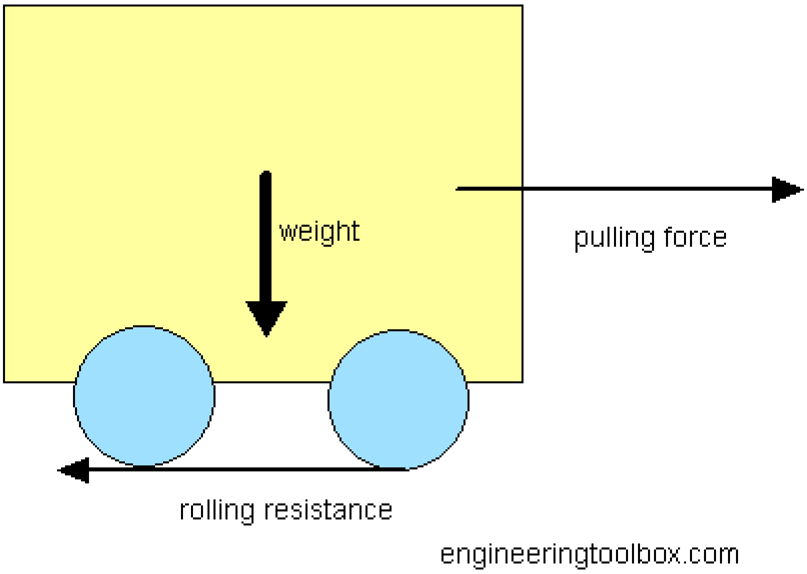
Rolling friction and rolling resistance

The force that resists the motion of a body rolling on a surface is called the **rolling resistance** or the **rolling friction**.



The *rolling resistance* can be expressed as

$F_r = c\ W$ *(1)*

where

F_r *= rolling resistance or rolling friction (N,* lb_f*)*

c = rolling resistance coefficient - dimensionless (coefficient of rolling friction - CRF)

$W = m\ a_g$

= normal force - or [weight](#) - of the body (N, lb_f*)*

m = mass of body (kg, lb)

a_g = *[acceleration of gravity](#) (9.81* m/s^2*, 32.174* ft/s^2*)*

The rolling resistance can alternatively be expressed as

$F_r = c_l\ W / r$ *(2)*

where

c_l *= rolling resistance coefficient - dimension length (coefficient of rolling friction) (mm, in)*

r = radius of wheel (mm, in)

Rolling Friction Coefficients

Some typical rolling coefficients:

Rolling Resistance Coefficient		
c	c_l *(mm)*	
0.001 - 0.002	0.5	railroad steel wheels on steel rails
0.001		bicycle tire on wooden track
0.002 - 0.005		low resistance tubeless tires
0.002		bicycle tire on concrete
0.004		bicycle tire on asphalt road
0.005		dirty tram rails
0.006 - 0.01		truck tire on asphalt
0.008		bicycle tire on rough paved road
0.01 - 0.015		ordinary car tires on concrete, new asphalt, cobbles small new
0.02		car tires on tar or asphalt
0.02		car tires on gravel - rolled new
0.03		car tires on cobbles - large worn
0.04 - 0.08		car tire on solid sand, gravel loose worn, soil medium hard
0.2 - 0.4		car tire on loose sand

Rolling Coefficients Cars

The rolling coefficients for air filled tires on dry roads can be estimated

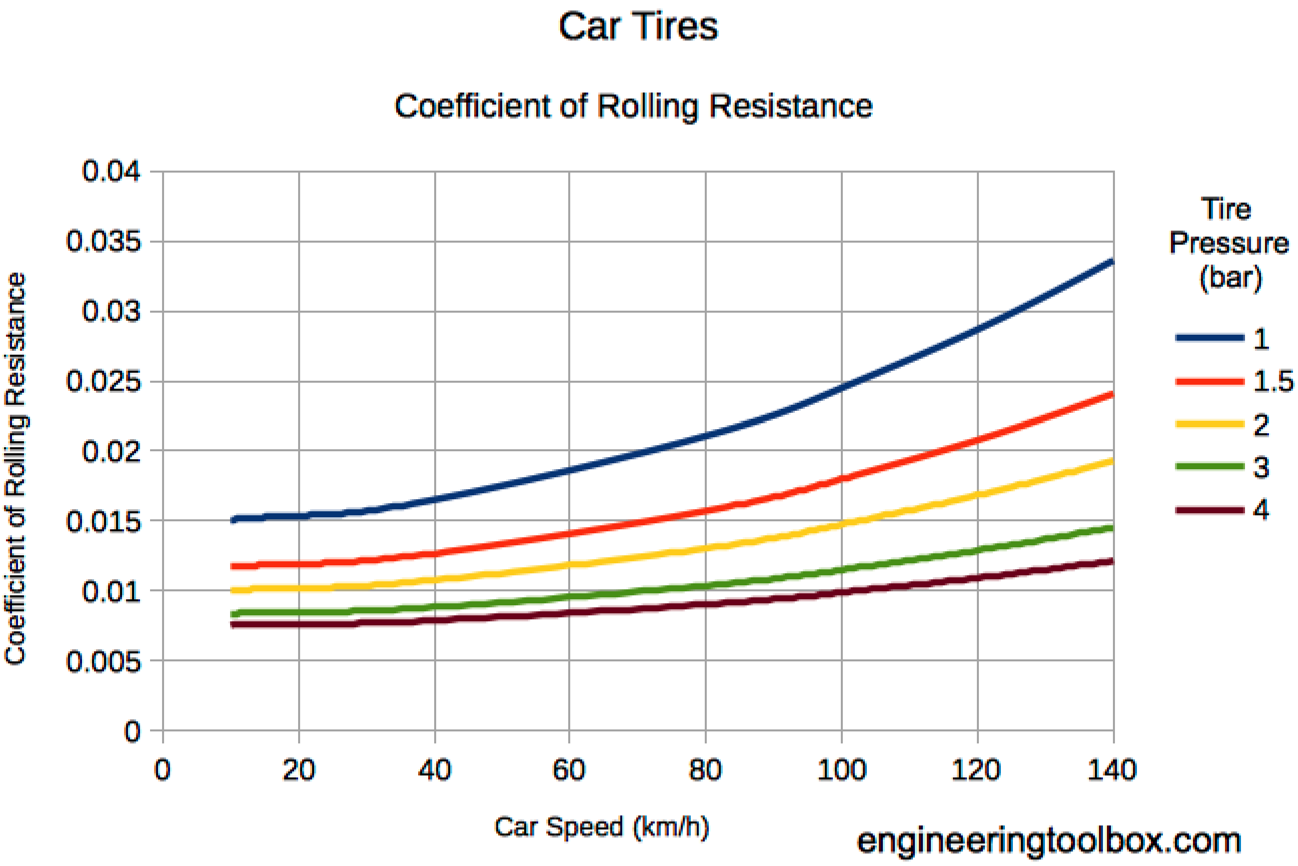
$c = 0.005 + (1 / p) (0.01 + 0.0095 (v / 100)^2)$

where

c = rolling coefficient

p = tire pressure (bar)

v = velocity (km/h)



- *1 bar = 10^5 Pa = 14.5 psi*
- *1 km/h = 0.6214 mph*

Example - The Rolling Resistance of a Car on Asphalt

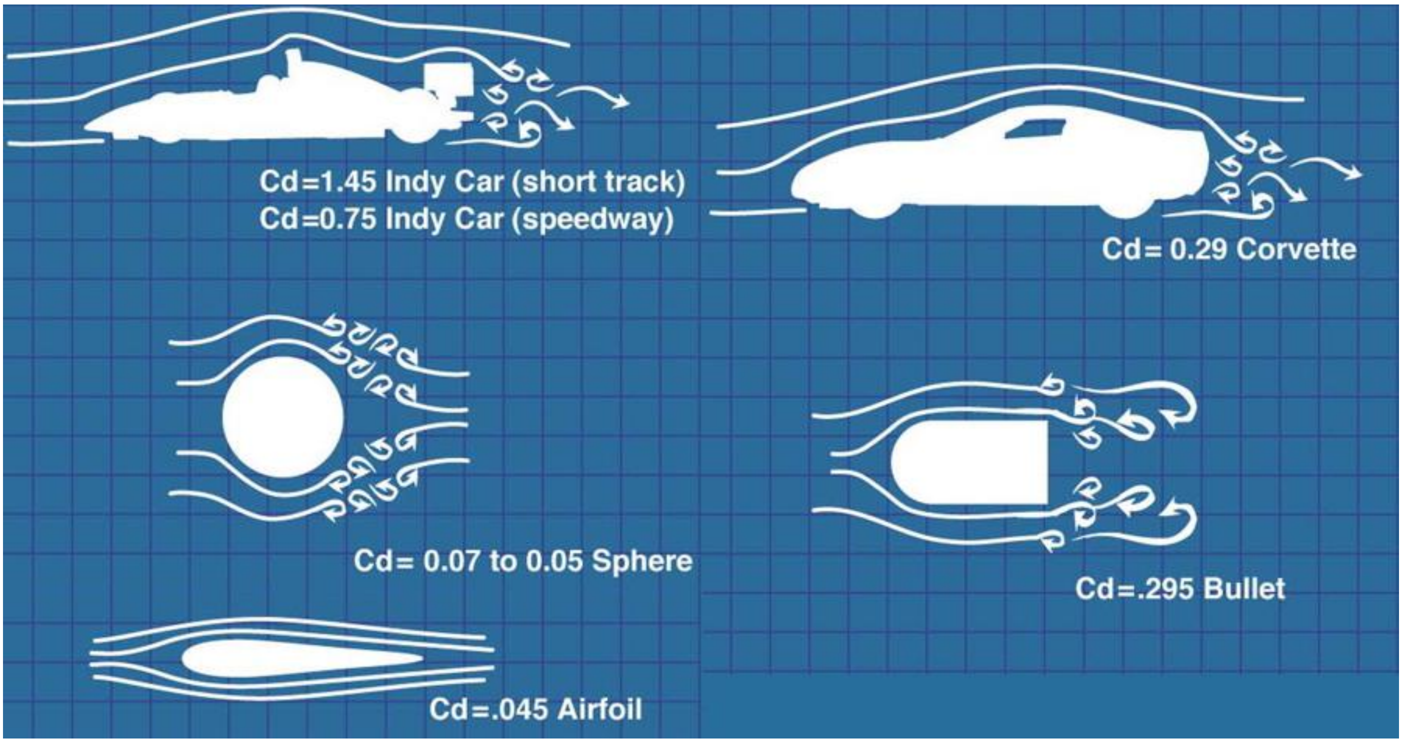
The rolling resistance of a car with weight *1500 kg* on asphalt with rolling friction coefficient *0.03* can be estimated as

$F_r = 0.03 (1500 kg) (9.81 m/s^2)$

= *441* N

= *0.44* kN

The drag coefficient of an object in a moving fluid



Any object moving through a fluid experiences drag - the net force in the direction of flow due to pressure and shear stress forces on the surface of the object.

The drag force can be expressed as:

$F_d = c_d \, 1/2 \, \rho \, v^2 \, A$ *(1)*

where

F_d *= drag force (N)*

c_d *= drag coefficient*

ρ = *density of fluid (1.2 kg/m³ for air at NTP)*

v *= flow velocity (m/s)*

A *= characteristic frontal area of the body (m²)*

The drag coefficient is a function of several parameters like shape of the body, Reynolds Number for the flow, Froude number, Mach Number and Roughness of the Surface.

The characteristic frontal area - *A* - depends on the body.

Objects drag coefficients are mostly results of experiments. The drag coefficients for some common bodies are indicated below:

Type of Object	**Drag Coefficient** ***- cd -***	**Frontal Area**
Laminar flat plate (Re=106)	0.001	
Dolphin	0.0036	wetted area
Turbulent flat plate (Re=106)	0.005	
Subsonic Transport Aircraft	0.012	
Supersonic Fighter,M=2.5	0.016	
Streamline body	0.04	π / 4 d2
Airplane wing, normal position	0.05	
Long stream-lined body	0.1	
Airplane wing, stalled	0.15	
Modern car like Toyota Prius	0.26	frontal area
Sports car, sloping rear	0.2 - 0.3	frontal area
Common car like Opel Vectra (class C)	0.29	frontal area
Hollow semi-sphere facing stream	0.38	
Bird	0.4	frontal area
Solid Hemisphere	0.42	π / 4 d2
Sphere	0.5	

Type of Object	Drag Coefficient *- cd -*	Frontal Area
Saloon Car, stepped rear	0.4 - 0.5	frontal area
Convertible, open top	0.6 - 0.7	frontal area
Bus	0.6 - 0.8	frontal area
Old Car like a T-ford	0.7 - 0.9	frontal area
Cube	0.8	s2
Bike racing	0.88	3.9
Bicycle	0.9	
Tractor Trailed Truck	0.96	frontal area
Truck	0.8 - 1.0	frontal area
Person standing	1.0 – 1.3	
Bicycle Upright Commuter	1.1	5.5
Thin Disk	1.1	π / 4 d2
Solid Hemisphere flow normal to flat side	1.17	π / 4 d2
Squared flat plate at 90 deg	1.17	
Wires and cables	1.0 - 1.3	
Person (upright position)	1.0 - 1.3	

Type of Object	Drag Coefficient *- cd -*	Frontal Area
Hollow semi-cylinder opposite stream	1.2	
Ski jumper	1.2 - 1.3	
Hollow semi-sphere opposite stream	1.42	
Passenger Train	1.8	frontal area
Motorcycle and rider	1.8	frontal area
Long flat plate at 90 deg	1.98	
Rectangular box	2.1	

Example - Air Resistance on a Normal Car

The force required to overcome air resistance for a normal family car with drag coefficient *0.29* and frontal area $2\ m^2$ in *90 km/h* can be calculated as:

$F_d = 0.29\ 1/2\ (1.2\ kg/m^3)\ ((90\ km/h)\ (1000\ m/km)\ /\ (3600\ s/h))^2\ (2\ m^2)$

$= \underline{217.5}\ N$

The work done to overcome the air resistance in one hour driving (90 km) can be calculated as

$W_d = (217.5\ N)\ (90\ km)\ (1000\ m/km)$

$= \underline{19575000}\ (Nm, J)$

The power required to overcome the air resistance when driving *90 km/h* can be calculated as

$P_d = (217.5\ N)\ (90\ km/h)\ (1000\ m/km)\ (1/3600\ h/s)$

$= \underline{5436}\ (Nm/s, J/s, W)$

$= \underline{5.4}\ (kW)$

Power, torque, efficiency and wheel force

Engine Power

Required power from an engine to keep a car at constant speed can be calculated as

$P = F_T v / \eta$ (1)

where

P = engine power (W)

F_T = *total forces acting on the car - rolling resistance force, gradient resistance force and aerodynamic drag resistance (N)*

v = velocity of the car (m/s)

η = overall efficiency in the transmission, normally ranging 0.85 (low gear) - 0.9 (direct drive)

For a car that accelerates the acceleration force must be added to the total force.

Example - Car and required Engine Power

The required engine power for a car driving on a flat surface with constant speed *90 km/h* with an aerodynamic resistance force *250 N* and rolling resistance force *400 N* and overall efficiency *0.85* - can be calculated as

$P = ((250\ N) + (400\ N))\ (90\ km/h)\ (1000\ m/km)\ (1/3600\ h/s) / 0.85$

$= 19118\ W$

$= \underline{19}\ kW$

Engine Torque or Moment

Engine torque or moment can be calculated

$T = P / (2 \pi n_{rps})$

$= 0.159 P / n_{rps}$

$= P / (2 \pi (n_{rpm} / 60))$

$= 9.55 P / n_{rpm}$ (2)

where

T = torque or moment (Nm)

n_{rps} = *engine speed (rps, rev/sec)*

n_{rpm} = engine speed (rpm, rev/min)

Example - Car and required Engine Moment

The moment delivered by the motor in the car above with the engine running at speed *1500 rpm* can be calculated as

T = 9.55 (19118 W) / (1500 rpm)

= 121 Nm

Wheel Force

The total force *(1)* acting on the car is equal to the traction force between the driving wheels and the road surface:

$F_w = F_T$

where

F_w = force acting between driving wheels and road surface (N)

The traction force can be expressed with engine torque and velocity and wheels sizes and velocities:

$F_w = F_T$

$= (T \eta / r) (n_{rps} / n_{w\_rps})$

$= (T \eta / r) (n_{rpm} / n_{w\_rpm})$

$= (2 T \eta / d) (n_{rpm} / n_{w\_rpm}) \quad (3)$

r = wheel radius (m)

d = wheel diameter (m)

n_{w_rps} = wheel speed (rps, rev/sec)

n_{w_rpm} = wheel speed (rpm, rev/min)

Note that curved driving adds a centripetal force to the total force acting between the wheels and the road surface.