Automotive Design
Braking System

• 3 Requirements
  - decelerate in a controlled repeatable manner
  - help maintain constant speed down hill
  - hold vehicle stationary on a flat or on a gradient
Should work in diverse conditions

- Slippery, wet and dry roads
- Rough or smooth road
- Split friction surfaces
- Straight line braking or when braking on a curve
- Wet or dry brakes
- New or worn linings
- Laden or unladen vehicle
- Vehicle pulling a trailer or caravan
- Frequent or infrequent applications of short or lengthy duration
- High or low rates of deceleration
- Skilled or unskilled drivers
Brake – Sub systems

- Energy source (muscular effort vacuum boost/power braking/surge brakes / spring brakes)

- Modulation System (to control brake force)

- Transmission systems (brake lines/tubes, brake hoses (flexible tube), rods /livers/cams/cables etc.)

- Foundation brakes
Four stages of Brakes system design

- Fundamental stage
  - choice of force distributing between axles
- Transmission System Design
  - sizing of master cylinder, rear & front wheel cylinders
- Foundation system design
  - to apply loads & torque
  - thermal, wear & noise characteristics
- Pedal assembly and vacuum boost system
Vehicle parameters required for brake system design

- Laden and unladen vehicle mass
- Static weight distribution when laden and unladen
- Wheelbase
- Height of center of gravity when laden and unladen
- Maximum vehicle speed
- Tyre and rim size
- Vehicle function
- Braking standards
Brake System Components & Configurations

- Pedal assembly
- Brake booster
  - to reduce manual pressure
  - vacuum booster (uses negative pressure in intake manifold)
- Master cylinder
  - initiates & control braking
  - two separate braking circuits (primary & secondary)
-2 pistons in the same cylinder
- If one system has a leak, the other takes care

Regulating valves
- When load transferred to the front, braking at rear need to be reduced

3 types
- Load sensitive (based on suspension displacement)
- Pressure sensitive
- Deceleration sensitive
Contd..

- Foundation brakes
  - Disc brakes/ Drum brakes
  - If both are discs, a small drum type parking brake also used

- Brake System Layout
  - 2 variants- II & X
Kinematics of Braking

\[ S_1 = Ut_1 \]

\[ S_t = S_1 + S_2 = Ut_1 + \frac{U^2}{2a} \]

\[ S_t = S_1 + S_2 = Ut_1 + \frac{U^2}{2a} \]
Assumptions

- instantaneous change in deceleration
- no driver reaction time
- no system response time
- no deceleration rise time
- no release time
Typical Measured Deceleration time-history

- Driver reaction time
  \[ t_0 - t_1 \]
  - driver responds & move his foot to the pedal
- Initial system response time
  \[ t_1 - t_2 \]
  - up to start of breaking force at tyre
- Deceleration rise time
  - time to reach peak deceleration
  \[ t_2 - t_3 \]
- Breaking time
  \( t_3 - t_4 \)
  - till vehicle stops
- Release time
  \( t_4 - t_5 \)
  - brake release starts to end of brake force
- Stopping time
  \( t_0 - t_4/t_5 \)
- Braking time
  \( t_1 - t_4/t_5 \)
Kinematics of braking

\[ S_1 = U(t_1 - t_0) \]

\[ S_2 = U(t_2 - t_1) \]

\[ S_3 = U(t_3 - t_2) - \frac{a_f (t_3 - t_2)^2}{6} \]

\[ S_4 = \frac{1}{2a_f} \left[ U^2 + \frac{a_f^2 (t_3 - t_2)^2}{4} - Ua_f (t_3 - t_2) \right] \]
Contd..

Stopping distance

\[ S_s = \sum_{i=1}^{4} S_i \]

Braking distance

\[ S_b = \sum_{i=2}^{4} S_i \]
Kinematics of Braking

\[ \sum F_x = M \ddot{x} \]

\[ -T_f - T_r - D - P \sin \theta = M \ddot{x} \]

\[ Md = T_f + T_r + D + P \sin \theta = T \]

\[ \int_{v_0}^{v_f} dv = -\frac{T}{M} \int_0^{t_b} dt \]

\[ x = \frac{M v_0^2}{2T} \]

\[ t_b = \frac{M v_0}{T} = \frac{v_0}{d} \]
For maximum deceleration

- both axles should be on verge of lock simultaneously

\[ Pz = T = P \mu \]

\[ z = \frac{d}{g} \]

- If \( d > g \), \( \mu > 1.0 \)

(depends on tyre compound)
Retardation force

- Primarily foundation braking
- Rolling resistance (=0.01g)
- Aerodynamic drag(proportional to \(v^2\) at high speed) =0.03g
- gradient(uphill/down hill)
- Drivetrain drag
  - can contribute to the braking effort or use brake torque
Tyre-road friction

- Brake force (and hence torque) can not increase unbounded
- Limited by tyre road friction
- Depends on tyre & road surface and road condition
  - Dry clean road: $0.8 < \mu < 1$
  - Icy surfaces: $0.05 \leq \mu \leq 0.1$
  - Wet surfaces contaminated by dirt: $0.2 \leq \mu \leq 0.65$
Mechanism of friction

- Adhesion (intermolecular bonds between rubber & surfaces)
- Hysteresis
  - Energy loss during rubber deformation during slip
- Both rely on slip

\[ \omega = \frac{v - \omega r}{v} \]
Friction depends on slip

- Adhesion & hysteretic phenomenon increase with slip up to 20% slip
- If slip > 20%, $\mu_b$ decreases
- Lateral brake force during turning depend on slip angle
- Lateral forces minimum when wheel is locked
Brake Proportioning

• If rear and front braking is not apportioned
  – Insufficient deceleration
  – Front axle lock (lack of steering control)
  – Rear axle lock (instability)
  – In either case – incomplete utilization of available friction (road adhesion)
load transfer during braking

• A variable brake effort ratio is required to provide ideal braking.

• Factors
  – Change in vehicle weight;
  – Change in weight distribution;
  – The effect of gradients (positive and negative);
  – Cornering, (also lateral forces);
  – Varying road surfaces and weather conditions;
  – Split friction surfaces where the coefficient of adhesion changes from front to rear
Effect of constant brake ratio

\[ M_d = T_f + T_r \]

\[ M_g z = T_f + T_r = P_z \]

\[ M \ddot{y} = \sum F_y = R_r + R_f - Mg = 0 \]

\[ I \ddot{\theta} = \sum M_{cg} = R_f a - R_r b - T_f h - T_r h = 0 \]

\[ R_f = \frac{Mgb}{l} + \frac{h}{l} (T_f + T_r) \]

\[ R_r = \frac{Mga}{l} - \frac{h}{l} (T_f + T_r) \]

\[ R_f = F_f + \frac{P_z h}{l} \]

\[ R_r = F_r - \frac{P_z h}{l} \]
If front axle locks first (fixed brake ratio)

\[ T_f = \mu R_f = \mu \left( F_f + \frac{Pzh}{l} \right) \]

- Consider brake ratio \( R = \frac{x_f}{x_r} = \frac{T_f}{T_r} \)

- Rear Brake force \( T_r = T_f \frac{x_r}{x_f} = \mu \left( F_f + \frac{Pzh}{l} \right) \frac{x_r}{x_f} \)

- Total Brake force \( T = Pz = T_f + T_r = \mu \left( F_f + \frac{Pzh}{l} \right) + \mu \left( F_f + \frac{Pzh}{l} \right) \frac{x_r}{x_f} \)

\[ T = Pz = \mu \left( F_f + \frac{Pzh}{l} \right) \frac{1}{x_f} \quad \text{OR} \quad T x_f = \mu \left( F_f + \frac{Pzh}{l} \right) \]

- Maximum braking deceleration \( z = \frac{l \mu F_f}{P(l x_f - \mu h)} \)
Similarly, if the rear axle locks first

- Deceleration if rear axle locks first

\[ z = \frac{l \mu Fr}{P(lx_r + \mu h)} \]

\[ \frac{T_f}{P} = x_f z \]

\[ T_{xf} = \mu \left( F_f + \frac{Pzh}{l} \right) \]

\[ \frac{T_r}{P} = x_r z \]

\[ T_{xr} = \frac{\mu}{P} \left( F_r - \frac{Pzh}{l} \right) \]

- \( T_{xf/r} \) ---- Available braking force
- \( T_{f/r} \) ------ Total Braking force
Which wheel locks first?

• Depends on which $z$ is lower (at $a$ or at $b$)?
• Once one wheel locks, adhesion utilization is not complete
• Enough brake force not generated by tyres
Brake efficiency \[ \eta = \frac{Z}{\mu} \]

- If front axle locks

\[
\frac{l \mu F_f}{P(l x_f - \mu h)} = \frac{F_f}{P\left(\frac{x_f - \mu h}{l}\right)}
\]

- If rear axle locks

\[
\frac{l \mu F_r}{P(l x_r + \mu h)} = \frac{F_r}{P\left(\frac{x_r + \mu h}{l}\right)}
\]
Graph of Efficiency, $\eta$

- Before point ‘a’, front axle lock happens
- After that Rear axle lock happens
- In both cases $\eta$ falls

![Graph showing efficiency changes with tyre-ground adhesion coefficient]
Deceleration vs adhesion

- To the right of ‘a’, during rear axle lock, efficiency is low
- Similarly to the right

![Graph showing deceleration vs adhesion with labels for optimum, front axle lock, and rear axle lock]
Adhesion utilization

- Adhesion utilization, $f$, is the theoretical coefficient of adhesion required to act at the tyre–road interface of a given axle for a particular value of deceleration.
- the minimum tyre–ground adhesion to sustain a given deceleration
- ratio of the braking force to the vertical axle load during braking.

For the front of the vehicle the adhesion utilization is defined by

$$f_f = \frac{T_f}{R_f} = \frac{x_f P_z}{F_f + \frac{P_{zh}}{l}}$$

Similarly, for the rear of the vehicle

$$f_r = \frac{T_r}{R_r} = \frac{x_r P_z}{F_r - \frac{P_{zh}}{l}}$$
• The optimum line --- unit gradient
• defines the ideal adhesion utilization
• brake system remains 100% efficient over all possible values of deceleration.
• K limit -- The upper limit on allowable adhesion utilization, defined in the EEC Braking Directive,
• remaining two lines define the axle adhesion characteristics for the vehicle.
• The point labelled a, ----- both axles are on the verge of lock.
• At other points --- axle having the highest adhesion utilization coefficient limits the braking performance
• braking is limited by front axle lock up to a deceleration of 0.52g.
• Thereafter braking is limited by rear axle lock.
• It is also possible to find from this diagram the maximum deceleration for a given coefficient of adhesion utilization.

Adhesion utilization, datum prototype vehicle
• does not meet the required standard
  • front axle adhesion curve does not lie above that of the rear axle for all values of deceleration between 0.15g and 0.8g.
• \( \therefore \) Change brake ratio in favour of the rear axle
  • point a to move up the optimum adhesion line.
• The limiting deceleration is set at 0.8g
• new brake ratio of \( \frac{x_f}{x_r} = \frac{0.803}{0.197} \).
• Gives a modified adhesion diagram
For category $M_1$ vehicles,
- adhesion utilization of the front axle must be greater than that of the rear
- for all load cases and deceleration between 0.15g and 0.8g.

**Between deceleration levels of 0.3g and 0.45g, an inversion of the adhesion utilization curves is allowed**
- provided the rear axle adhesion curve does not exceed the line defined by $k = z$ by more than 0.05.

**Applicable within the area defined by the lines $k = 0.8$ and $z = 0.8$.**

ensures that the rear wheels do not lock in preference to the front wheels and

proportion of braking effort exerted at the front of the vehicle is limited
- the braking system does not become too inefficient.
**Front axle lock & vehicle stability**

- Lateral disturbance: side force $F_y$ due to gradient, sidewind or left to right brake
- Resultant force $F_R$ due to inertia force $F_x$ and lateral force $F_y$ causes a slip angle $\alpha$.
- $F_R$ is the direction in which the vehicle centre of gravity is moving.
- Lateral force $F_y$ balanced by side forces generated at the tyre
  - Front axle is locked ---- no side force at the front wheels
  - Side force is developed solely by the rolling rear wheels.
  - Gives rise to a total moment of $S_t b$.
- **This yaw moment has a stabilizing effect**
  - *longitudinal axis aligns with the CG direction*
  - *reduces the initial slip angle $\alpha$.*
- **∴ when the front axle is locked,**
  - vehicle cannot respond to any steering inputs
Rear axle lock and vehicle stability

- In rear axle lock
  - The torque is destabilizing
  - Causes uncontrolled yaw
- Vehicle should always have a preferred front axle lock
- Choose fixed brake ratio such that for $\mu=1$, both axles lock together at $1g$

\[
\frac{x_f}{x_r} = \frac{F_f + \frac{Ph}{l}}{F_r - \frac{Ph}{l}}
\]

- Shall ensure front axle lock on all surfaces