Vehicle Performance

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Lesson 1:
Tractive efforts and road loads

Outline

- DESCRIPTION OF VEHICLE MOTION
  - Longitudinal motion
- 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

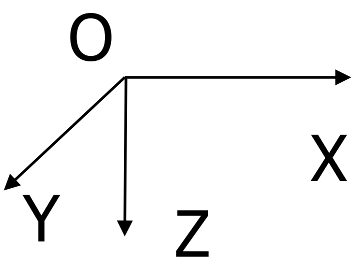
- T. Gillespie. « Fundamentals of vehicle Dynamics », 1992, Society of Automotive Engineers (SAE)
- R. Bosch. « Automotive Handbook ». 5th edition. 2002. Society of Automotive Engineers (SAE)
- J.Y. Wong. « Theory of Ground Vehicles ». John Wiley & sons. 1993 (2nd edition) 2001 (3rd edition).
- W.H. Hucho. « Aerodynamics of Road Vehicles ». 4th edition. SAE International. 1998.
- M. Eshani, Y. Gao & A. Emadi. Modern Electric, Hybrid Electric and Fuel Cell Vehicles. Fundamentals, Theory and Design. 2nd Edition. CRC Press.

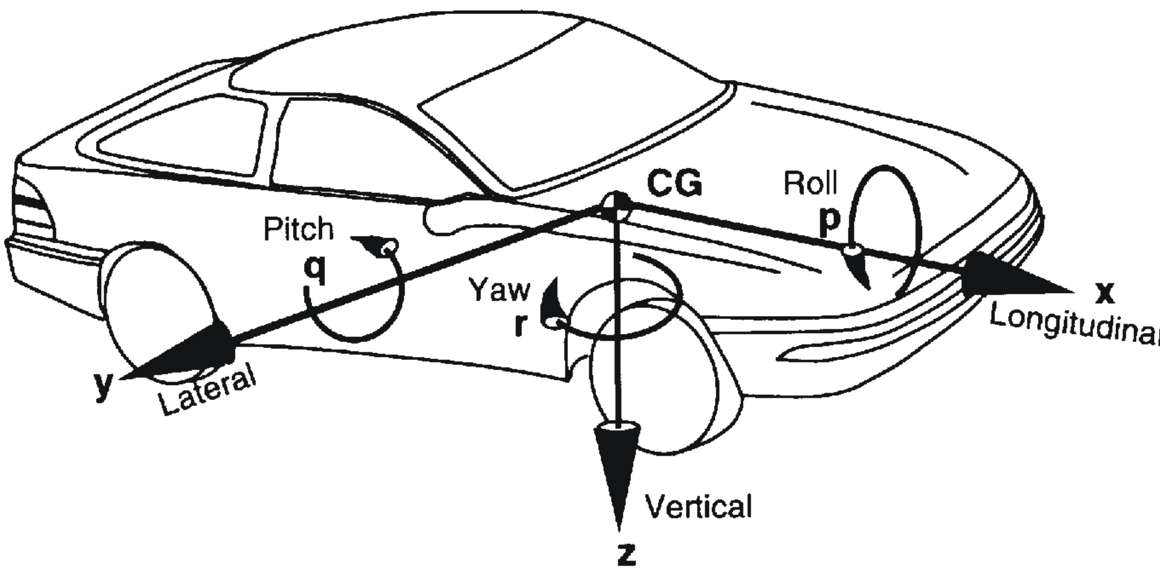
Assumptions and definitions

Assumptions

- The vehicle is made of several components or subsystems
- We consider the motion of the system as a whole
- During acceleration, braking, turn, the vehicle is considered as a rigid body motion and is characterized by its geometry, its mass and inertia properties

Reference frames





Inertial coordinate system OXYZ

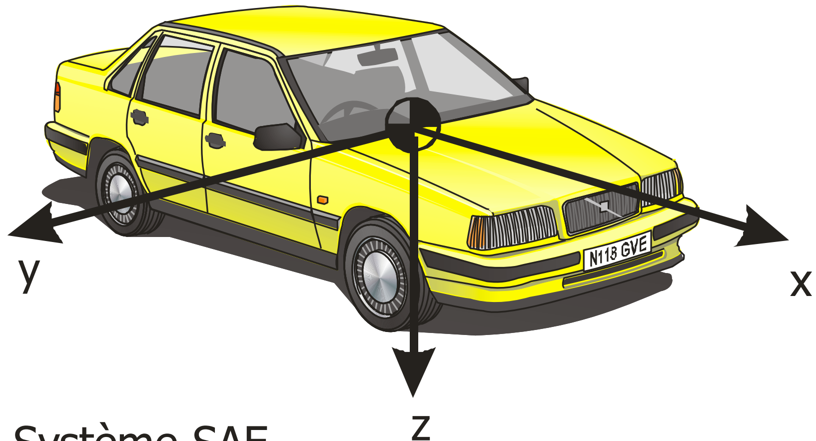
Local reference frame oxyz attached to the vehicle body - SAE (Gillespie, fig. 1.4)

Reference frames

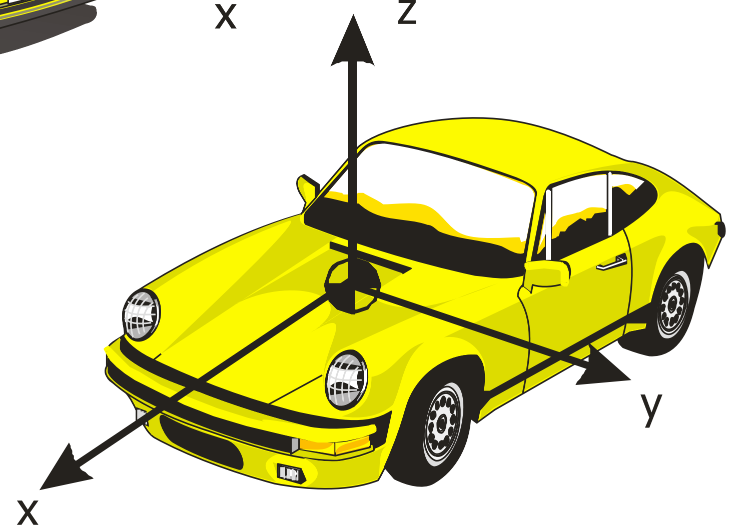
- Inertial reference frame
  - X direction of initial displacement or reference direction
  - Y right side travel
  - Z towards downward vertical direction

- Vehicle reference frame (SAE):
  - x along motion direction and vehicle symmetry plane
  - z along vertical direction pointing to the center of the earth
  - y in the lateral direction on the right-hand side of the driver towards the downward vertical direction
  - o, origin at the center of mass

Reference frames



Système SAE

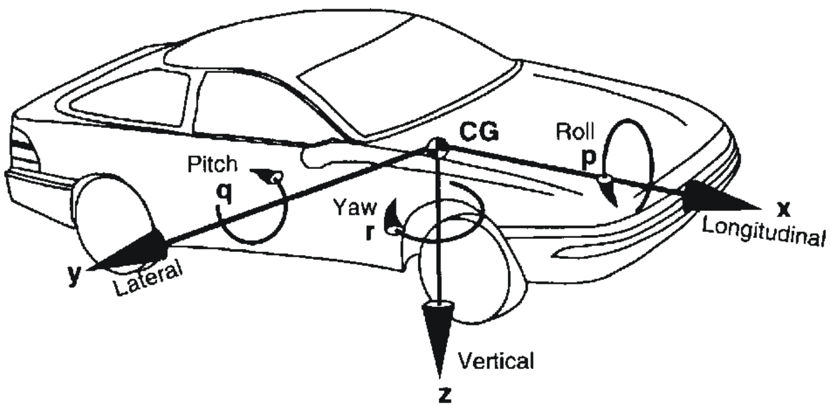


Système ISO

Comparison of conventions of SAE and ISO/DIN reference frames

Local velocity vectors

- Vehicle motion is often studied in car-body local systems
  - u forward speed (+ if in front)
  - v side speed (+ to the right)
  - w vertical speed (+ downward)
  - p rotation speed about a axis (roll speed)
  - q rotation speed about y (pitch)
  - r rotation speed about z (yaw)



Forces

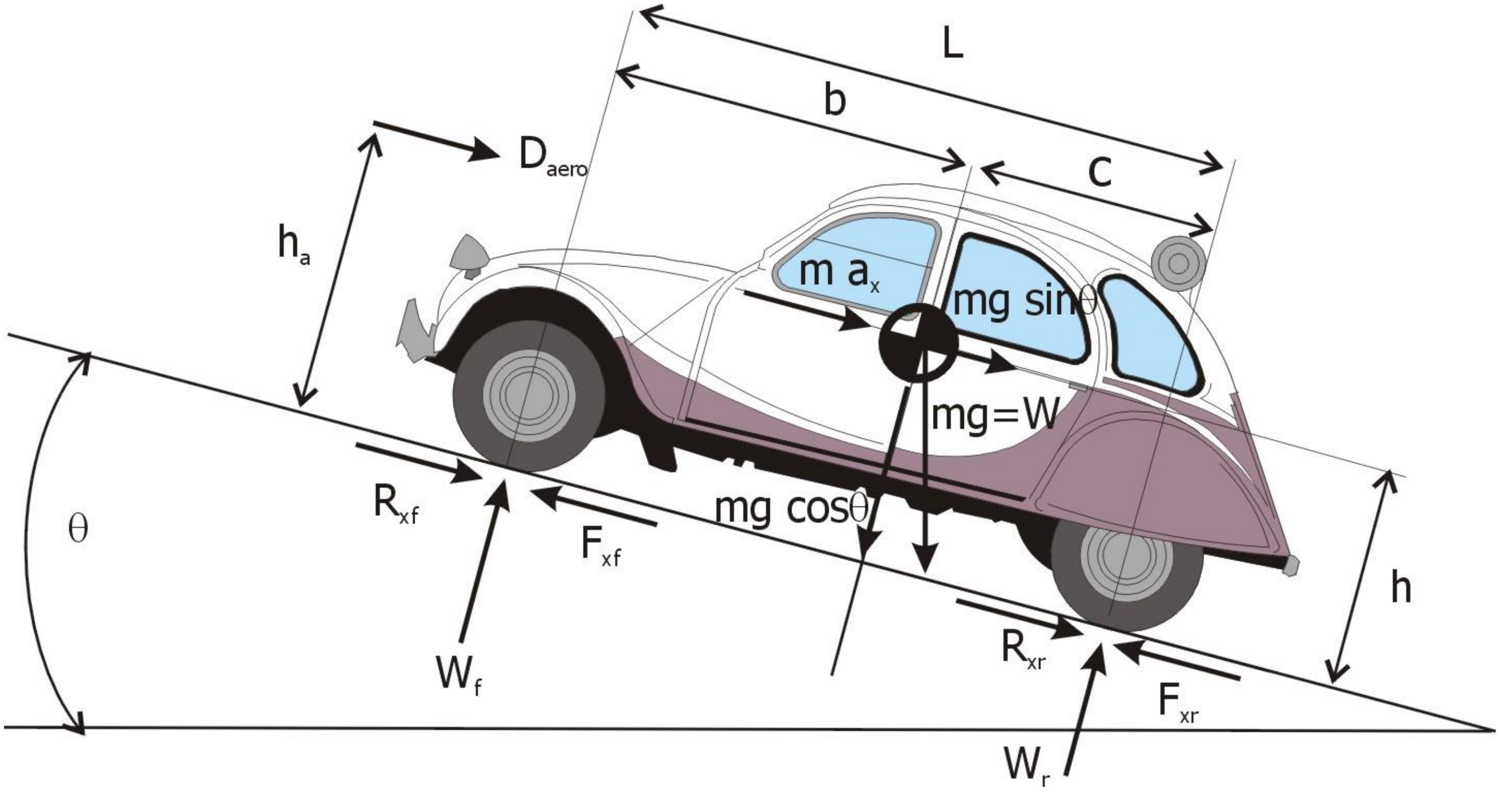
- *Forces and moments are accounted positively when acting onto the vehicle and the positive direction with respect to the considered frame*

- Corollary
  - A positive F_x force is propelling the vehicle forward
  - The reaction force of the ground onto the wheels is accounted negatively.

- Because of the inconveniency of this definition, the SAEJ670e « Vehicle Dynamics Terminology » is naming as normal force a force acting downward while vertical forces are referring to upward forces

Equilibrium of longitudinal motion

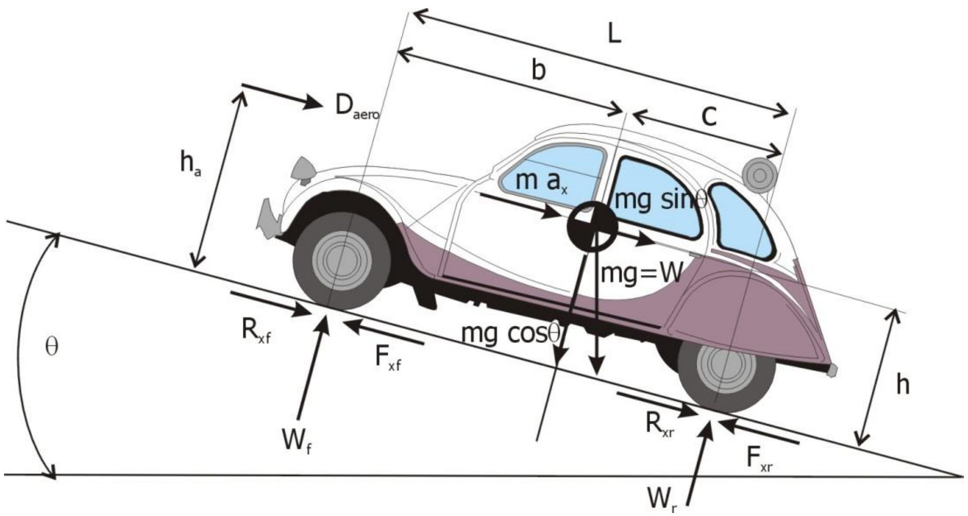
Longitudinal motion



Longitudinal equilibrium

- Newton-Euler equations

$$\sum F_x = m\frac{d}{dt}(u) = ma_x$$
$$\sum F_z = m\frac{d}{dt}(w) = 0$$
$$\sum M_y = \frac{d}{dt}(\boldsymbol{J}\omega)_y = 0$$



- Equilibrium

$$ma_x = \sum_i F_{x\,i} - \sum_i R_{x\,i} - mg\sin\theta - D_{Aero}$$
$$0 = mg\cos\theta - W_f - W_r$$
$$0 = W_f\,b - W_r\,c + \sum_i F_{xi}h - \sum_i R_{xi}h + D_{Aero}(h_A - h)$$

Longitudinal equilibrium

- Equilibrium along forward x direction

$$\boxed{ma_x = \sum_i F_{xi} - \sum_i R_{xi} - mg\sin\theta - D_{Aero}}$$

- Equation of vehicle longitudinal motion

$$\boxed{ma_x = F_x - R_{rl} - mg\sin\theta - D_A - R_{h,x}}$$

- In energy form

$$\boxed{\mathcal{P}_x = m\frac{du}{dt}u + \mathcal{P}_R = \frac{d}{dt}(\frac{1}{2}mu^2) + \mathcal{P}_R}$$

Newton’s law of motion

- Newton’s law for longitudinal motion:

$$\boxed{F_T = F_{AERO} + F_{RR} + mg\sin\theta + m_e\frac{dV}{dt}}$$

- The traction force F_T is used to face the resistance forces and to accelerate the vehicle

- Driving resistance forces:
  - Aerodynamics forces
  - Rolling resistance forces
  - Slope forces

Driving resistance forces

- Aerodynamic drag

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

- Rolling resistance forces

$$\boxed{F_{RR} = mg\cos\theta\; f_{RR}}$$

- Slope resistance

$$\boxed{F_{SLOPE} = mg\sin\theta}$$

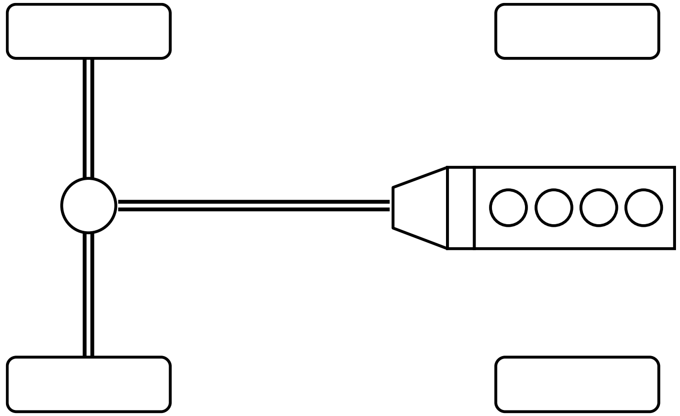
Power train tractive effort

Power and tractive effort

POWER AT WHEELS

- The power that comes to the wheels is the engine power multiplied by the efficiency of the transmission efficiency η

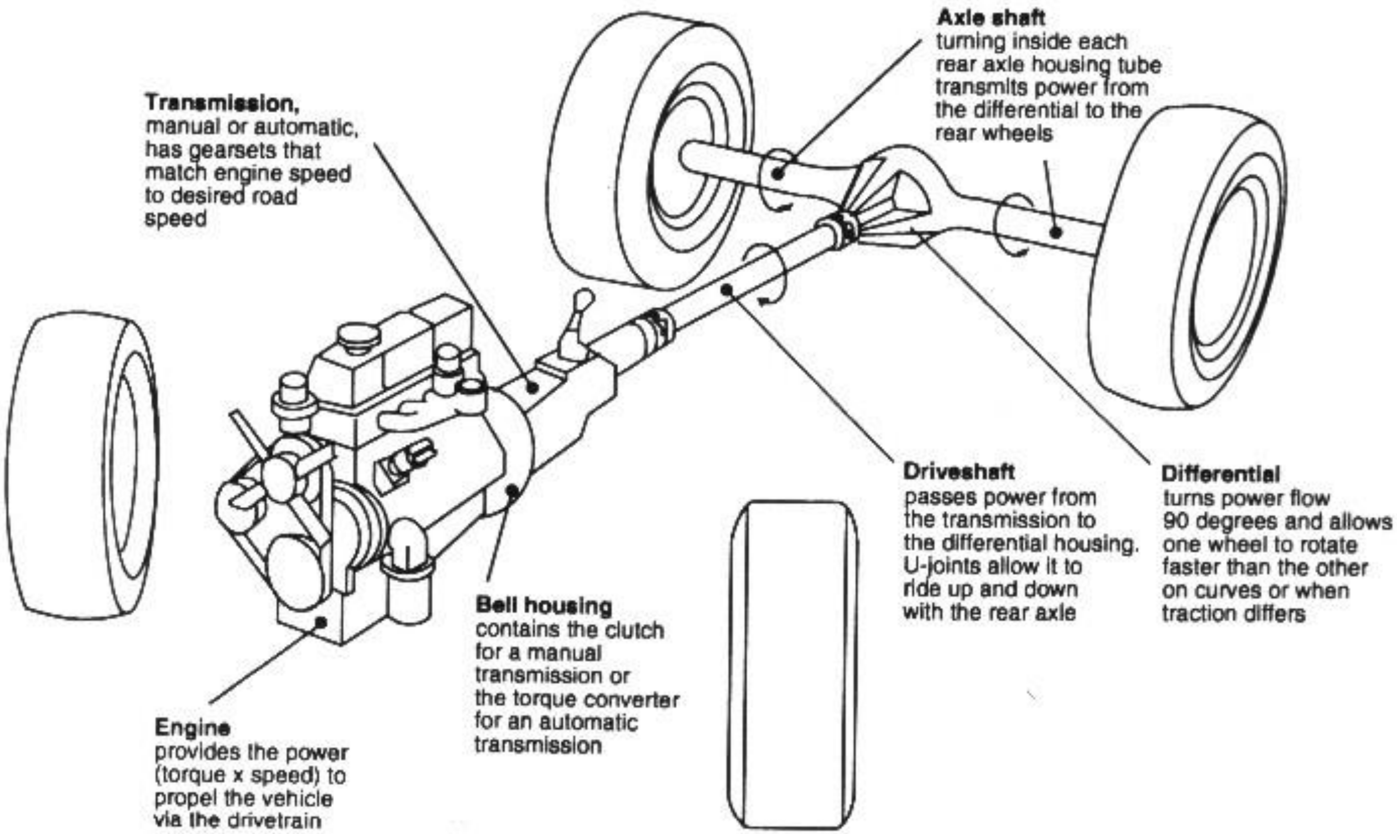
$$\mathcal{P}_w = \eta \, \mathcal{P}_p$$



- The driveline efficiency η :
  - Clutch
  - Gear box
  - Differential and transfer box
  - Kinematic joints

$$\eta = \eta_{clutch} \, \eta_{box} \, \eta_{dif} \, \eta_{joints}$$

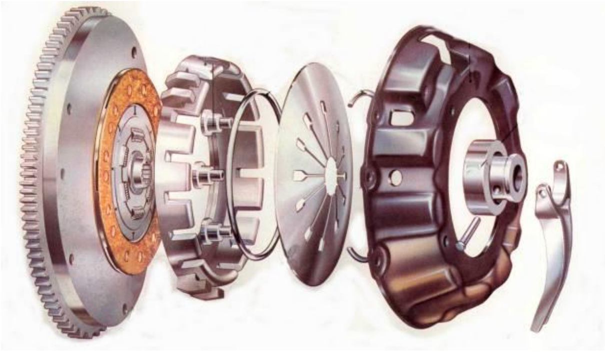
Propulsion system

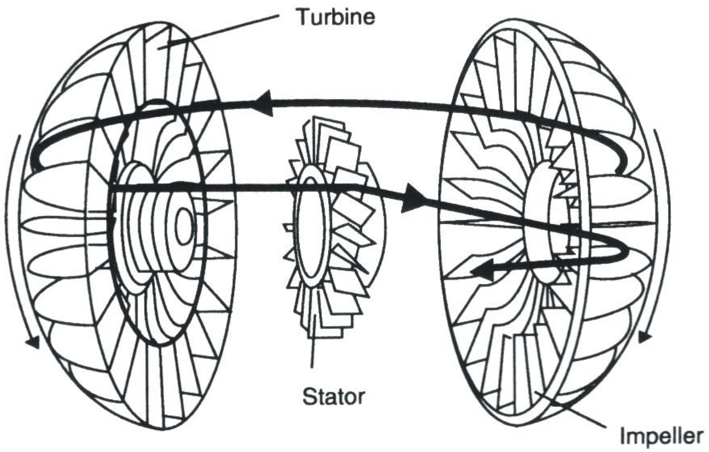


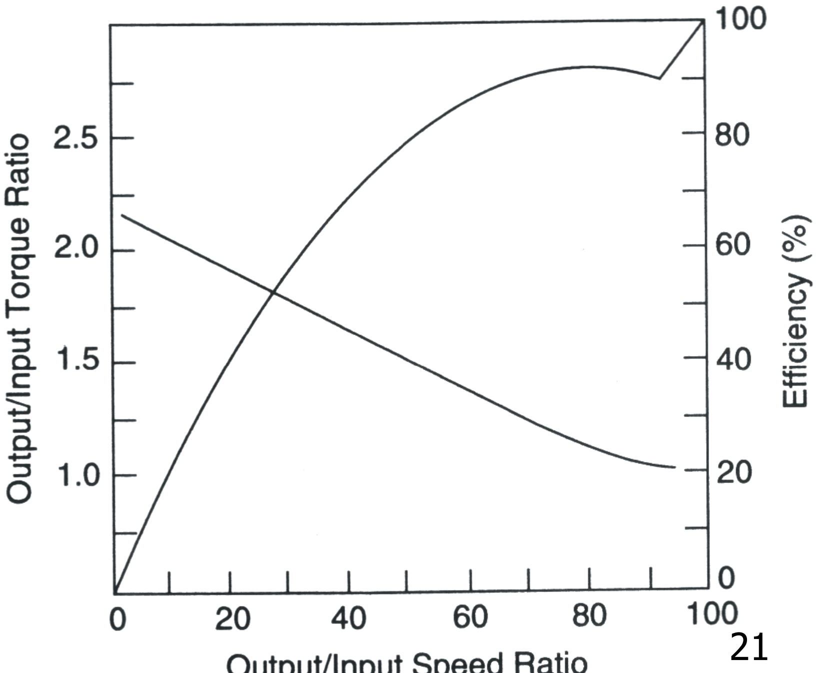
Gillespie, Fig 2.3

Friction and hydraulic clutches

- Clutch efficiency
  - Friction clutch $\eta=1$
  - Hydraulic coupler: $\eta\sim0.9$

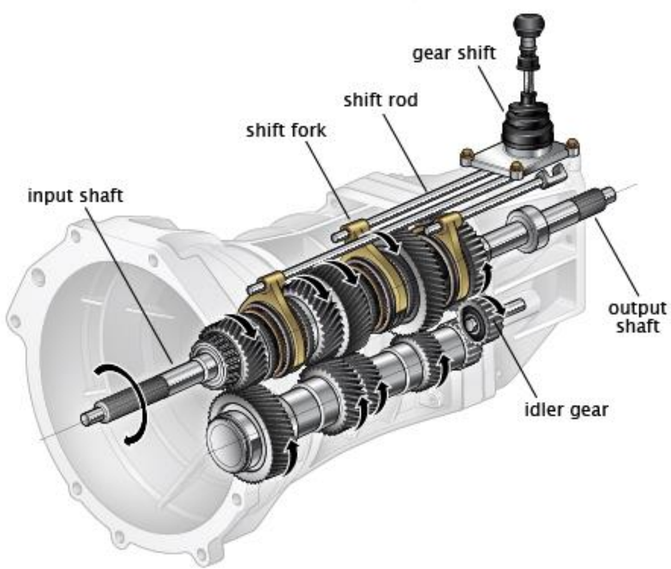


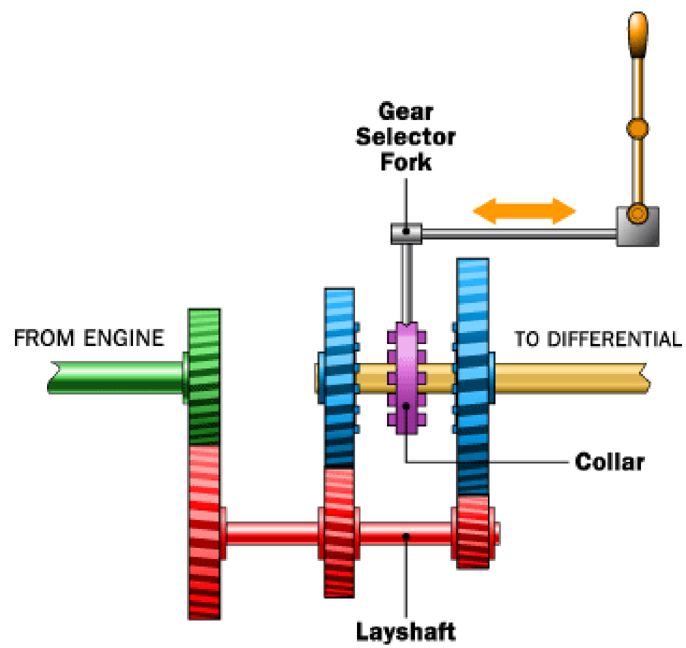




Power and tractive efforts at wheels

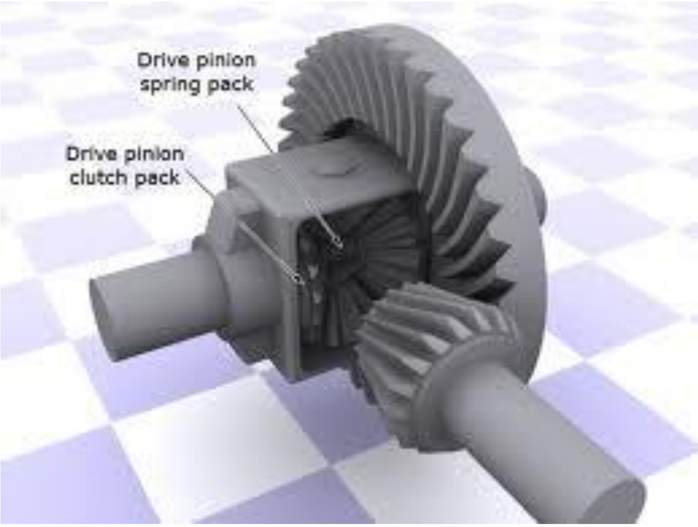
- Manual gearbox efficiency:
  - Efficiency of a pair of gear (good quality) η= 99% to 98.5 %
  - Gear box: double gear pairs: η = 97.5%
  - Gear box: direct drive: η = 100%





Differential system

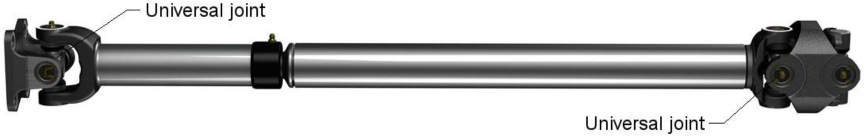
- Efficiency of differential
  - Longitudinal layout: 90° change of direction (bevel pair) + offset of the shaft (hypoid gear): η = 97,5 %
  - Transversal layout: no bevel → good quality gear pair: η = 98,75%



Driveshafts

- Propeller shaft efficiency
  - The propeller shaft transmitting torque from the gearbox to the rear axle

$$\eta_{tm} = \eta_U^2 = 0.99^2 = 0.98$$



- Driveshaft efficiency
  - Constant velocity joints
  - Rzeppa
  - Tripod

$$\eta_{DS} = \eta_{RZP}\,\eta_{TRP} = 0.99^2 = 0.98$$

Power and tractive effort

Global efficiency in various situations

	Gear ratio	Longitudinal layout	Transversal layout
Friction clutch	Normal	1. 0,975. 0,975 = 0,95	1. 0,975 0,985 = 0,96
	Direct	1. 1. 0,975 = 0,975	x
Hydraulic coupling	Normal	0,88 0,975 0,975 = 0,86	0,88 0,975 0,985 = 0,865
	Direct	0,88 1. 0,975 = 0,88	x

Power and tractive effort

WHEEL TRACTIVE EFFORT

- Power at wheels and power at the plant

$$\mathcal{P}_w = F_w \, v \qquad \qquad \mathcal{P}_p = C_p \, \omega_p$$

- Gear ratio i>1

$$\omega_p = i \, \omega_w \qquad \qquad i = i_{box} \, i_{dif}$$

- Displacement speed and rotation speed of the wheels

$$v = \omega_w \, R_e$$

  - Re: effective rolling radius of the tire

Power and tractive effort

TRACTIVE FORCE

- Relation between plant rotation speed and traveling speed

$$\boxed{v = \frac{R_e}{i}\,\omega_p}$$

- Transmission length R/i
  - Indicates the travelling speed for a given plant rotation speed.

  - Generally given in km/h per rpm of the plant
  - Example 30 km/h per 1000 tr/min

$$\frac{R_e}{i} = \frac{30/3,6}{1000\ 2\,\pi/60} = 0,07958\ m$$

Power and tractive effort

TRACTIVE FORCES

- It follows

$$F_w \, v \;=\; \eta \; C_p \, \omega_p$$

$$F_w \;=\; \eta \; C_p \, \frac{\omega_p}{v}$$

- Then the tractive force writes

$$\boxed{F_w \;=\; \eta \; C_p \, \frac{\omega_p}{\omega_w R_e} \;=\; \eta \; C_p \, \frac{i}{R_e}}$$

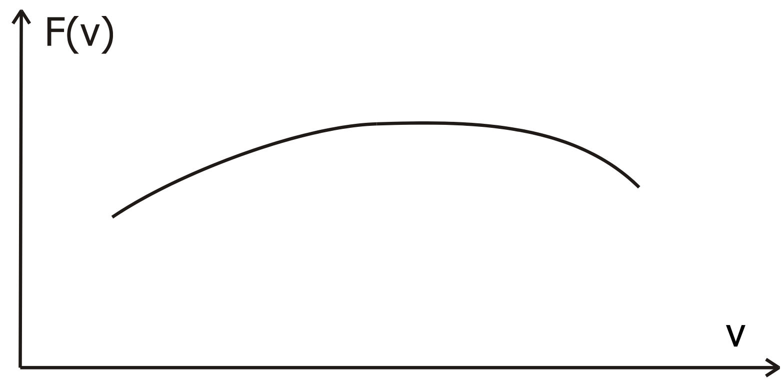
Tractive force vs vehicle speed

- For a given transmission ratio r, one has:

$$\omega_p = i\,\omega_w = v\frac{i}{R_e} \qquad\qquad C_p(\omega_p) = C_p(v\frac{i}{R_e})$$

- So for a given transmission ratio, one gets the tractive force in terms of the vehicle speed

$$F_w = \eta\frac{i}{R_e}\ C_p(v\frac{i}{R_e})$$

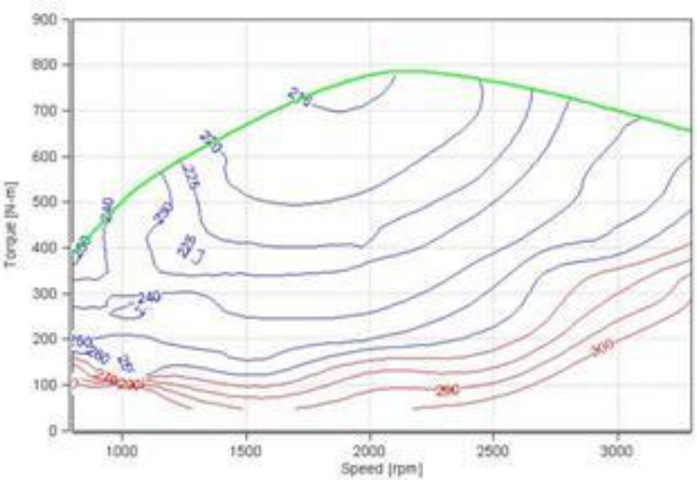


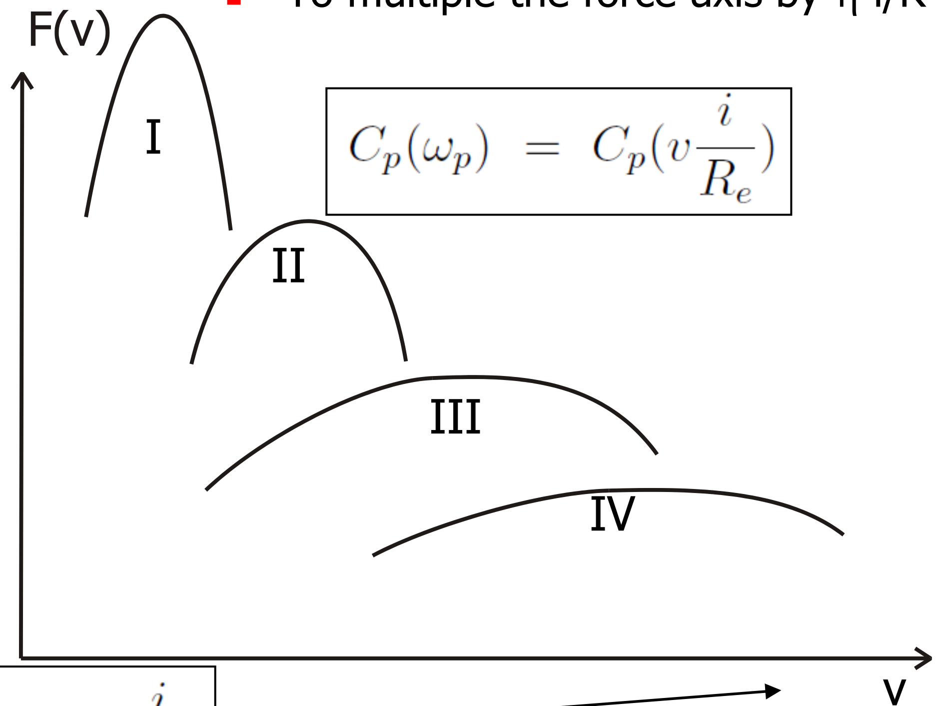
- Plotting the curves requires
  - Multiplying the speed curve by R/i
  - Multiplying the tractive force by η i/R

Tractive force vs vehicle speed

$$F_w = \eta \frac{i}{R_e} \; C_p(v \frac{i}{R_e})$$

- To draw the tractive force curve, you have to:
  - To multiply the speed axis by R/i
  - To multiple the force axis by η i/R

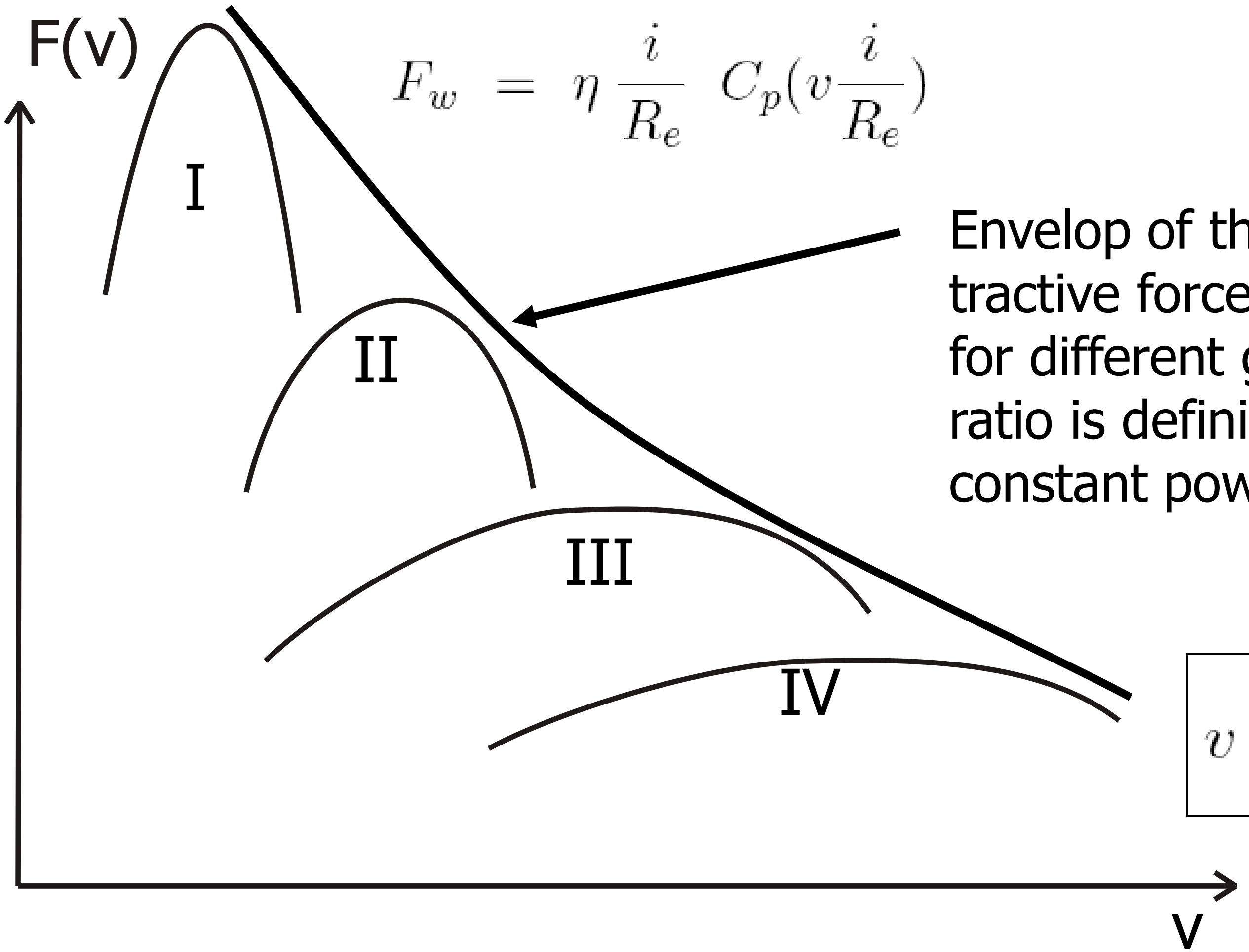




$$C_p(\omega_p) = C_p(v \frac{i}{R_e})$$

$$\omega_p = i\,\omega_w = v \frac{i}{R_e}$$

Tractive force vs vehicle speed



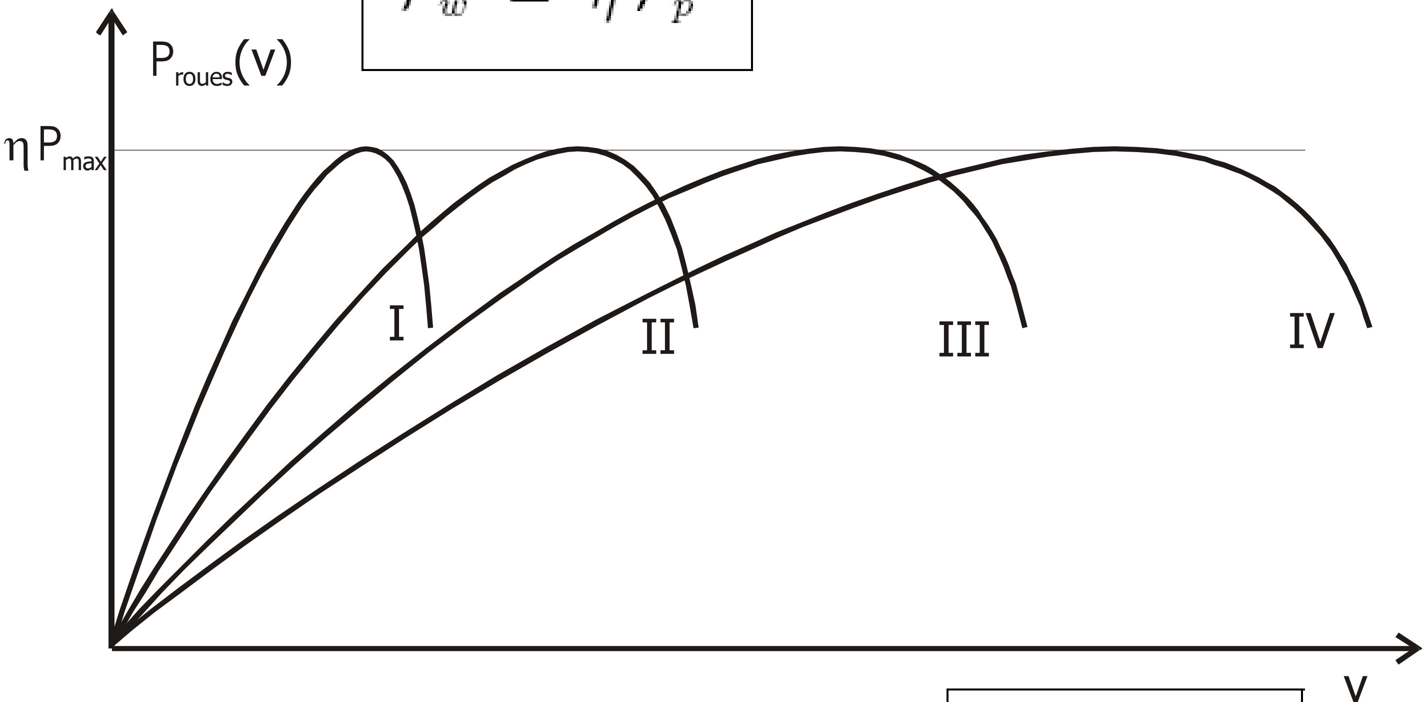
$$F_w = \eta \frac{i}{R_e} C_p(v \frac{i}{R_e})$$

Envelop of the tractive force curves for different gear ratio is defining a constant power (1/v)

$$\boxed{v = \frac{R_e}{i} \omega_p}$$

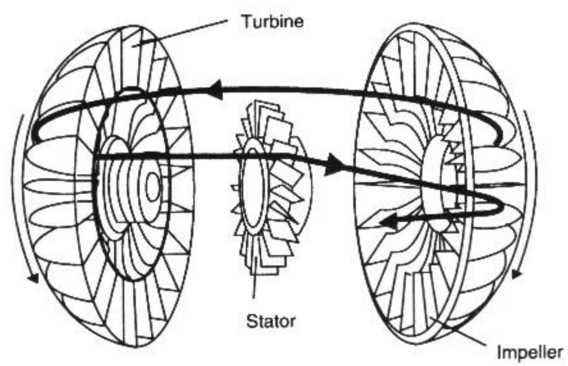
Tractive power vs vehicle speed

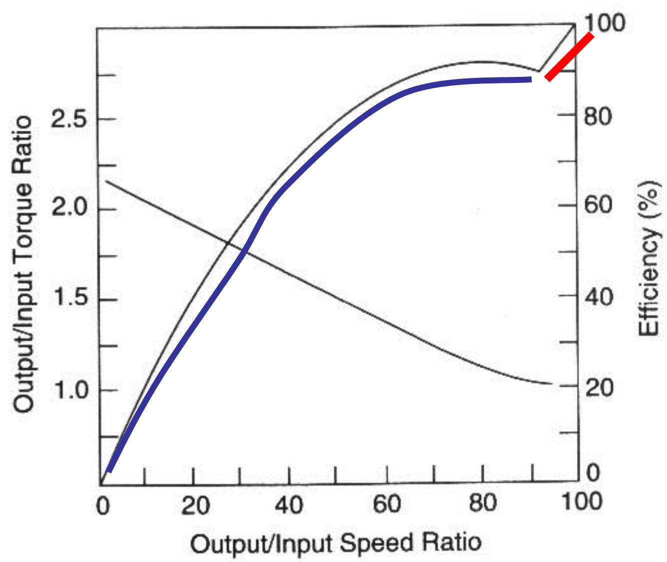
$$\mathcal{P}_w = \eta\,\mathcal{P}_p$$



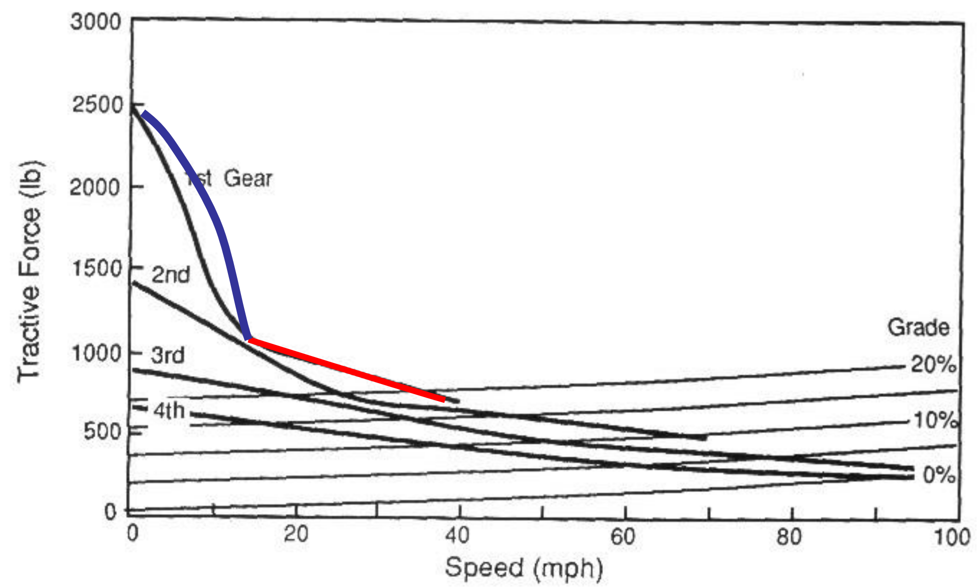
$$v = \frac{R_e}{i}\,\omega_p$$

Tractive force vs vehicle speed





Effect of automatic transmission and hydraulic clutch



Gillespie, Fig 2.5, 2.6

Vehicle resistance

Vehicle 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.

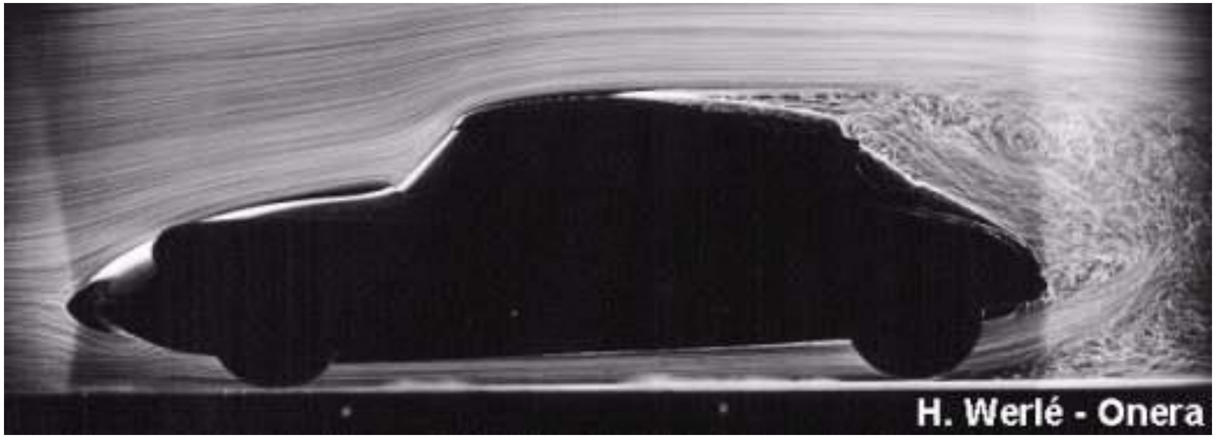
- The air flow is very complex because of
  - The ground effect that affects deeply the flow
  - The wheel spinning that interact strongly with the vehicle air flow.
  - The internal aerodynamic flow is necessary to cool the engine compartment and the air conditioning of the cabin, but it introduces 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 distributions giving rise to a net force pointing backward

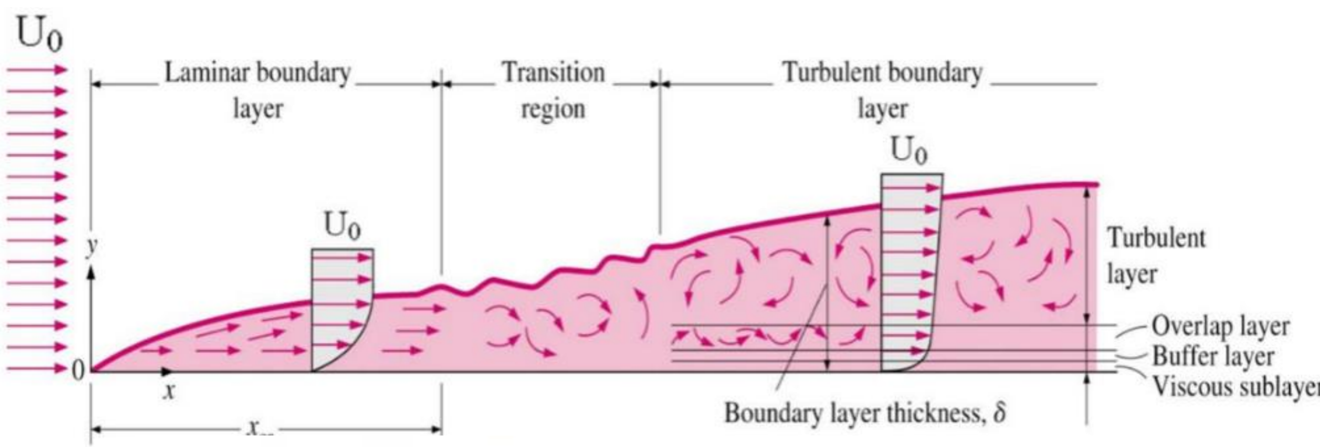
    Because of Mach and Reynolds numbers, the fluid flow is incompressible and non viscous (except in the boundary layers)

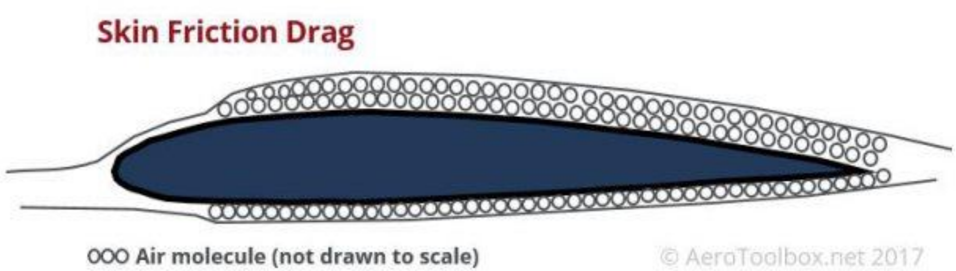
    Large vortices are present because of the bluff body geometry and the boundary layers are not attached



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

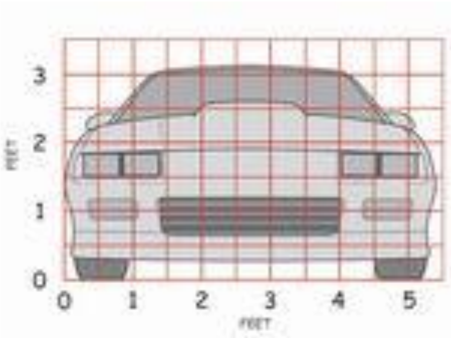




Estimating the aerodynamic drag

- Drag force

$$\boxed{F_{a\acute{e}ro} = \frac{1}{2}\rho\, V^2 S C_x}$$



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

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

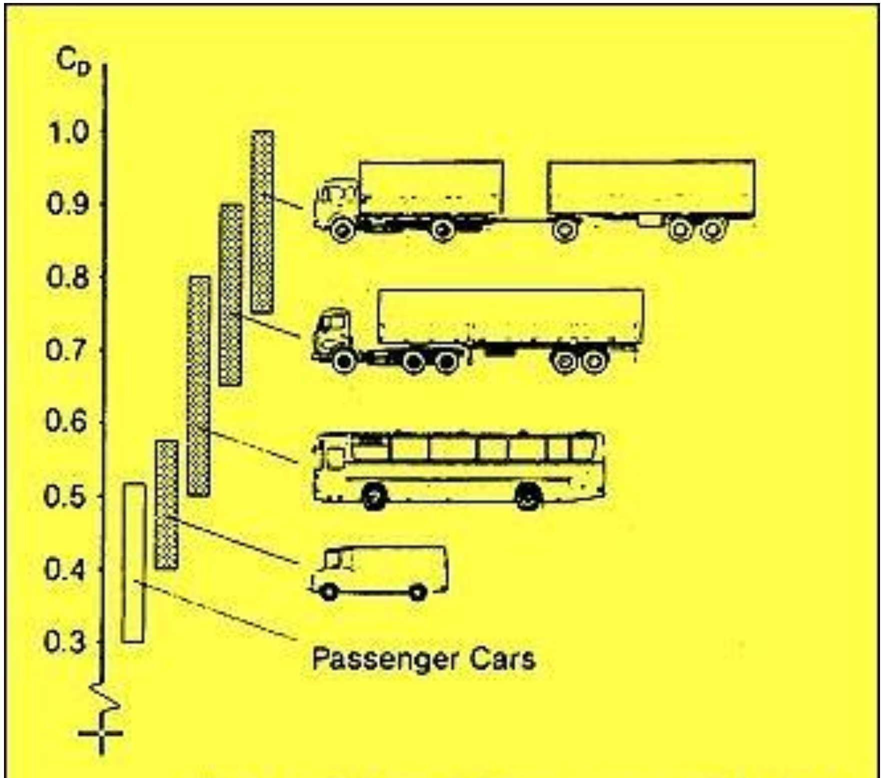
Typical drag coefficient of automobiles

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

Main sources of the drag of passenger car

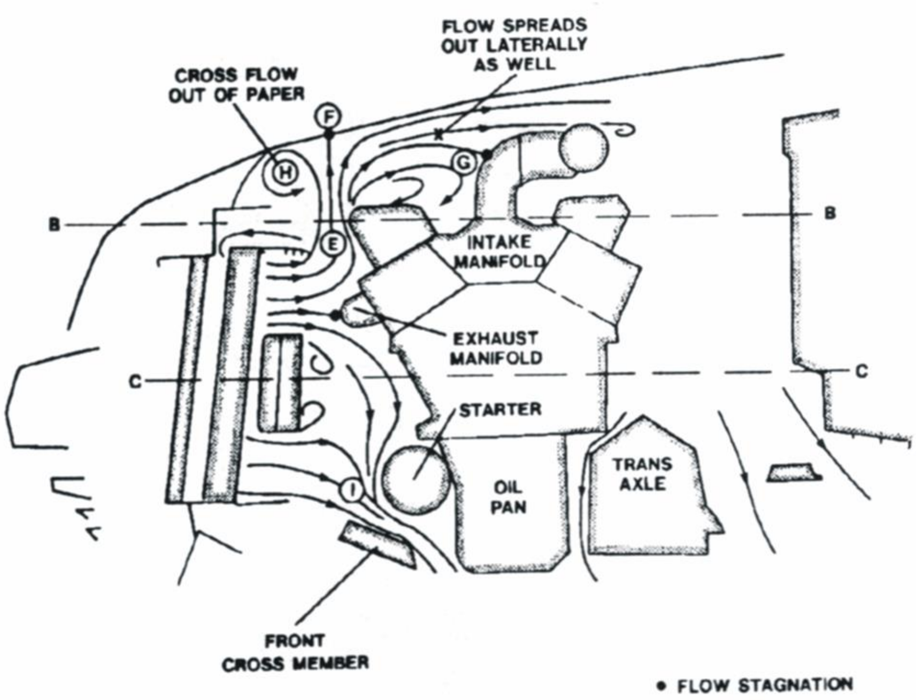
DRAG COEFFICIENT COMPONENT	TYPICAL VALUE	
Forebody	0.05	
Afterbody	0.14	
Underbody	0.06	
Skin Friction	0.025	
Total Body Drag	0.275	65%
Wheels and wheel wells	0.09	
Drip rails	0.01	
Window recesses	0.01	
External mirrors	0.01	
Total Protuberance Drag	0.12	28%
Cooling system	0.025	
Total Internal Drag	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

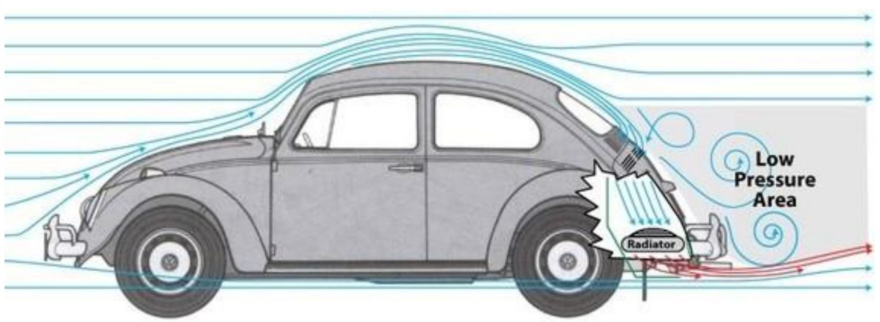
- 65% of drag comes from the body shape (front, back, floor, skin)
  - Large potential of reduction, especially for the back of the car to control the separation flows
- Influence as well of
  - Wheels (21%)
  - Details (7%)
  - Internal aerodynamics (6%)

Influence of air in engine compartment



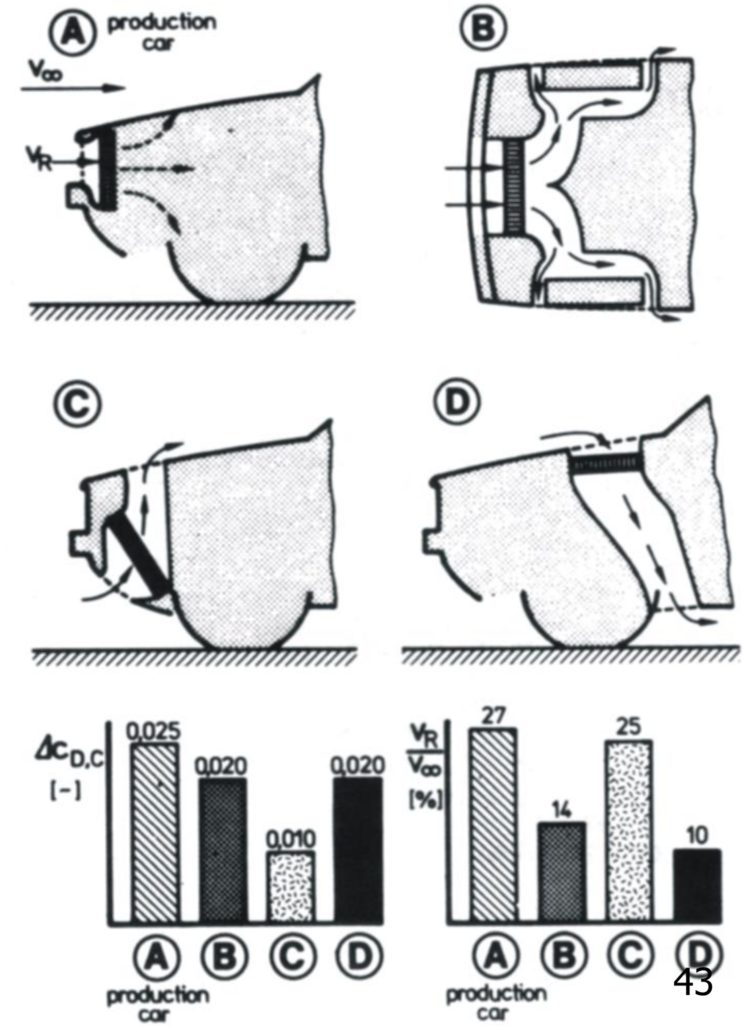
Gillespie: Fig 4.16 influence of engine cooling air flow

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



Influence of air in engine compartment

- Design of engine cooling to allow the air to flow through the engine compartment with the minimum drag
- Reduction of air intakes to satisfy the needs



Gillespie: Fig 4.17 influence of engine cooling air flow

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 alternate motion in the sidewalls and in 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

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

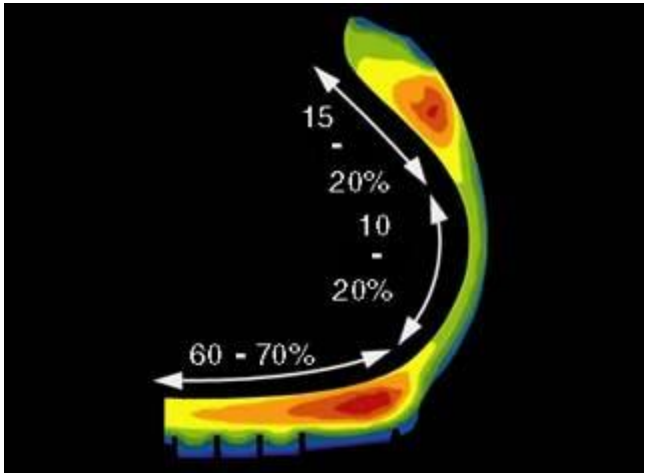
The coefficient f_{RR} is the rolling resistance coefficient

- **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

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

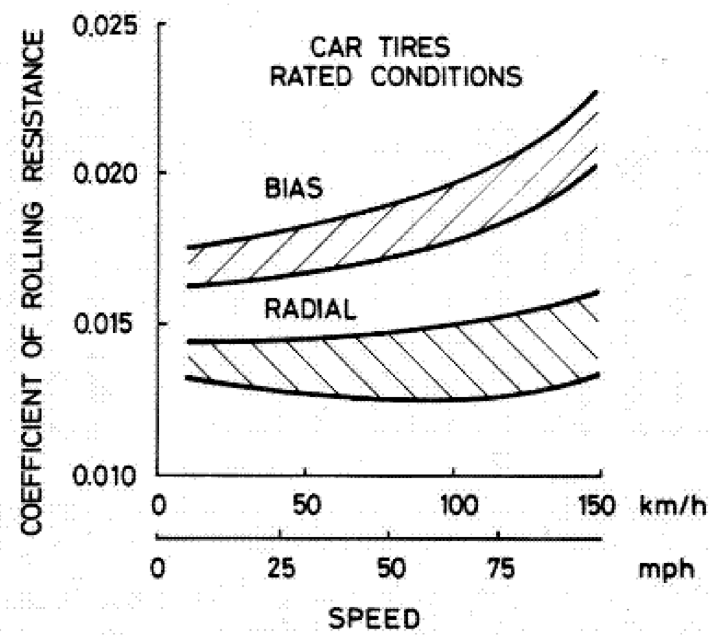
- Other sources:
  - Frictions during slippage
  - Air ventilation inside and outside



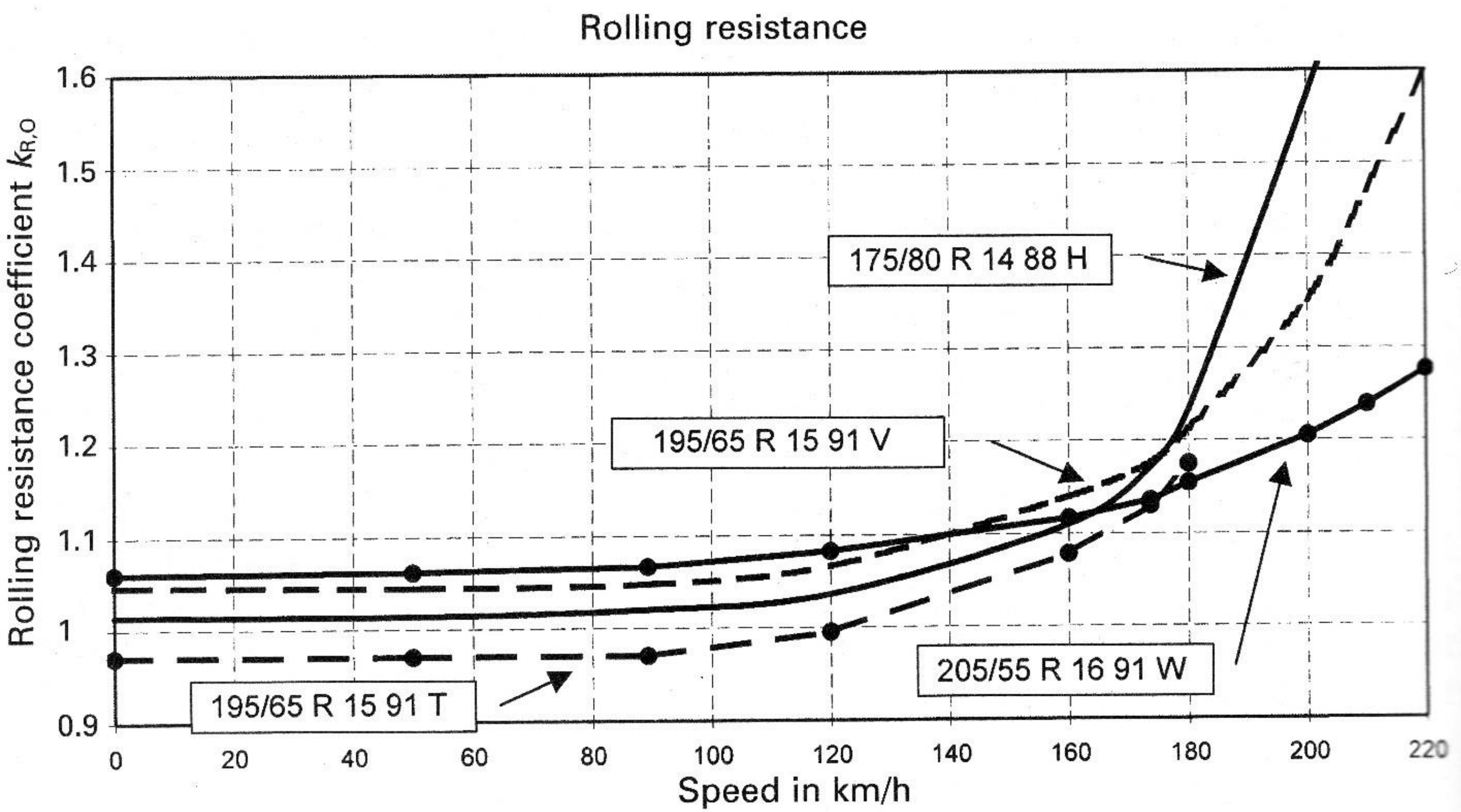
- Example: truck tire at 130 km/h
  - 90-95 % = hysteresis
  - 2-10 % friction
  - 1.5 – 3.5 % aerodynamic dissipation

Rolling resistance forces

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



Rolling resistance forces

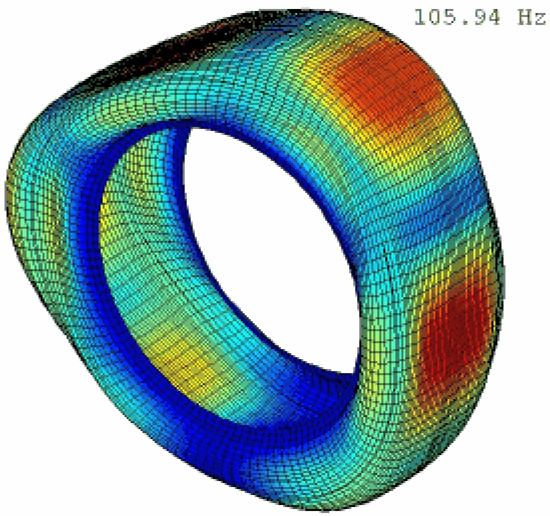


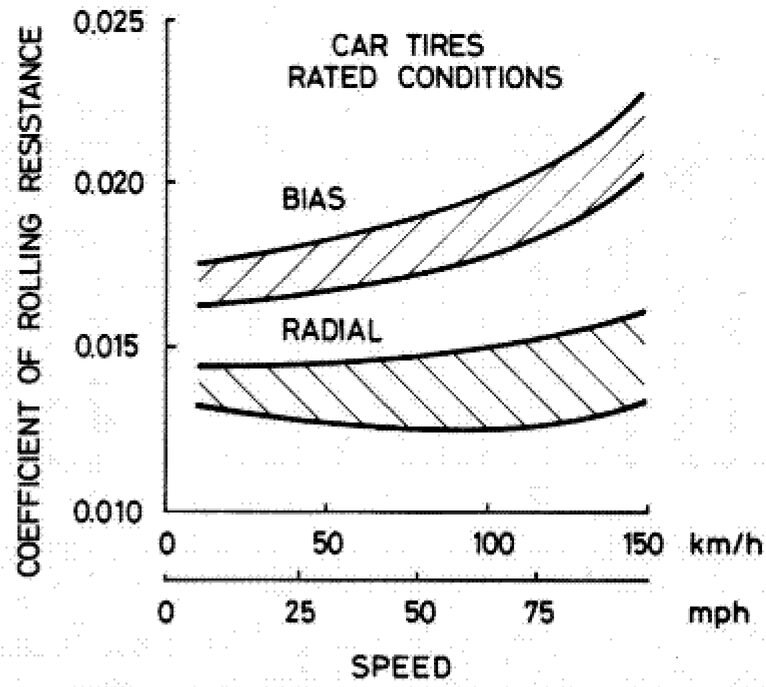
Influence of load index

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

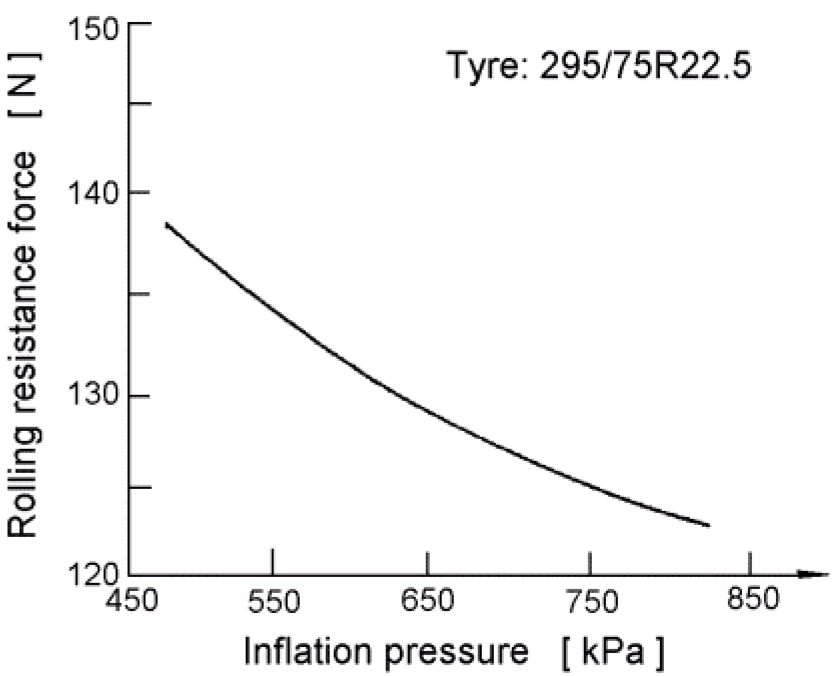
Rolling resistance forces



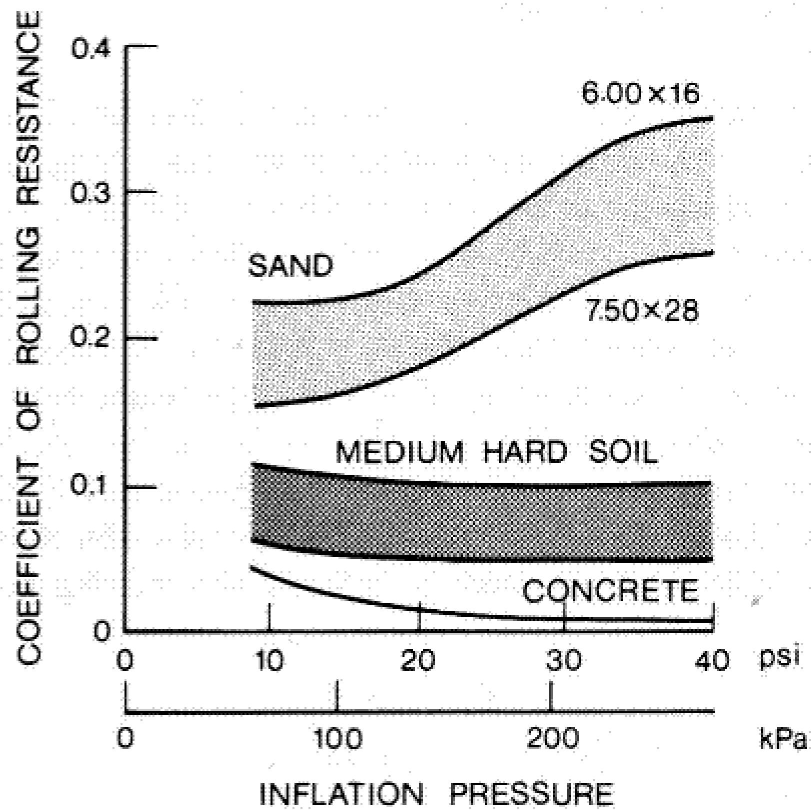


Influence of speed

Rolling resistance forces



Influence of inflation pressure



Influence of the terrain stiffness

Estimation of rolling resistance coefficient

- A typical formula given by Wong

  Radial tires for passenger cars with a nominal inflation pressure p and smooth road profile:

$$f_{RR} = 0,0136 \; + \; 0,4\,10^{-7}\,V^2 \quad \text{V in km/h}$$

- Approximation provided by tables (ex Automotive handbook, Bosch)

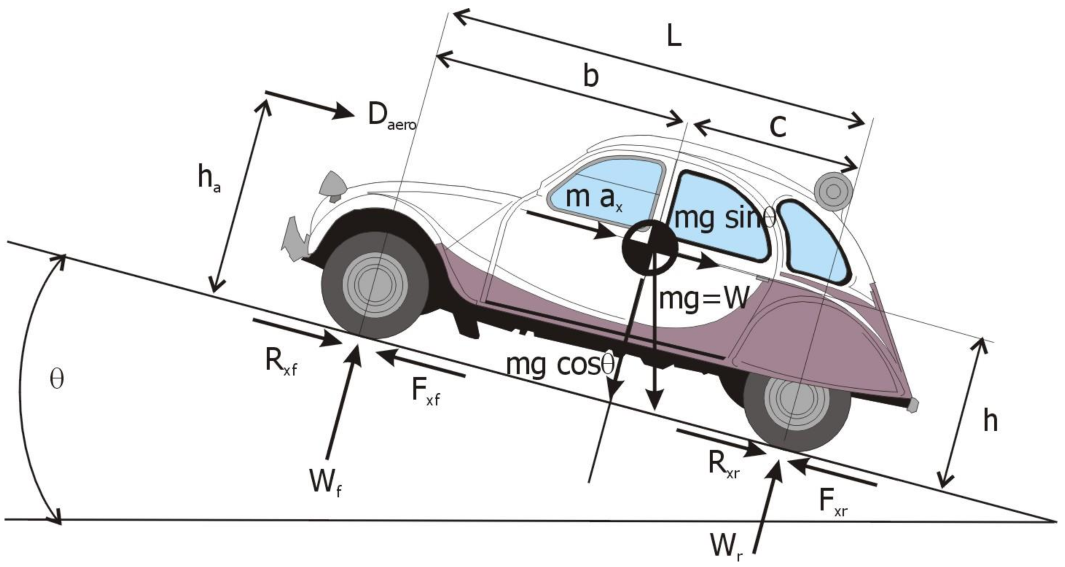
Road surface	Coefficient of rolling resistance f
Pneumatic car tires on	
Large sett pavement	0.015
Small sett pavement	0.015
Concrete, asphalt	0.013
Rolled gravel	0.02
Tarmacadam	0.025
Unpaved road	0.05
Field	0.1...0.35
Pneumatic truck tires on	
concrete, asphalt	0.006...0.01
Strake wheels in field	0.14...0.24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

$$f_{RR} = f_0 \; + \; f_2\,V^2$$

Resistance force due to grading

- Expression of grading resistance

$$\boxed{F_{grading} = mg \sin\theta}$$



Expression of road load

- General form of the vehicle resistance

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

- General formulation

$$F_{res} = A + Bv^2$$

  - 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

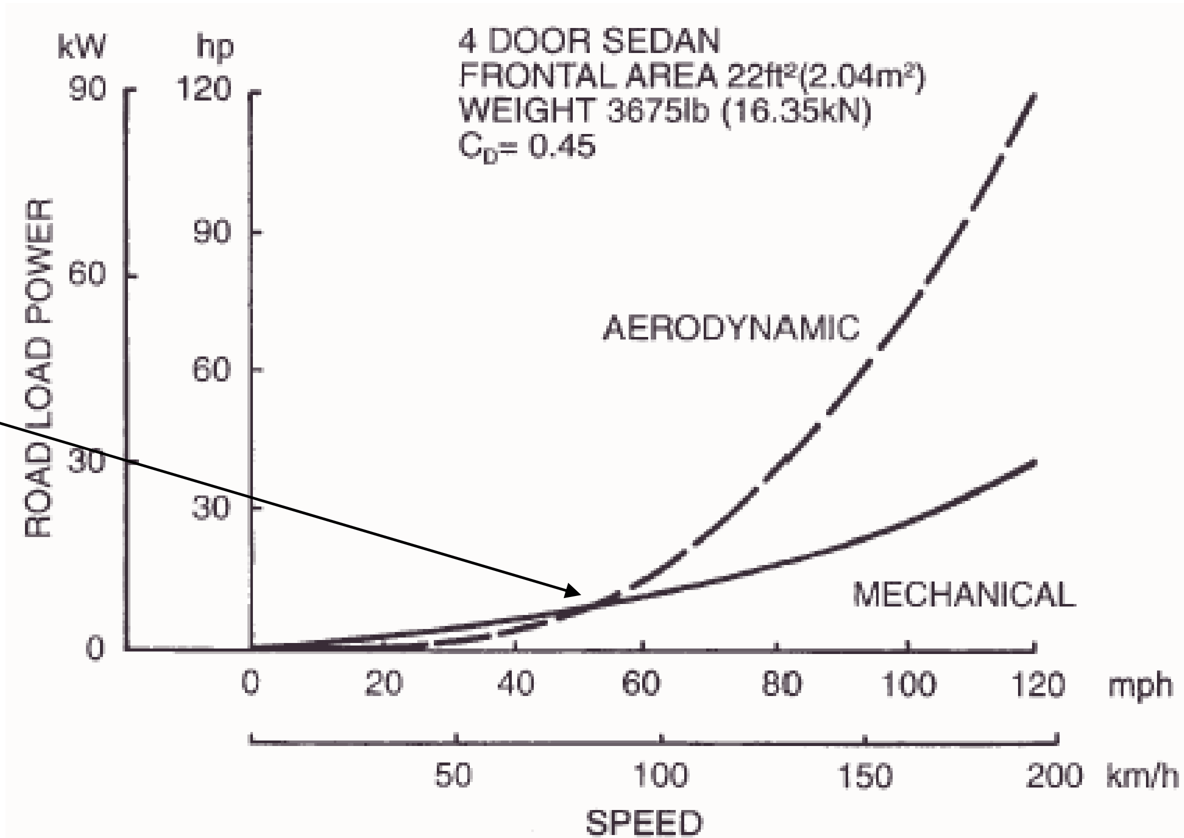


Fig. 3.3 Power requirements of a full-size passenger car as a function of speed. (Reproduced with permission of the Society of Automotive Engineers from reference 3.1.)