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

-Transmition 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)

Contd..

-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..

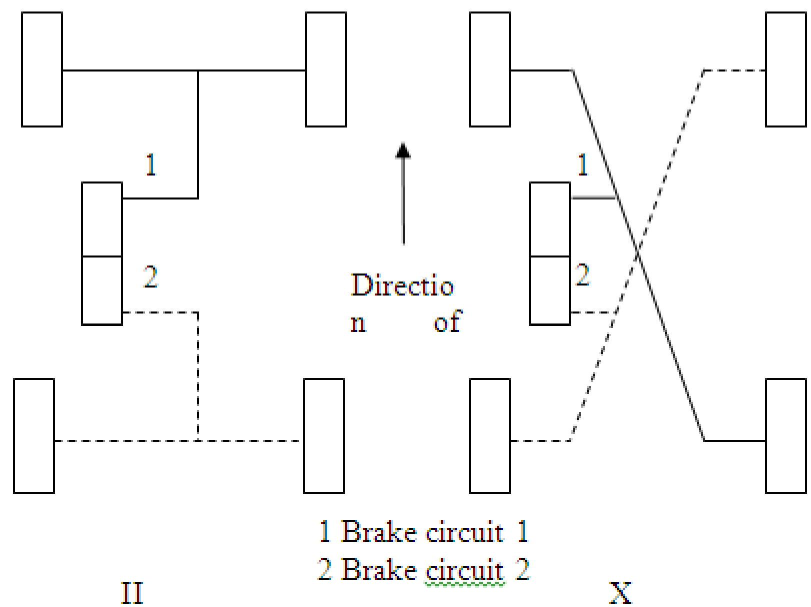
- Foundation brakes

  -Disc brakes/ Drum brakes

  -If both are discs , a small drum type parking brake also used

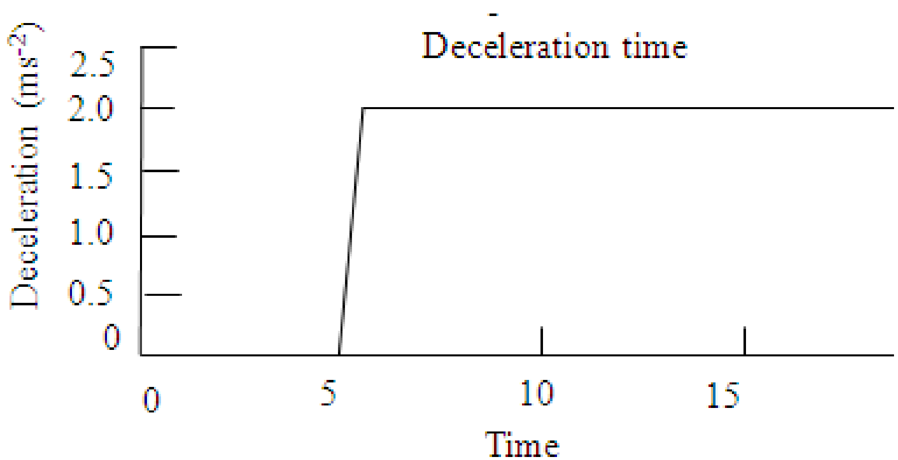
- Brake System Layout

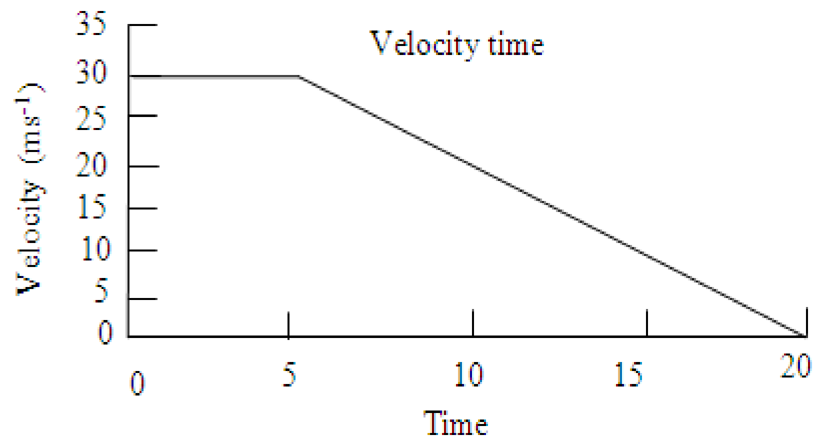
  -2 variants-II & X



Common brake system layouts

Kinematics of Braking

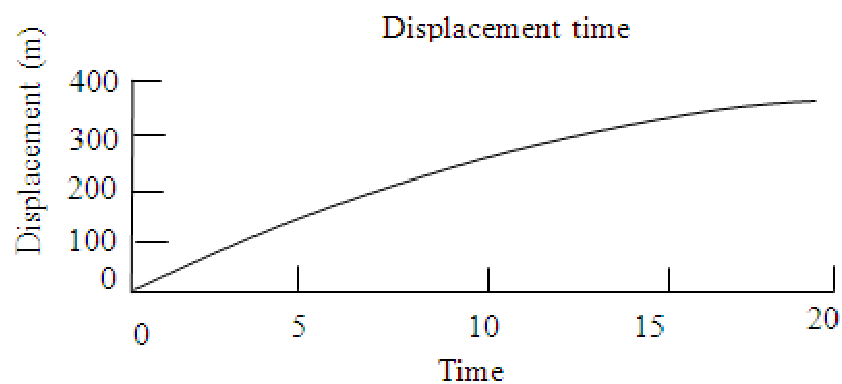




$$S_1 = Ut_1$$

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

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



Contd..

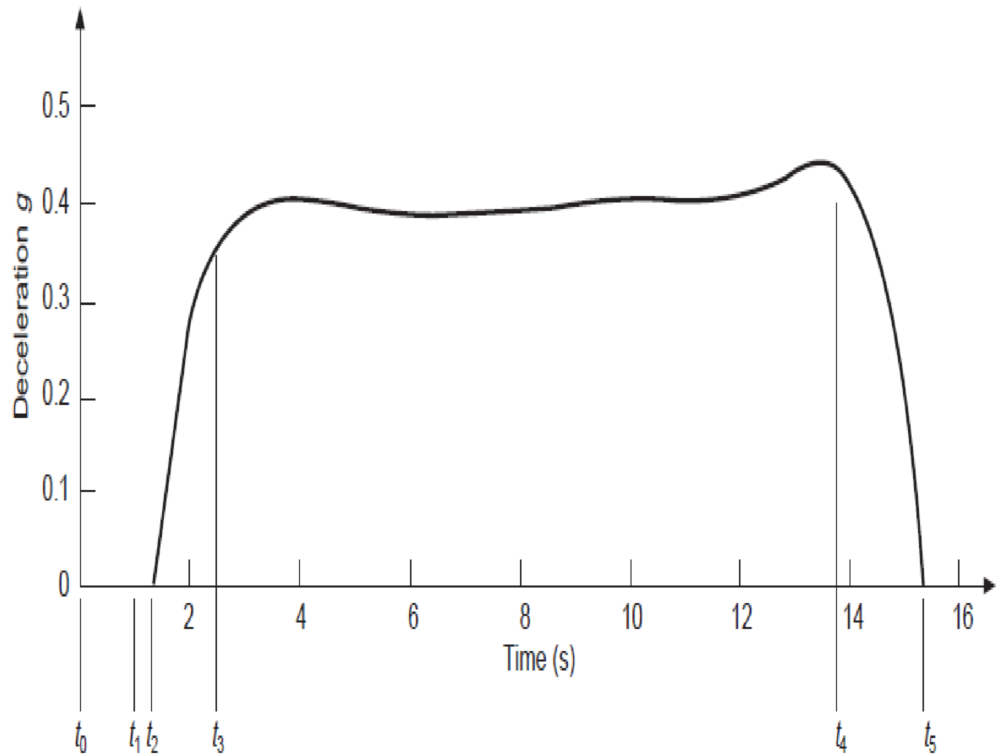
Assumptions

-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



Contd..

- Breaking time

  t_3-t_4

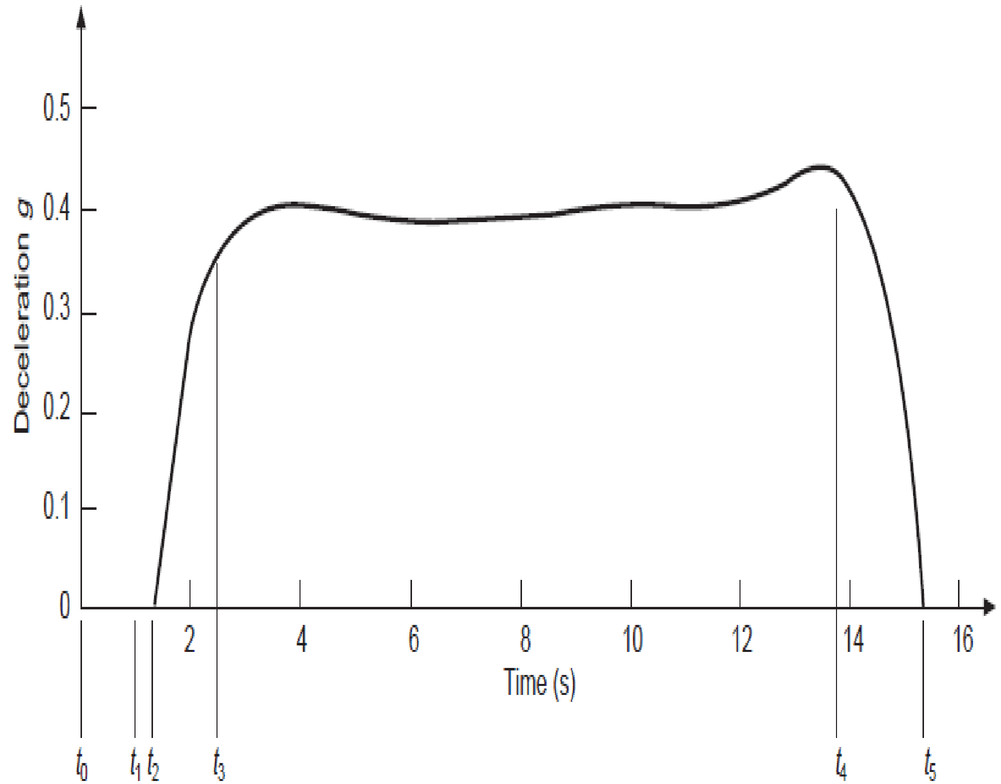
  -till vehicle stops
- Release time

  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



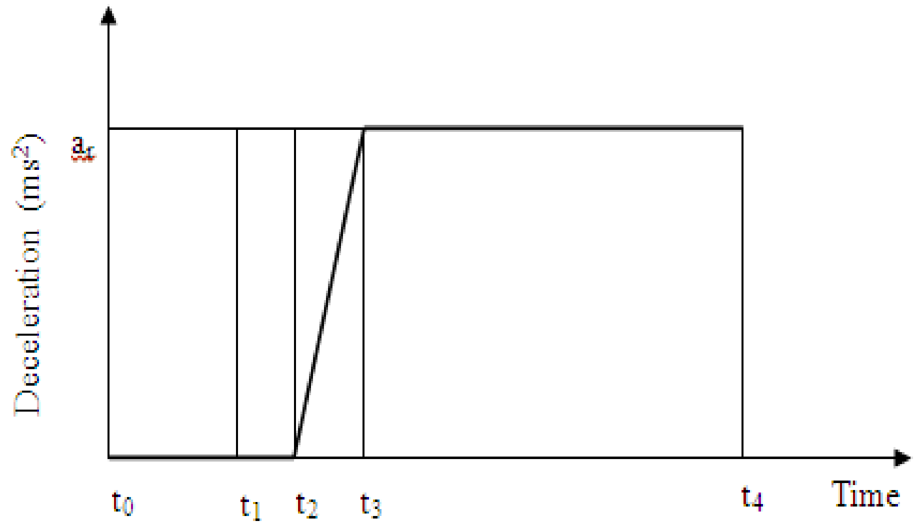
Kinematics of braking

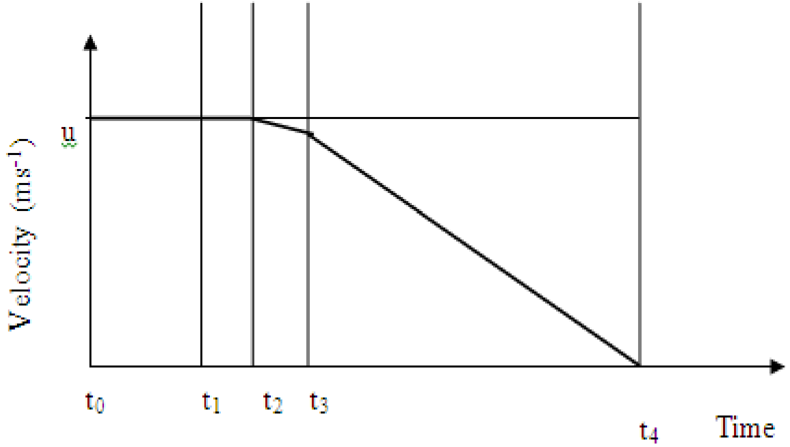
$S_1 = U(t_1 - t_0)$

$S_2 = U(t_2 - t_1)$

$$S_3 = U\left(t_3 - t_2\right) - \frac{a_f\left(t_3 - t_2\right)^2}{6}$$

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





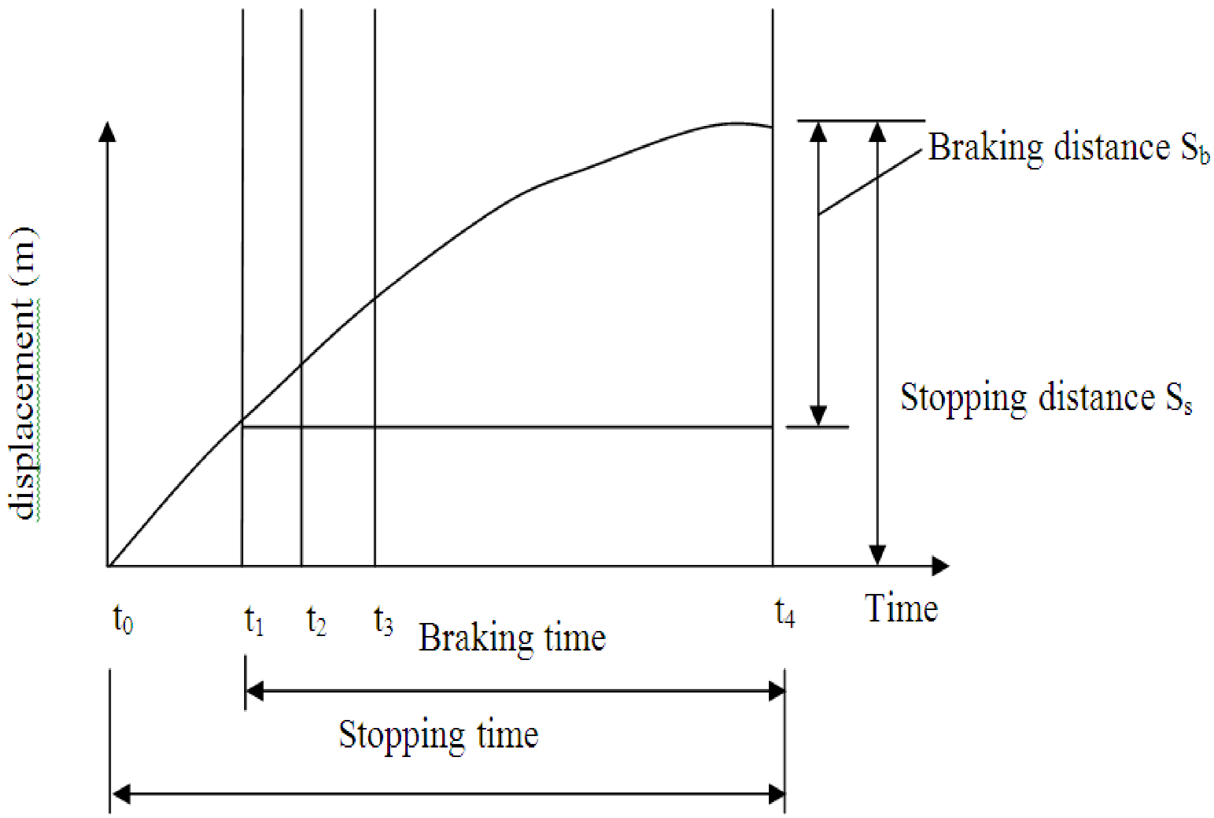
Contd..

Stopping distance

$$S_s = \sum_{i=1}^{4} S_i$$

Braking distance

$$S_b = \sum_{i=2}^{4} S_i$$



Kinematics of Braking

$$\sum F_X = M\ddot{x}$$

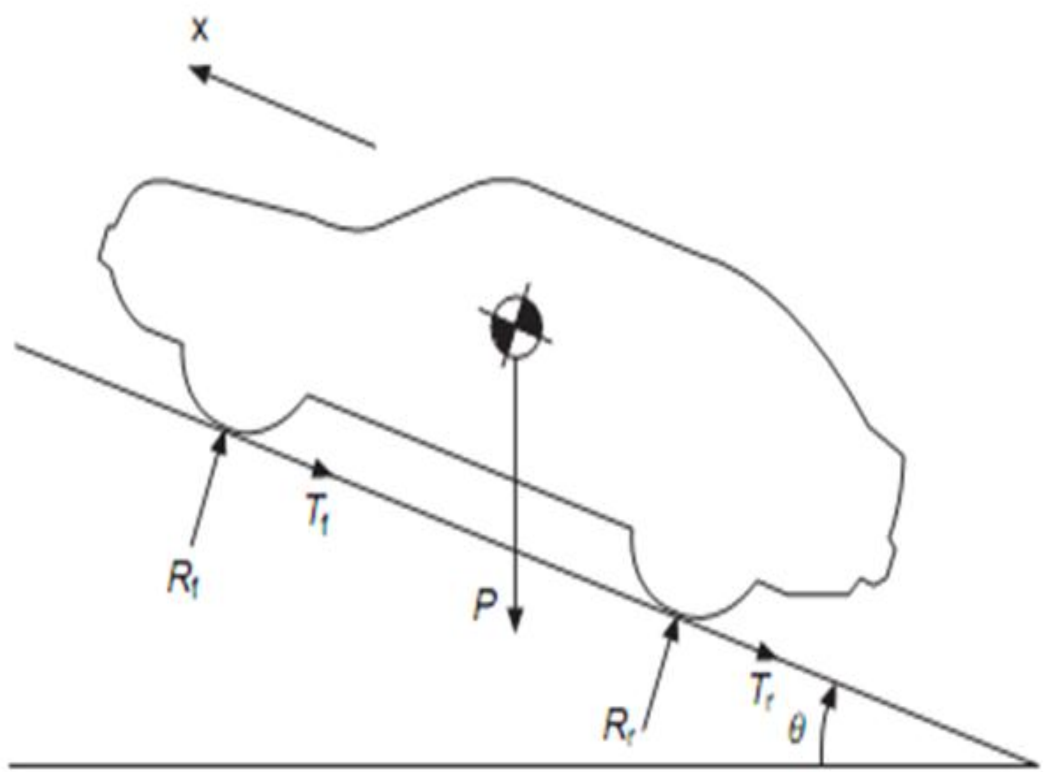
$$-T_f - T_r - D - P\sin\theta = M\ddot{x}$$

$$Md = T_f + T_r + D + P\sin\theta = T$$

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

$$x = \frac{Mv_0^2}{2T}$$

$$t_b = \frac{Mv_0}{T} = \frac{v_0}{d}$$



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 $0.05\leq\mu\leq0.1$

-wet surfaces contaminated by dirt $0.2\leq\mu\leq0.65$

Mechanism of friction

-Adhesion(intermolecular bonds between rubber & surfaces)

-hysteresis

- energy loss during rubber deformation during slip

-both rely on slip $= \frac{v - \omega r}{v}$

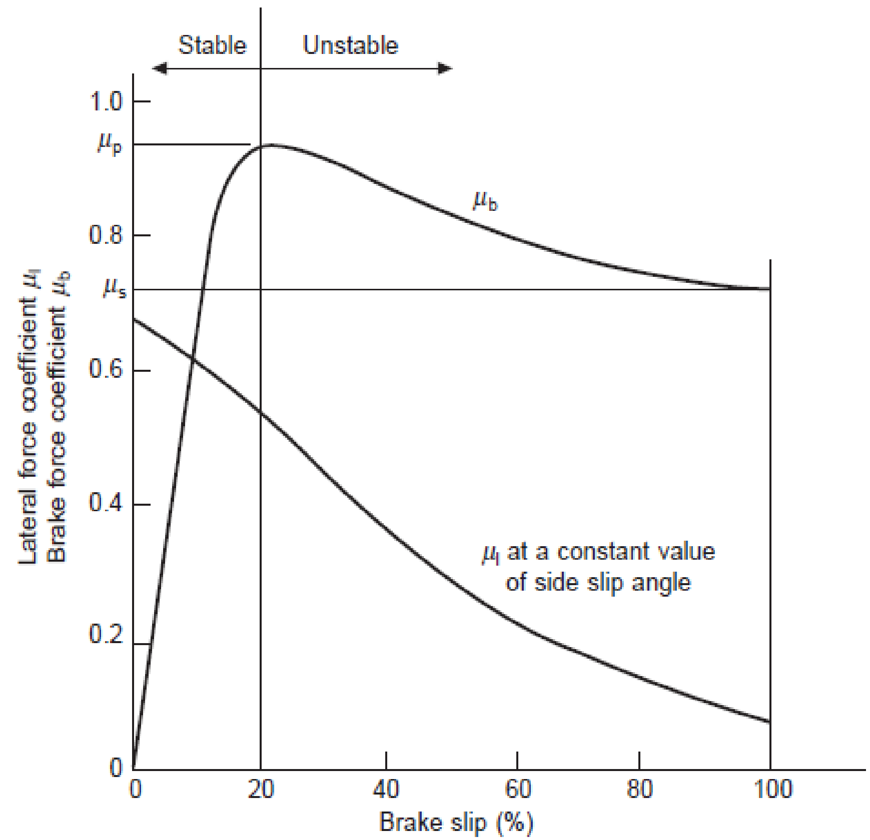
Friction depends on slip

-adhesion & hysteretic phenomenon increase with slip up to 20% slip

-if slip> 20% , μ_b decreases

-lateral brake force during turning depend on slip angle

-lateral forces minimum when wheel is locked



Brake force against wheel slip

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

$$Md = T_f + T_r$$

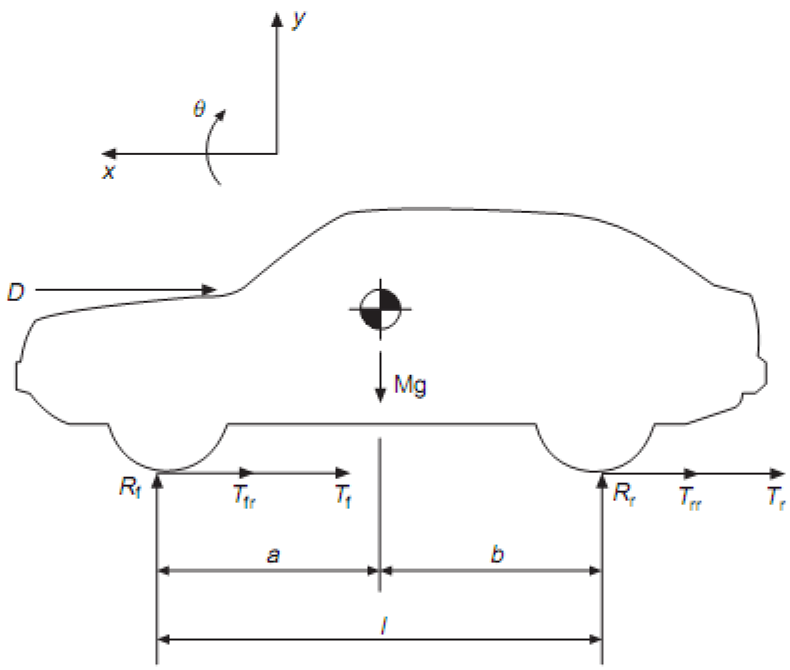
$$Mgz = T_f + T_r = Pz$$

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

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

$$R_f = \frac{Mgb}{l} + \frac{h}{l}\left(T_f + T_r\right) \qquad R_f = F_f + \frac{Pzh}{l}$$

$$R_r = \frac{Mga}{l} - \frac{h}{l}\left(T_f + T_r\right) \qquad R_r = F_r - \frac{Pzh}{l}$$



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 $R = \frac{x_f}{x_r} = \frac{T_f}{T_r}$

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

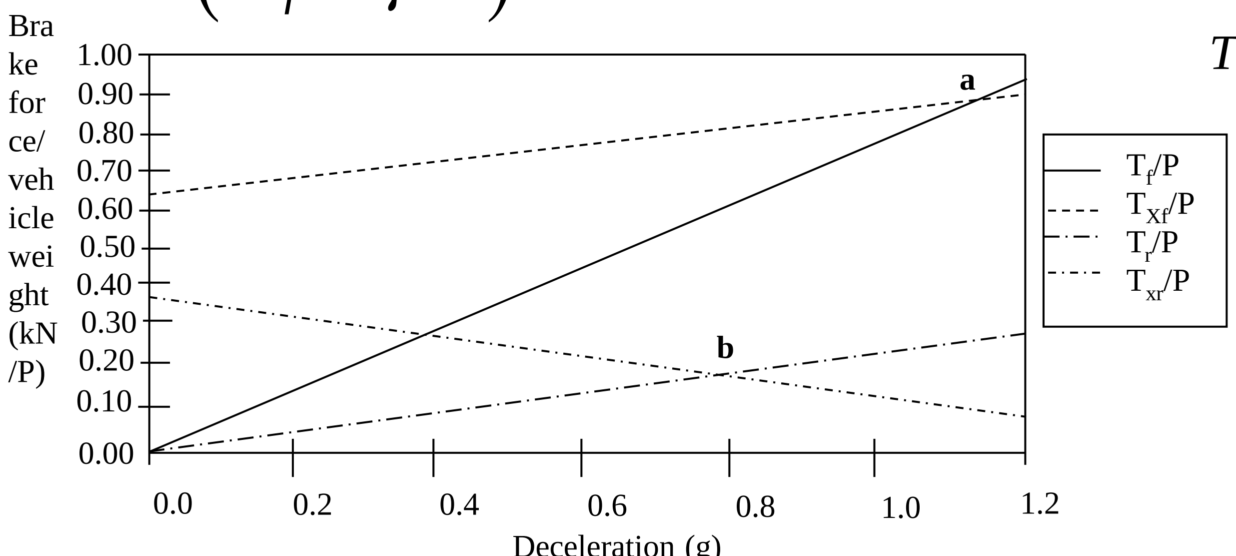
$$T = Pz = \mu\left(F_f + \frac{Pzh}{l}\right)\frac{1}{x_f} \quad \text{OR} \quad Tx_f = \mu\left(F_f + \frac{Pzh}{l}\right)$$

- Maximum braking deceleration $z = \frac{l\mu F_f}{P\left(lx_f - \mu h\right)}$

Similarly, if the rear axle locks first

- Deceleration if rear axle locks first

$$z = \frac{l\mu F r}{P\left(l x_r + \mu h\right)}$$



$$\frac{T_f}{P} = x_f z$$

$$Tx_f = \mu\left(F_f + \frac{Pzh}{l}\right)$$

$$\frac{T_r}{P} = x_r z$$

$$\frac{Tx_r}{P} = \frac{\mu}{P}\left(F_r - \frac{Pzh}{l}\right)$$

- $T_{xf/r}$ ---- 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

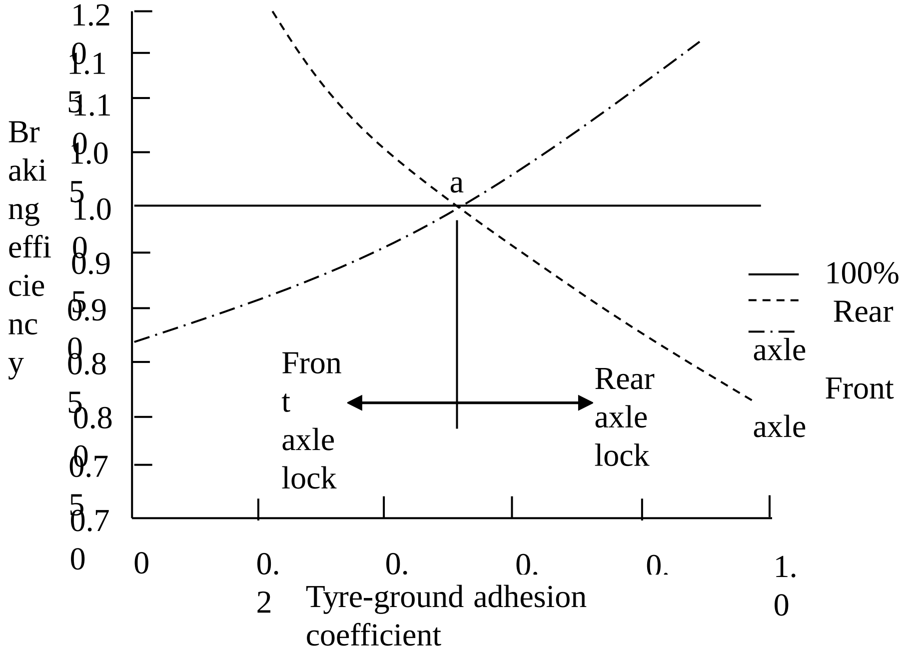
$$= \frac{\frac{l\mu F_f}{P\left(lx_f - \mu h\right)}}{\mu} \qquad = \frac{F_f}{P\left(x_f - \frac{\mu h}{l}\right)}$$

- If rear axle locks

$$= \frac{\frac{l\mu F_r}{P\left(lx_r + \mu h\right)}}{\mu} \qquad = \frac{F_r}{P\left(x_r + \frac{\mu h}{l}\right)}$$

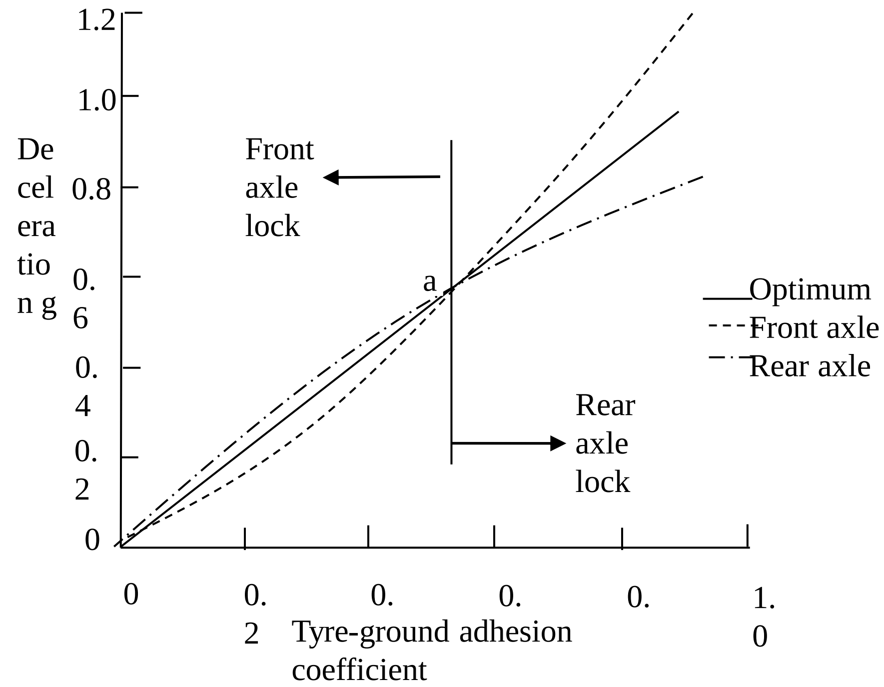
Graph of Efficiency, η

- Before point 'a', front axle lock happens
- After that Rear axle lock happens
- In both cases η falls



Deceleration vs adhesion

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



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.*

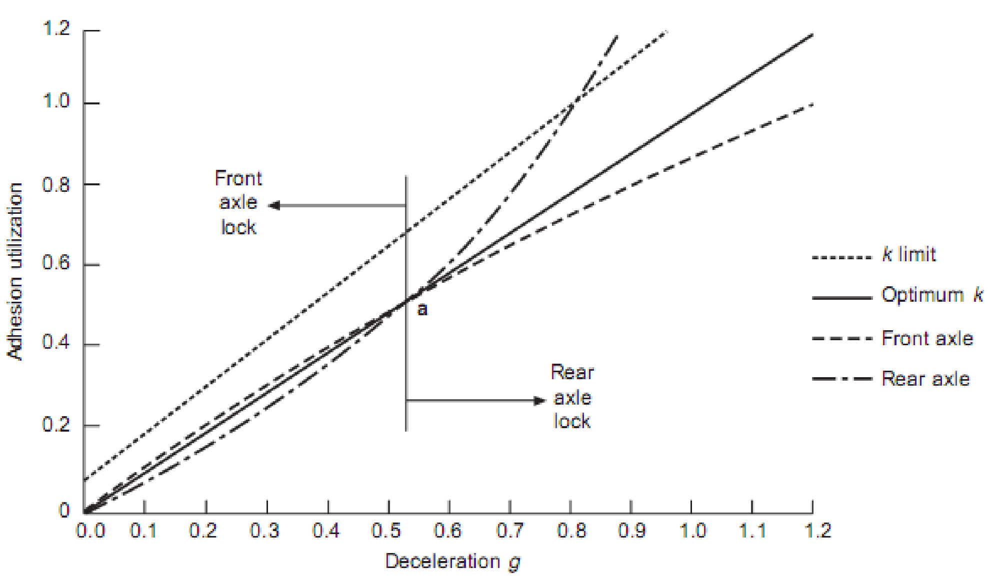
For the front of the vehicle the adhesion utilization is defined by

$$f_f = \frac{T_f}{R_f} = \frac{x_f Pz}{F_f + \frac{Pzh}{l}}$$

Similarly, for the rear of the vehicle

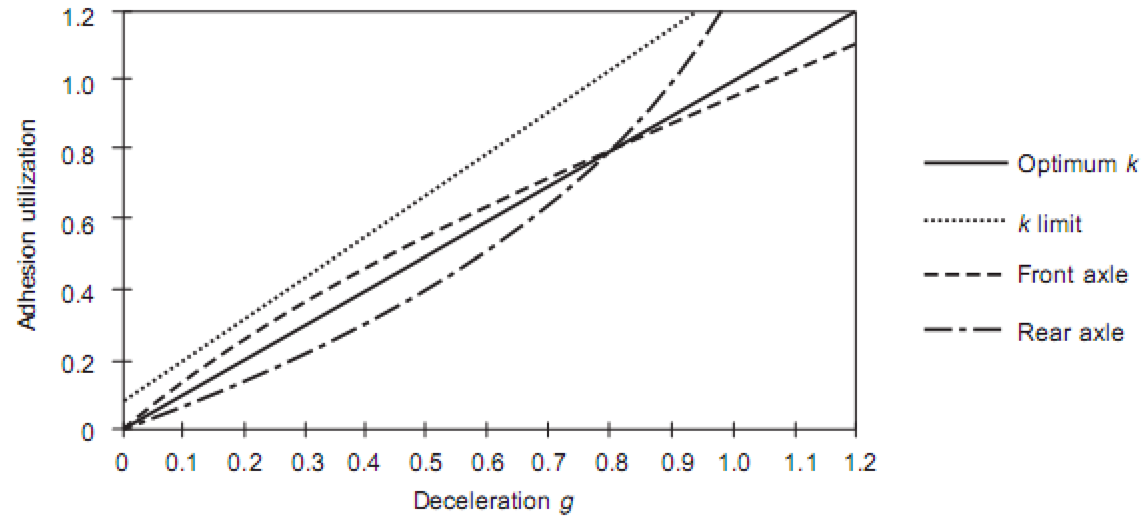
$$f_r = \frac{T_r}{R_r} = \frac{x_r Pz}{F_r - \frac{Pzh}{l}}$$

- 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.

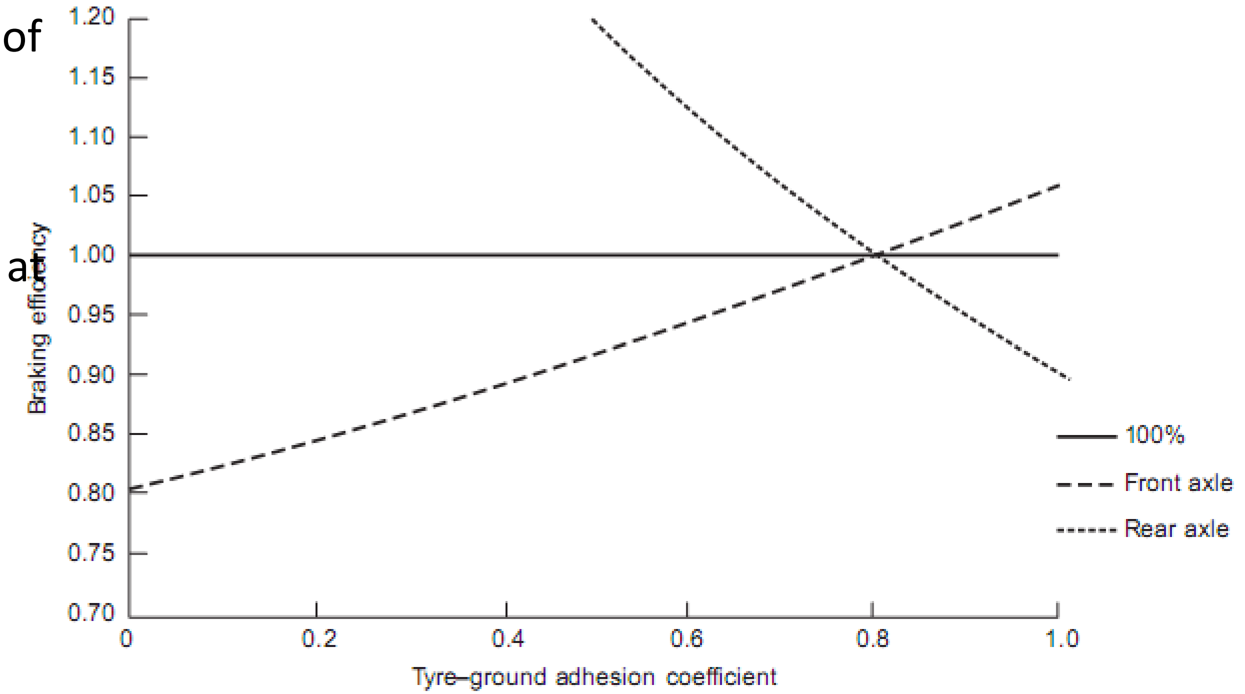


Adhesion utilization, datum prototype vehicle

- 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.
- ∴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

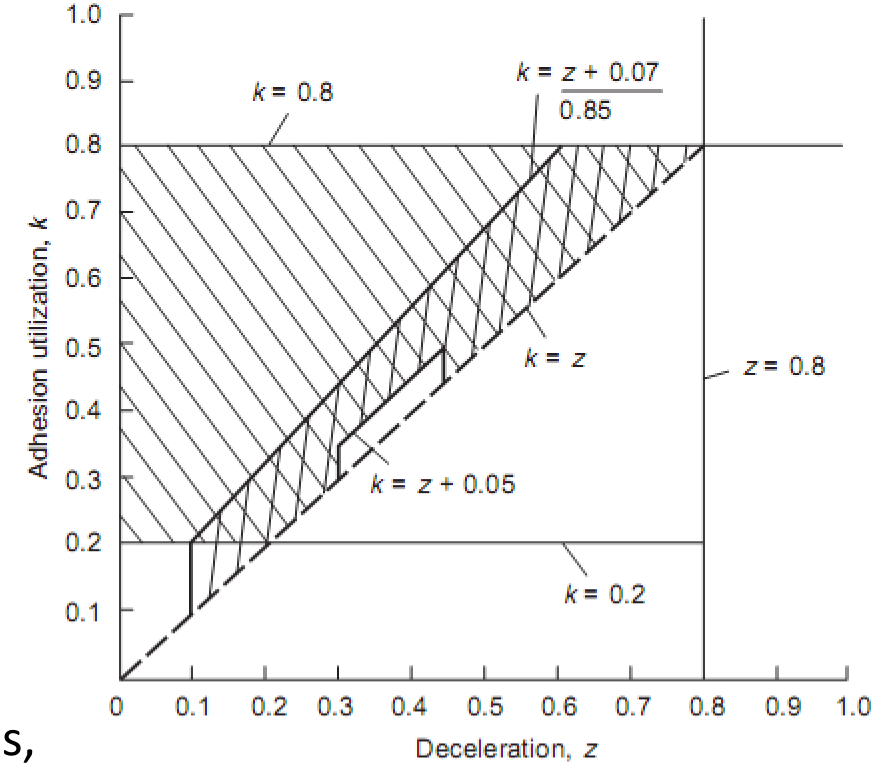


Adhesion utilization, modified prototype vehicle



Brake system efficiency of modified prototype vehicle with variable brake ratio

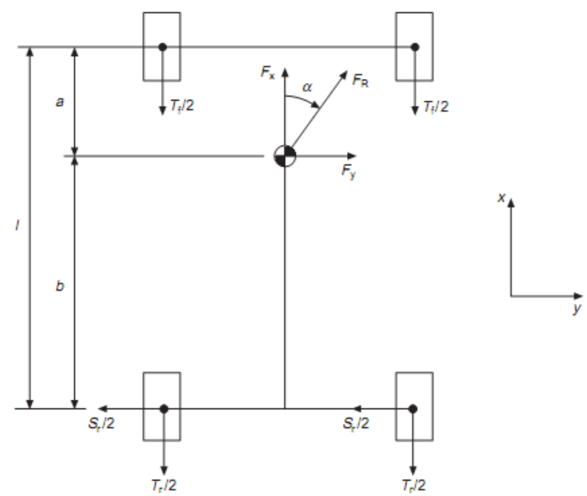
Adhesion utilization diagram for a category M_1 vehicle



- 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 0.15*g 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 α.
- 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 $S_r b$.
- *This yaw moment has a stabilizing effect*
  - *longitudinal axis aligns with the CG direction*
  - *reduces the initial slip angle α.*
- ∴ 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 detabilizing
  - Causes uncontrolled yaw
- Vehicle should always have a preferred front axle lock
- Choose fixed brake ratio such that for μ=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 a surfaces