MODULE 6

AERODYNAMICS

SYLLABUS:

Aerodynamic drag: pressure drag, air resistance opposing motion of a vehicle, equations, after flow wake, drag coefficients, various body shapes, base drag, vortices, trailing vortex drag, attached transverse vortices.

Aerodynamic lift: -lift coefficients, vehicle lift, underbody floor height versus aerodynamic lift and drag, aerofoil lift and drag, front end nose shape.

Car body drag reduction: -profile edge chamfering, bonnet slope and wind screen rake, roof and side panel chamfering, rear side panel taper, underbody rear end upward taper, rear end tail extension, underbody roughness.

Aerodynamic lift control: - underbody dams, exposed wheel air flow pattern, partial enclosed wheel air flow pattern, rear end spoiler, negative lift aerofoil wings.

After body drag: - square back drag, fast back drag, hatch back drag, notch back drag.

AERODYNAMIC DRAG:

PRESSURE DRAG:

- The pressure drag is also called as form drag.
- The form drag or pressure drag contributes to 55 to 60% in the vehicle.
- The pressure drag mainly depends up on the longitudinal section of the vehicle body.
- It plays an important role as its contribution is maximum.
- The selection of body profile is important for low drag.
- From Fig, it can be seen that the vortices are created at the rear when viscous air flows over and past a solid form. It causes the flow to deviate from smooth stream line flow.
- Pressure drag can be minimized by streamlining any solid form exposed to the air flow.

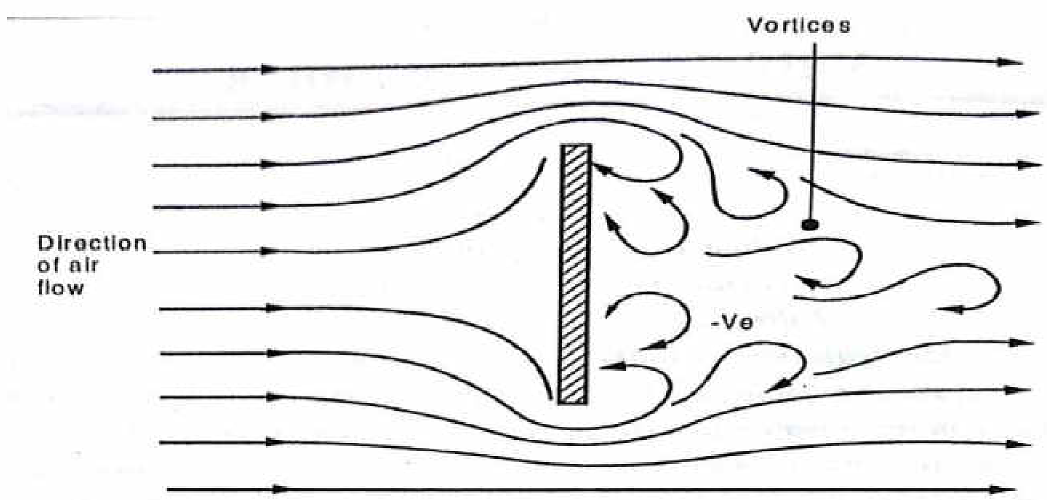


Fig. 6.1 Pressure Drag on Flat Plate

AIR RESISTANCE OPPOSING THE MOTION OF A VEHICLE:

- The opposing resistance of a body passing through air can be calculated.
- From Fig. 6.2, assume that a flat plate body is held against a flow of air and that the air particles are in elastic and simply drop away from the perpendicular flat surface.

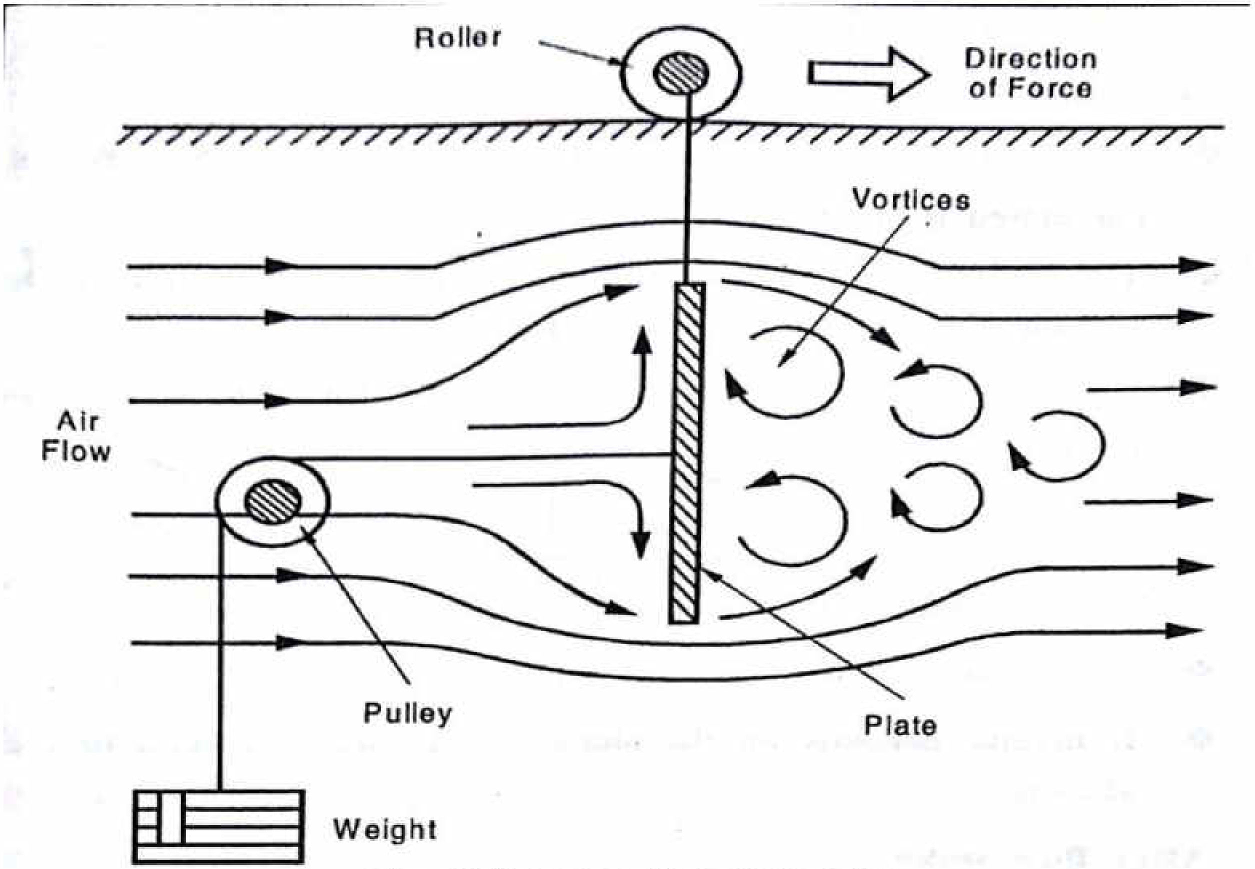


Fig. 6.2 Pressure Drag Apparatus

- The density of air is 1.225 kg/m3 (Approximate mass of 1.225 kg is taken).
- Let,

  Mass = m (kg)

  Volume = Q (m^3)

$$\rho = \frac{m}{Q}\ (\frac{kg}{m^3})$$

$$m = \rho Q\ (kg)$$

Density of air flow = ρ (kg/m^3)

Frontal area of plate = A (m^2)

Velocity of air striking surface = V (m/s)

Volume of air striking plate per second = Q = AV (m^3/s)

Mass movement of air per second = ρQ = ρAV

Since,

Momentum of this air (mV) = ρAV^2

Therefore, momentum lost by air per second = ρAV^2

From Newton's second law, force on plate = ρAV^2

It can be seen that the actual experimental force (F) is proportional to AV^2

Therefore, air resistance, $\mathbf{F = C_D AV^2}$

C_D – coefficient of drag. It mainly **depends on the shape of the body exposed to the air stream.**

AFTER FLOW WAKE:

- It is the turbulent volume of air created at the rear end of a forward moving car.
- The wake has a cross sectional area. It is equal to the area of rear vertical boot panel plus the rearward projected area.

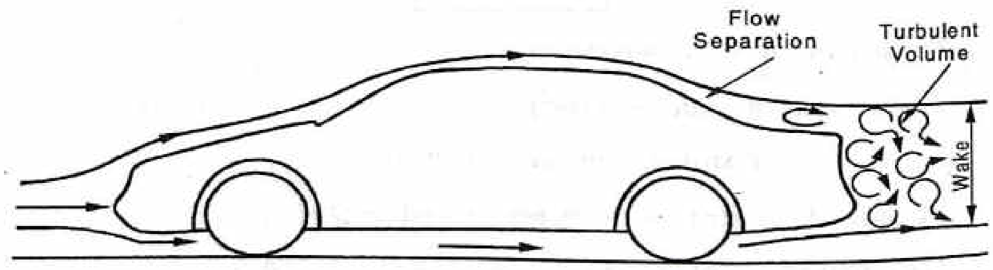


Fig. 6.3 After Flow Wake

DRAG COEFFICIENT:

- It is a measure of the effectiveness of a streamline aerodynamic body shape in minimizing the air resistance to forward motion of a vehicle.
- A low drag coefficient makes the streamline shape of the vehicle's body to move easily with reduced resistance.
- The poor streamlining of the body causes a high drag coefficient. Therefore, there is a high air resistance when the vehicle is in motion.
- Drag coefficient for various type of vehicles:

Vehicle Type	Drag coefficient
(i) Light van	0.3 - 0.5
(ii) Sport car	0.28 - 0.4
(iii) Saloon car	0.2 - 0.4
(iv) Buses and coaches	0.4 - 0.8

DRAG COEFFICIENTS AND VARIOUS BODY SHAPES:

- A comparison of the air flow resistance for various shapes in terms of drag coefficient is given as follows:
  1. Circular plate: (fig 6.4 a)
     - Air flow is head on, and there is an immediate end on pressure difference.
     - At the rim, the flow separation takes place.
     - It gives a large vortex wake and correspondingly high drag coefficient of 1.15.
  2. Cube: (fig 6.4 b)
     - Air flow is head on but a boundary layer around the side delays the flow separation.
     - But there is a large vortex wake and a coefficient of drag 1.05.

3. Sixty-degree cone: (fig 6.4 c)
   - In this cone shaped solid, the air flows towards the cone apex.
   - Then it spreads outwards parallel to the shape of cone surface.
   - The drag coefficient of cone shaped solid is 0.5.
4. Sphere: (fig 6.4 d)
   - In this, air flows towards the sphere.
   - Then it is, diverted which is shown in Fig.
   - There is a slight reduction in the vortex wake.
   - The coefficient drag is 0.47 which is lesser than cone.
5. Tear drop: (fig 6.4 e)
   - The streamline shape can maintain a boundary layer before flow separation occurs almost to the end of its tail.
   - In this, the coefficient of drag is 0.05 which is a lower value.

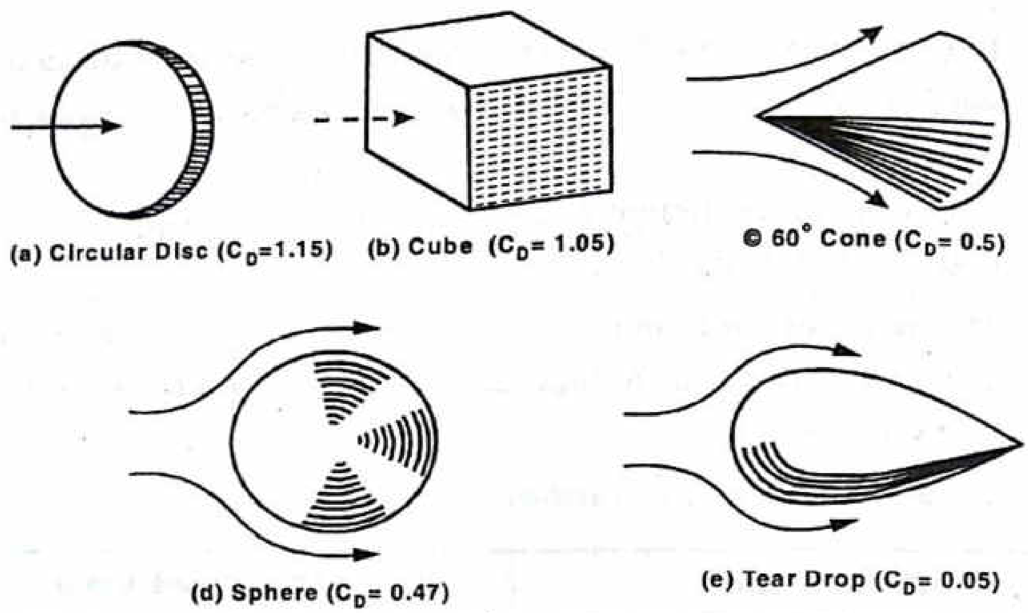


Fig. 6.4 Drag Coefficient for Various Shaped Solids

BASE DRAG:

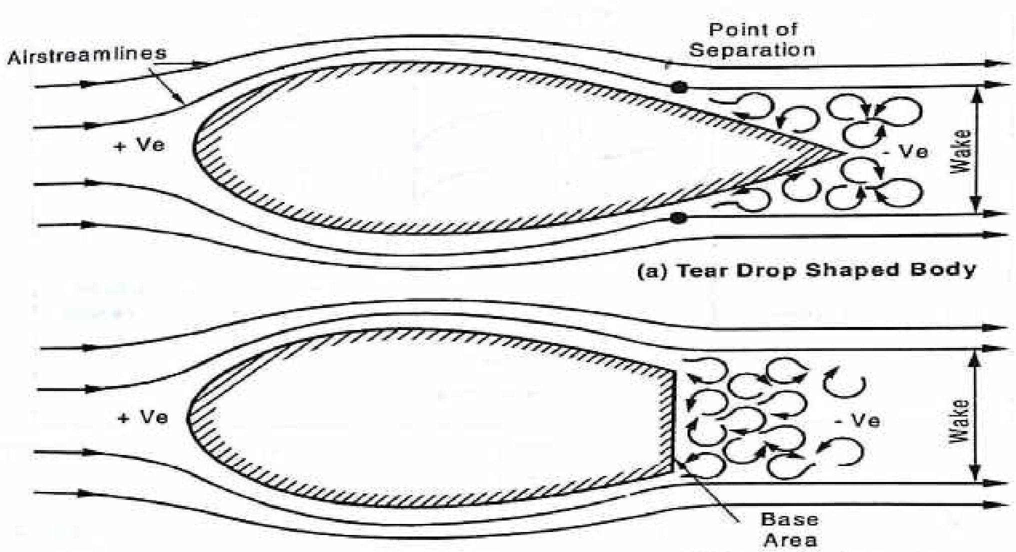


Fig. 6.5 Base Drag (b) Bobtailed Tear Drop

- The shape of the car body also influences the pressure drag.
- Referring Fig. 6.5, the cut off cross-section area where the flow separation occurs is called as "Base area".
- The negative vortex pressure generated is called as "Base drag".
- While designing a car, a taper slightly towards the rear end is followed.
- Therefore, the flow separation occurs beyond the rear axle.

VORTICES:

- When the vehicle is in motion, the vortices are formed around various regions.
- Vortices can be described as a swirling air mass with an annular cylindrical shape.
- At the periphery, the rotary speed is minimum. It increases gradually and near the centre, it is maximum.
- The pressure within the vortex is below the atmospheric pressure. In the inner region, the pressure is lower but higher pressure is found at the outer region.

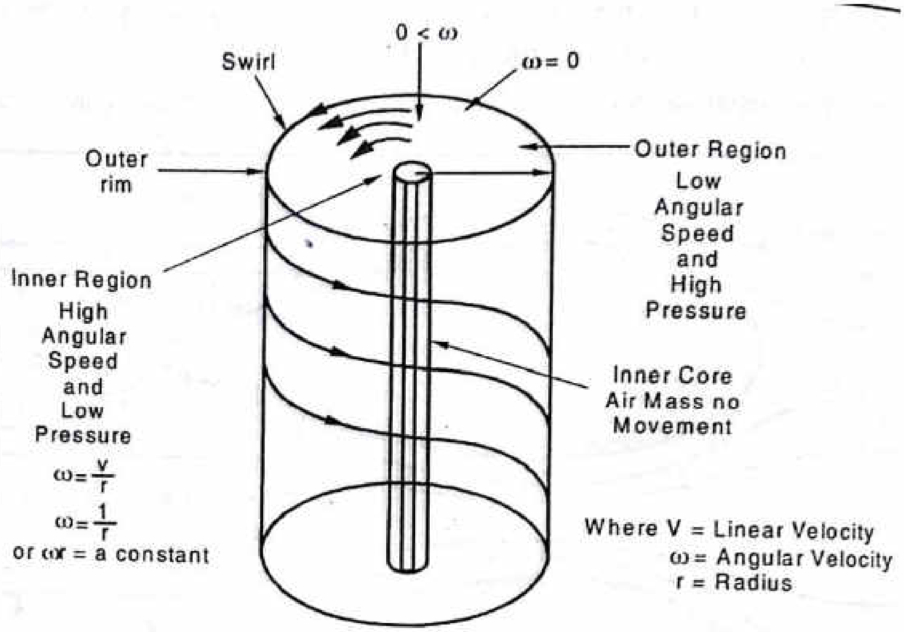


Fig. 6.6 The Vortex

1. **TRAILING VORTEX DRAG:**

- By considering a car (aero foil shape), trailing vortex drag can be studied.
- The trailing vortex drag is given in Fig.
- The air moves between the space under body and ground, and over the upper body profile surfaces, when the air flows from the front to the rear of the car.
- The air pressure is higher in the under-body air stream. But, the air pressure is lower at top surface's air stream.
- The air moves from the high-pressure region to low pressure region.
- The lower and upper air streams interact along the side-to-top profile edges on opposite sides of the body to form an inward rotary air motion.
- This continues to whirl for some distance beyond the rear end of forward moving car.
- The rear styling of the car is important for vortices.

- The negative (below atmospheric) pressure is created in the wake of trailing vortices at the rear of the car.
- It attempts to draw it back in the opposite direction to the forward propelling force. This resistance is called as the "trailing vortex drag"

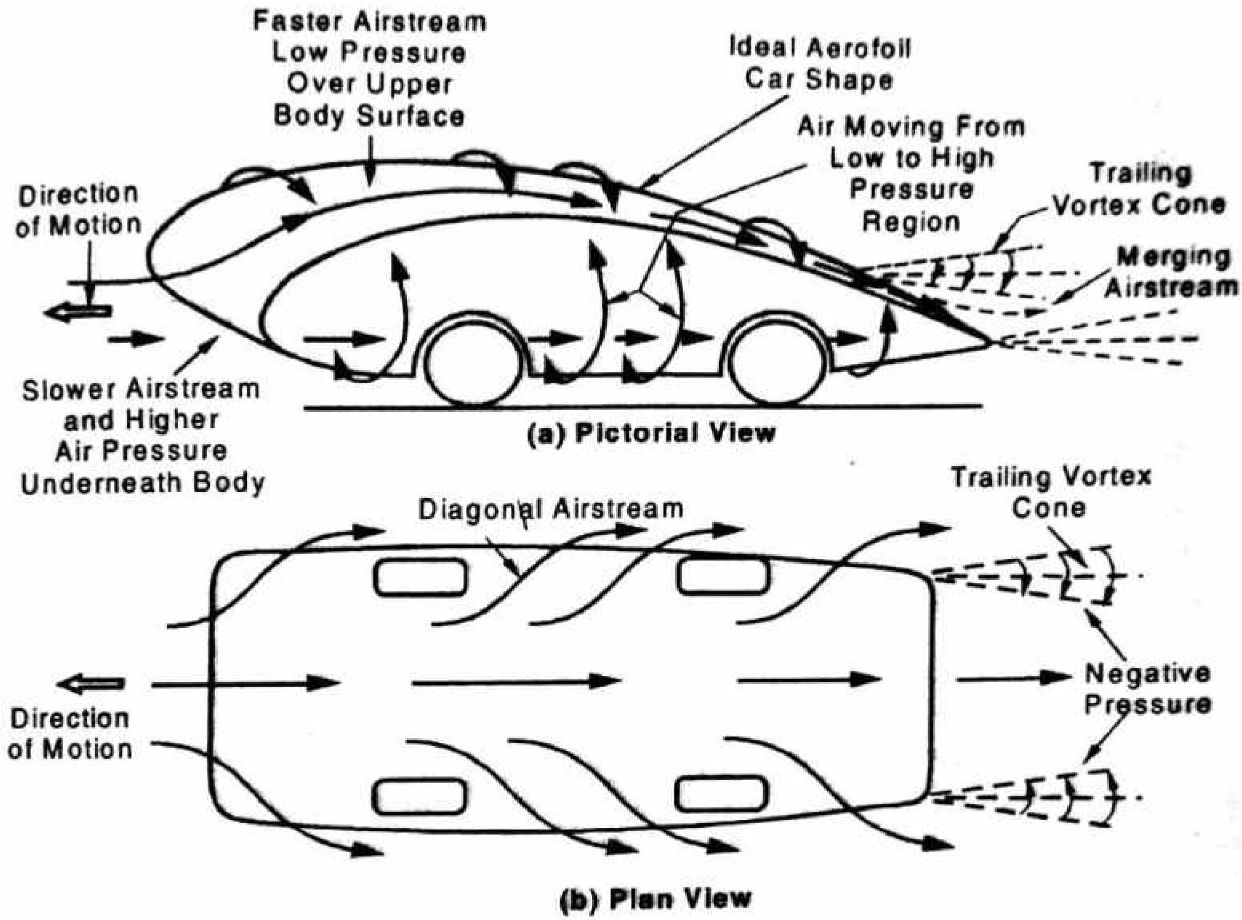


Fig. 6.7 Establishment of Trailing Vortices

2. ATTACHED TRANSVERSE VORTICES:

- Attached transverse vortices are generated by separation bubbles that form between the bonnet and front wind screen the rear screen and boot lid and the boot and rear light panel.
- The front attached vortices work their way around the 'A' post. Then, they stretch along the side windows of the car's rear and beyond.
- Any over spill from the attached vortices in the rear window and light panel regions combine and strengthens the side panel vortices.
- In return, the products of the secondary transverse vortices combine and enlarge the main trailing vortices.

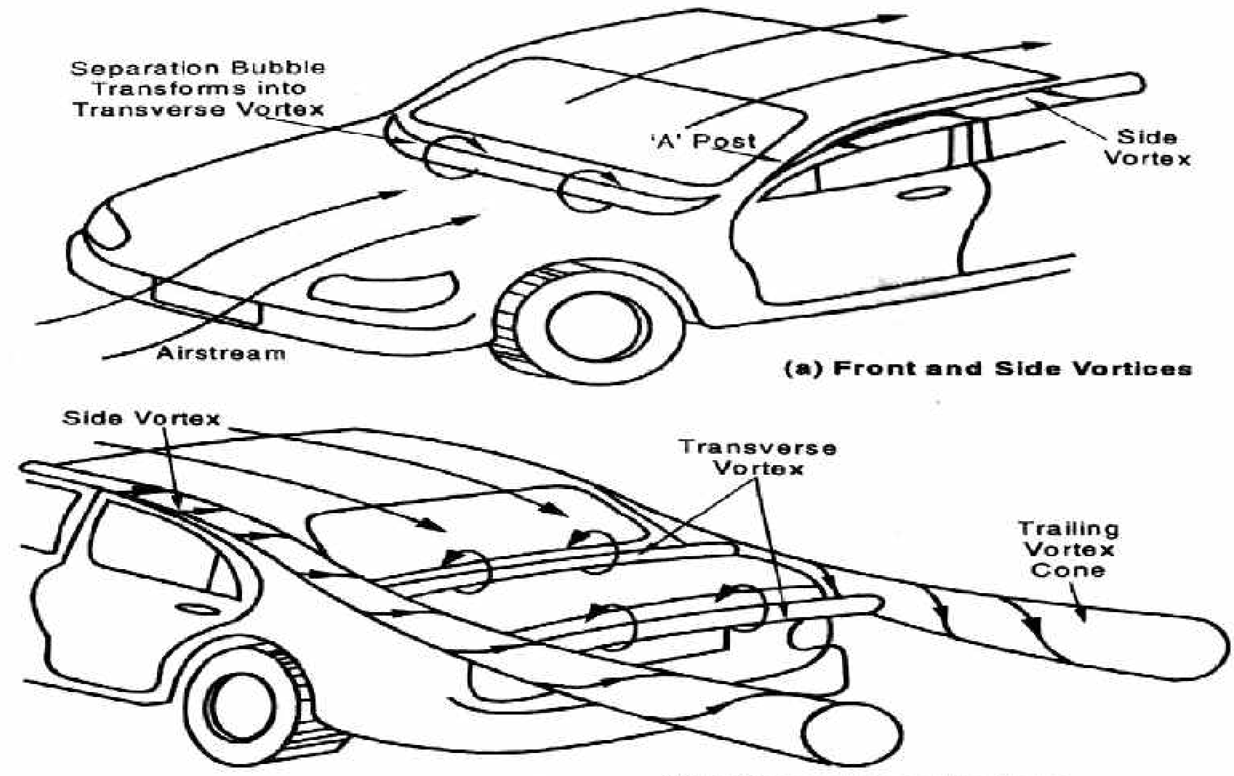


Fig. 6.8 Notch Back Transverse and Trailing Vortices

AERODYNAMIC LIFT

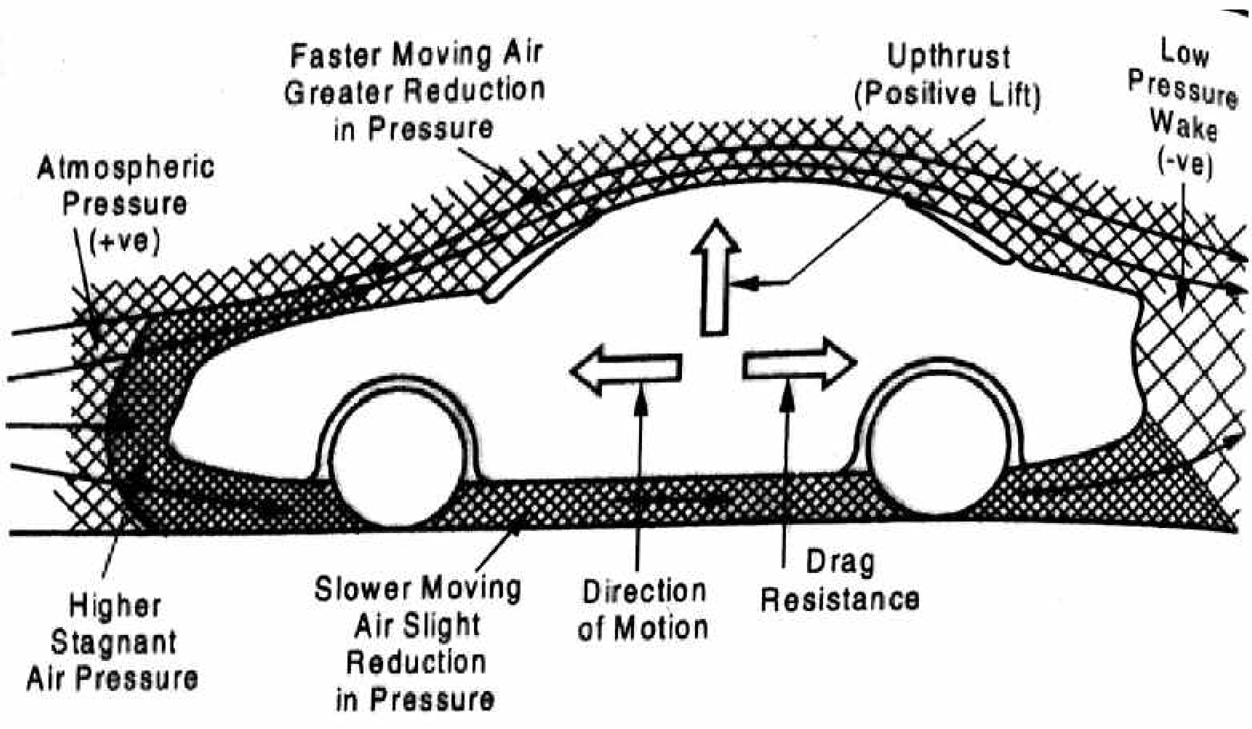


Fig. 6.9 Aerodynamic Lift

Lift Coefficients:

- The aerodynamic lift coefficient is represented as C_L. It is a measure of the variation in pressure created above and below a vehicle's body.
- Hence, a resultant up thrust (or) down thrust may be produced.
- It mainly depends upon the body shape.

- The positive lift reduces the tyre to ground grip.
- The negative lift increases the tyre's road holding.

Vehicle lift:

- The aerodynamic lift of a car is given in Fig. 6.9
- When a car travels along the road, the air stream moving over the upper surface of the body from front to rear has to move further than the underside stream.
- Therefore, the direct slower moving underside and the indirect faster moving top side air stream generates a high pressure underneath the car than over it.
- The resultant vertical pressure generated between the upper and under surfaces reduce a net up thrust/lift.
- The lift magnitude depends on style profile, distance of the under floor and vehicle speed.
- The positive lift is greater in this vehicle.
- It also tends to increase with square of vehicle speed.
- There is a reduction in the tyre to ground grip.
- If the uplift between the front and rear of the car varies, then the slip angles produced by front and rear tyres will not be equal.
- Hence, neutral steer characteristics cannot be obtained. Therefore, the uncontrolled lift will decrease the vehicle's road holding. This causes steering inability.

Underbody floor height Vs aerodynamic lift and drag:

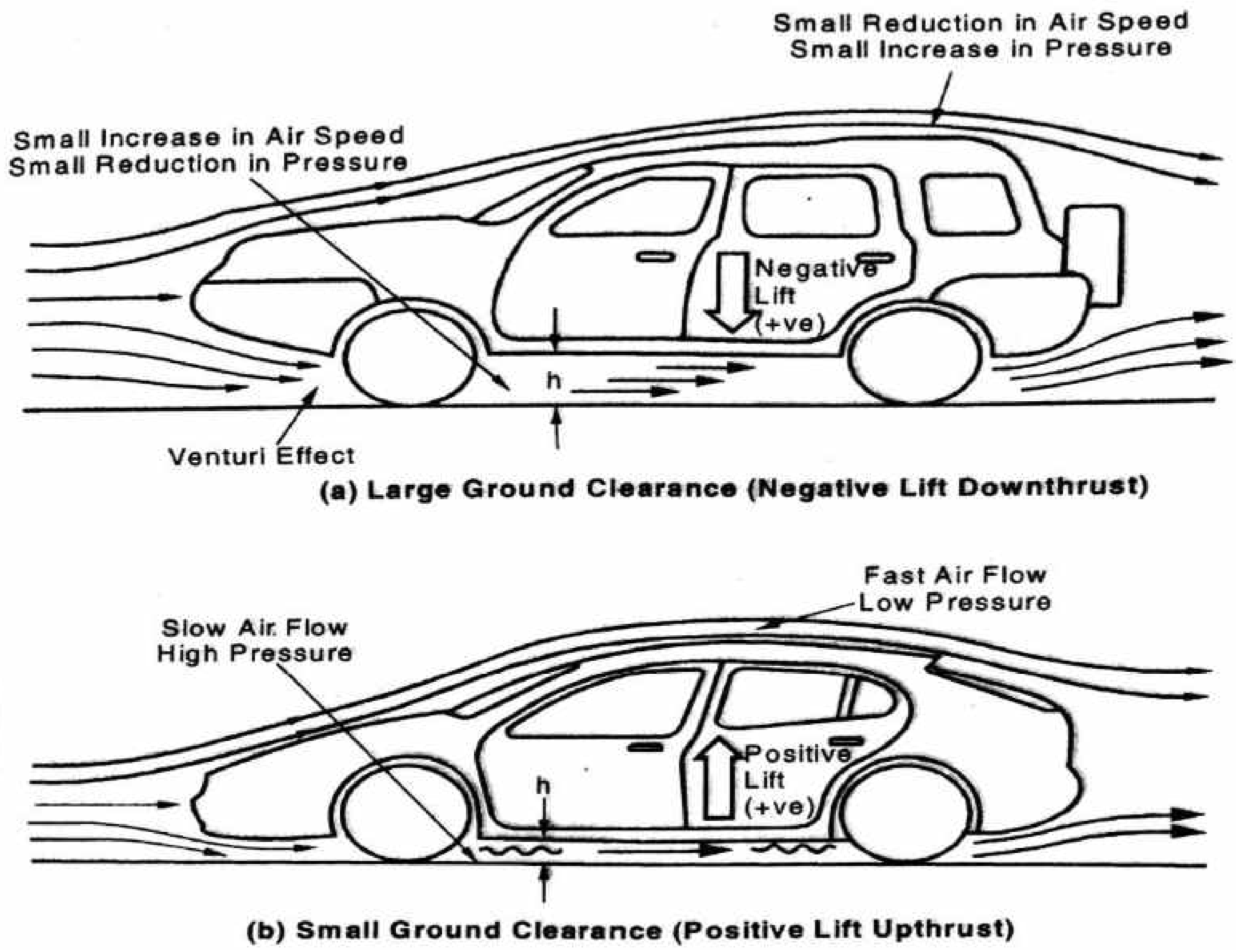


Fig. 6.10 Effect of Underfloor to Ground Clearance on the Surrounding Air Speed, Pressure and Aerodynamic

- The effect of under floor to ground clearance on the surrounding air speed, pressure and aerodynamic lift are shown in Fig. 6.10.
- The car body is subjected to a slight negative lift force with a large underfloor to ground clearance.
- As the under-floor surface moves nearer to the ground, the underfloor air space becomes a venturi.
- It causes the air to move faster under the body.
- But further reduction in the underfloor to ground clearance makes restriction for under body air flow.
- For larger ground clearance, negative lift down thrust is produced.
- The positive lift up thrust is generated for small ground clearance.
- The graph (shown in Fig. 6.11) gives more detail about positive lift up thrust and negative lift down thrust.
- The lift coefficient Vs h/b ratio is plotted in the graph.

Aero foil lift and drag:

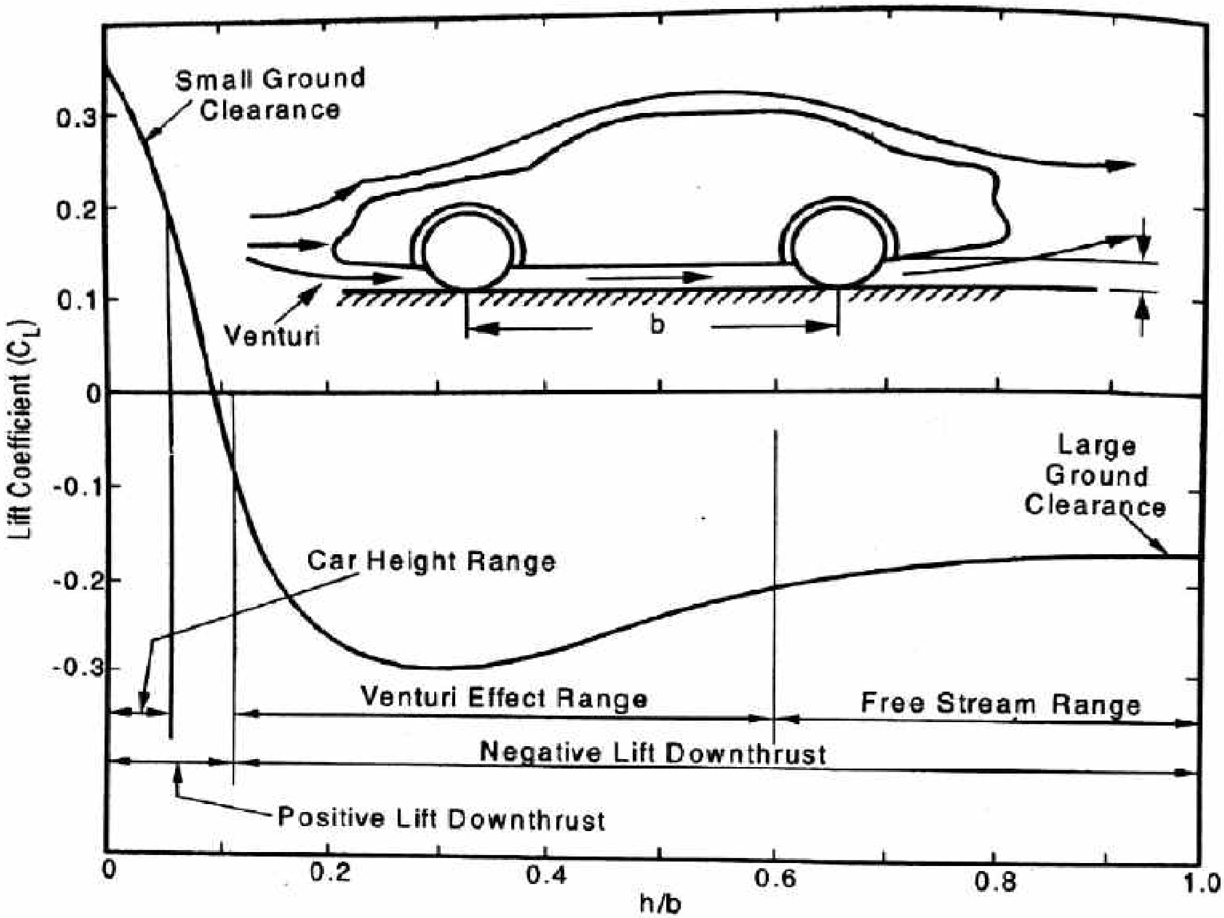


Fig. 6.11 Aerodynamics Lift Versus Ground, Floor Height

- Any object moving, the air stream has some form of lift and drag.
- By considering (shown in Fig. 6.12(a)) a flat plate in inclined position, the reactions forces are noted.
- The air pressure above the surface of the plate is reduced but underneath it is increased.
- From Fig, 6.12(b), it can be seen that the horizontal and vertical components of the resultant reaction represent both drag and lift respectively.

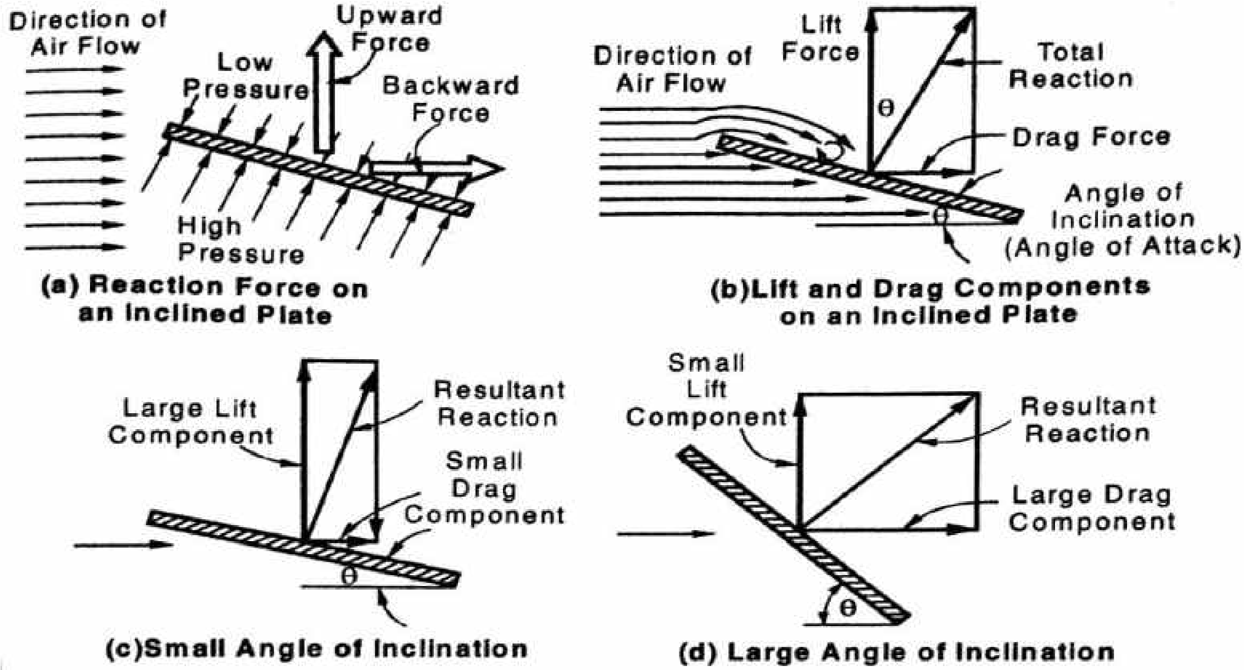


Fig. 6.12 Lift and Drag on a Plate Inclined at a Small Angle to the Direction of Air Flow

- From Fig. 6.12(c) and (d), if the angle of inclination increases, the upward lift component will be smaller and the backward drag component will increase.
- As the angle of inclination decreases, the lift increases and the drag decreases.

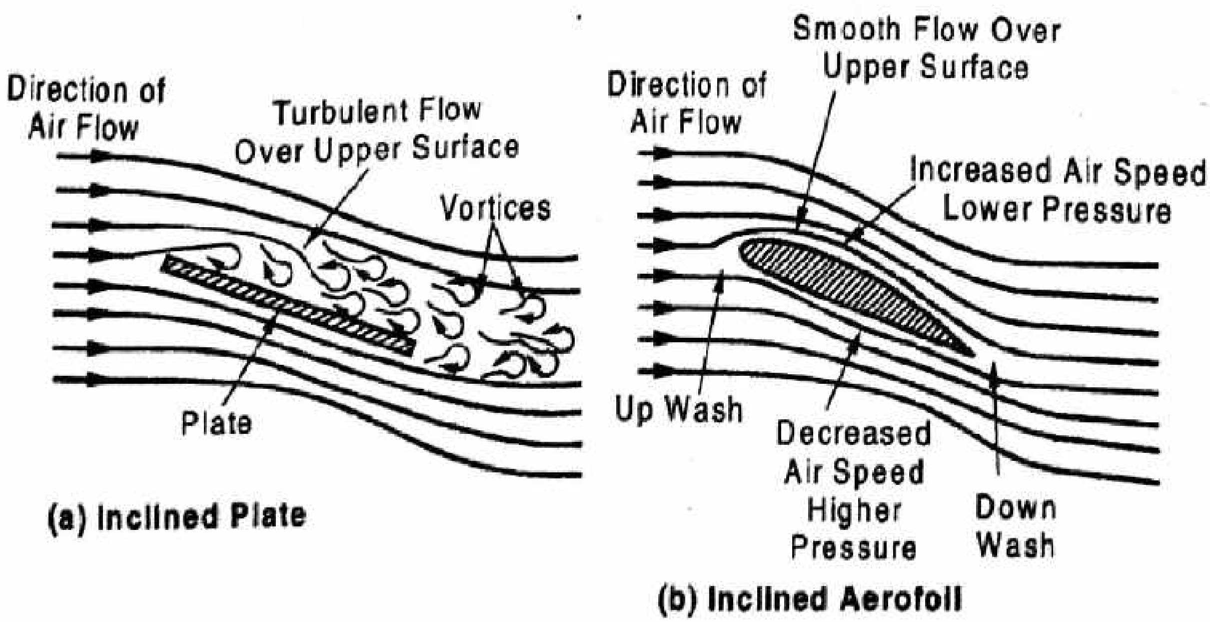


Fig. 6.13 Air Flow Over a Flat Plate and Aerofoil Inclined at a Small Angle

- From Fig. 6.13(a) and (b), if an aerofoil profile is used [instead of state plate], the air stream over the top surface will move further and faster.
- At this time, greater pressure variation is produced between the upper and lower surfaces. Hence the aerodynamic lift increases.
- It promotes a smooth airflow over the upper surface.
- The lift and drag coefficient Versus angle of inclination is shown in Fig. 6.13(c).

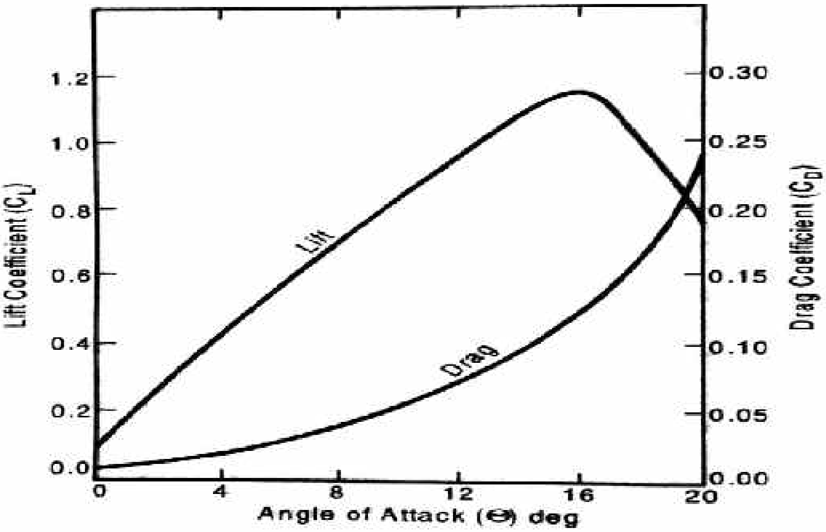


Fig. 6.13 (c)Lift and Drag Coefficient Versus Angle of Inclination (attack)

Front end nose shape:

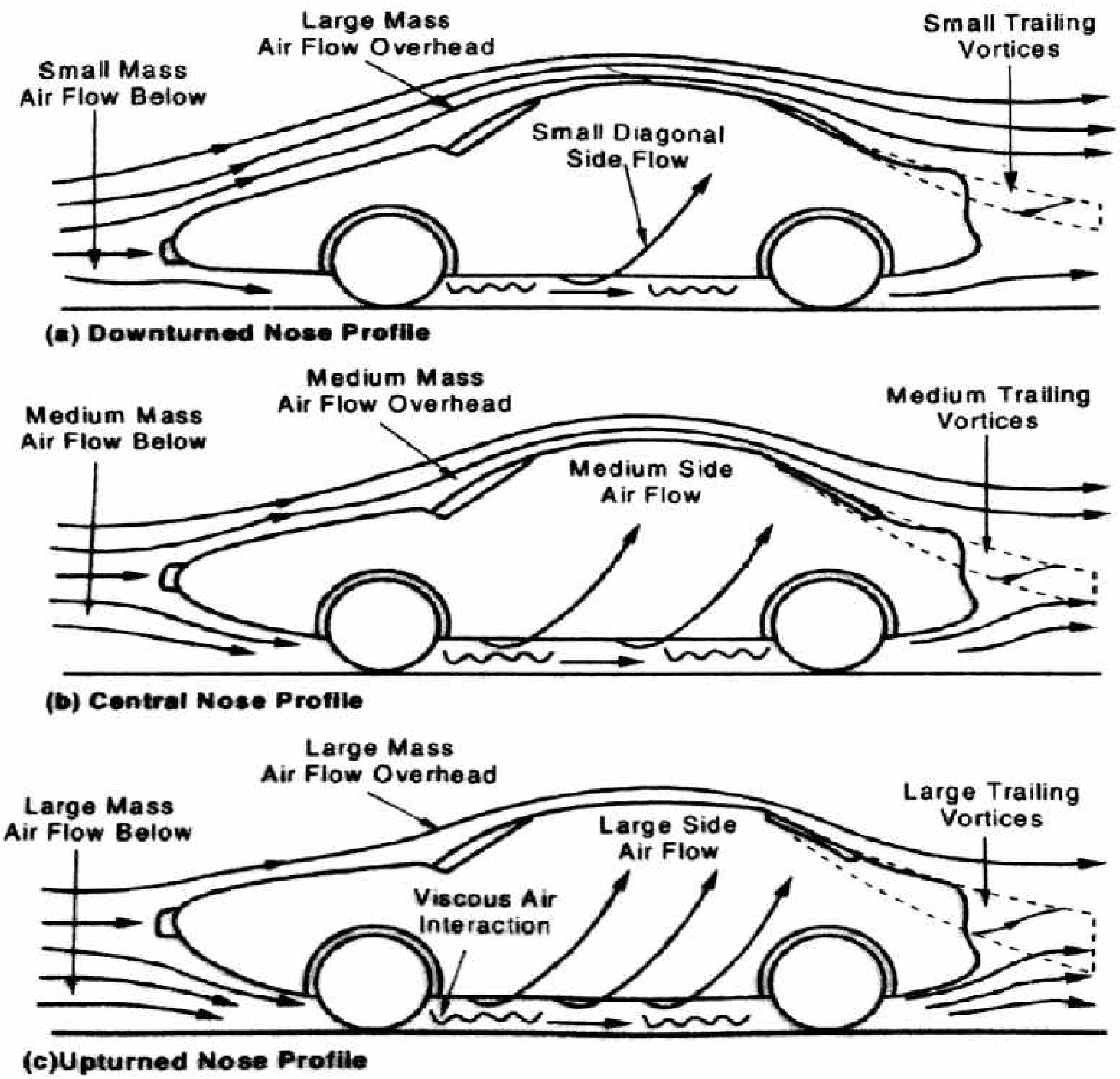


Fig. 6.14 A Greatly Exaggerated Air Mass Distribution Around a Car Body for Various Nose Profiles

- By changing the front end nose shape, the drag coefficient can be reduced.
- From Fig. 6.14(a), (downward nose profile) the larger mass of air flows on the upper side but only small amount of air flows below the lower side of the vehicle body.
- In a central nose profile, (shown in Fig. 6.14(b)) the air movement on the upper and lower surfaces are approximately equal.
- In a upturned nose profile, (shown in Fig. 6.14(c)) larger air mass movement is on the downward side. In the upper side, there is smaller amount of air mass movement.

CAR BODY DRAG REDUCTION:

- The factors effecting car body drag are:
  1. Profile edge rounding (or) Chamfering
  2. Bonnet slope and wind screen rake angle
  3. Roof and side panel cambering
  4. Rear side panel taper
  5. Under body rear end upward taper
  6. Rear and tail extension
  7. Underbody roughness

1. Profile edge rounding (or) Chamfering:

- If the edge radius (or) chamfer increases, the aerodynamic lift and drag will decrease.

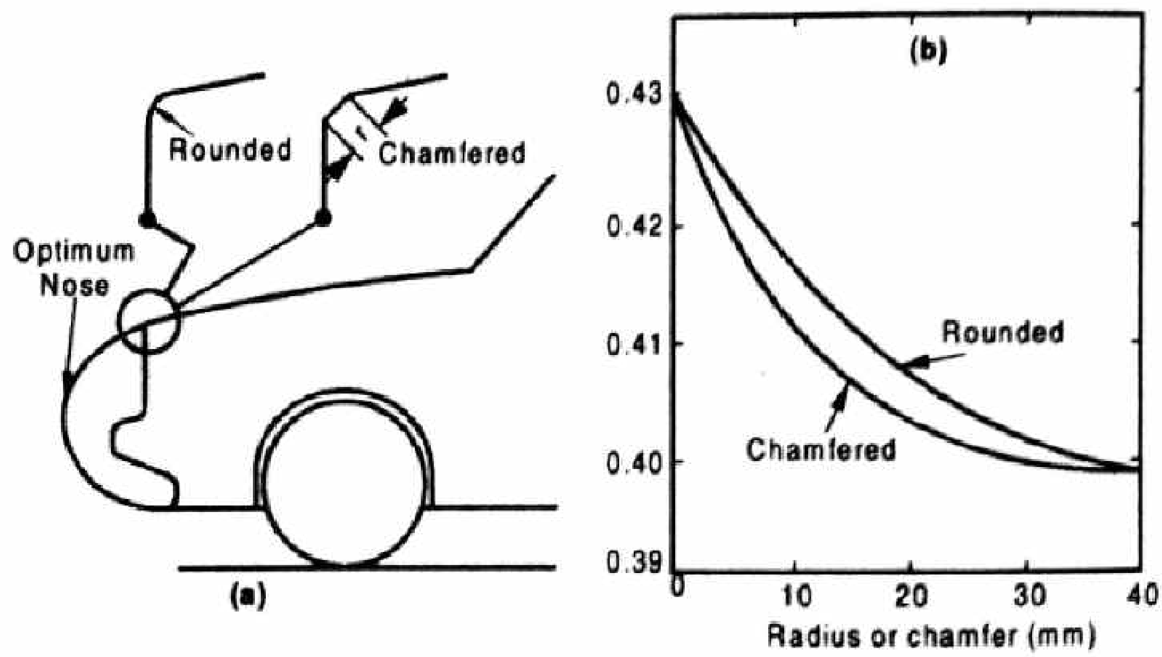


Fig. 6.15 Influence of Forebody Bonnet (hood) Edge Shape on Drag Coefficient

- rounded and chamfered edge are shown in Fig. 6.15(a).
- From Fig. 6.15(b), it can be seen that the drag coefficient reduces from 0.43 to 0.4 in the rounded and chamfered edge nose.
- For larger radius, the minimum value of drag coefficient (C_D) is obtained.

2. Bonnet slope and wind screen rake angle:

- The bonnet slope and wind screen rake angle are shown in Fig. 6.16
- By increasing the bonnet slope angle, the drag coefficient C_D is reduced to minimum value (0.39 to 0.32).
- From Fig. 6.16, it can be seen that the drag coefficient C_D is minimized drastically for larger wind screen rake angle (C_D - 0.38 to 0.3).

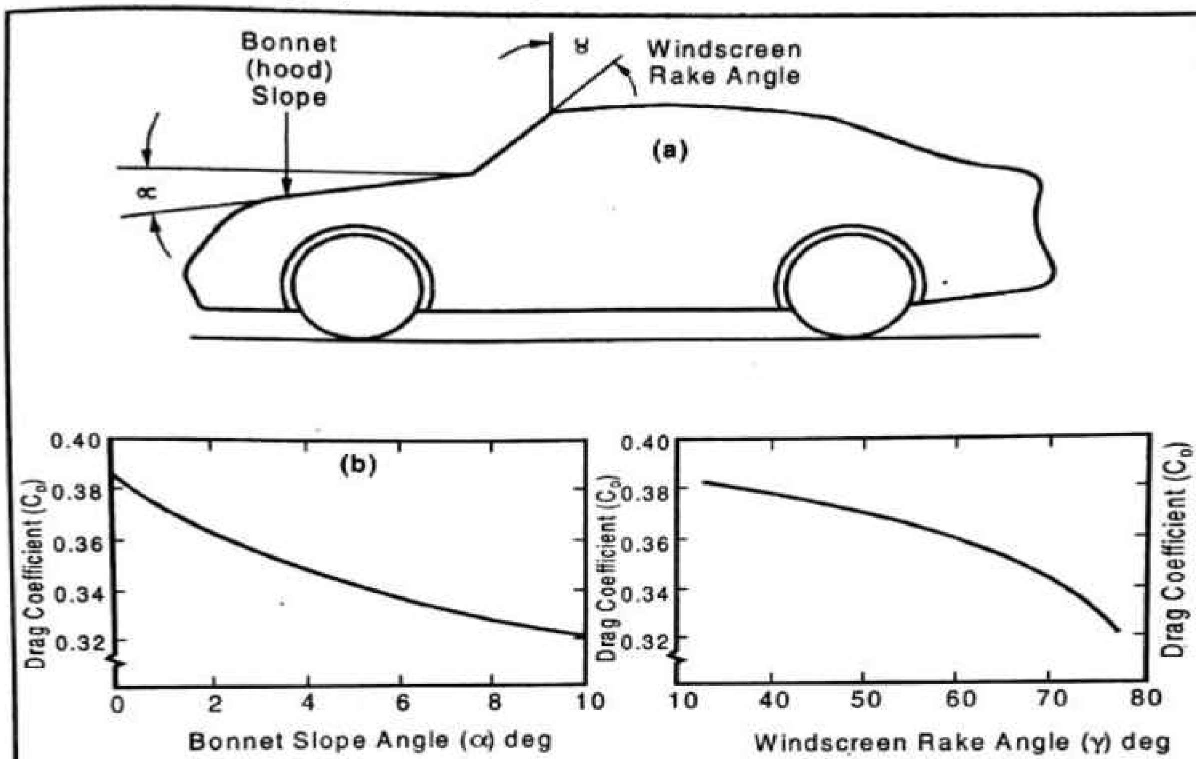


Fig. 6.16 Bonnet Slope and Windscreen Rake Angle Versus Drag Coefficient

3. Roof and side panel cambering:

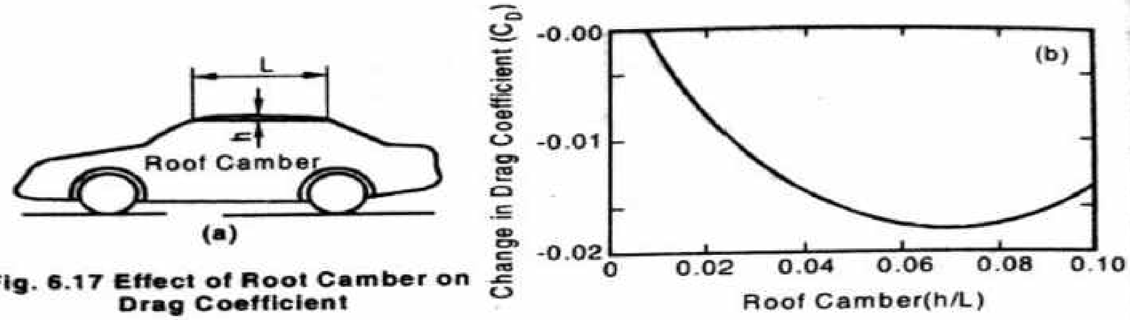


Fig. 6.17 Effect of Root Camber on Drag Coefficient

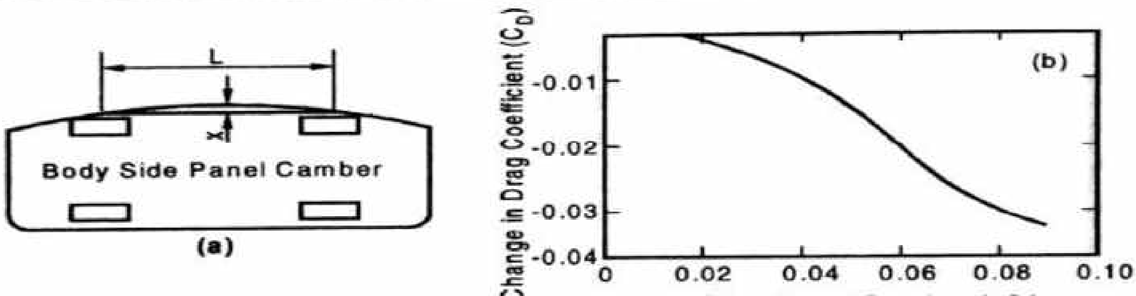


Fig. 6.18 Effect of Side Panel Camber on Drag Coefficient

- The effect of roof camber and side panel on drag coefficient is shown in Fig. 6.17 and Fig. 6.18.
- The drag coefficient (C_D) is reduced by cambering the roof and the side panels.
- The change in drag coefficient Vs roof camber (h/l)) gives U shaped curve. The reduction in drag coefficient with small amounts of side panel cambering is noted.

4. **Rear side panel taper:**

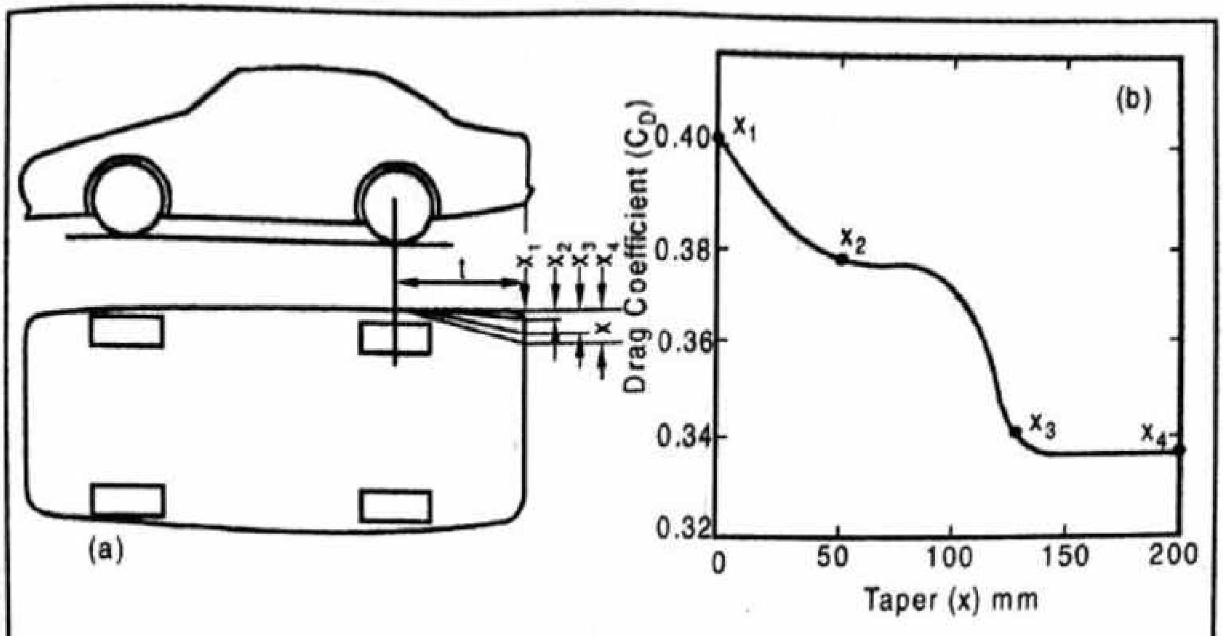


Fig. 6.19 Effort of Rear Side Panel Taper on Drag Coefficient

- The effect of rear panel taper side on drag coefficient is shown in Fig. 6.19.
- The drag coefficient (C_D) is reduced by tapering inwards the rear side panel.
- A marked reduction in drag coefficient with both 50 mm and 125 mm rear end contraction on either side of the car are seen.

5. **Rear side panel taper:**

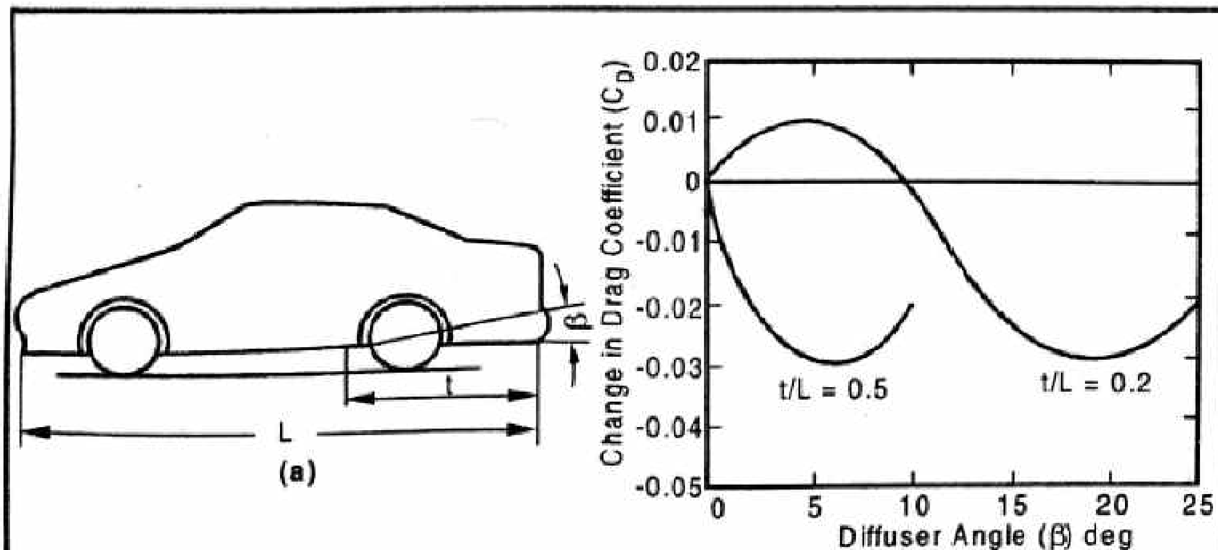


Fig. 6.20 Effect of Rear End Upward Taper on Drag Coefficient

- The effect of rear end upward taper on drag coefficient is shown in Fig. 6.20.
- By varying the diffuser angle, the drag coefficient can be reduced.
- Selecting the ratio of length of taper to overall car length and diffuser angle are very important for obtaining best results.
- The value of t/L (0.5 and 0.2) is noted in the graph.

6. **Rear and tail extension:**

- The effect of rear end tail extension on drag coefficient is shown in Fig. 6.21.
- For larger tail extension (5720 mm), the coefficient of drag value obtained is minimum, [i.e., $C_D = 0.11$]
- For smaller tail extension (700 mm), the C_D value is not reduced [i.e., $C_D = 0.3$]

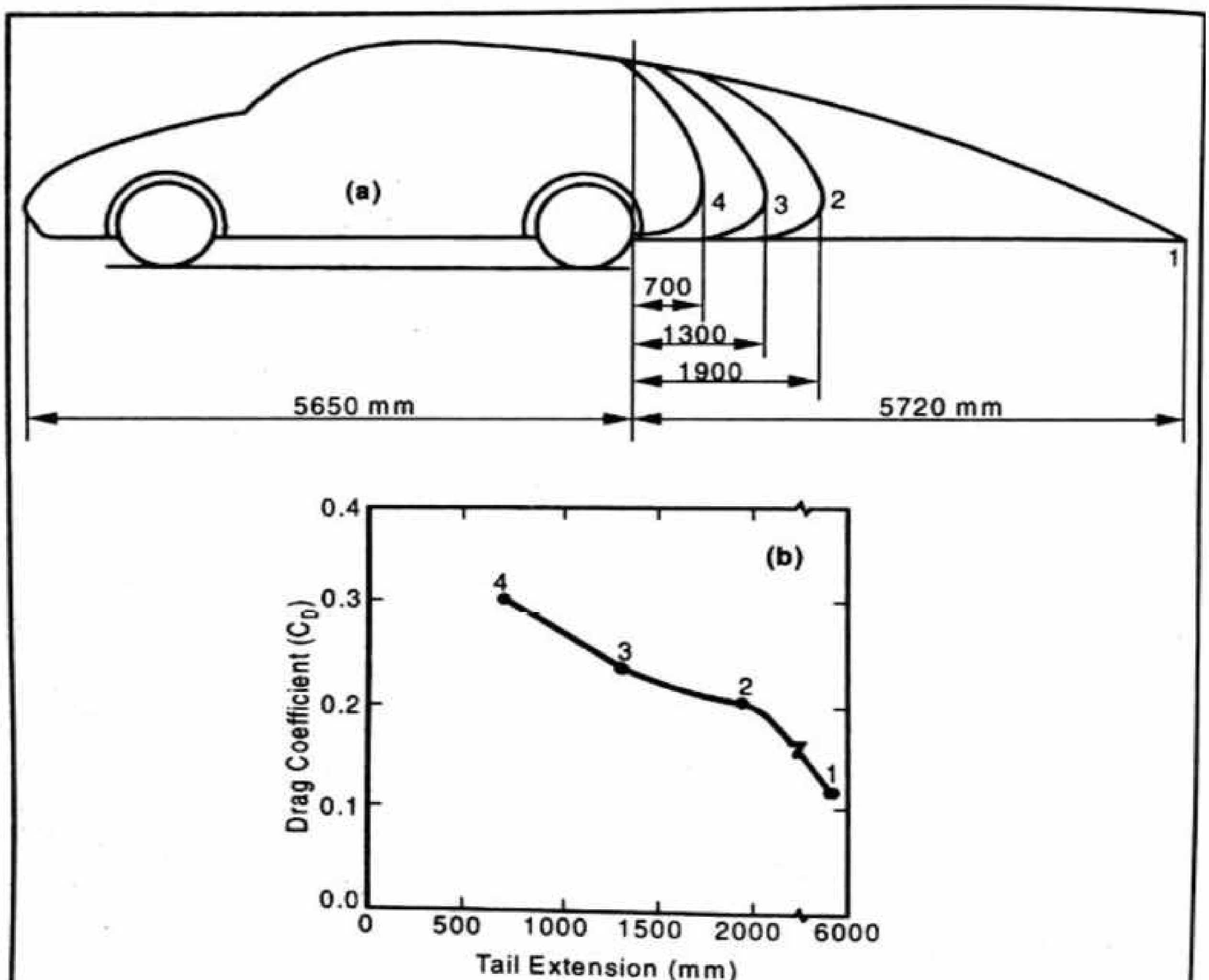


Fig. 6.21 Effect of Rear End Tail Extension on Drag Coefficient

7. **Underbody roughness:**

- The effect of underbody roughness on coefficient of drag is shown in Fig. 6.22.
- For smaller ground clearance, if the roughness value increases then the drag coefficient will be increased.
- For larger ground clearance value, minimum drag coefficient is obtained. (Comparing to smaller ground clearance)

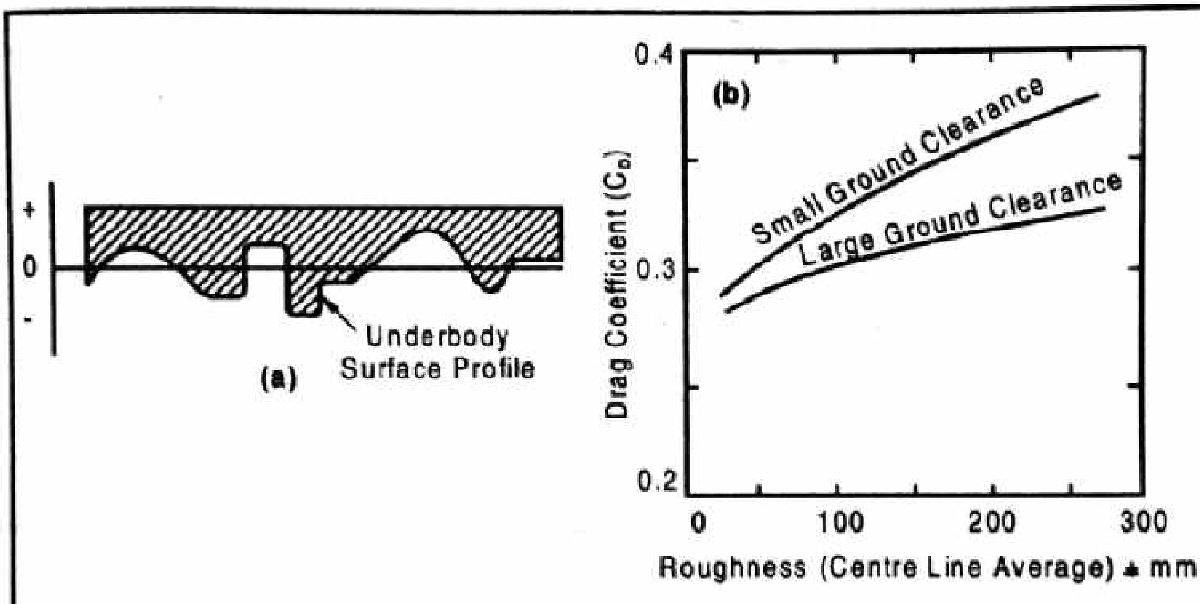


Fig. 6.22 Effect of Underbody Roughness on Drag Coefficient

AERODYNAMIC LIFT CONTROL

- The different methods for controlling aerodynamic lift are:
  1. Underbody dams
  2. Exposed wheel air flow pattern
  3. Partial enclosed wheel air flow pattern
  4. Rear end spoiler
  5. Negative lift aerofoil wings

1. Underbody dams:

- The effects of underbody front and rear end air dams relative to the lift and drag coefficient is shown in Fig. 6.23.
- Using the rear end underfloor air dam, the increase of underfloor air flow pressure raises the aerodynamic up thrust. Hence the positive lift is produced.
- Using the front-end underfloor air dam, the underfloor air flow pressure is reduced. Hence, aerodynamic down thrust is generated (i.e. Negative lift).

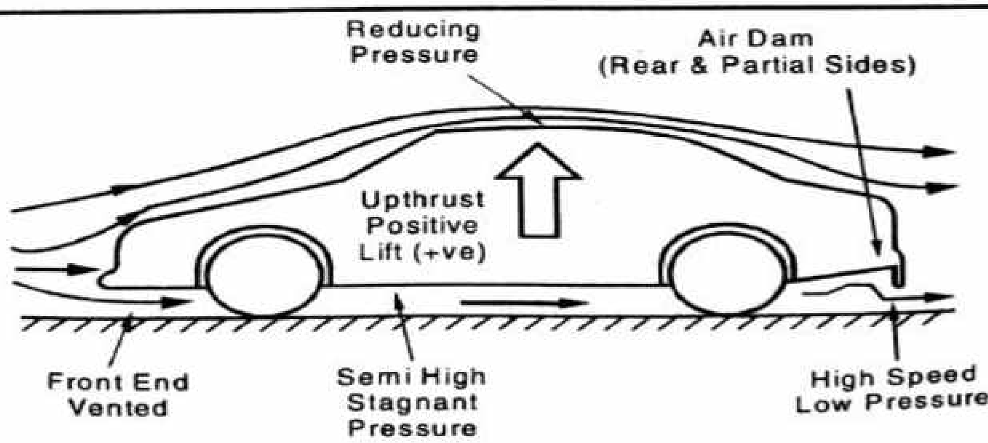


Fig. 6.23 (a) Rear End Underbody Air Dam

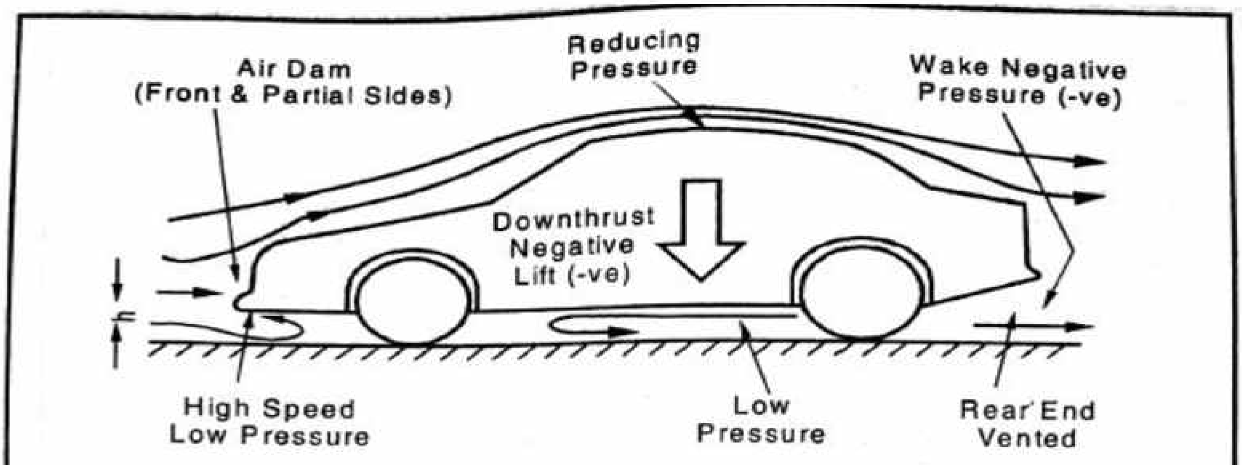


Fig. 6.23 (b) Front End Underbody Air Dam

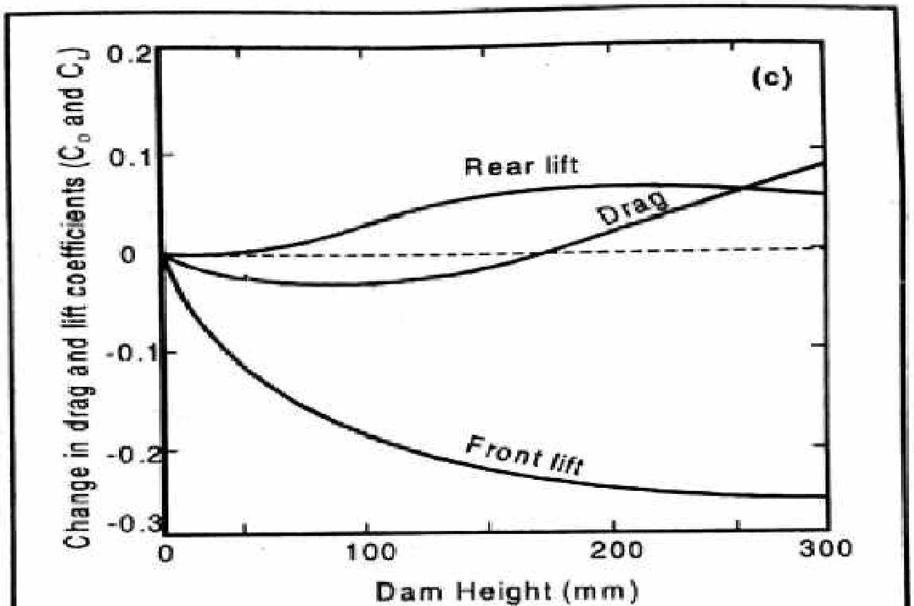


Fig. 6.23 Effect of Underbody Front and Rear End Air Dams Relative to the Lift and Drag Coefficient

2. **Exposed wheel air flow pattern:**

- When a wheel rotates for some distance on the ground, air due to its viscosity attaches itself to the tread.
- This in turn induces some of the surrounding air to be dragged around with it.
- The exposed wheel's air flow pattern can be seen in Fig. 6.24.
- In the lower region of the wheel, the flow of air will be stagnant but majority of air stream will flow against the wheel rotation.
- Then, it separates from vortex rim and continues to flow towards the rear.
- A series of turbulent vortices can be seen (shown in Fig. 6.24(b)).
- The air pressure distribution (around the wheel) will give a positive pressure build up in the stagnant air flow front region.

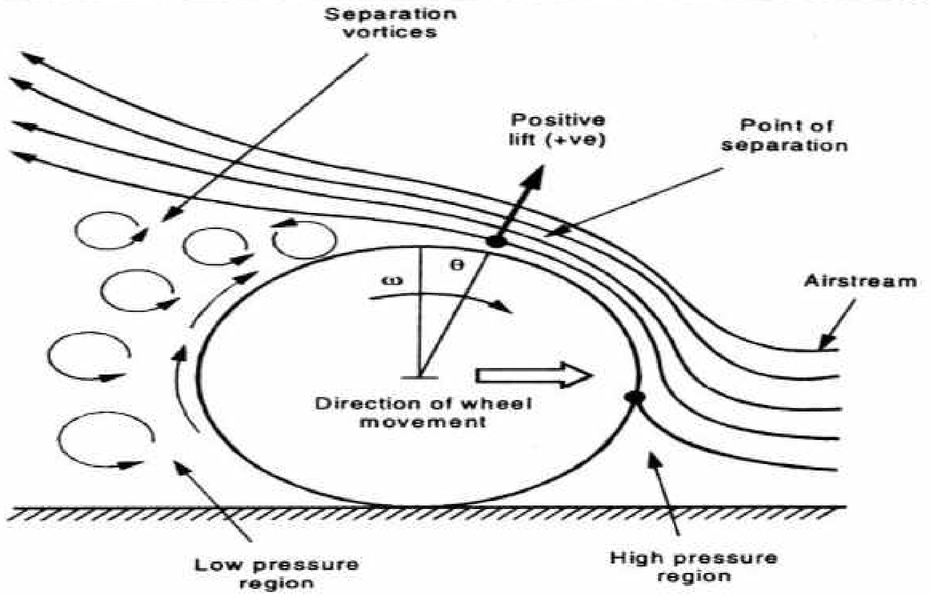
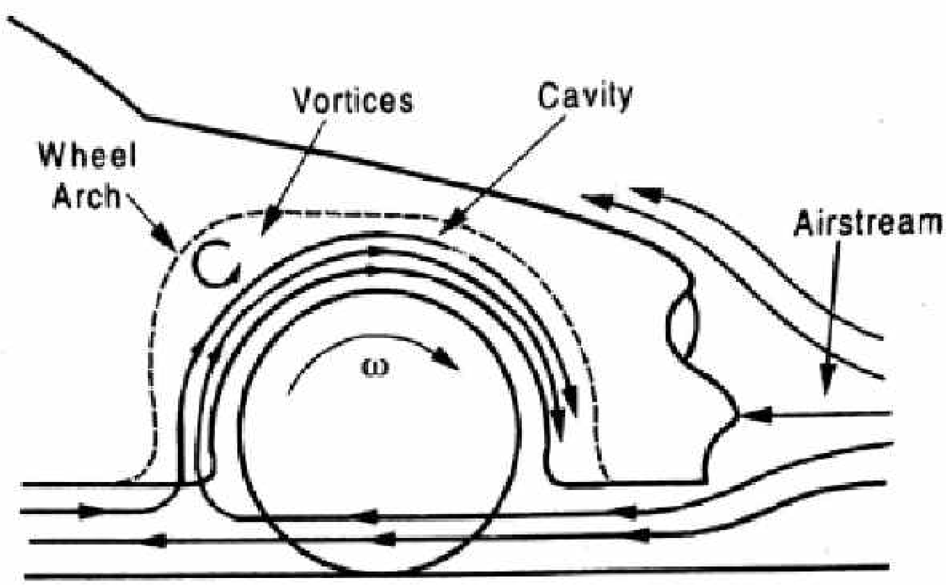


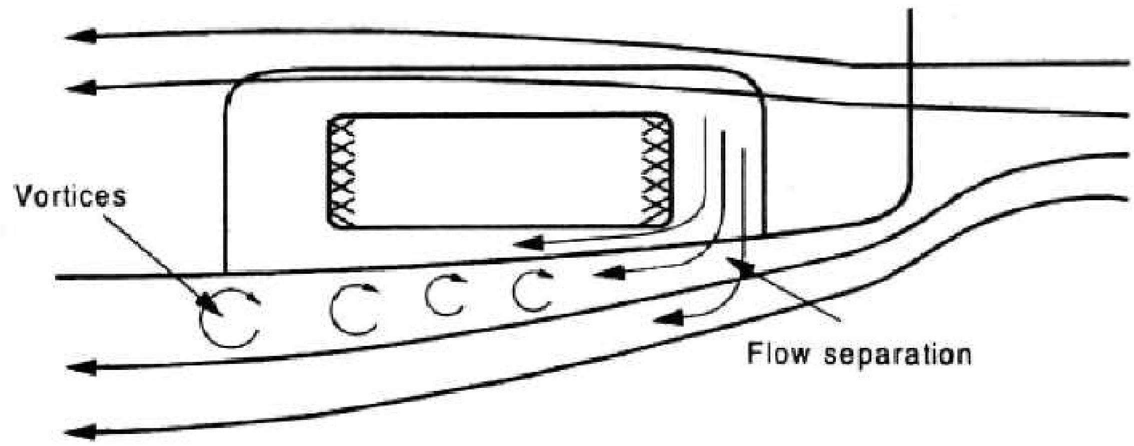
Fig. 6.24(b) Air flow pattern with wheel rolling on the ground

3. **Partial enclosed wheel air flow pattern:**

- The air flow under the car's front initially moves faster than the main stream.
- At the rotating wheel, the flow pattern can be seen in Fig. 6.25
- The air entrapped in the wheel arch cavity circulates towards the upper front of wheel due to a slight pressure build up.
- Then it is expelled through the front-end wheel to the mudguard gap which is a lower pressure in both a downward and sideward direction.
- The effect of underside ground clearance on both lift and drag coefficient is shown in Fig. 6.25.



(a) Side View



(b) Plan view

Fig. 6.25 Wheel Arch Air Flow Pattern

- Increasing the h/D ratio, the wheel drag coefficient is reduced. Also, the wheel lift coefficient is decreased gradually.

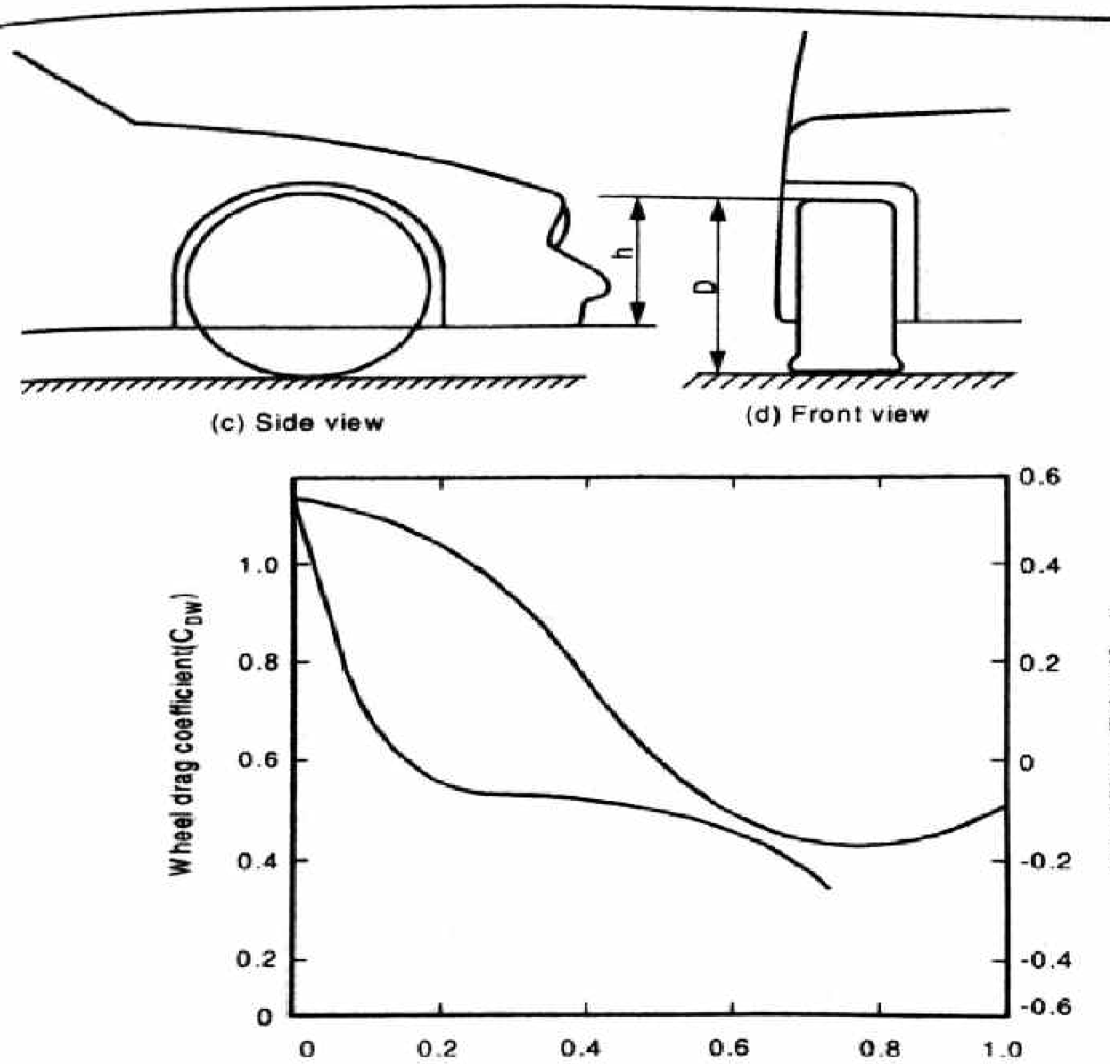


Fig. 6.25 (E) Effect of Underside Ground Clearance on Both Lift and Drag Coefficients

4. **Rear end spoiler:**

- The effect of rear end spoiler on both lift and drag coefficients is shown in Fig. 6.26.
- A lip (or) small aerofoil spoiler is attached to the car boot's rear end. It interrupts the smooth streamline air flow thereby slowing down the air flow and increasing the upper surface local air pressure which effectively raises the downward force known as negative lift.
- By increasing the spoiler lip height, there is a general increase in front lift and the rear lift decreases, (from graph)
- But the drag coefficient drops initially and marginally increases.

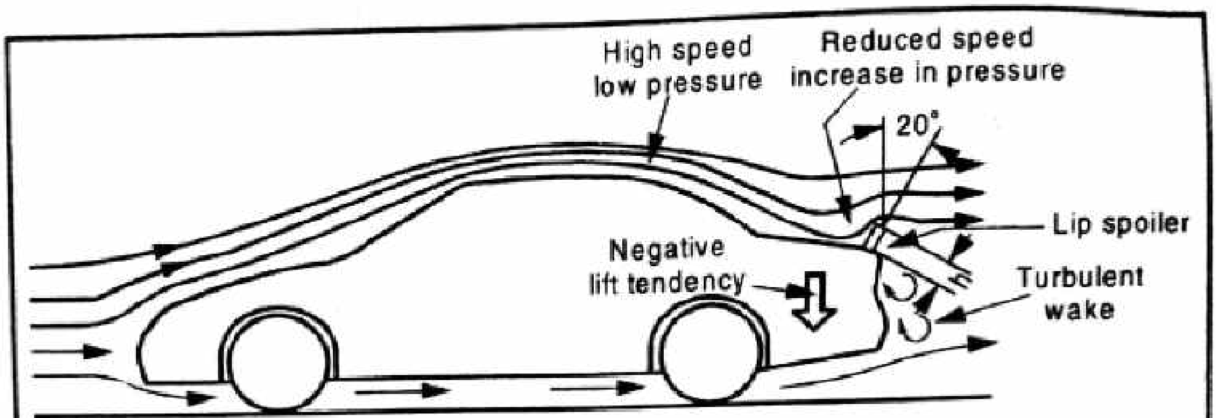


Fig. 6.26(a)

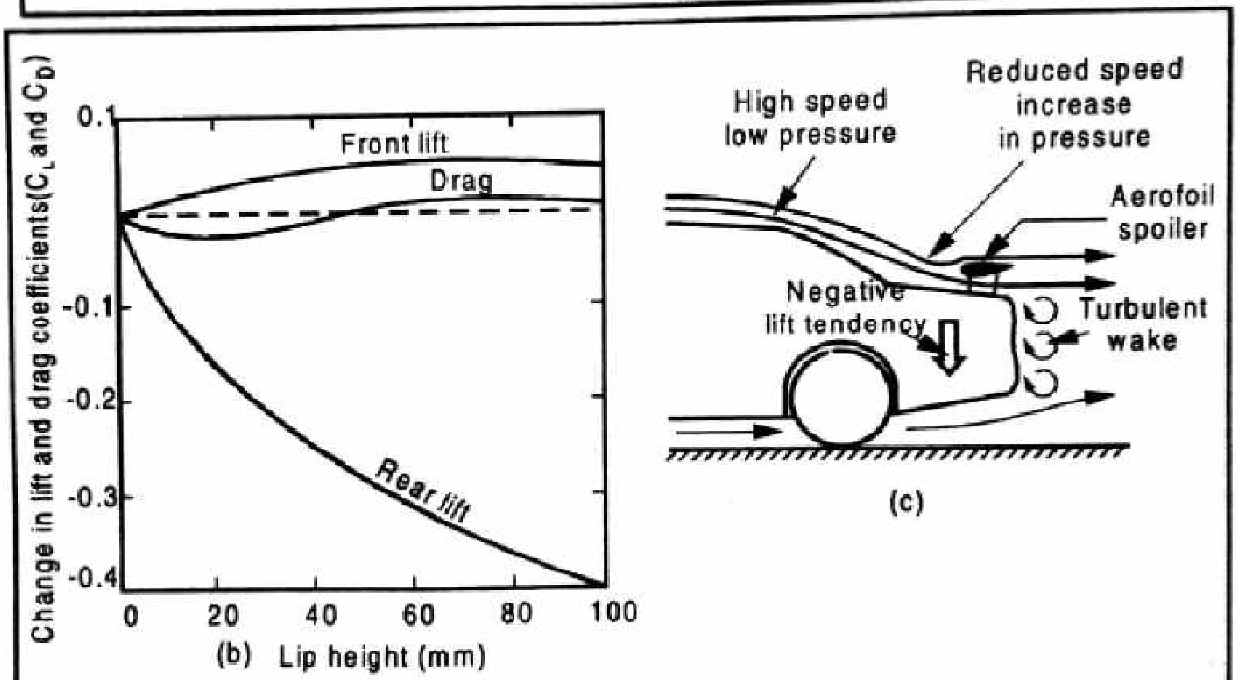


Fig. 6.26 Effect of Rear End Spoiler on Both Lift and Drag Coefficients

5. **Negative lift aerofoil wings:**

- The negative lift aerofoil wing is shown in Fig. 6.27.
- A negative lift wing is attached to the rear end of the car to generate a downward thrust.
- This enables the traction generated by the rear driving wheels to be increased.
- By enlarging the lilt angle of wing, more negative lilt (downforce) is produced.
- In racing car, aerofoil wing is attached as shown in Fig. 6.27.