دانشگاه سمنان

Semnan University
Faculty of Mechanical Engineering

دانشکده مهندسی مکانیک

دانشکده مهندسی مکانیک

درس طراحی سیستم های شاسی خودرو

Vehicle Chassis Systems Design

Chapter 4 – Road Loads

Class Lecture

- ***Contents:***

AERODYNAMICS

- Aerodynamics contribution in "road load“
  - Drag
  - Lift (or down load)
  - Lateral forces
  - Moments in roll, pitch and yaw
  - Noise
- These also impact fuel economy, handling and NVH (Noise, vibration, and harshness).
- Arise from two sources:
  - Form (or pressure) drag
  - Viscous friction

AERODYNAMICS

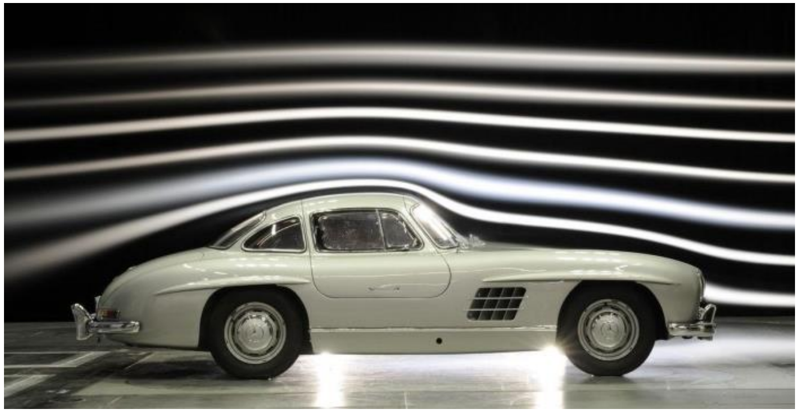
- Mechanics of Air Flow Around a Vehicle
  - Relationship between velocity and pressure (Bernoulli's Equation)

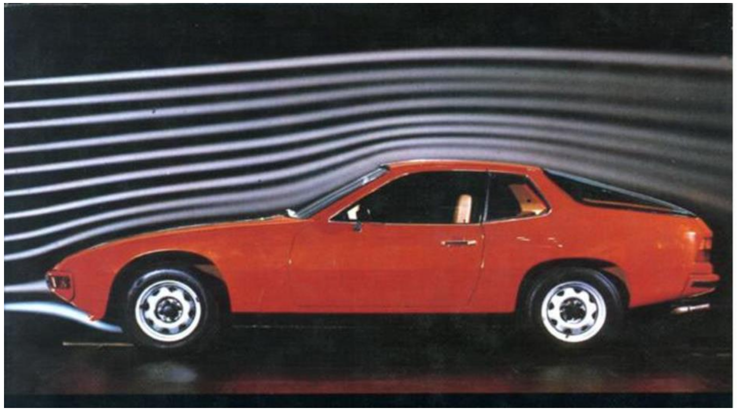
$$P_{static} + P_{dynamic} = P_{total}$$

$$P_s + 1/2\, \rho\, V^2 = P_t$$

ρ = Density of air

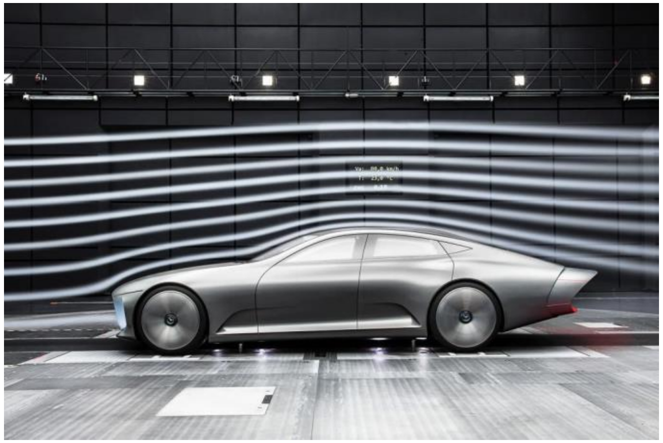
V = Velocity of air (relative to the car)





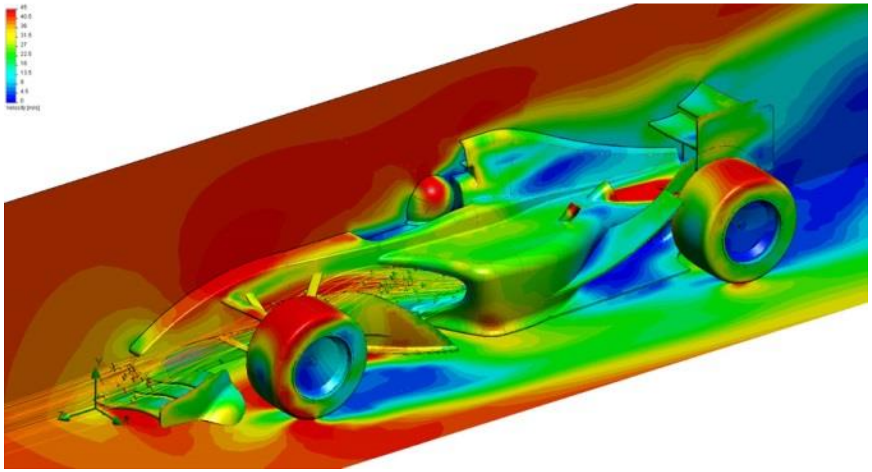
AERODYNAMICS

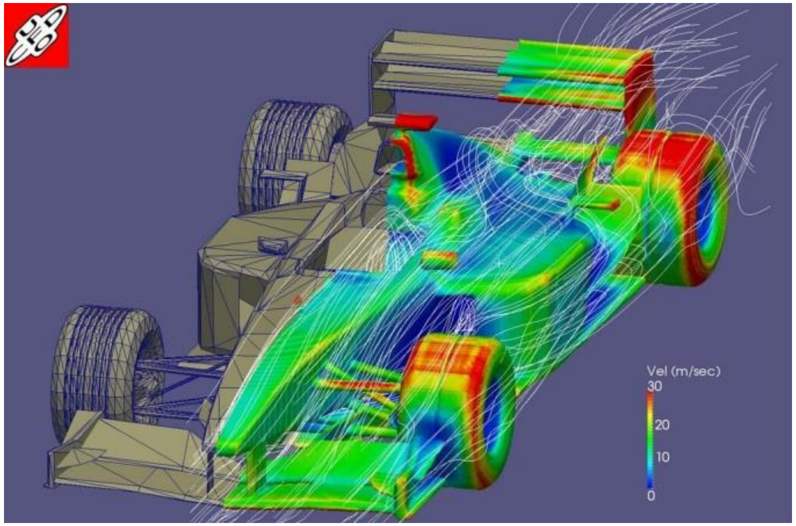
- Mechanics of Air Flow Around a Vehicle
  - Visualizing Streamlines:
    - ✓ Vehicle as stationary and the air moving (as in a wind tunnel)
    - ✓ Using smoke streams



Aerodynamics

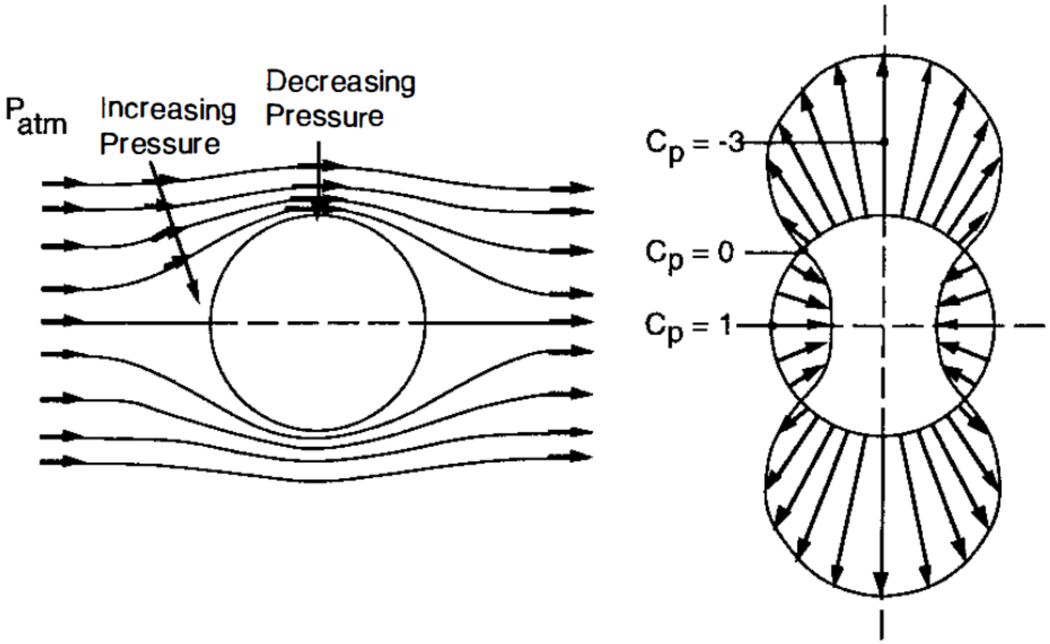
- Mechanics of Air Flow Around a Vehicle
  - Visualizing Streamlines:
    - ✓ Using simulation software





AERODYNAMICS

- Mechanics of Air Flow Around a Vehicle
  - Pressure and velocity distribution (Ideal Flow)
    - ✓ Increasing Velocity → Decreasing Pressure
    - ✓ Decreasing Velocity → Increasing Pressure



Aerodynamics

Mechanics of Air Flow Around a Vehicle

- In the absence of friction the air would simply flow up over the roof and down the back side of the vehicle, exchanging pressure for velocity and finally there would be no drag produced.

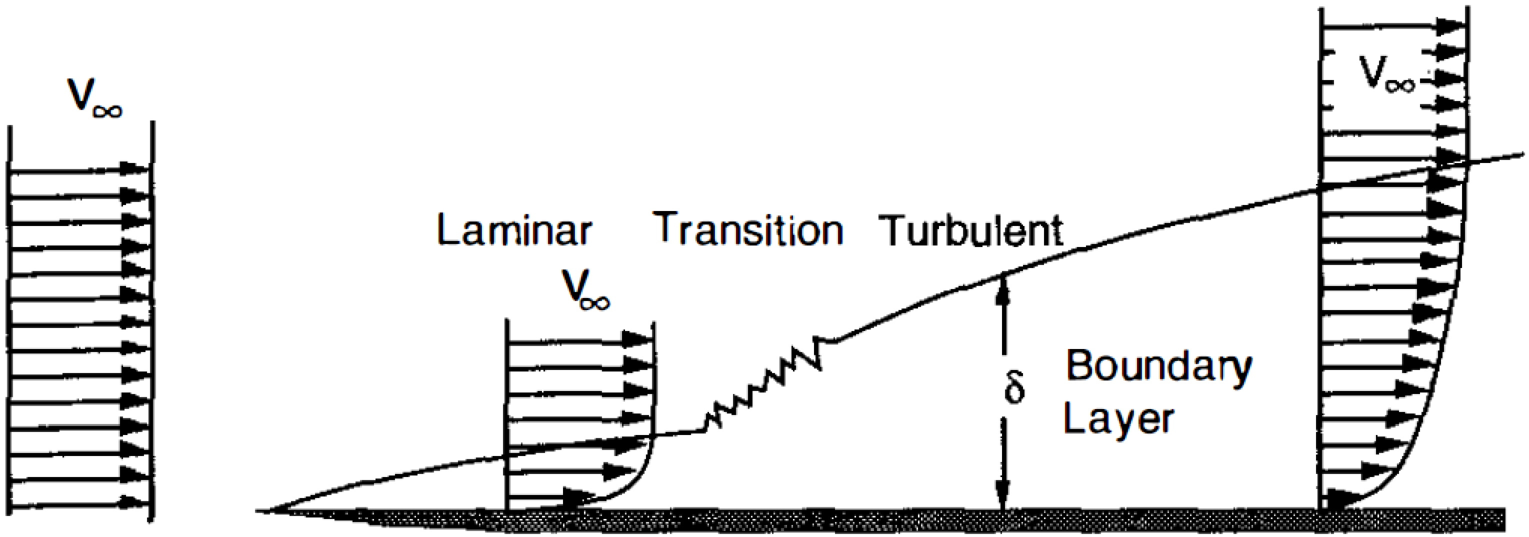
- However, we know that drag is produced!

- The drag is due:
  - ✓ Friction of the air on the surface of the vehicle
  - ✓ The way the friction alters the main flow down the back side of the vehicle

- Its explanation comes about from understanding the action of boundary layers in the flow over an object.

AERODYNAMICS

- Mechanics of Air Flow Around a Vehicle
  - Its explanation comes about from understanding the action of boundary layers in the flow over an object.

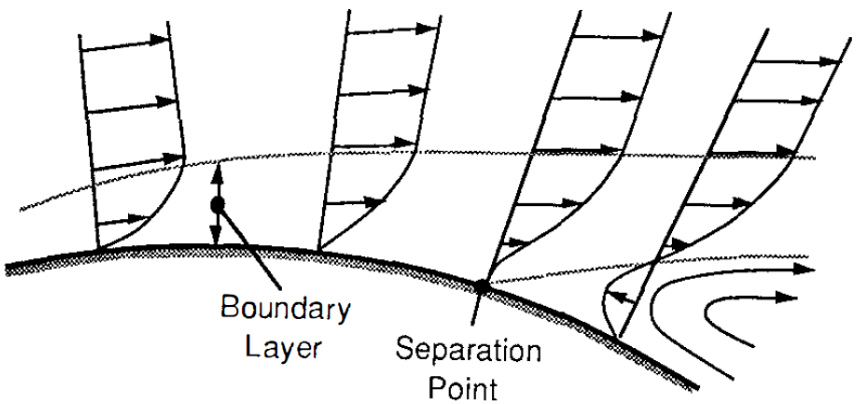


AERODYNAMICS

- Mechanics of Air Flow Around a Vehicle
  - Approaching the body, all air is traveling at a uniform velocity (laminar flow)
  - As it flows past the body, the air contacting the surface must drop to zero velocity due to friction on the surface.
  - Thus a velocity profile develops near the surface, and for some distance.
  - This region of reduced velocity is known as the "boundary layer".
  - The boundary layer begins with zero thickness and grows.

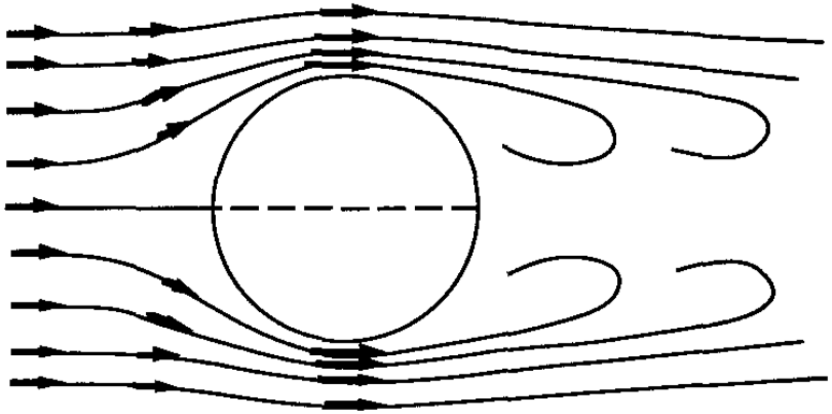
Aerodynamics

- Mechanics of Air Flow Around a Vehicle
  - Initially, it too is laminar flow, but will eventually break into turbulent flow.
  - The increasing pressure acts to decelerate the flow in the boundary layer, which causes it to grow in thickness.
  - Thus it produces what is known as an "adverse pressure gradient."
  - The point where the flow stops is known as the "separation point."



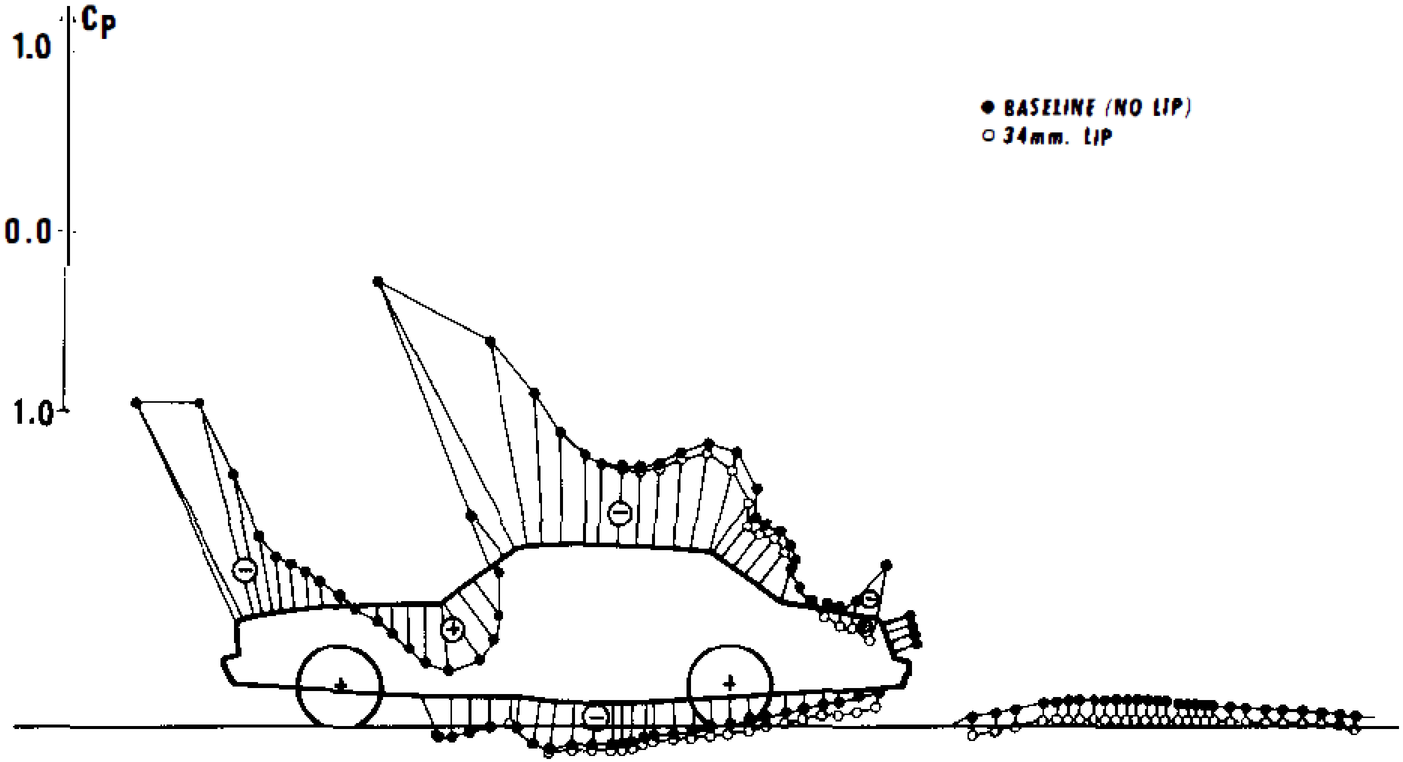
AERODYNAMICS

- Mechanics of Air Flow Around a Vehicle
  - At separation point, the main stream is no longer "attached" to the body but is able to break free and continue in a more or less straight line.
  - The pressure in this region drops below the ambient.
  - Vortices form and the flow is very irregular in this region.
  - Under the right conditions, a von-Karman Vortex Street may be formed, which is a periodic shedding of vortices.



AERODYNAMICS

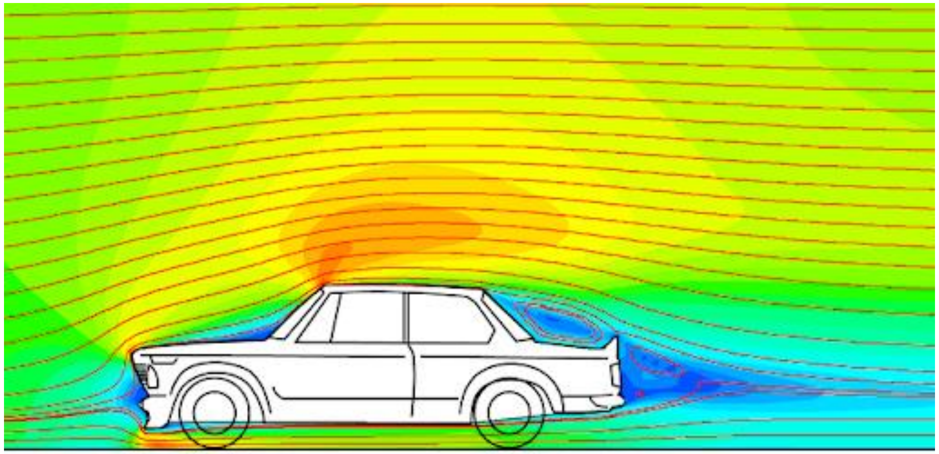
- Pressure Distribution on a Vehicle
  - Experimentally measured static pressure distribution (Negative or Positive)

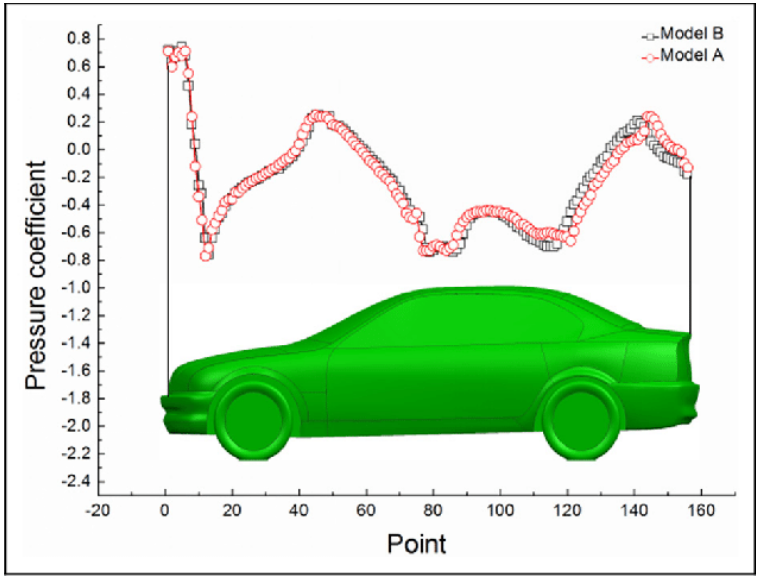


PRESSURE COEFFICIENTS PLOTTED NORMAL TO SURFACE

Aerodynamics

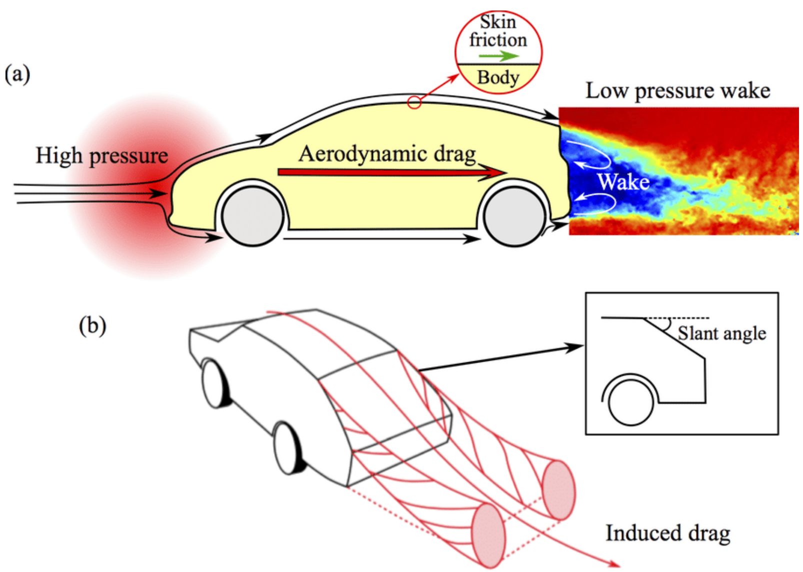
- Pressure Distribution on a Vehicle
  - Simulation results

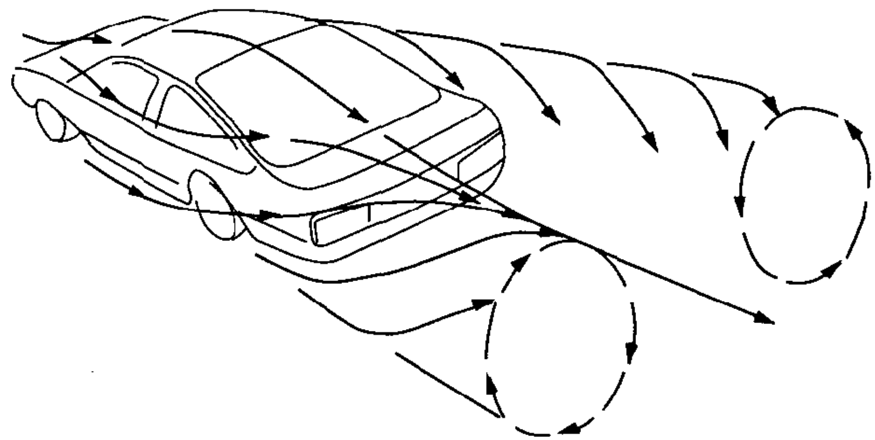


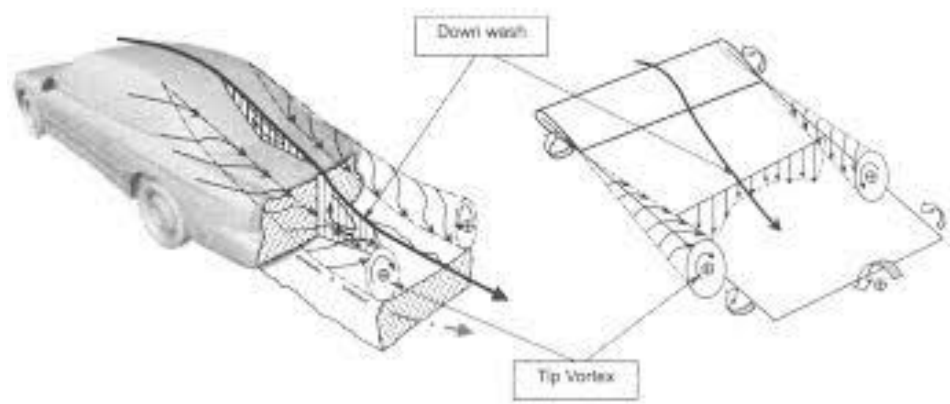


Aerodynamics

- Trailing vortices behind car

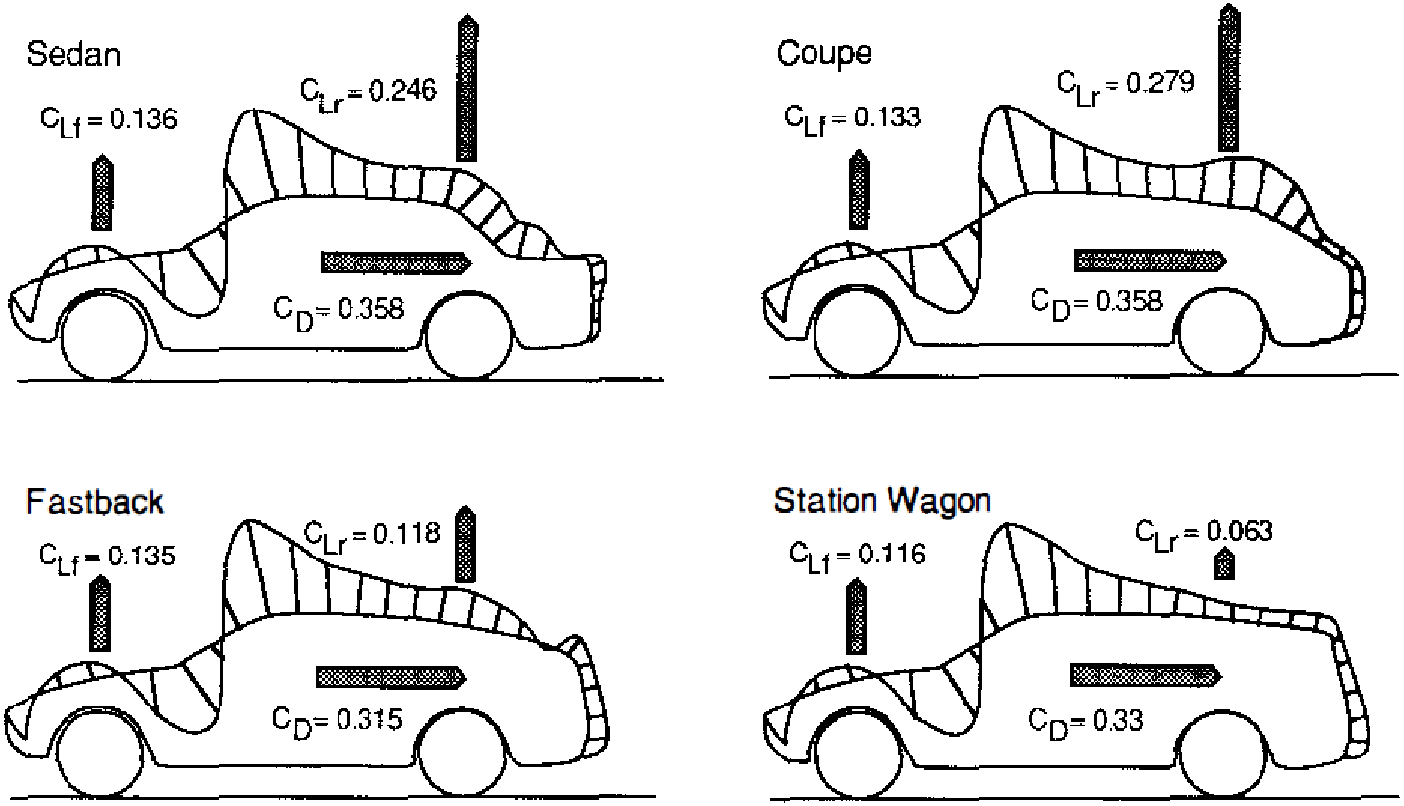






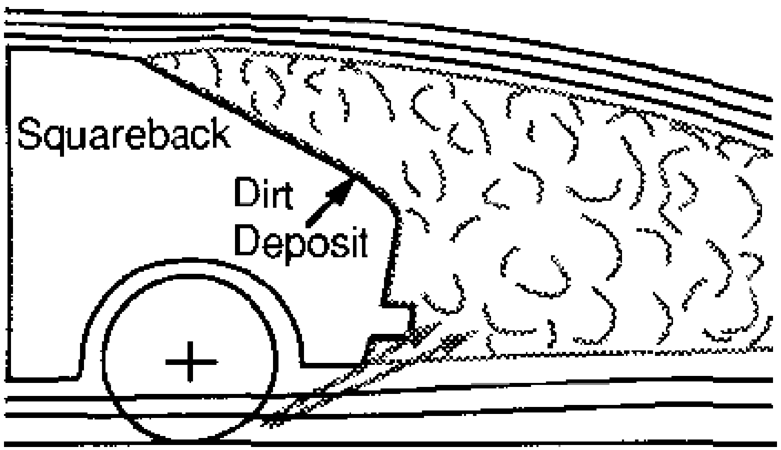
AERODYNAMICS

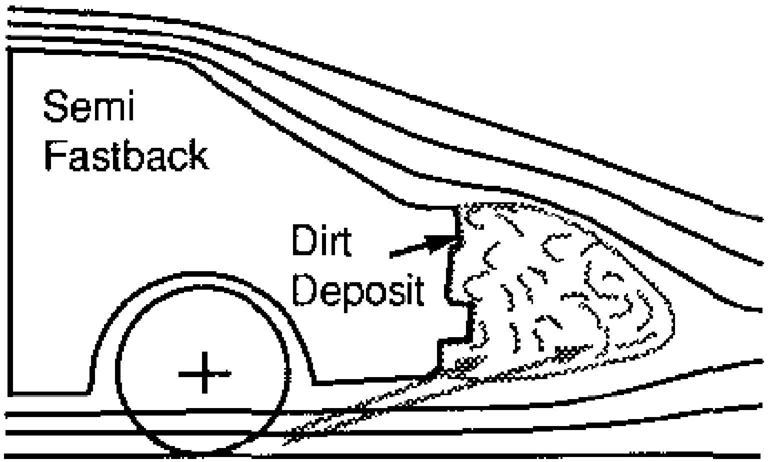
- Aerodynamic drag and lift forces (rear and front)



AERODYNAMICS

- Effect of separation point on dirt deposition at the rear

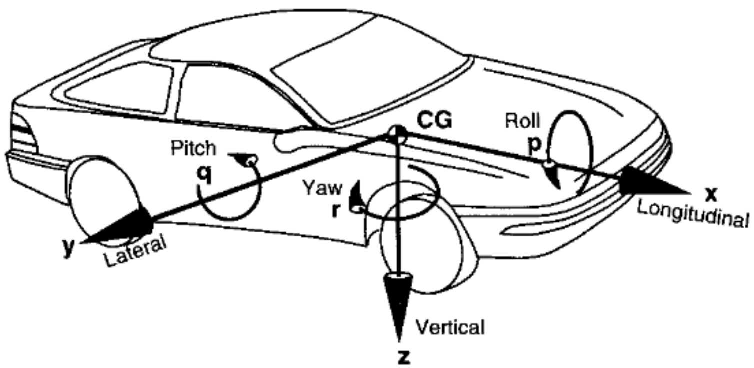




Aerodynamic Forces

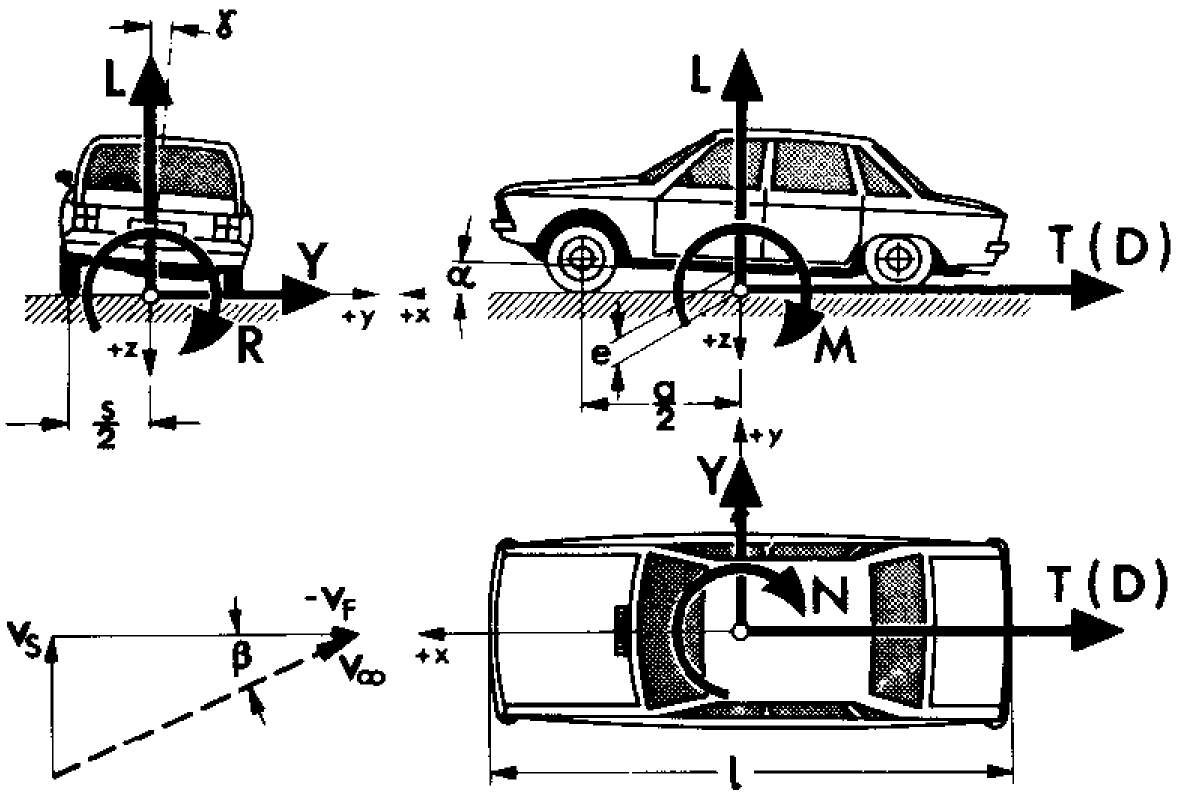
- Aerodynamic forces
  - Three forces and three moments

Direction	Force	Moment
Longitudinal (x-axis, positive rearward)	Drag	Rolling moment
Lateral (y-axis, positive to the right)	Sideforce	Pitching moment
Vertical (z-axis, positive upward)	Lift	Yawing moment



Aerodynamic Forces

- Aerodynamic forces
  - The origin for the axis system is defined in SAE J1594



Aerodynamic Forces

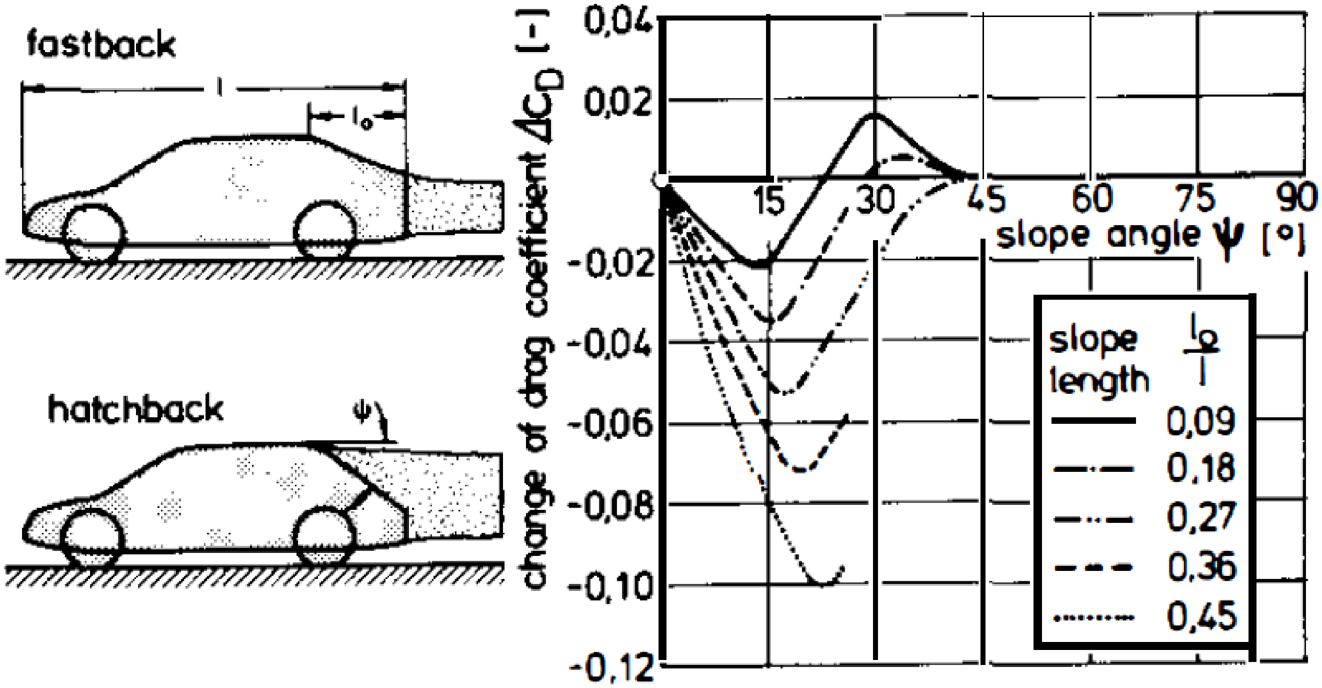
- Drag Components
  - Approximately 65% of the drag arises from the body
  - The major contributor is the afterbody because of the drag produced by the separation zone at the rear.
  - The maximum potential for drag reduction is possible in this area.

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

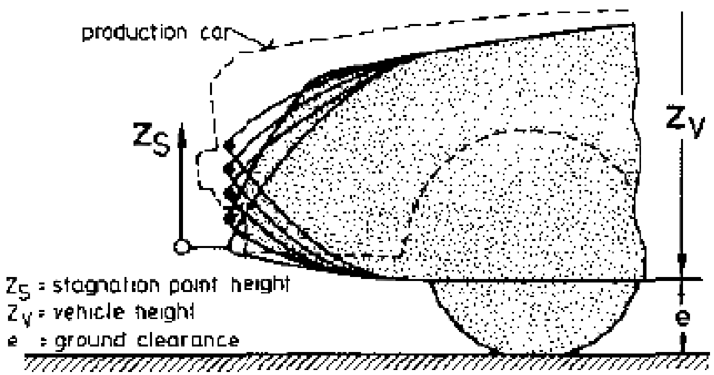
AERODYNAMIC FORCES

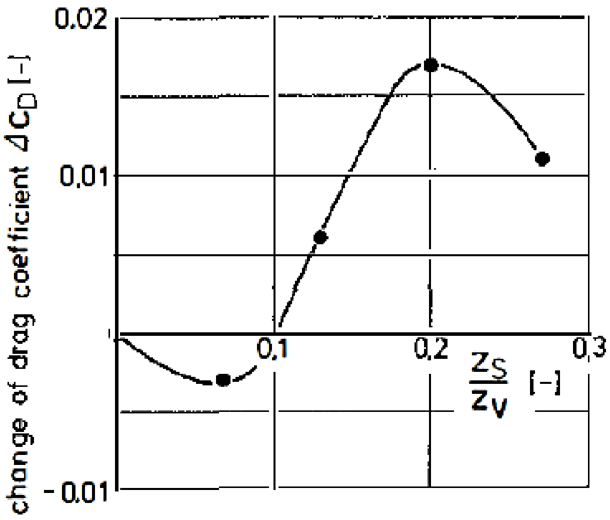
- Drag Components
  - Influence of rear end inclination angle on the drag



Aerodynamic Forces

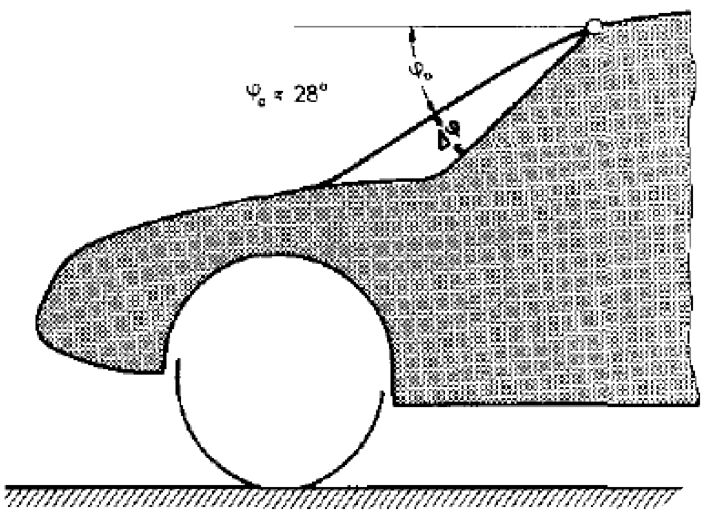
- Drag Components
  - Forebody drag is influenced by design of the front end and windshield angle.
  - This point location determines the location of the streamline flowing to the stagnation point. This streamline is important as it establishes the separation of flow above and below the body.
  - A rounded low hood line can yield reductions of 5 to 15% in the overall drag coef.

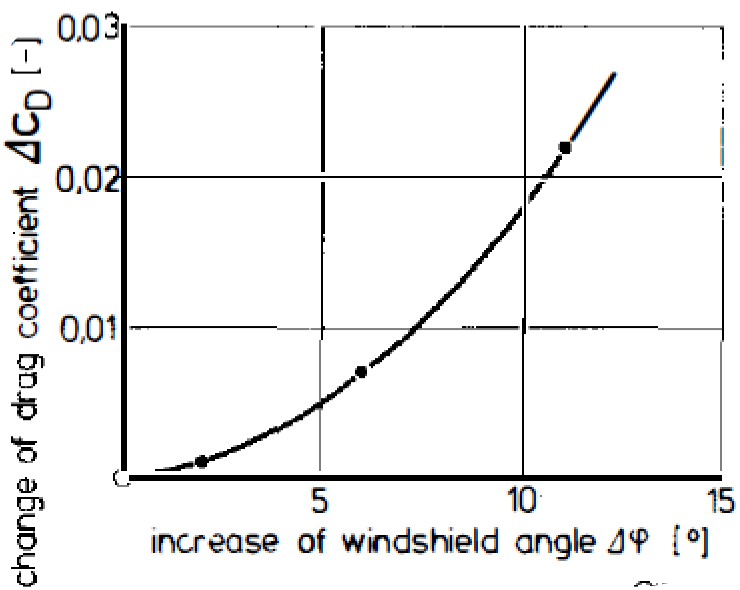




Aerodynamic Forces

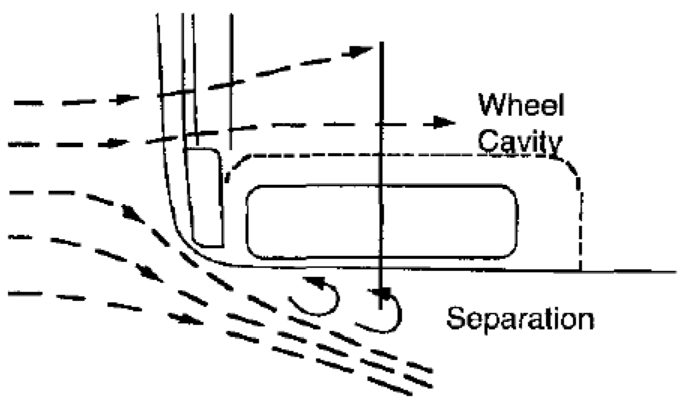
- Drag Components
  - Influence of windshield angle on drag
    - ✓ The windshield establishes the flow direction as it approaches the horizontal roof.
    - ✓ Shallow angles reduce drag, but complicate vehicle design

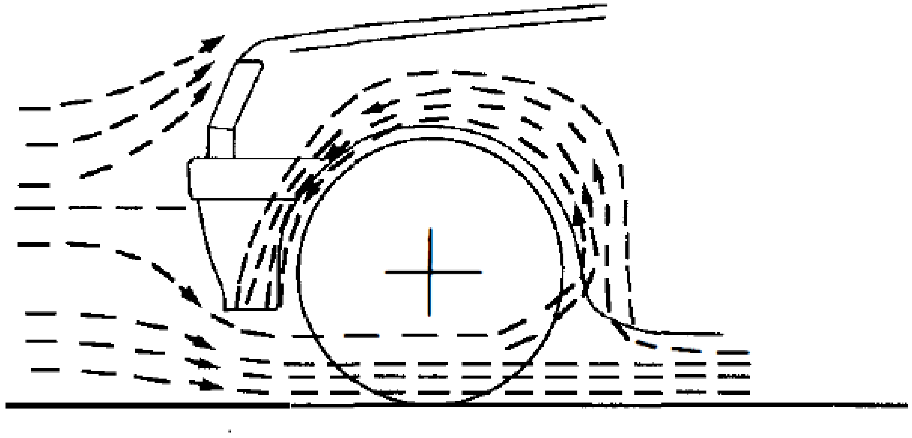




Aerodynamic Forces

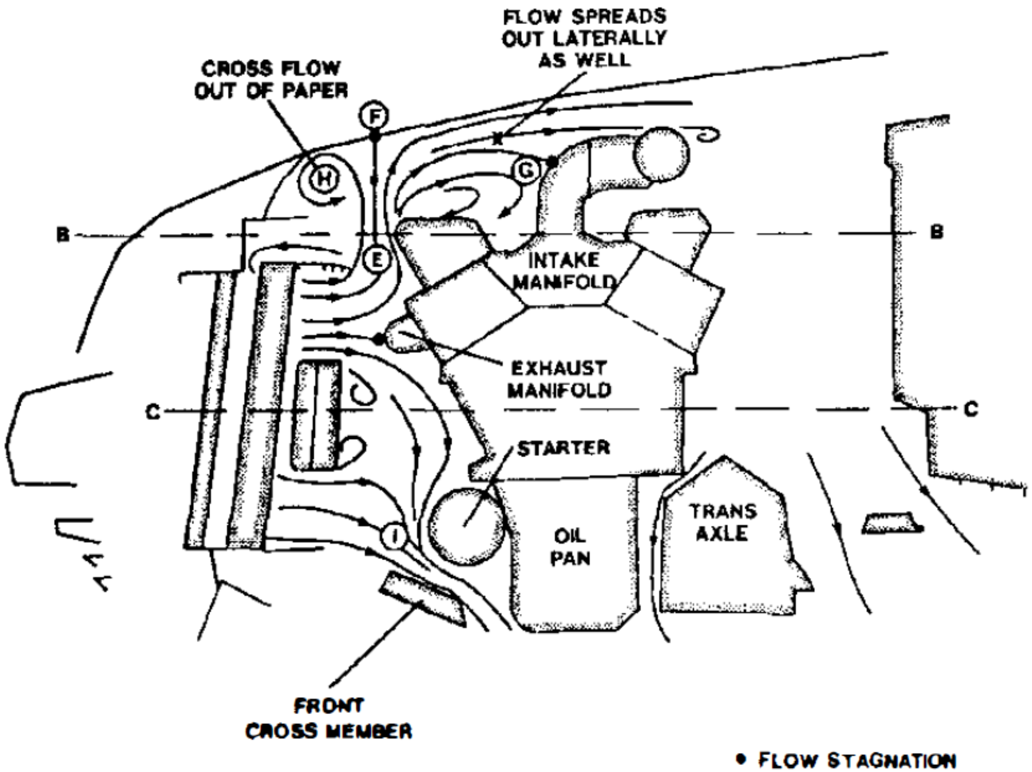
- Drag Components
  - The underbody is a critical area generating body drag.
  - The recognized fix for minimizing this drag is use of a smooth underbody panel.
  - Significant drag develops at the wheels because of the turbulent, recirculating flow in the cavities.





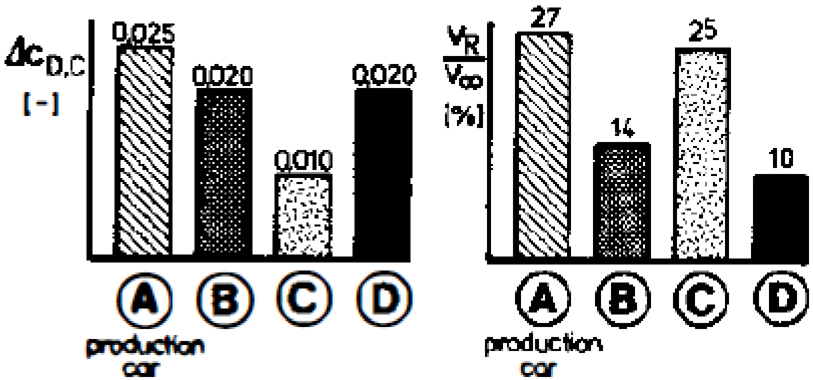
Aerodynamic Forces

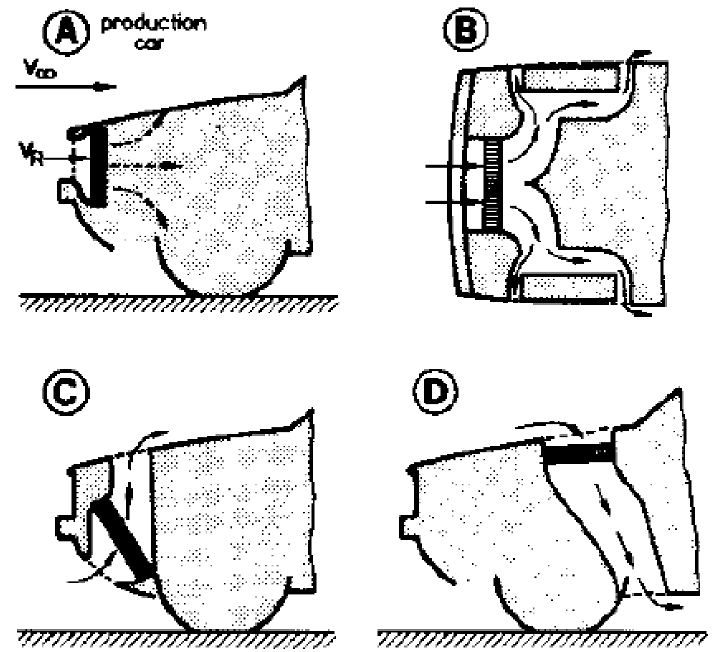
- Drag Components
  - The cooling system is the last major contributor to drag.



Aerodynamic Forces

- Drag Components
  - Flow management in the cooling system can affect the drag coefficient by 0.025
  - The drag contribution from this source is normally taken to be the difference in drag measured with the cooling system inlets open and covered





Aerodynamic Forces

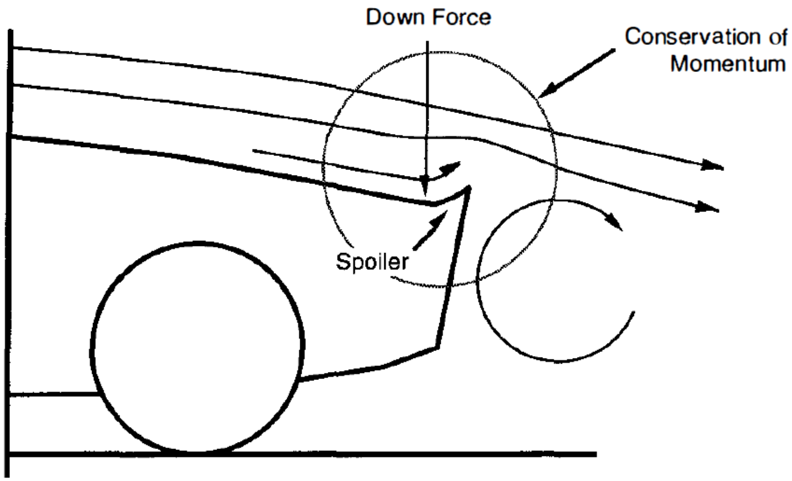
- Aerodynamic Aids
  - Bumper Spoilers
    - ✓ Aerodynamic surfaces to block and redirect the shear flow that impacts on the underbody components
    - ✓ While the spoiler contributes pressure drag, at least with a shallow depth the reduction in underbody drag is more significant.

Aerodynamic Forces

- Aerodynamic Aids
  - Air Dams
    - ✓ Air dams are flow-blocking surfaces installed at the perimeter of the radiator to improve flow through the radiator at lower vehicle speeds.
    - ✓ The improvement derives from the decreased pressure behind the radiator/fan, and may reduce drag

AERODYNAMIC FORCES

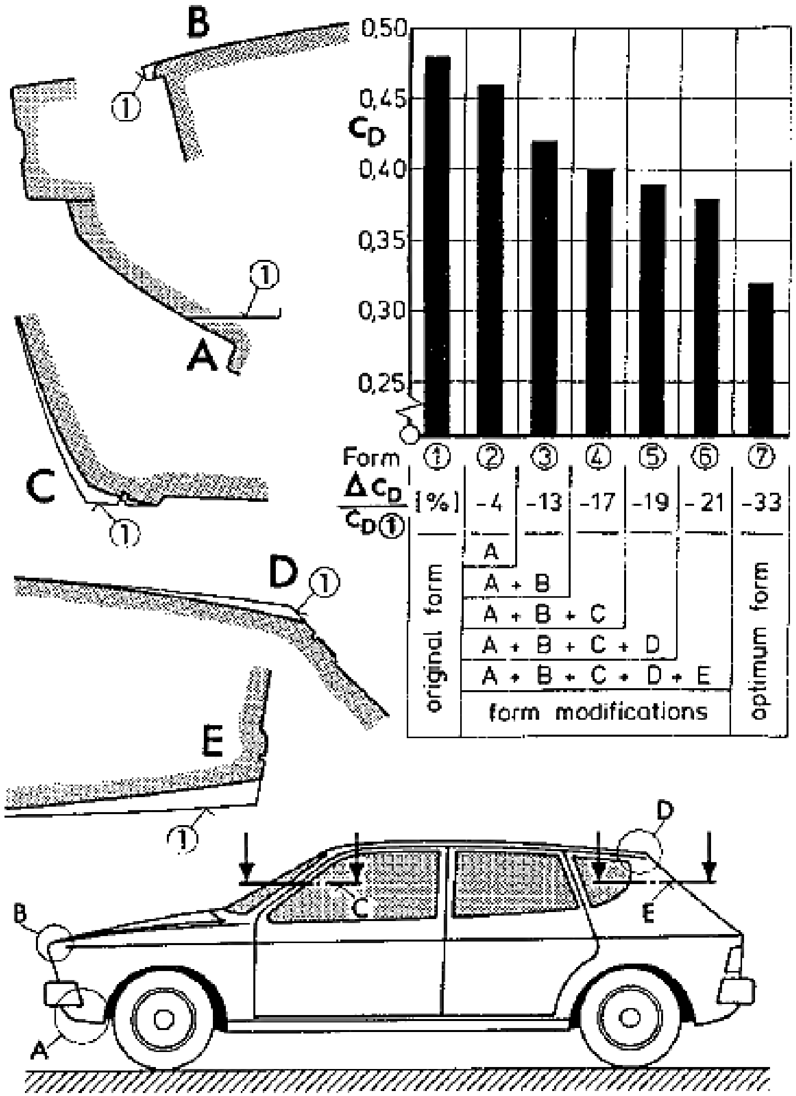
- Aerodynamic Aids
  - Deck Lid Spoiler
    - ✓ Spoilers and air foils on the rear deck may serve several purposes
      - Creating a down force to reduce rear lift
      - Stabilize the vortices in the separation flow



  - Window and Pillar Treatments…

AERODYNAMIC FORCES

- Aerodynamic Aids
  - Optimization
    1) Adaptation of streamlined shapes from other disciplines
    2) Application of the knowledge of fluid mechanics
    3) Current efforts to optimize the numerous details of the design



Aerodynamic Forces

- Drag
  - Because air flow over a vehicle is so complex, it is necessary to develop semi-empirical models
  - Aerodynamic drag: $D_A = 1/2\, \rho\, V^2\, C_D\, A$

    C_D = Aerodynamic drag coefficient
    A = Frontal area of the vehicle
    ρ = Air density

  - Dynamic pressure of the air: $1/2\, \rho\, V^2$
  - The drag coefficient C_D , is determined empirically for the car.

Aerodynamic Forces

- Drag
  - Air density
    - US units

$$\rho = 0.00236 \left(\frac{P_r}{29.92}\right) \left(\frac{519}{460 + T_r}\right)$$

P_r = Atmospheric pressure in inches of mercury
T_r = Air temperature in degrees Fahrenheit

    - Metric units

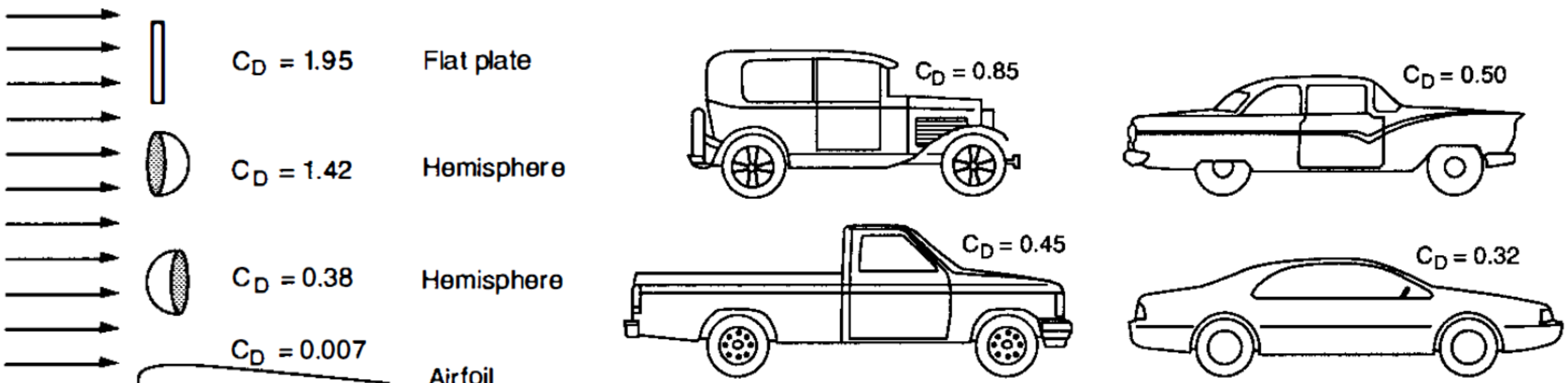
$$\rho = 1.225 \left(\frac{P_r}{101.325}\right) \left(\frac{288.16}{273.16 + T_r}\right)$$

P_r = Atmospheric pressure in kiloPascals
T_r = Air temperature in degrees Celsius

Aerodynamic Forces

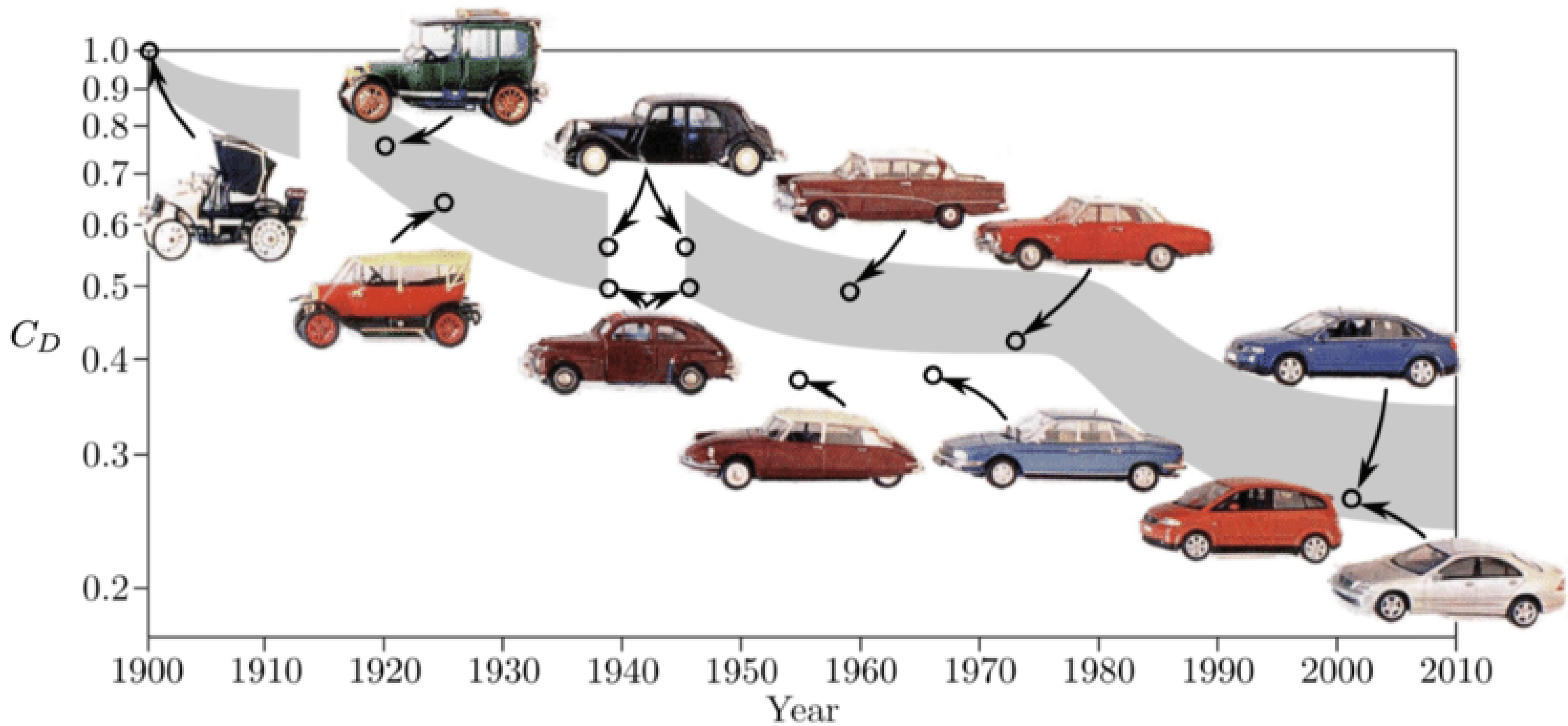
- Drag Coefficient

$$C_D = \frac{D_A}{\frac{1}{2}\rho V^2 A} = \frac{\text{Drag force}}{(\text{Dynamic pressure})\ (\text{area})}$$



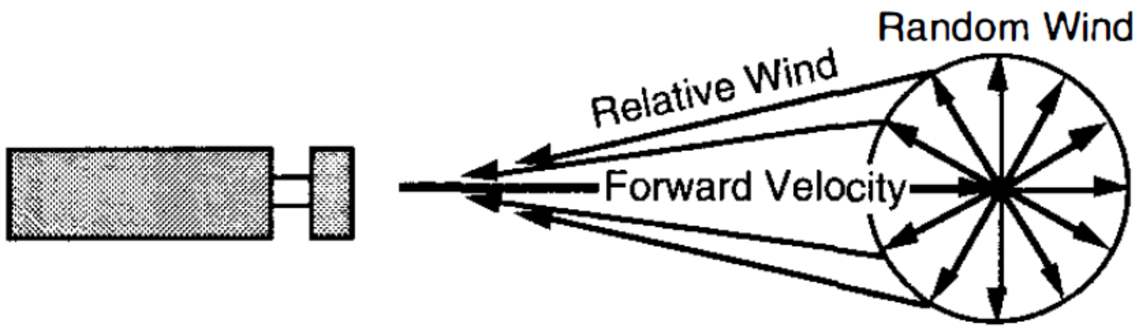
Aerodynamic Forces

- Drag Coefficient



AERODYNAMIC FORCES

- Side wind
  - In practice, a vehicle driving along a road experiences atmospheric winds in addition to the wind component arising from its speed.



  - The relative wind seen by the vehicle will consist of the large component due to its speed, plus a smaller atmospheric wind component in any direction

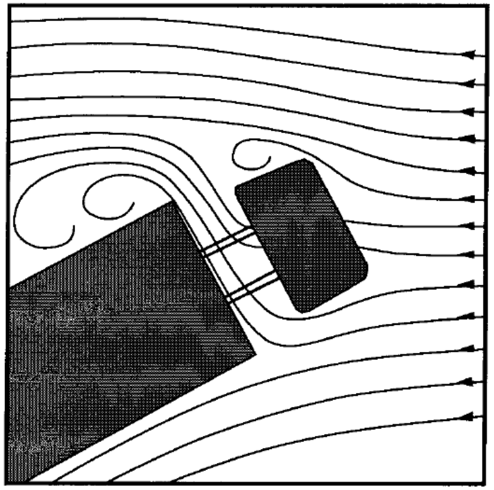
Aerodynamic Forces

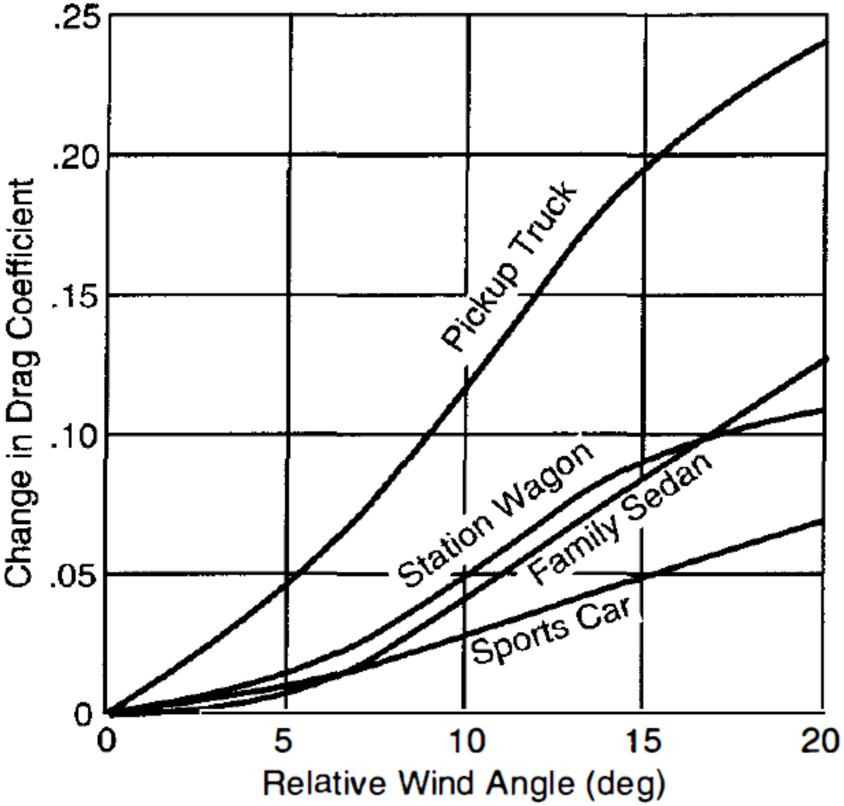
- Side wind
  - Total velocity

$$V = V_v + V_w$$

V_v = Vehicle speed

V_w = Wind speed



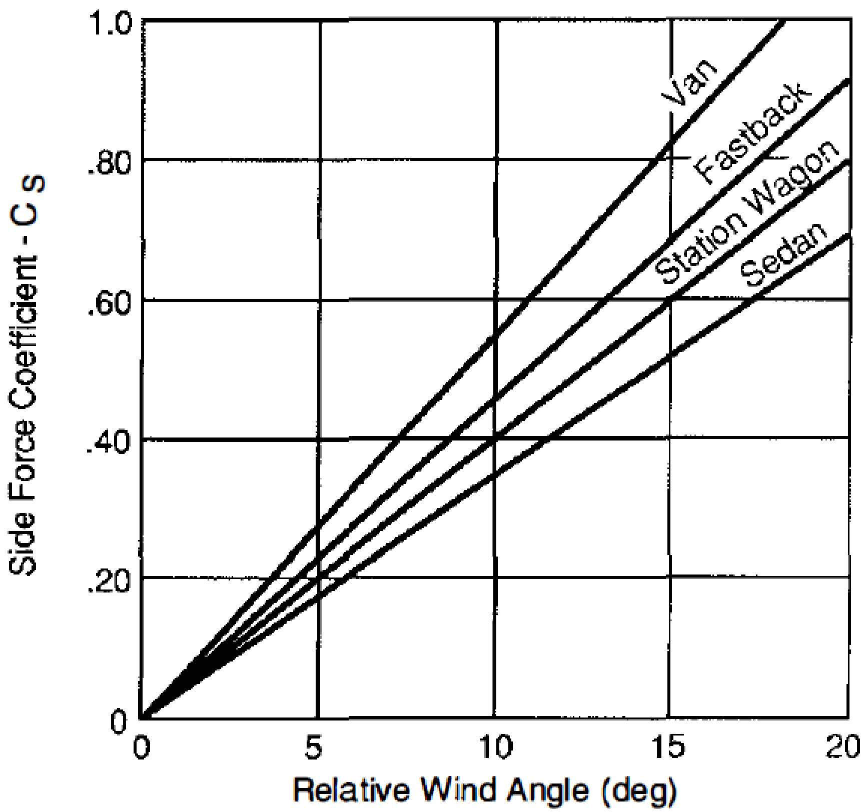


Aerodynamic Forces

- Side Force

$$S_A = 1/2\, \rho\, V^2\, C_S\, A$$

S_A = Side force
V = Total wind velocity
C_S = Side force coefficient
A = Frontal area



✓ Side force coefficient is function of the relative the relative wind angle.

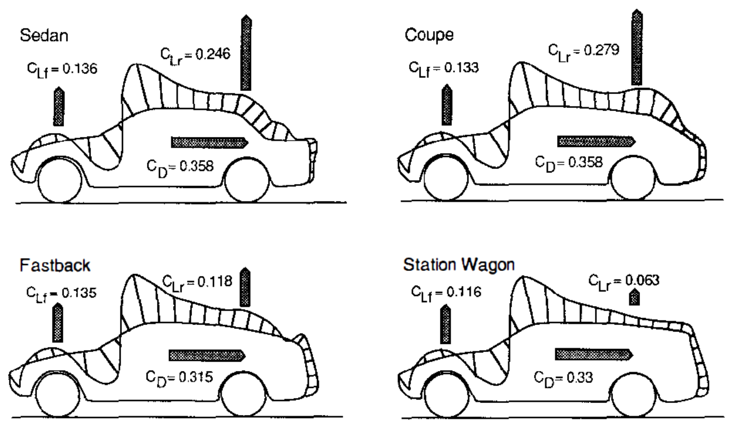
Aerodynamic Forces

- Lift Force

$$L_A = 1/2\,\rho\, V^2 C_L\, A$$

L_A = Lift force
C_L = Lift coefficient
A = Frontal area

- At zero wind angle, lift coefficients normally fall in the range of 0.3 to 0.5 for modern passenger cars.
- But under crosswind conditions the coefficient may increase dramatically reaching values of 1 or more.



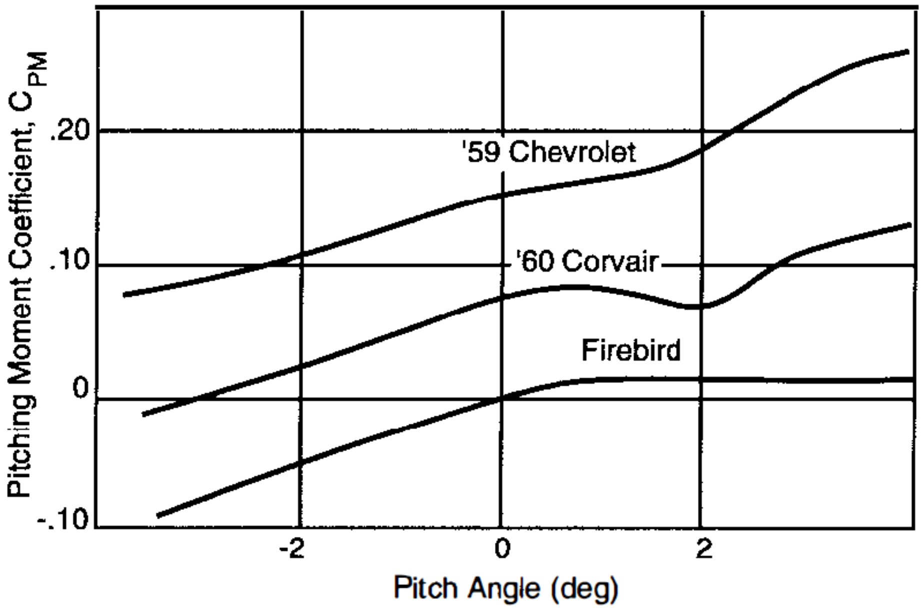
Aerodynamic Forces

- Pitching Moment

$$PM = 1/2\, \rho\, V^2\, C_{PM}\, A\, L$$

PM = Pitching moment
C_{PM} = Pitching moment coefficient
A = Frontal area
L = Wheelbase

- Most modem cars have a pitching moment in the range of 0.05 to 0.2, and it is quite sensitive to the angle of attack on the vehicle.

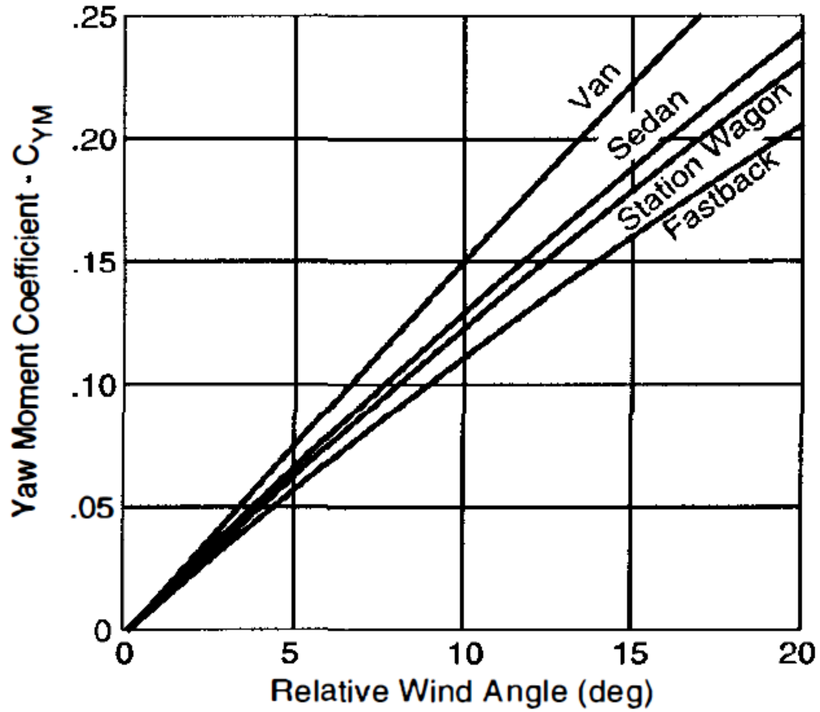


Aerodynamic Forces

- Yawing Moment

$$YM = 1/2\, \rho\, V^2\, C_{YM}\, A\, L$$

YM = Yawing moment
C_{YM} = Yawing moment coefficient
A = Frontal area
L = Wheelbase



Aerodynamic Forces

- Rolling Moment

$$RM = 1/2\ \rho\ V^2\ C_{RM}\ A\ L$$

RM = Rolling moment
C_{RM} = Rolling moment coefficient
A = Frontal area
L = Wheelbase

- The rolling moment coefficient is sensitive to wind direction much like the yawing moment coefficient
- The slope of the rolling moment coefficient ranges from 0.018/deg to 0.04/deg

Aerodynamic Forces

- Crosswind Sensitivity
  - Generally refers to the lateral and yawing response of a vehicle in the presence of transverse wind disturbances which affect the driver's ability to hold the vehicle in position and on course.

  - Key elements:
    - ✓ Aerodynamic properties
    - ✓ Vehicle dynamic properties (weight distribution, tire properties, and suspensions)
    - ✓ Steering system characteristics (compliances, friction and torque assist)
    - ✓ Driver closed-loop steering behavior and preferences

Rolling Resistance

- The other major vehicle resistance force on level ground is the rolling resistance of the tires.

$$R_x = R_{xf} + R_{xr} = f_r W$$

R_{xf} = Rolling resistance of the front wheels

R_{xr} = Rolling resistance of the rear wheels

f_r = Rolling resistance coefficient

W = Weight of the vehicle

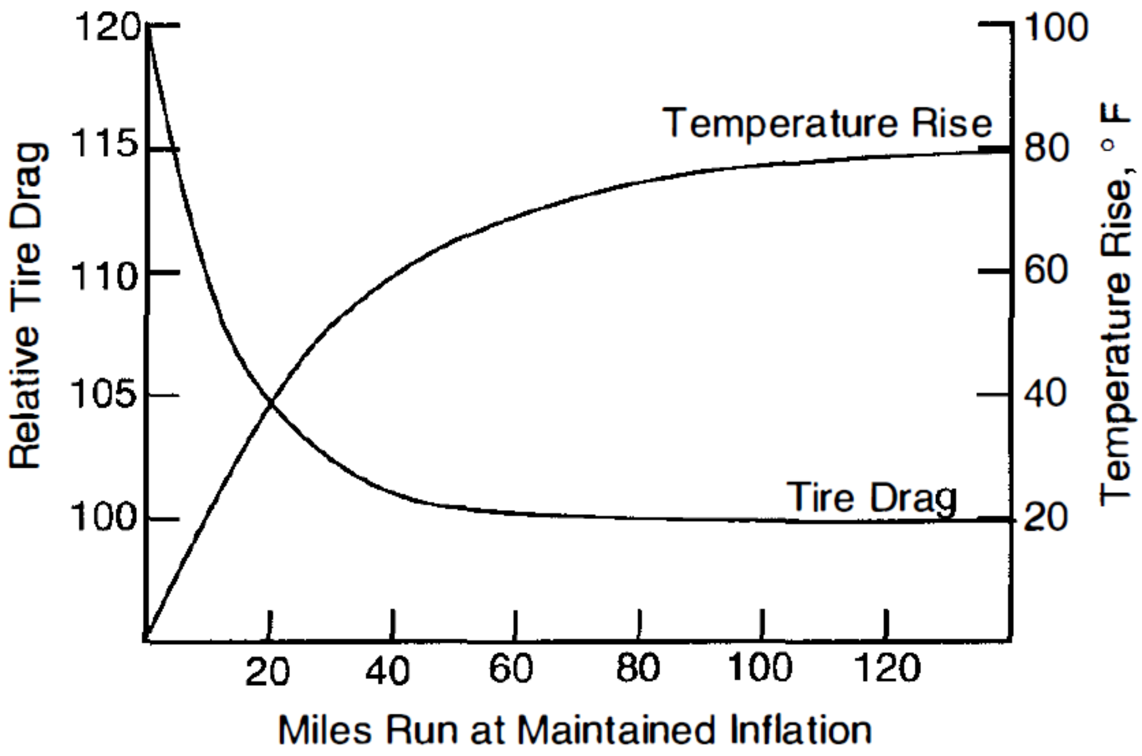
- At low speeds on hard pavement, the rolling resistance is the primary motion resistance force.
- Aerodynamic resistance becomes equal to the rolling resistance only at speeds of 50-60 mph.

Rolling Resistance

- Mechanisms responsible for rolling resistance:
  1) Energy loss due to deflection of the tire sidewall near the contact area
  2) Energy loss due to deflection of the tread elements
  3) Scrubbing in the contact patch
  4) Tire slip in the longitudinal and lateral directions
  5) Deflection of the road surface
  6) Air drag on the inside and outside of the tire
  7) Energy loss on bumps

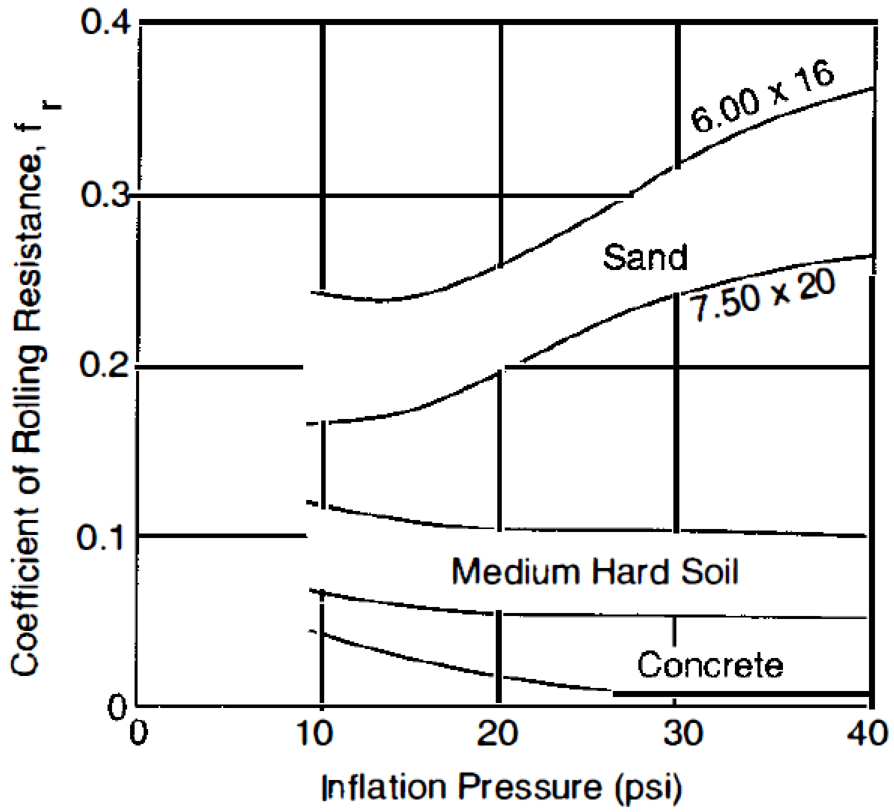
Rolling Resistance

- Factors Affecting Rolling Resistance
  - Tire Temperature



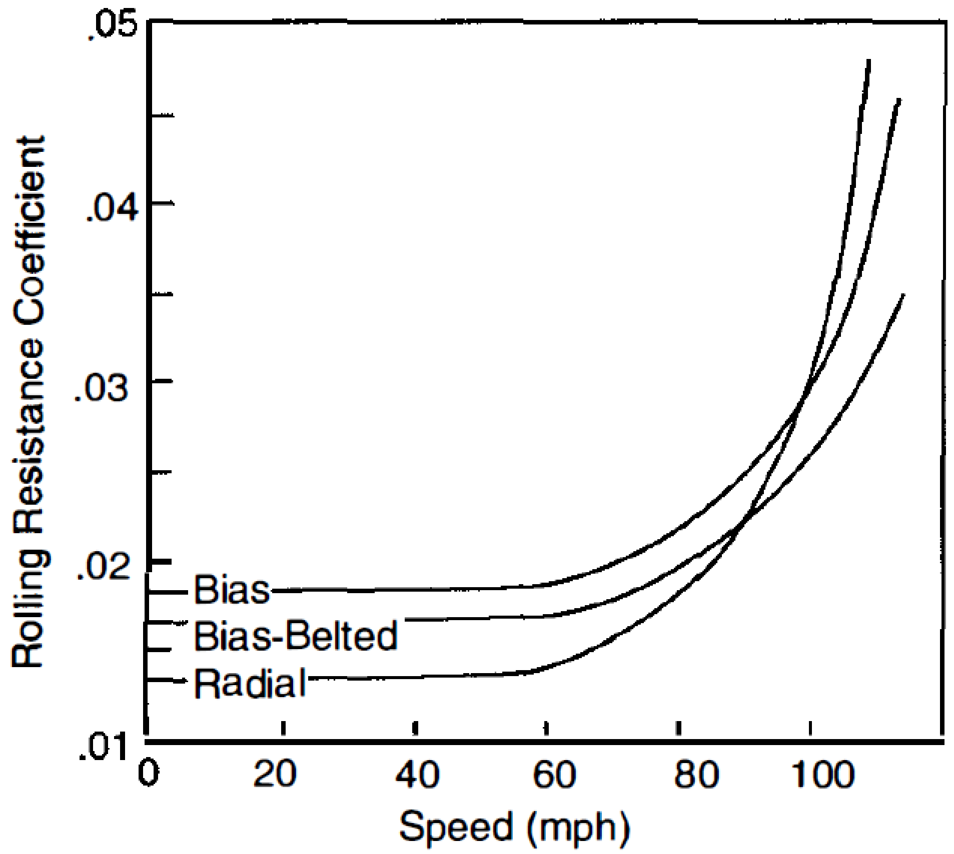
Rolling Resistance

- Factors Affecting Rolling Resistance
  - Tire Inflation Pressure/Load



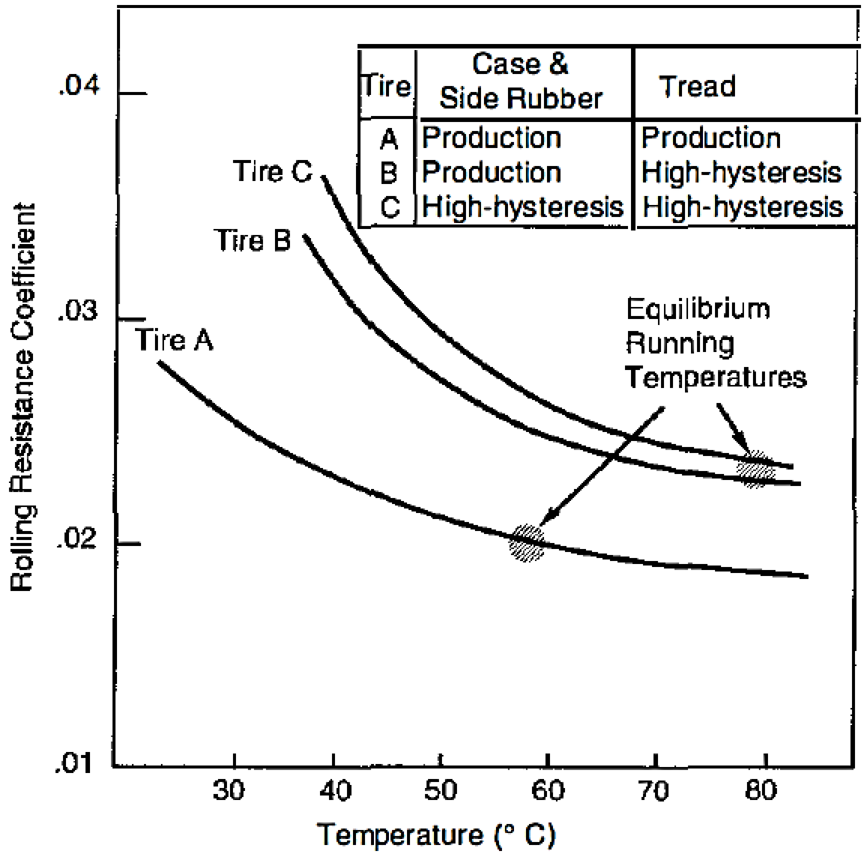
Rolling Resistance

- Factors Affecting Rolling Resistance
  - Velocity
    - ✓ The sharp upturn in coefficient at high speeds is caused by a high-energy standing wave developed in the tire carcass just behind the tire contact patch.



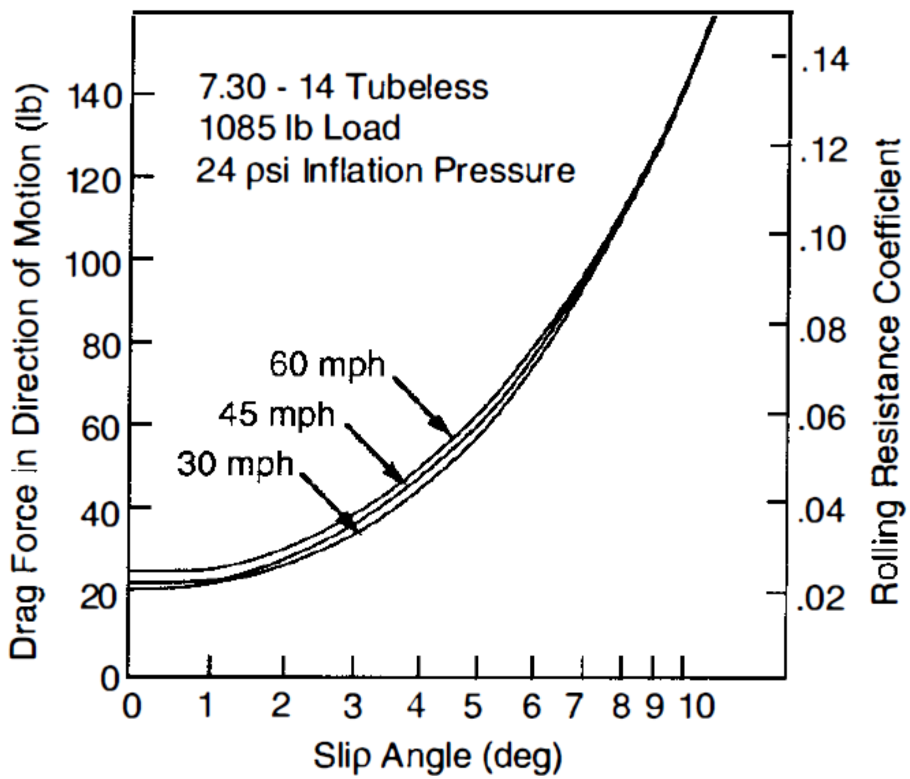
Rolling Resistance

- Factors Affecting Rolling Resistance
  - Tire Material and Design



Rolling Resistance

- Factors Affecting Rolling Resistance
  - Tire Slip
    - ✓Wheels transferring tractive or braking forces show higher rolling resistance due to wheel slip



Rolling Resistance

- Factors Affecting Rolling Resistance
  - Typical Coefficients

$$f_r = \frac{R_x}{W} = C\,\frac{W}{D}\sqrt{\frac{h_t}{w}}$$

R_x = Rolling resistance force
W = Weight on the wheel
C = Constant reflecting loss and elastic characteristics of the tire material
D = Outside diameter
h_t = Tire section height
w = Tire section width

Rolling Resistance

- Factors Affecting Rolling Resistance
  - At the most elementary level, the rolling resistance coefficient may be estimated as a constant.
  - f_r :

Vehicle Type	Concrete	Surface Medium Hard	Sand
Passenger cars	0.015	0.08	0.30
Heavy trucks	0.012	0.06	0.25
Tractors	0.02	0.04	0.20

Rolling Resistance

- Factors Affecting Rolling Resistance
  - At lower speeds the coefficient rises approximately linearly with speed

$$f_r = 0.01\ (1 + V/100)$$

V = Speed in mph

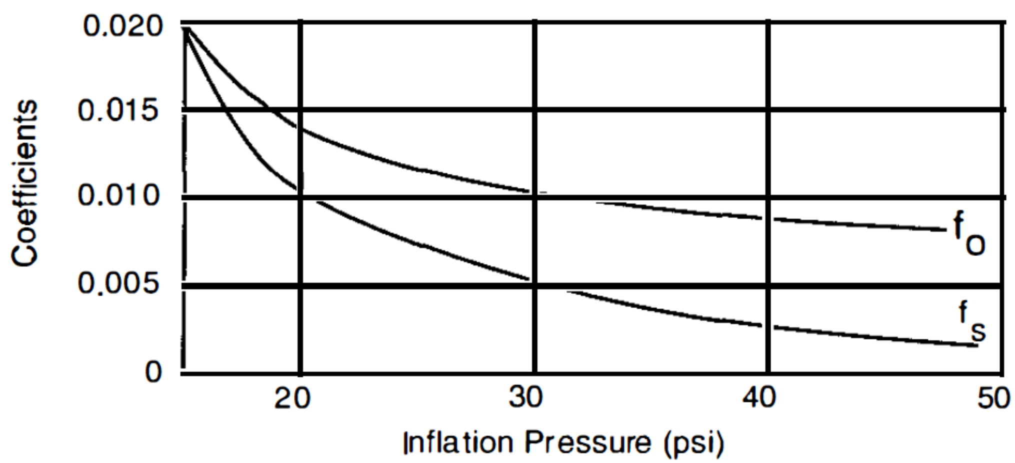
  - Over broader speed ranges:

$$f_r = f_o + 3.24\ f_s\ (V/100)^{2.5}$$

V = Speed in mph

f_o = Basic coefficient

f_s = Speed effect coefficient



ROLLING RESISTANCE

- Factors Affecting Rolling Resistance
  - Rolling resistance of heavy truck tires of both the radial and bias-ply types

$$f_r = (0.0041 + 0.000041\ V)\ C_h \quad \text{Radial tires}$$

$$f_r = (0.0066 + 0.000046\ V)\ C_h \quad \text{Bias-ply tires}$$

V = Speed in mph

C_h = Road surface coefficient

= 1.0 for smooth concrete

= 1.2 for worn concrete, brick, cold blacktop

= 1.5 for hot blacktop

ROLLING RESISTANCE

- Rolling resistance is clearly a minimum on hard, smooth, dry surfaces.
- A worn-out road almost doubles rolling resistance.
- On wet surfaces, higher rolling resistance is observed probably due to the cooler operating temperature of the tire which reduces its flexibility.

TOTAL ROAD LOADS

- The summation of the rolling resistance, aerodynamic forces and grade forces constitutes the propulsion load for the vehicle, and is normally referred to as "road load.“

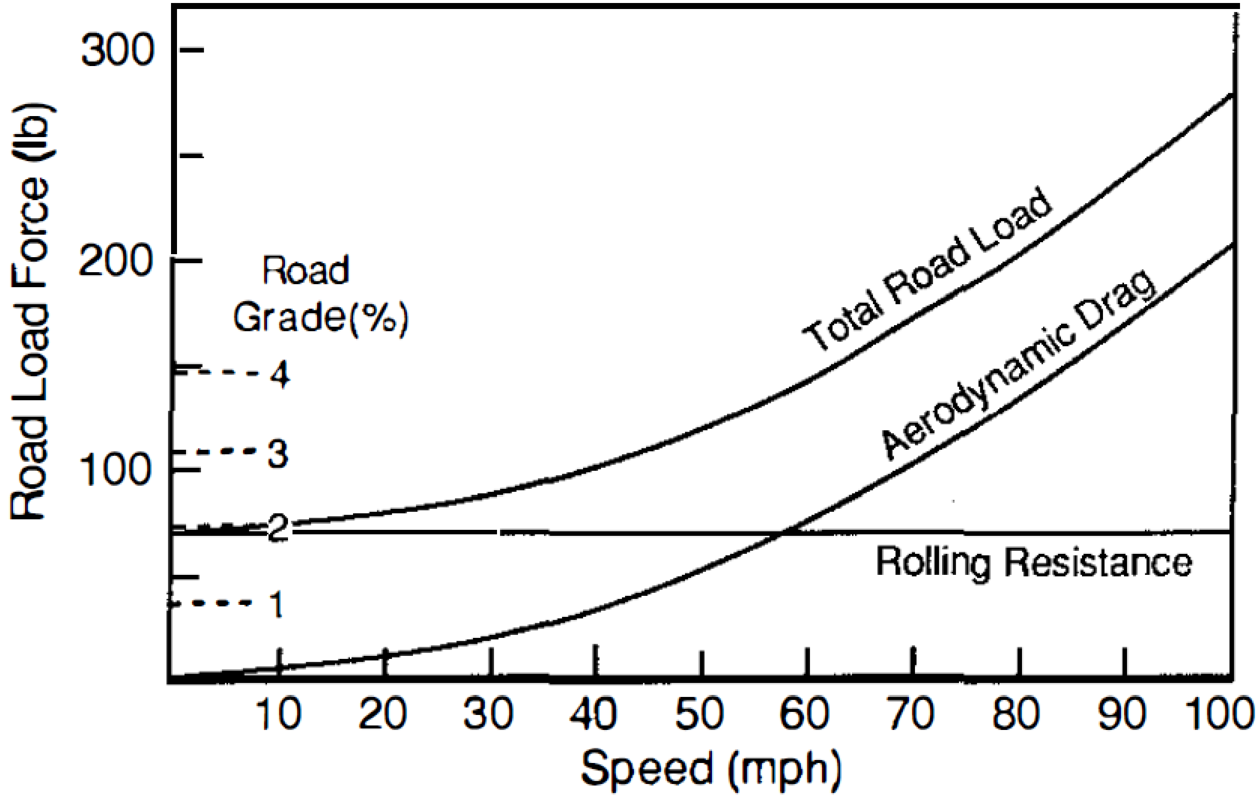
$$R_{RL} = f_r W + 1/2 \rho V^2 C_D A + W \sin\theta$$

- The road load horsepower

$$HP_{RL} = R_{RL} V/550 = (f_r W + 1/2 \rho V^2 C_D A + W \sin\theta) V/550$$

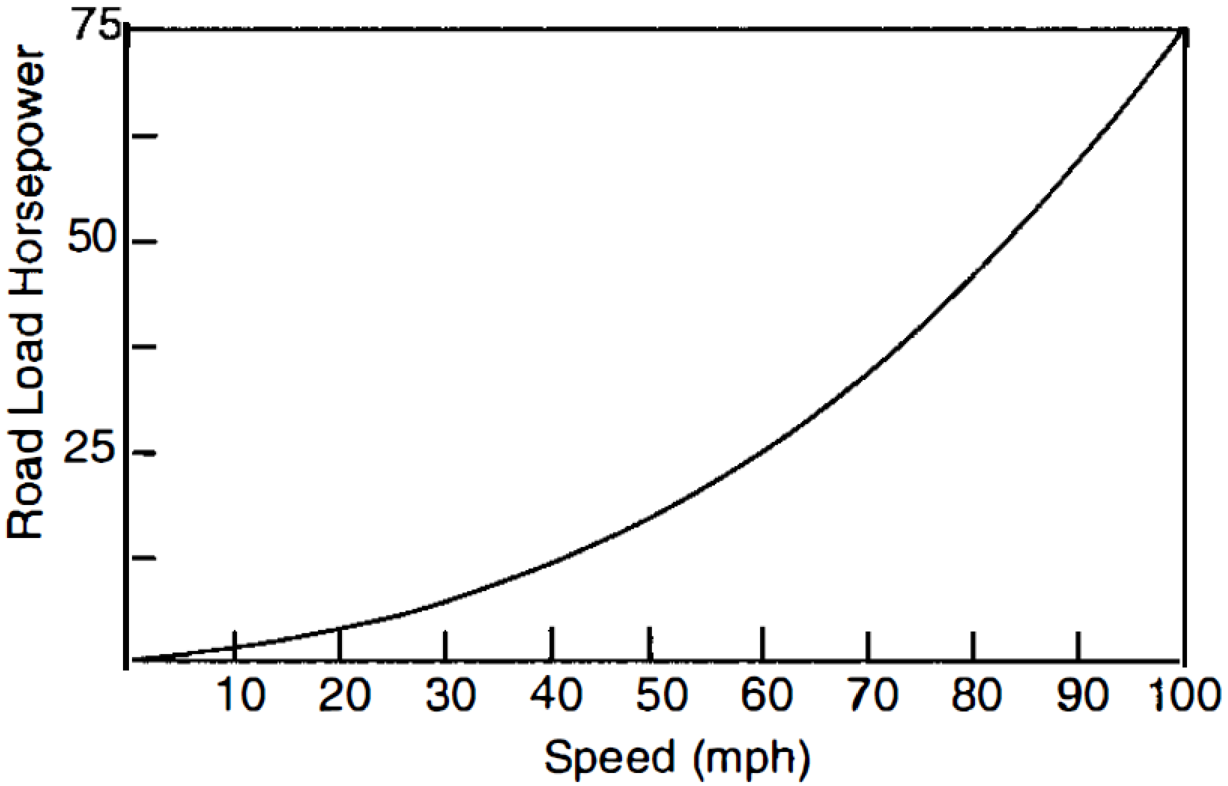
Fuel Economy Effects

- Road Load plot



FUEL ECONOMY EFFECTS

- Road Load power plot



Fuel Economy Effects

- Today, aerodynamic and rolling resistance forces are of particular interest for their effect on fuel consumption.
- The exact improvements in fuel economy are difficult to predict because of the uncertainty about the ways cars are used and driven.