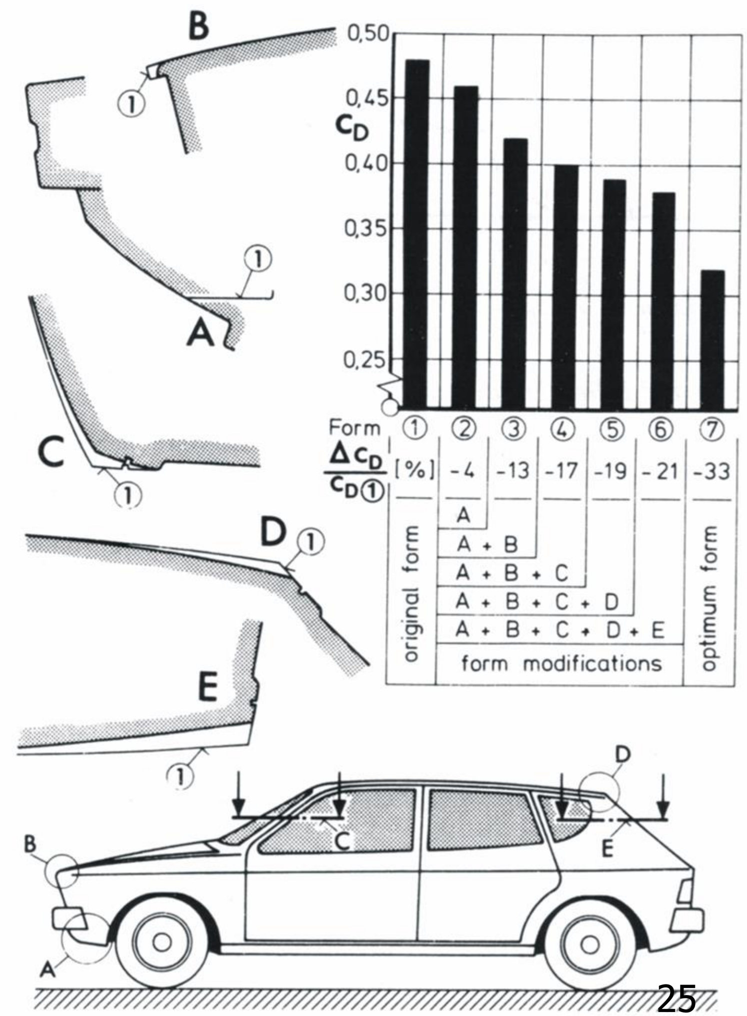
- Redesign of the engine cooling to facilitate the air flow through the engine compartment with a minimum pressure drop
- Reduction of air intakes to satisfy the needs



Gillespie: Fig 4.17 influence of engine cooling air flow

Influence of shape details

- The body details have a non negligible impact on the drag
- They deserve a special attention because they can be the source of flow separations
- The smoothness of the body is important to reduce the drag but also the aerodynamic noise



Gillespie: Fig 4.19 Optimization of body details

Rolling resistance forces

- Under free rolling conditions, it is necessary to apply a torque to maintain the motion and counteract the rolling resistance moment.

- The rolling resistance is covering a large number of phenomena of different natures:
  - The energy dissipation in the tire due to the hysteresis of the material due to the cyclic deformation of the sidewalls and of the tread blocks
  - Air drag inside and outside the tire
  - The scrubbing of the tire on the ground
  - The friction in the driveline
  - The dissipation of energy in the shock absorber
  - The misalignment of the tires, the longitudinal and lateral slip
  - The deformation of the road surface

Rolling resistance forces

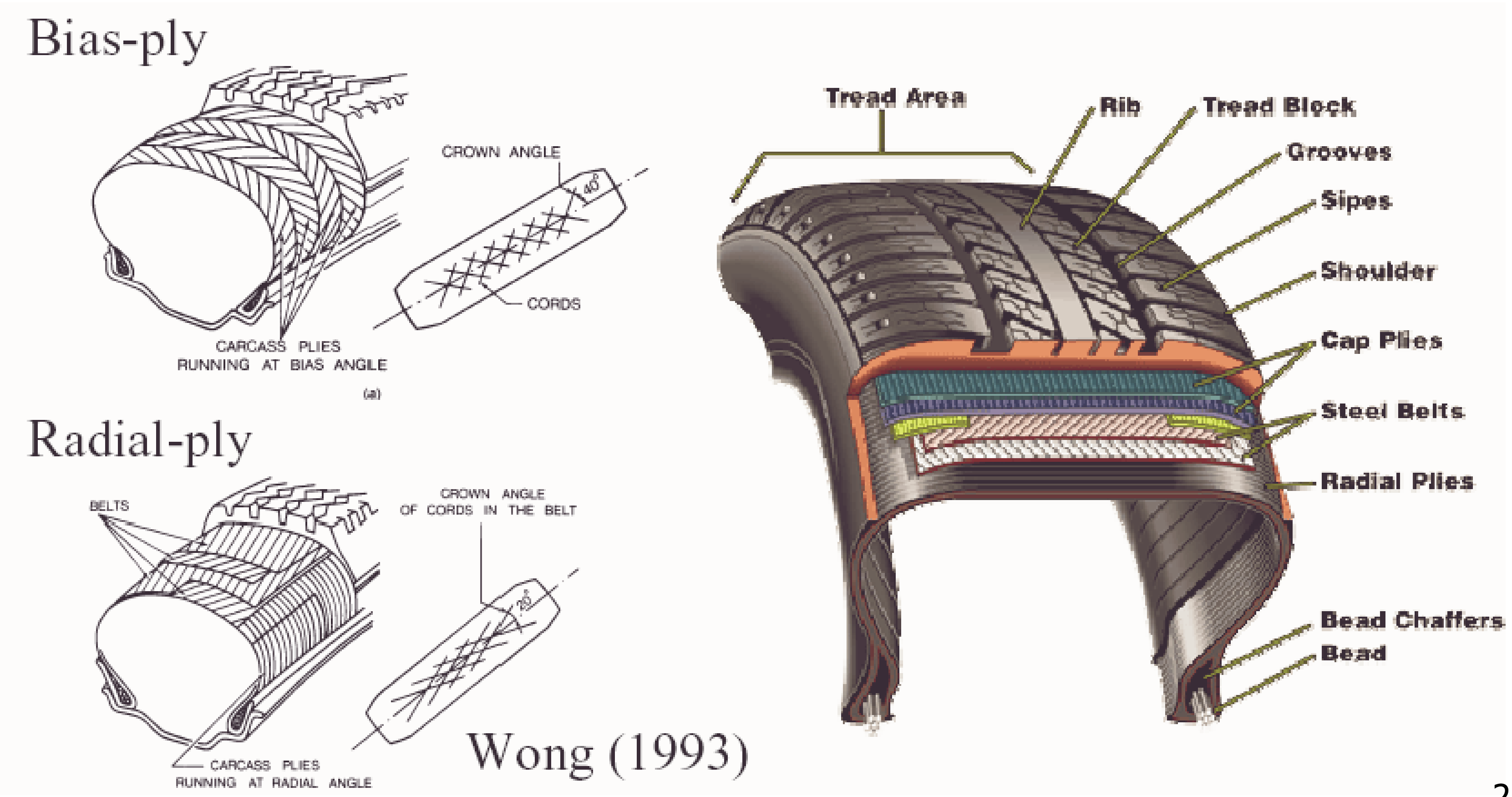
- Experiments show that generally, the global rolling resistance force are with a very good agreement using a linear model as a function of the vertical force applied onto the tire

$$F_{RR} = f_{RR} F_z = f_{RR}\, mg \cos\theta$$

  The coefficient f_{RR} is the rolling resistance coefficient

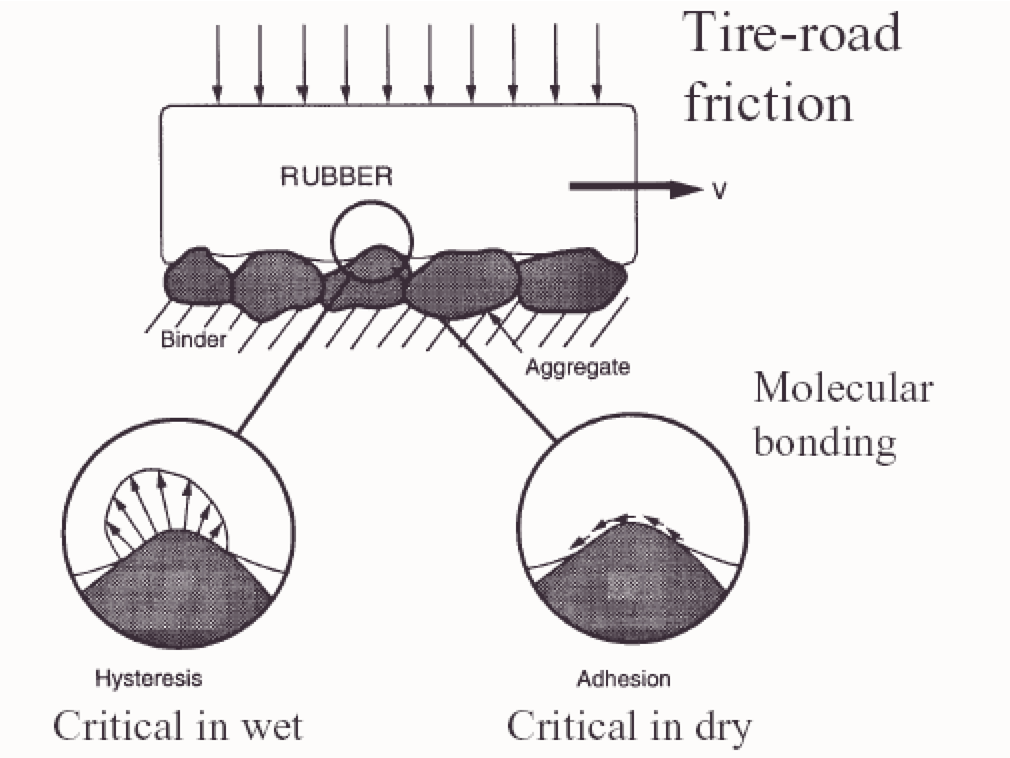
- **The rolling resistance coefficient,** ratio between the rolling resistance force and the normal force encompasses the complicated and interdependent physical properties of the tire and the ground.

Rolling resistance forces



Rolling resistance forces

Mechanism of force generation at ground–tire interaction



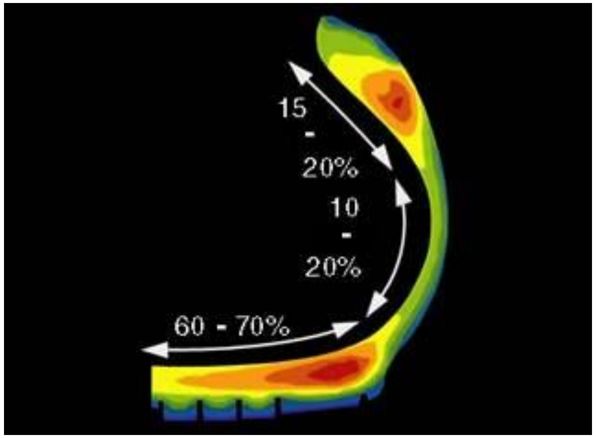
Gillespie. Fig 10.4 & Fig10.5

Rolling resistance forces

- <u>1st cause:</u> hysteresis of the tire materials (viscoelastic rubber) because of deformation cycle

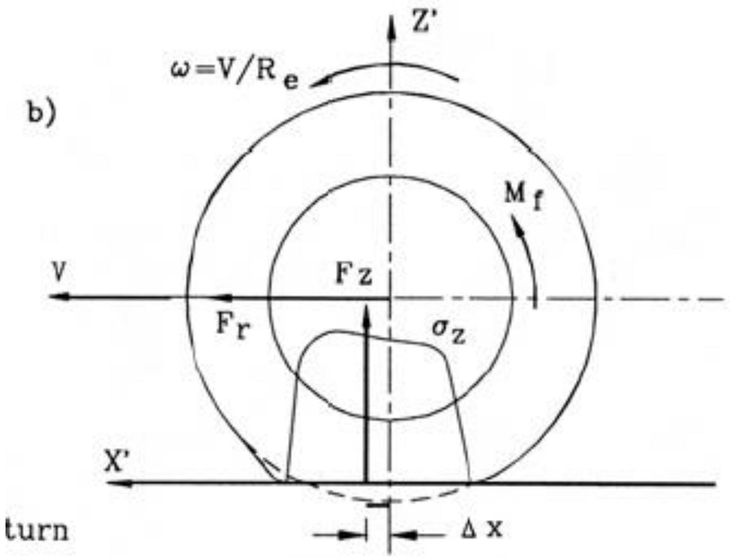
- <u>Other (secondary) sources:</u>
  - Frictions during slippage
  - Air ventilation inside and outside

- Example: set of truck tires at 130 km/h
  - 90-95 % = hysteresis
  - 2-10 % friction
  - 1.5 – 3.5 % aerodynamic dissipation



Rolling resistance forces

- The resulting contact force is located in front of the theoretical contact point.
- The pressure distribution gives rise to a rolling resistance moment that is statically equivalent to a resistance force in the contact patch



$$M_{RES} = F_z \Delta x + M_{fr}$$

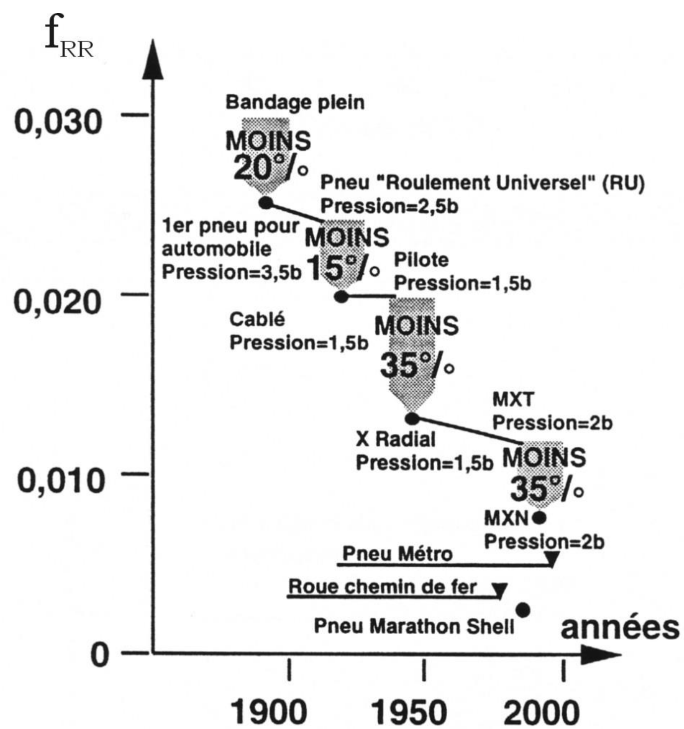
$$M_{RES} = F_{RR}\, R_e$$

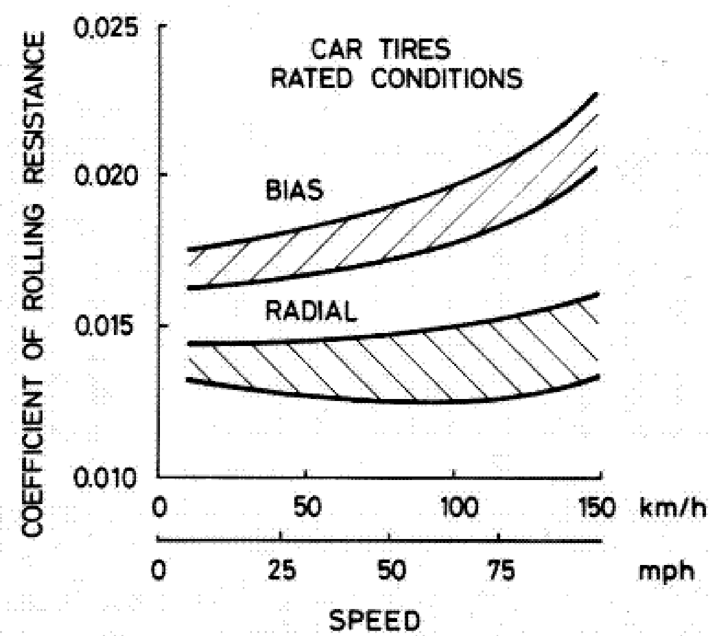
$$F_{RR} = \frac{F_z \Delta x + M_{fr}}{R_e}$$

$$F_{RR} \simeq \frac{\Delta x}{R_e} F_z = f_{RR}\, F_z$$

Rolling resistance forces

- The rolling resistance is influenced by the **tire structure and construction**:
  - The rolling resistance of bias tires is higher than radial tires

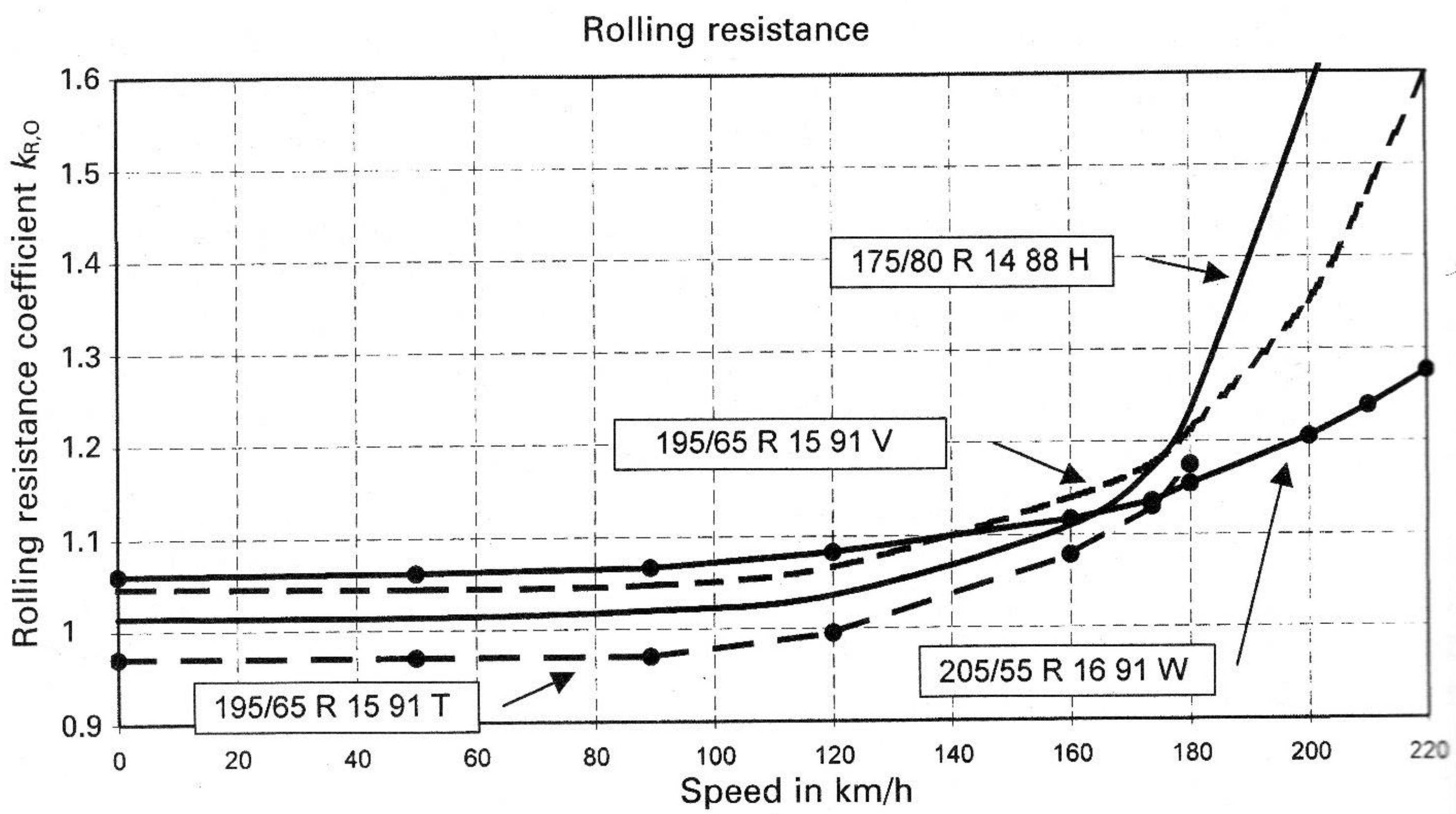




Rolling resistance forces

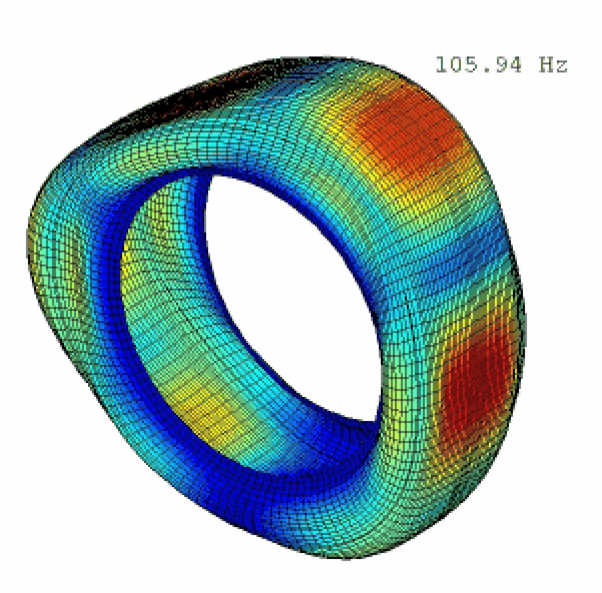
- The **operating conditions** mainly:
  - The inflating pressure: the rolling resistance is reduced for a higher inflation pressure
  - The vehicle speed: one observes a slight increase with v at low speed. A dramatic increase after a critical speed because of the development of high-energy standing waves
  - The longitudinal and lateral slip: the rolling resistance increases as the square of the side slip.
  - The rolling resistance is much higher on soft and smooth ground because of the deformation work of the soil
  - The rolling resistance is also higher on wet ground or in snow

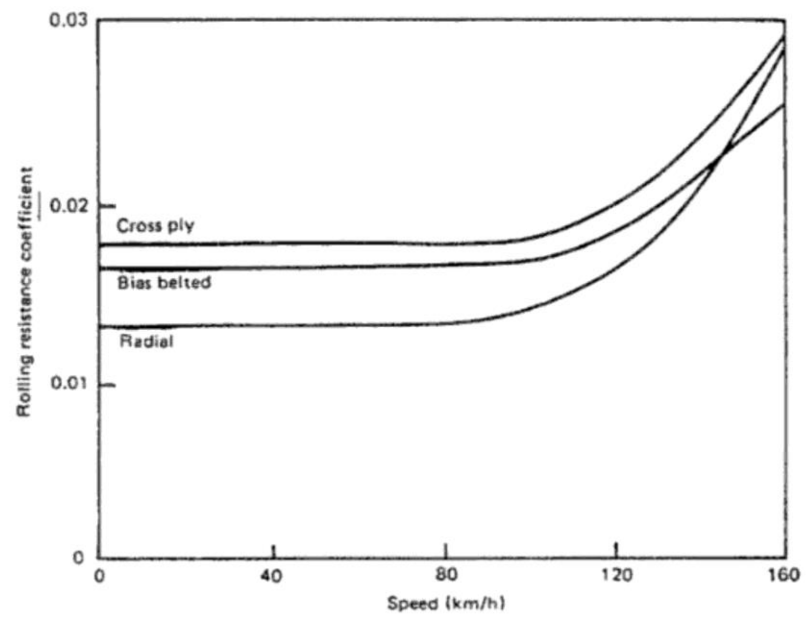
Rolling resistance forces



Influence of load index and speed

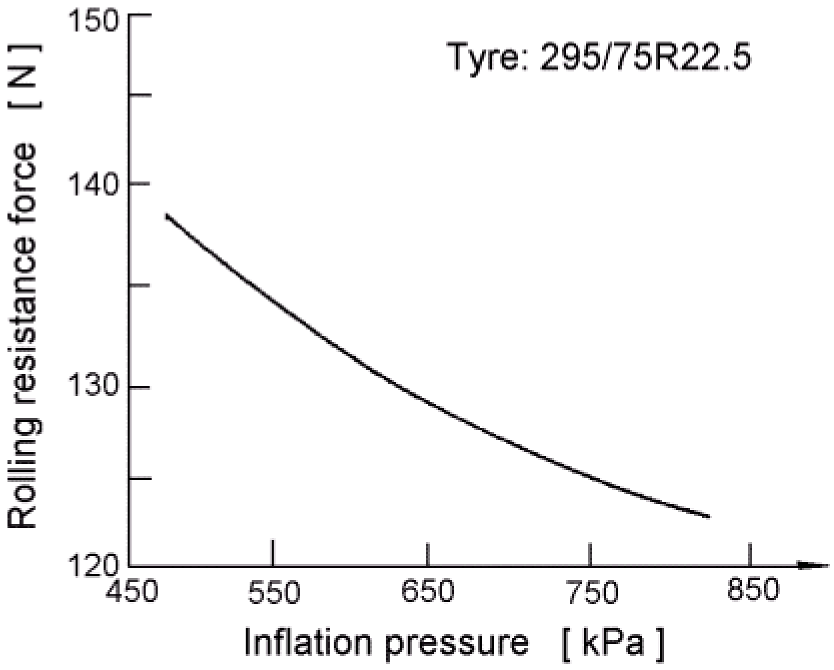
Rolling resistance forces



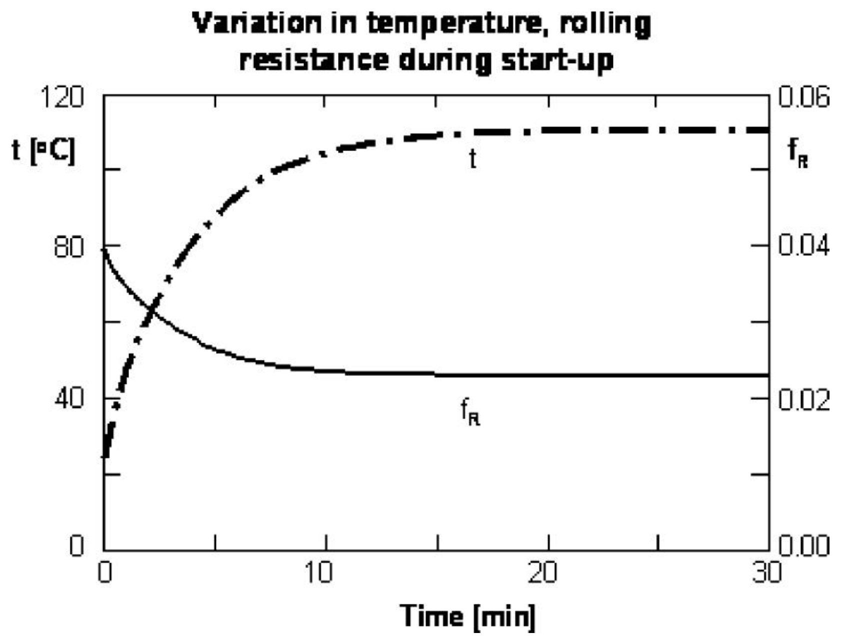


Influence of speed

Rolling resistance forces



Influence of inflation pressure

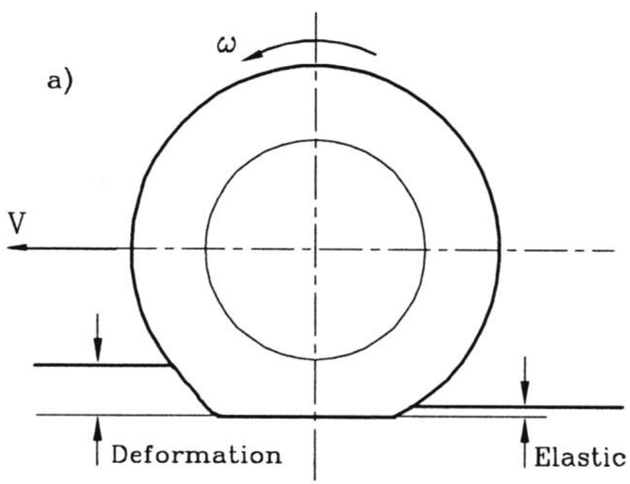


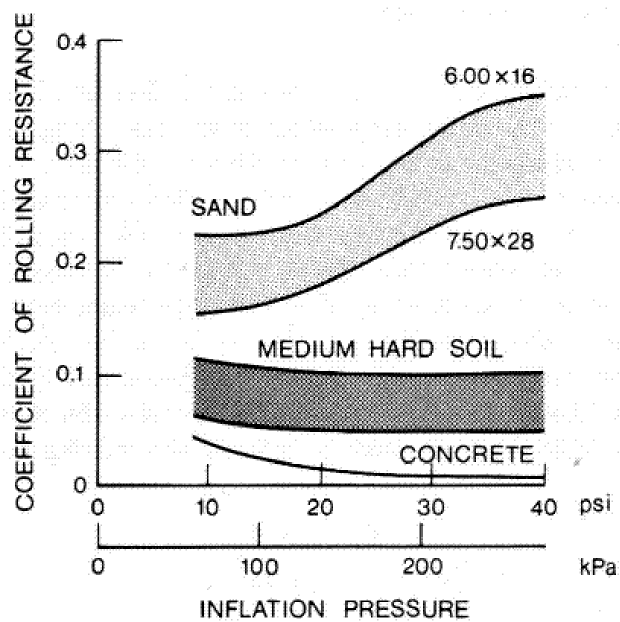
Influence of temperature

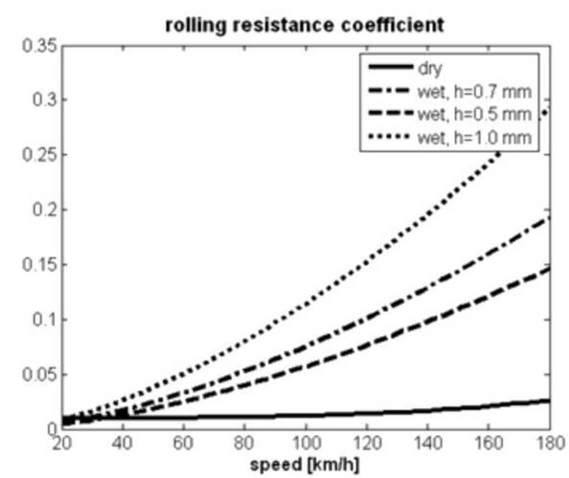
Rolling resistance forces

- The rolling resistance is much higher on soft and smooth ground because of the deformation work of the soil

- The rolling resistance is also higher on wet ground or in snow







Influence of water depth

Influence of the terrain stiffness

Estimation of tire rolling resistance

- Order of magnitude given by the Automotive handbook (Bosch)

Road surface	Coefficient of rolling resistance f
Pneumatic car tires on	
Large sett pavement	0.015
Small sett pavement	0.015
Concrete, asphalt	0.013
Rolled gravel	0.02
Tarmacadam	0.025
Unpaved road	0.05
Field	0.1...0.35
Pneumatic truck tires on concrete, asphalt	0.006...0.01
Strake wheels in field	0.14...0.24
Track-type tractor in field	0.07...0.12
Wheel on rail	0.001...0.002

Estimation of tire rolling resistance

- For instance, Wong formula for radial tires:

$$f_{RR} = 0.0136 + 0.4\,10^{-7}\,V^2 \quad \text{V in km/h}$$

- Influence of inflating pressure and normal load

$$f_{RR} = 5.0\,10^{-3} + \frac{10.55\,10^{-3}}{p} + \frac{12.4\,10^{-6}\,v^2}{p}$$

  - with v in m/s and p, the inflating pressure in bar

- Influence of inflating pressure and normal load

$$f_{RR} = \frac{K'}{1000}\left(5.1 + \frac{5.5\,10^5 + 90\,F_z}{p} + \frac{1100 + 0.0388\,F_z}{p}\,v^2\right)$$

  - with v in m/s and p, the inflating pressure in bar

Generic expression of rolling resistance

- Generic expression of rolling resistance coefficient of radial tires:

$$f_{RR} = f_0 + f_2 v^2 \quad \mathrm{v\ in\ m/s}$$

Estimation of tire rolling resistance

- ADVISOR Model developed in collaboration with Michelin

$$F_{RR} = p^{\alpha} F_z^{\beta} (a + b v + c v^2)$$

- p is the tire pressure in MPa
- F_z is the tire load in kg
- V is the vehicle speed in m/s
- α, β, a, b, and c are coefficients used to fit the experimental rolling resistance data

- Experimental values
  - β ~1
  - α ~ -1/2

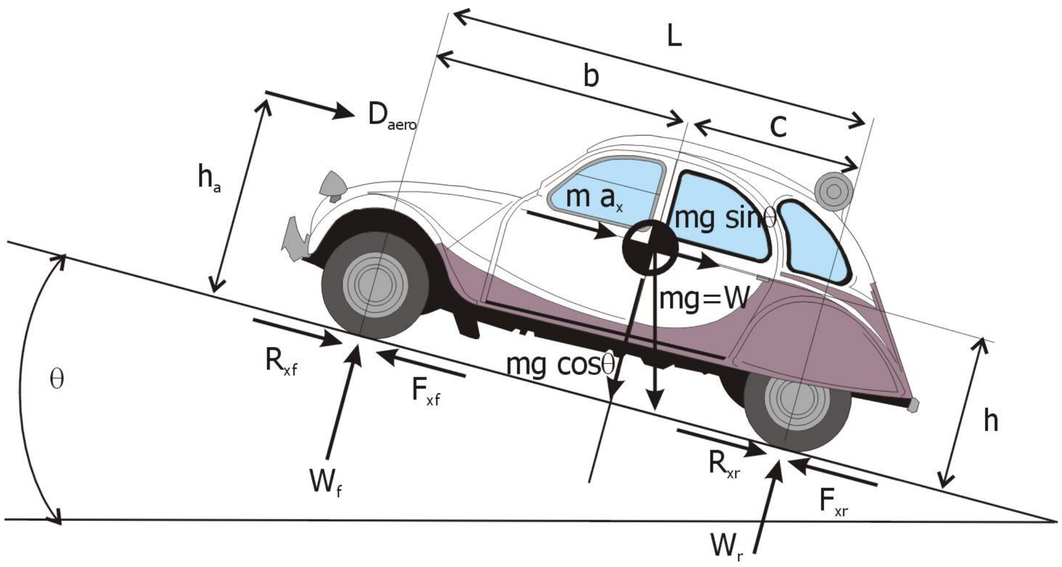
Estimation of tire rolling resistance

2001 OE Fitments	Size	alpha	beta	a	b	c	mass [kg]	SMERF [N]	SMERF P	SMERF Z
Mercury Cougar	P205/60R15	-0.4815	1.0051	6.82E-02	2.32E-04	1.20E-06	8.23	24.75	260	4051.5
Kia Optima	P205/60R15	-0.4745	0.9552	1.50E-01	4.87E-04	1.18E-06	9.51	35.98	260	4051.5
Mazda 626	P205/60R15	-0.4243	0.9568	1.59E-01	3.44E-04	1.25E-06	10.55	48.63	260	4051.5
Volkswagen Eurovan	P205/60R16	-0.4428	0.9036	2.11E-01	6.00E-04	2.17E-06	10.42	40.53	260	4223.1
Honda Accord EX Coupe V6	P205/60R16	-0.3388	0.9375	1.01E-01	1.59E-04	9.93E-07	9.71	43.32	260	4223.1
Dodge Stratus ES										
Toyota Camry	P205/65R15	-0.3937	0.8901	1.66E-01	3.50E-04	2.09E-06	9.71	37.41	260	4360.3
Honda Accord LX & EX Sedan V6	P205/65R15	-0.3947	0.9468	1.13E-01	1.89E-04	2.24E-06	10.35	40.78	260	4360.3
Hynudai XG300	P205/65R15	-0.3191	0.9076	1.23E-01	1.96E-04	1.52E-06	10.52	47.35	260	4360.3
Lexus ES 300										
Nissan Maxima										
Saturn L Series										
Subaru Outback	P225/60R16	-0.4814	0.9463	1.47E-01	3.69E-04	2.38E-06	12.95	38.33	260	5012.7
Ford Crown Victoria	P225/60R16	-0.3881	0.9550	1.03E-01	1.46E-04	2.19E-06	11.08	47.21	260	5012.7
Dodge Intrepid	P225/60R16	-0.5888	1.0921	7.93E-02	1.18E-04	3.52E-07	15.29	55.69	260	5012.7
Lincoln Town Car										
Ford F150	P235/70R16	-0.4704	1.0129	8.49E-02	1.16E-04	2.64E-06	12.86	51.14	260	6180.3
Mazda Tribute LX & ES	P235/70R16	-0.4003	0.9315	1.39E-01	2.20E-04	1.90E-06	14.26	57.88	260	6180.3
	P235/70R16	-0.4090	0.9765	1.06E-01	1.11E-04	1.52E-06	14.26	61.20	260	6180.3
Ford Explorer	P235/75R15	-0.5007	0.9141	2.55E-01	4.69E-04	3.49E-06	13.30	54.08	260	6317.5
Dodge Dakota	P235/75R15	-0.4797	0.9464	2.08E-01	2.56E-04	3.94E-06	13.31	65.11	260	6317.5
Chevy Trailblazer	P235/75R15	-0.2601	0.8275	2.00E-01	2.50E-05	4.18E-06	13.80	71.30	260	6317.5
Mercury Mountaineer										
Mitsubishi Montero Sport ES										

Resistance force due to grading

- Expression of grading resistance

$$\boxed{F_{GRADING} = m\,g\,\sin\theta}$$



Expression of road load

- General form of the vehicle resistance

$$F_{RES} = F_{AERO} + F_{RR} + F_{GRADE}$$

- General formulation

$$F_{RES} = A + B\,v^2$$

  - with A, B > 0

$$A = m\,g\,\cos\theta\,f_0 + m\,g\,\sin\theta$$
$$B = 1/2\,\rho\,S\,C_x + m\,g\,\cos\theta\,f_2$$

Evolution of road loads with vehicle speed

Wong, Fig 3.3

50 mph = 80 km/h

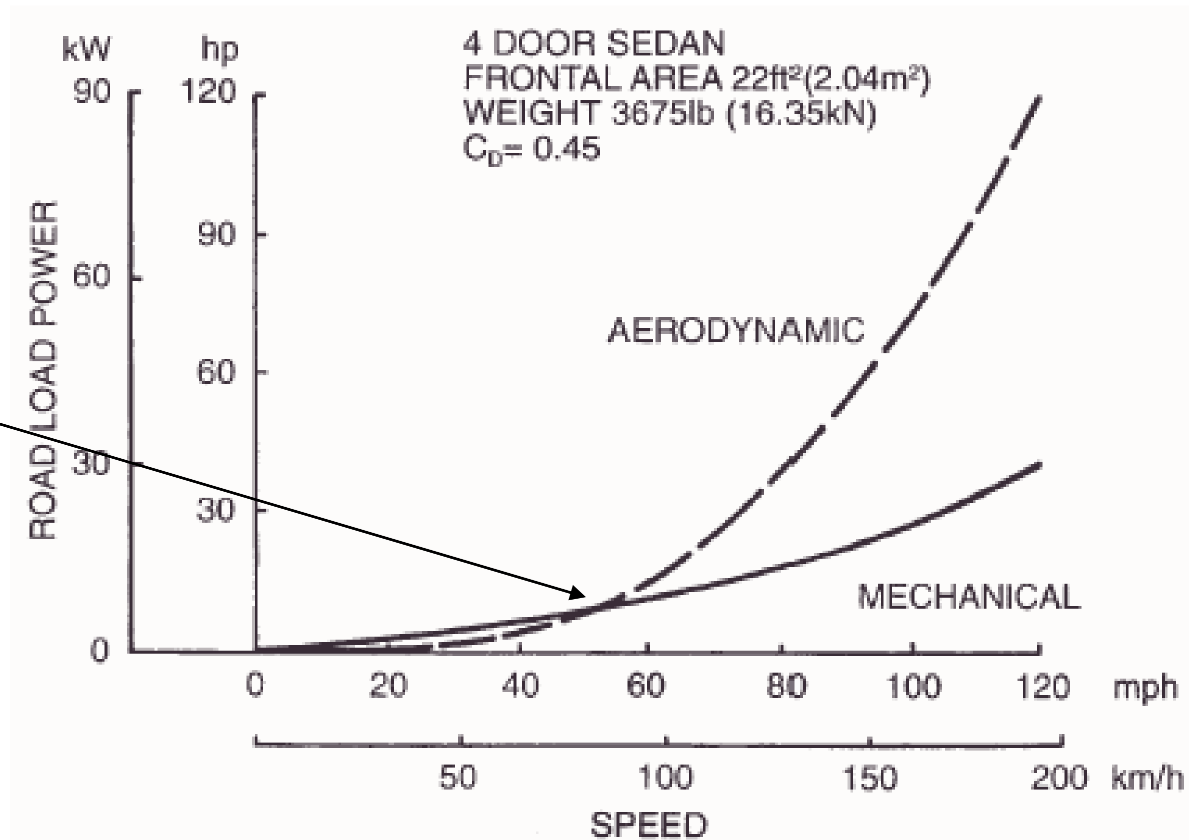


Fig. 3.3 Power requirements of a full-size passenger car as a function of speed. (Reproduced with permission of the Society of Automotive Engineers from reference 3.1.)

Evolution of road loads with vehicle speed

- For passenger cars, the rolling resistance dominates until a break-event speed of about 80 km/h
- For heavy duty vehicle, the rolling resistance is still dominant till max speed.
- Grading forces can easily be as large as the aerodynamic drag and the rolling resistance on level road

Evolution of road loads with vehicle speed