Session-2

Thursday 17-12-2009; 2.00 PM-3.30 PM

Acceleration and Braking Performance

- Acceleration Performance:
  - Power Limited Acceleration
  - Traction Limited Acceleration
- Braking Performance:
  - Braking forces
  - Braking Performance
  - Wheel Lockup
  - Brake Proportioning
  - ABS

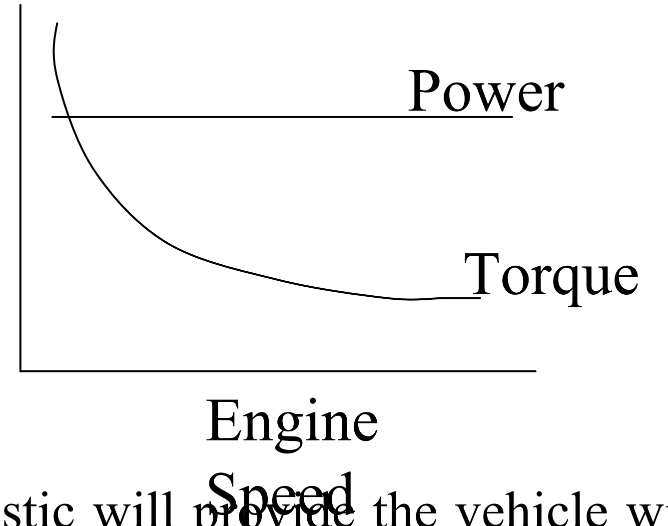
Acceleration Performance

- Acceleration Performance Can be studied as
  – Engine Power Limited Acceleration
  – Traction Limited Acceleration
- Engine Power Limited Acceleration
  – The acceleration performance depends on
    - Engine Characteristics
    - Power to Weight Ratio
    - Power Train Inertia
- Traction Limited Acceleration
  – Assuming adequate power from the engine, the acceleration is limited by the coefficient of performance between the tyre and road

Engine Power Limited Acceleration

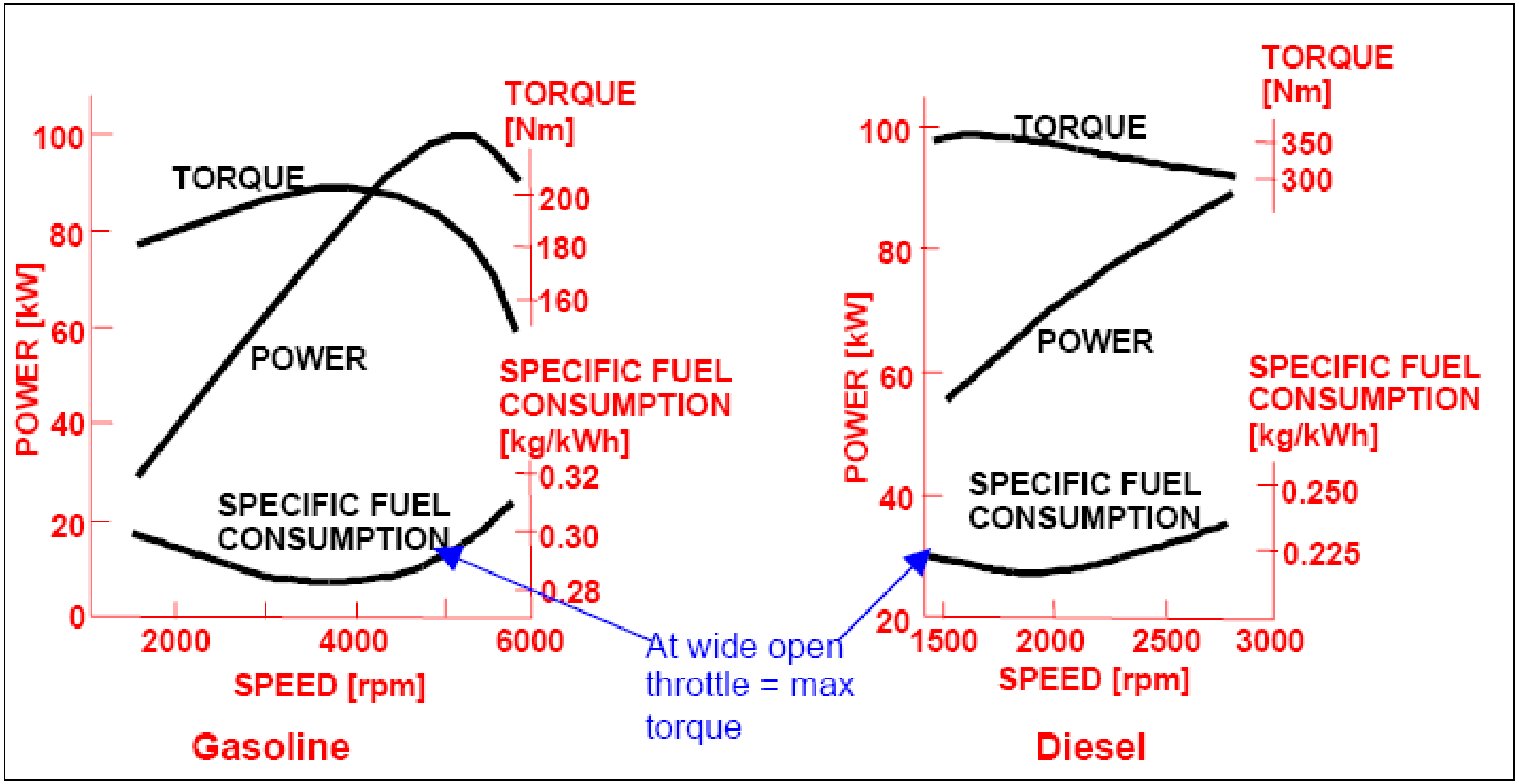
Comments on Engine Characteristics

- For vehicular applications, the ideal performance characteristics of a power plant are constant output power over the full range
- The engine output torque varies with speed hyperbolically



- This characteristic will provide the vehicle with high tractive effort at low speeds where demands for acceleration, drawbar pull or grade climbing capability are high
- The series wound DC motor and steam engine provide such characteristics
- The internal combustion engine has less favourable performance characteristics, and can be used only with a suitable transmission

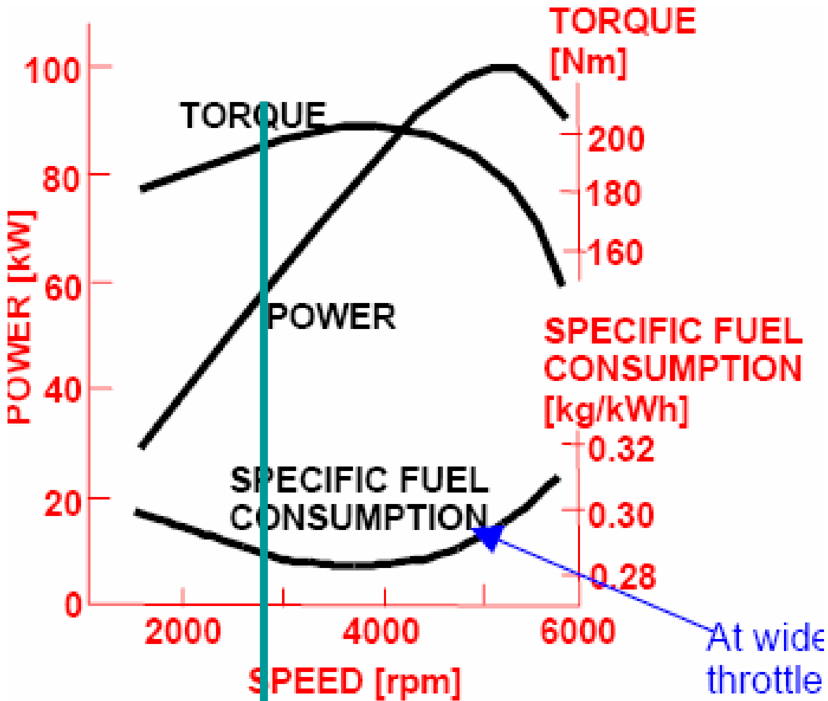
Engine Characteristics

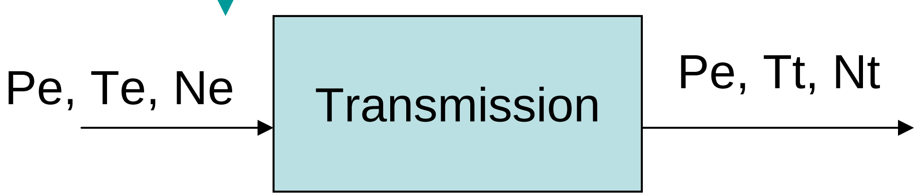


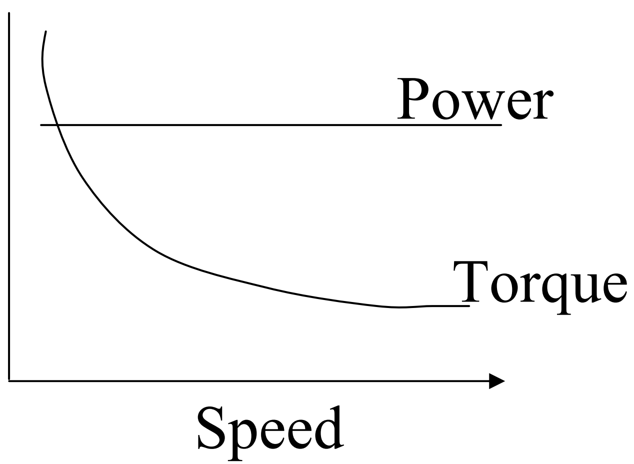
Engine characteristic curves.

- **For an ICE in a typical passenger car:- Max T 100-300 Nm (trucks 10 times higher)**
- **Max T occurs at 2500-4500 rpm (trucks 1000-1500 rpm)**
- **Diesel Engine suitable for Heavier Vehicles**

Transmission





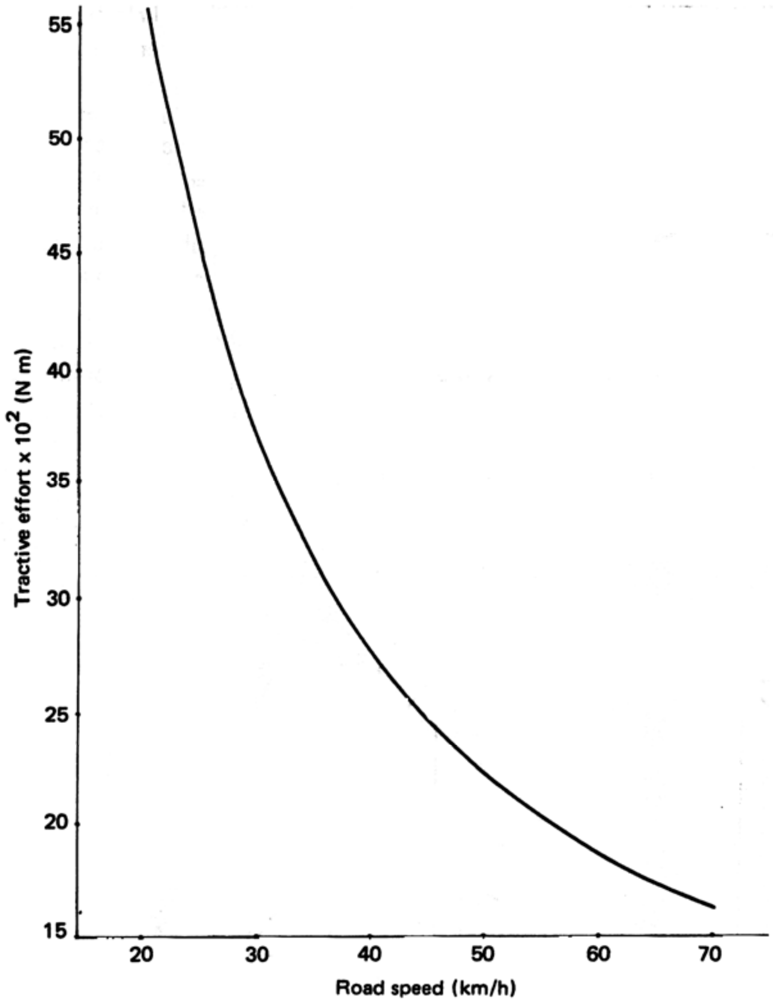


Constant Power And Tractive –Effort / Road-Speed Curves

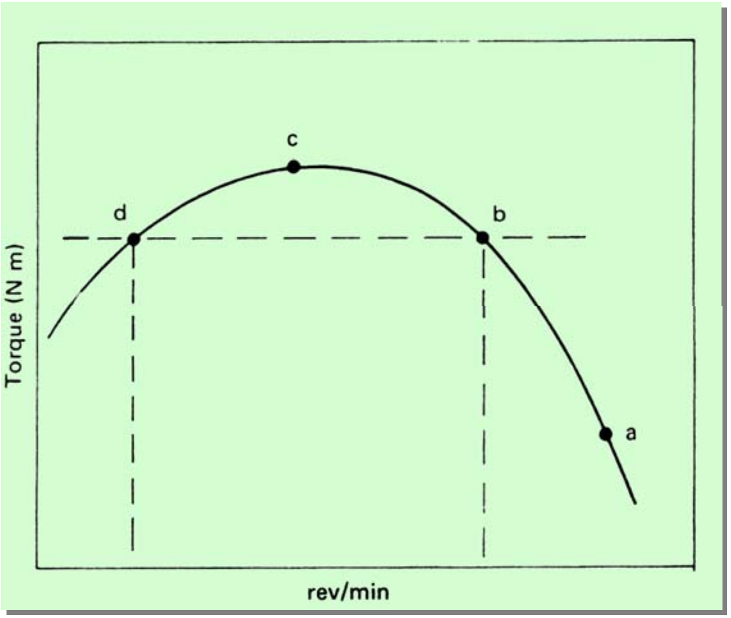
$$TE = \frac{\text{Power at roadwheels}}{\text{Velocity}} = \frac{P_r}{V} \quad \text{N}$$

- Power at the roadwheel is the product of tractive effort and velocity it follows that tractive effort is proportional to the power and inversely proportional to the road speed.
- A curve of constant power will produce an ideal form of tractive effort curve.
- Need for Transmission

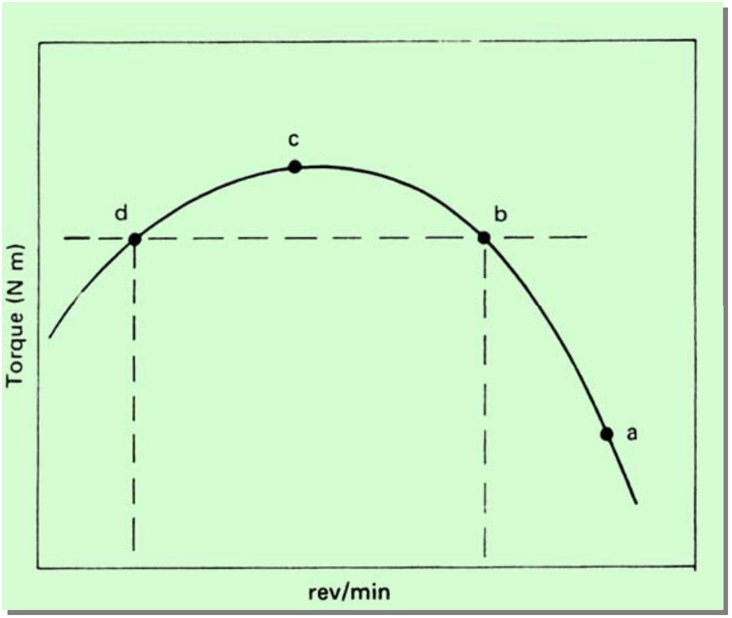
Curve Of Constant Power



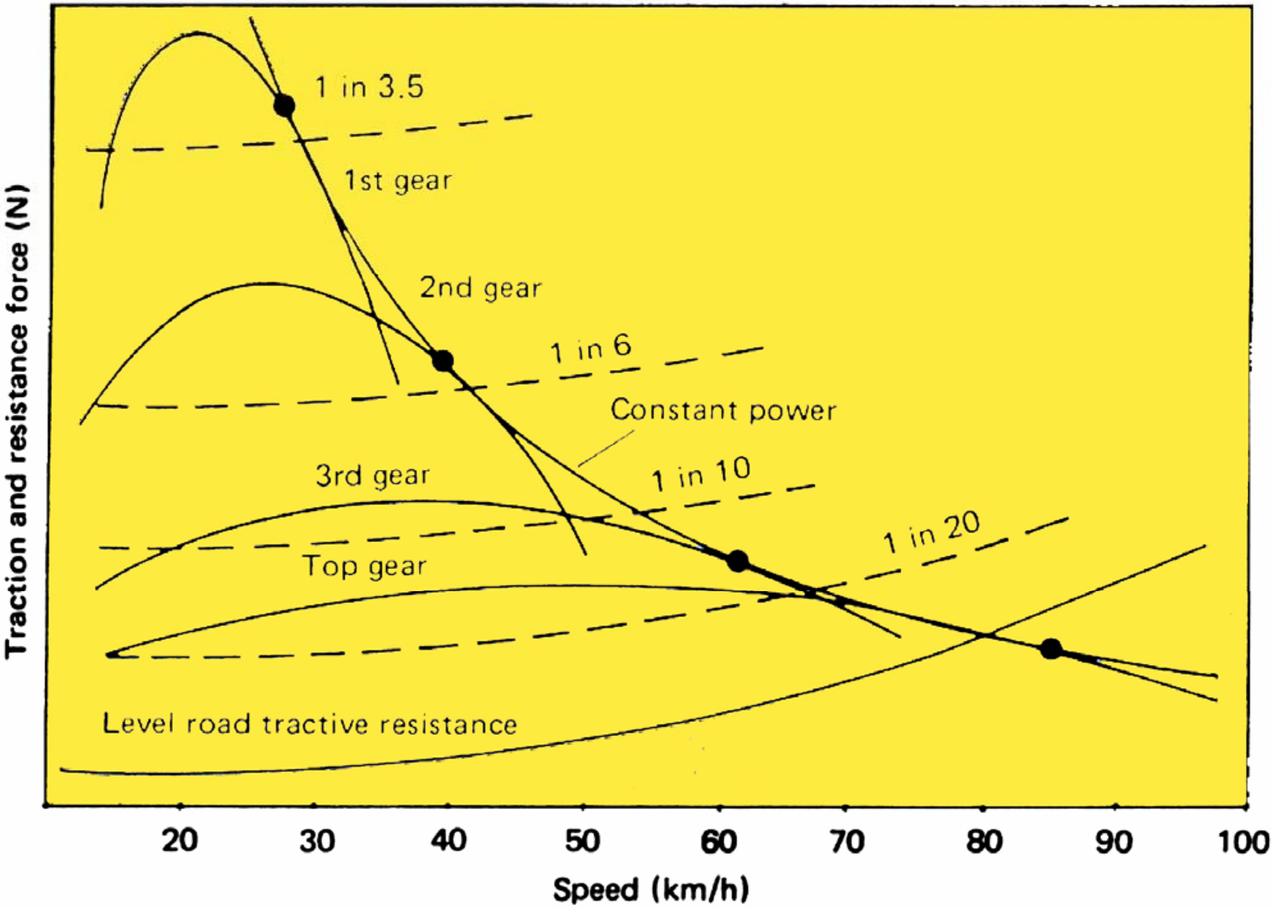
- As road speed falls the tractive effort increases in proportion to the increased resistance, thereby providing very stable conditions.



- If the vehicle looses road speed from point ‘a’, due to increased resistance, both the road speed and engine RPM would fall, but the rising torque may restore a uniform road speed without the necessity to change gear.
- If point ‘c’ or ‘d’ of the curve applied, any slight increase in resistance would introduce unstable conditions due to falling torque, and would necessitate a rapid change down to a lower gear ratio to improve torque.



- The speed of stable running is a point slightly higher than that of maximum torque, such as point ‘b’, but point ‘d’ would prove very unstable although it shares the same torque value as point ‘b’.

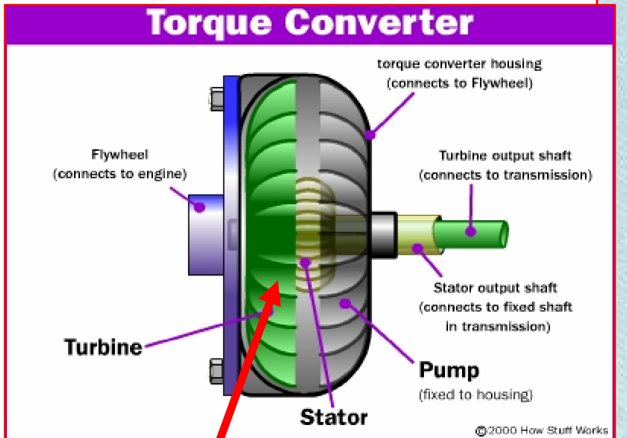


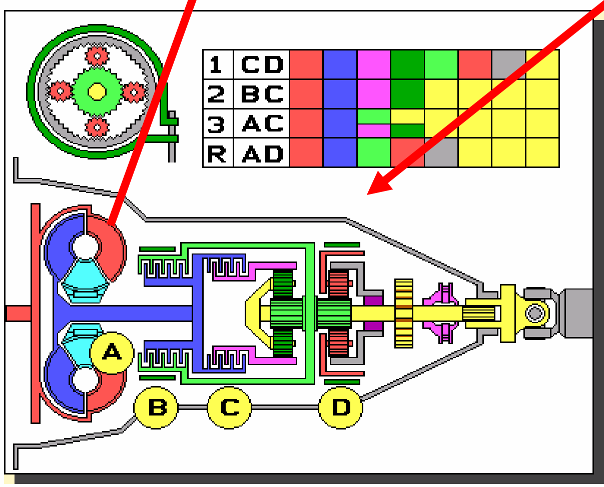
- If a point of stability such as point ‘b’ (on Torque v/s rev/min curve)is marked on the tractive effort curve for each gear ratio, and these points are joined together, a curve should be produced which bears a close relationship to the constant power curve – or ideal tractive effort curve.

Transmission Types and Performance

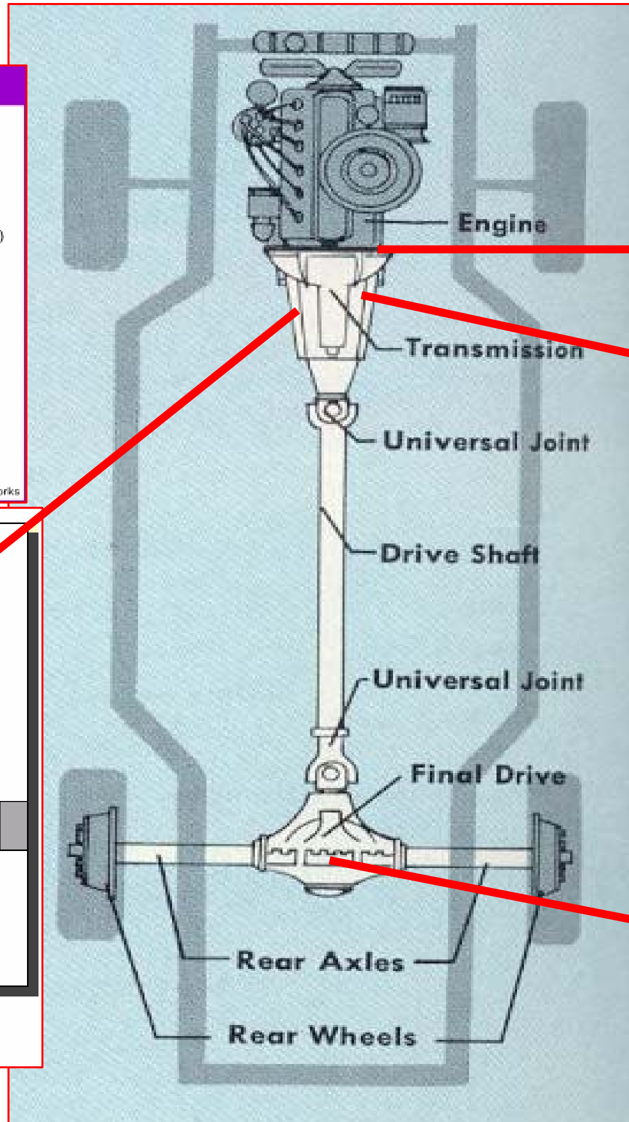
- The ICE characteristics is different from ideal characteristics, to achieve the required behaviour transmission is required
- Transmission includes all of those systems or subsystems employed for transmitting the engine power to the drive wheels or sprockets
- Transmission Types
  - Manual Transmission
  - Automatic Transmission with a Torque Converter
  - Continuously Variable Transmission (CVT)

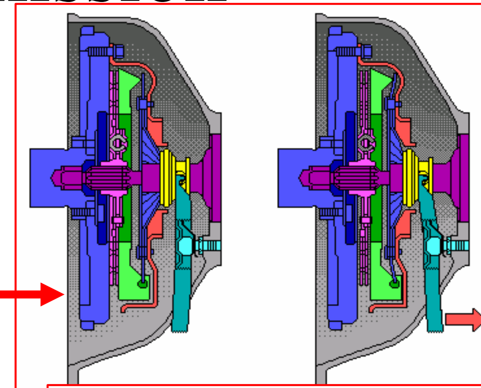
Manual and Automatic Transmission

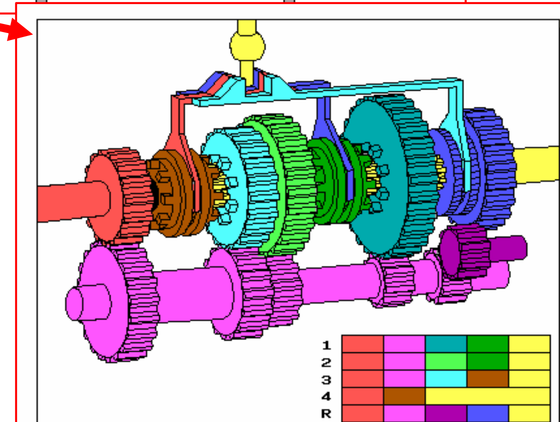


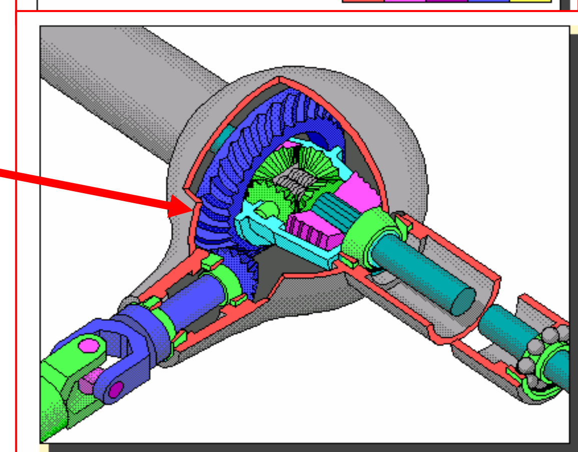


Automatic Transmission







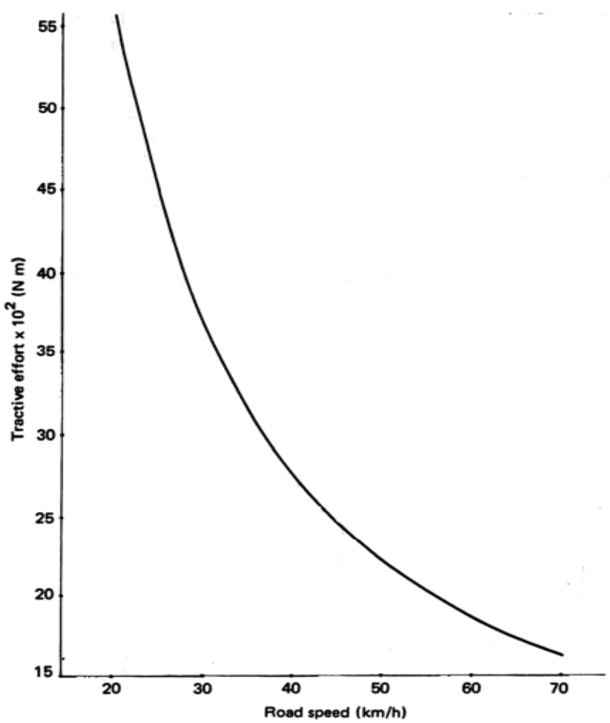


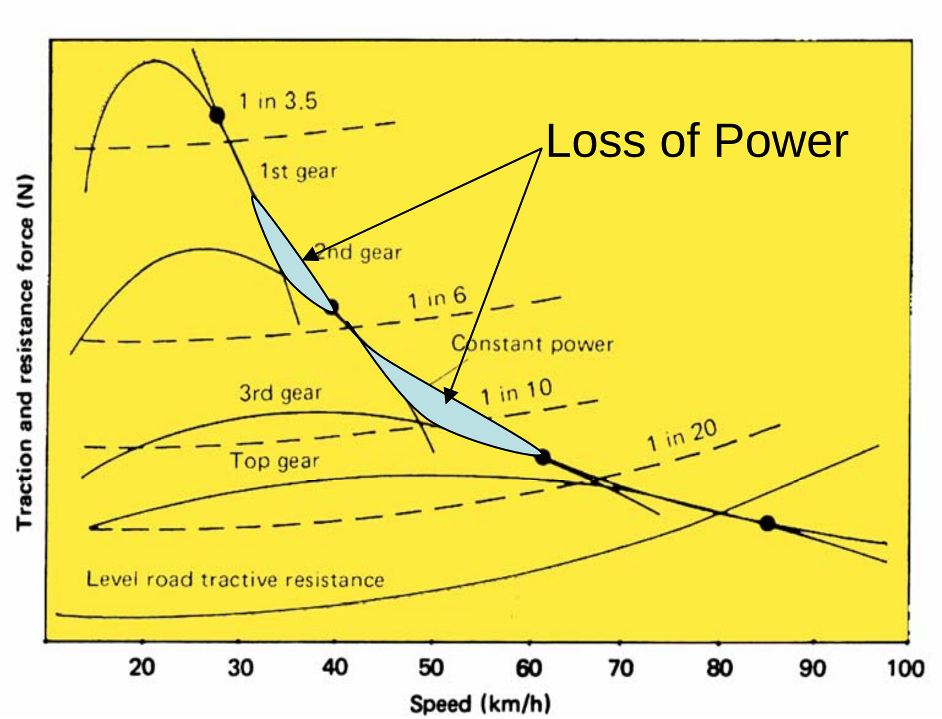
Manual and Automatic Transmission Systems.

Transmission Characteristics

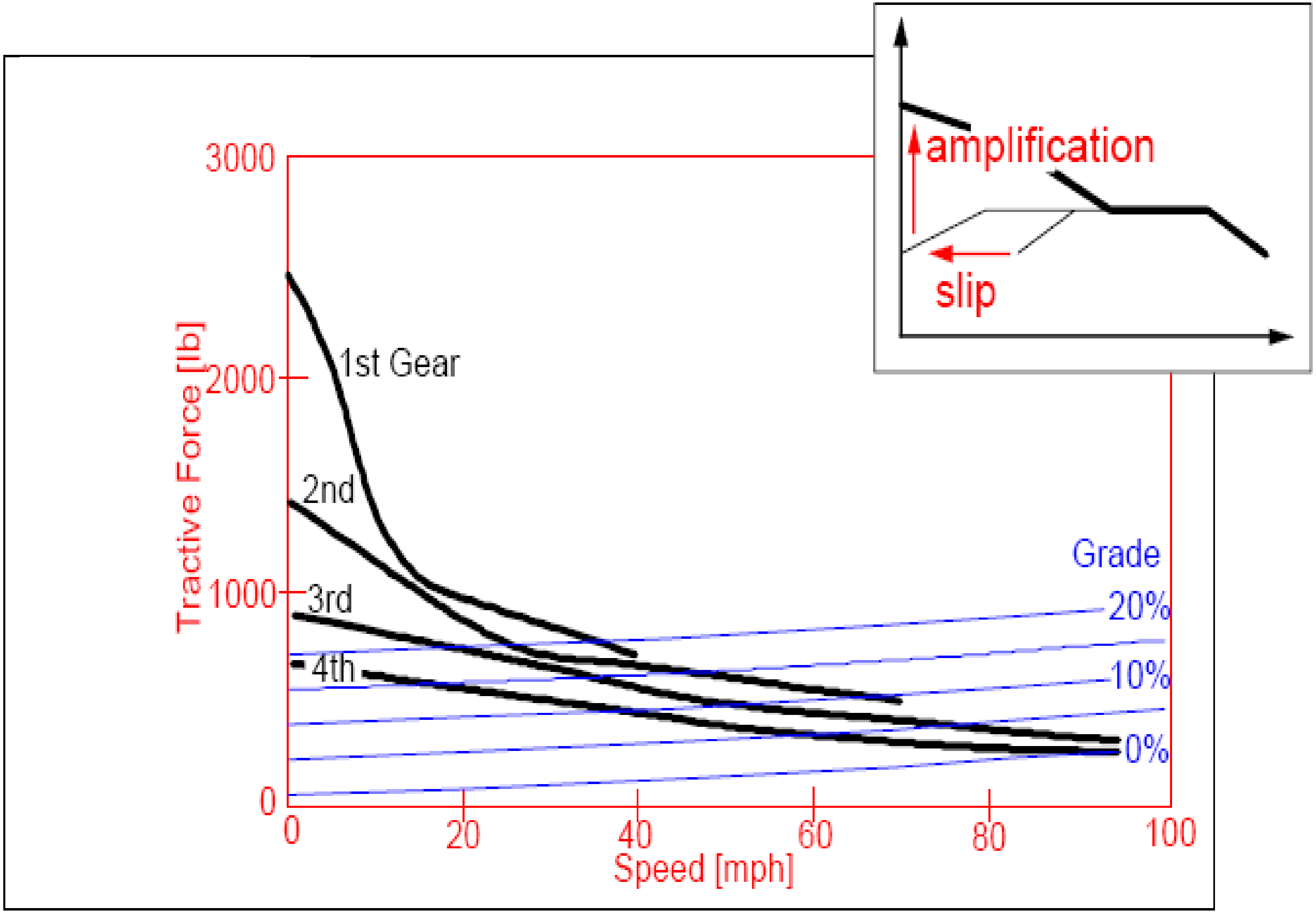
(Manual Transmission)

- The tractive force generated by the engine/power train is $\dfrac{T_e N_{tf} \eta_{tf}}{r}$
- It is the effort available to overcome road load forces and accelerate the vehicle.
- This is shown for a four-speed manual transmission



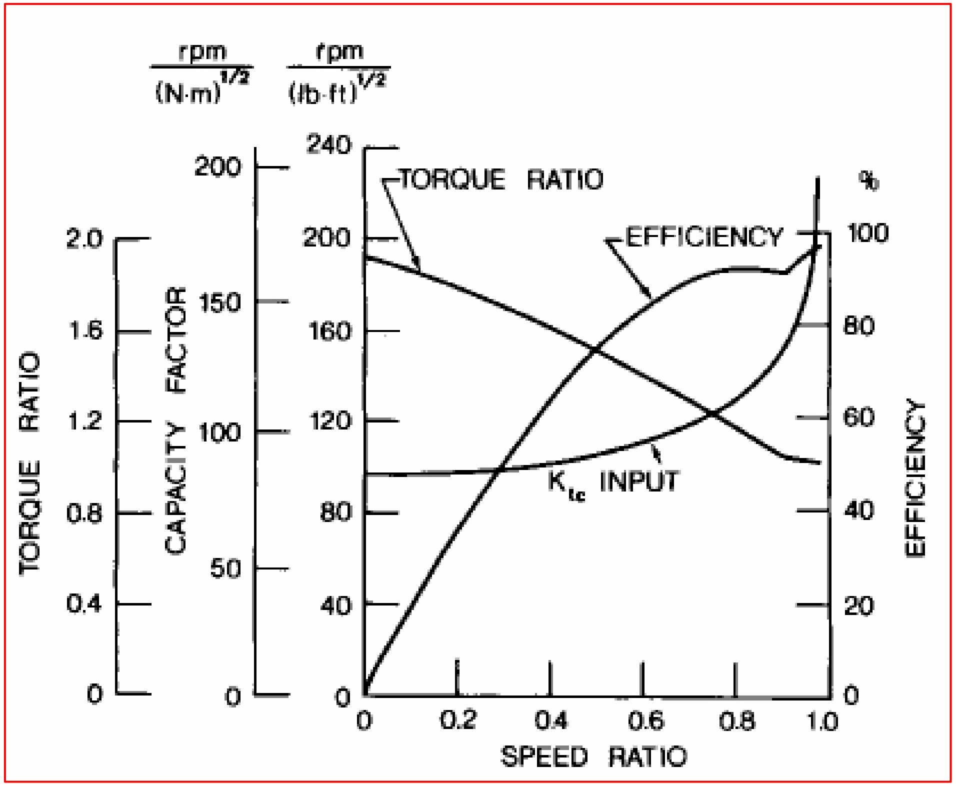


Automatic Transmission



Automatic Transmission Characteristics Curves.

Performance Characteristics of a Torque Converter

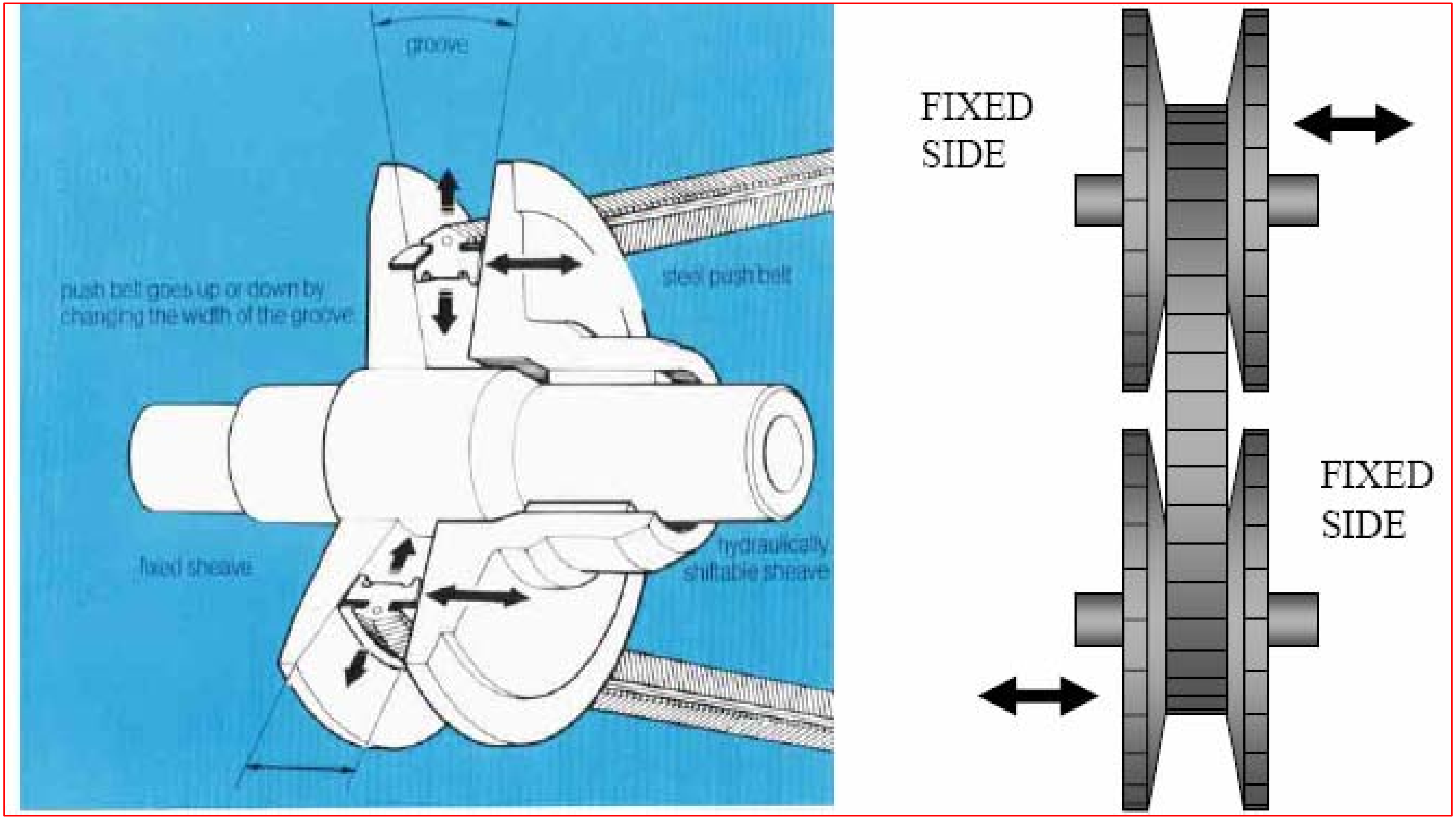


Performance Characteristic Curves.

Torque Converter

- The speed ratio R_ω is the output angular speed divided by the input angular speed. You specify a range of speed ratio values from 0 up to, but not including, 1.
  - $R_\omega = \min[\omega_I/\omega_T, \omega_T/\omega_I]$
- The torque ratio $R\tau$ is the output torque divided by the input torque.
  - $R_\tau = \tau_{output} / \tau_{input}$
- The capacity factor K is the input speed divided by the square root of the input torque.
  - $K = \max[\omega_I, \omega_T] / \sqrt{\tau_{input}}$
- τ_{input} is the torque flowing into the shaft with the larger speed, and τ_{output} is the torque flowing into the shaft with the smaller speed.

Continuously Variable Transmission



Continuously Variable Transmission System.

CVT Benefits

- No gear shift
- Continuous transmission of torque
- Control of engine speed independently of vehicle speed
- Ability to operate engine at peak power over wider range of vehicle speeds
- Ability to operate at most fuel efficient point for required output

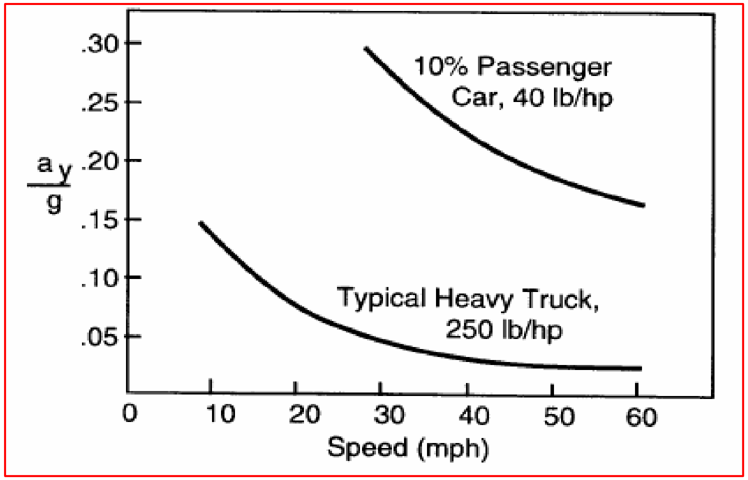
Effect of Power To Weight Ratio on Acceleration Performance

- The ratio of engine power to vehicle weight is the first-order determinant of acceleration performance.

$$a_x = \frac{F_x}{M} = 1000 \frac{g}{V} \frac{P}{W} \quad m/s^2$$

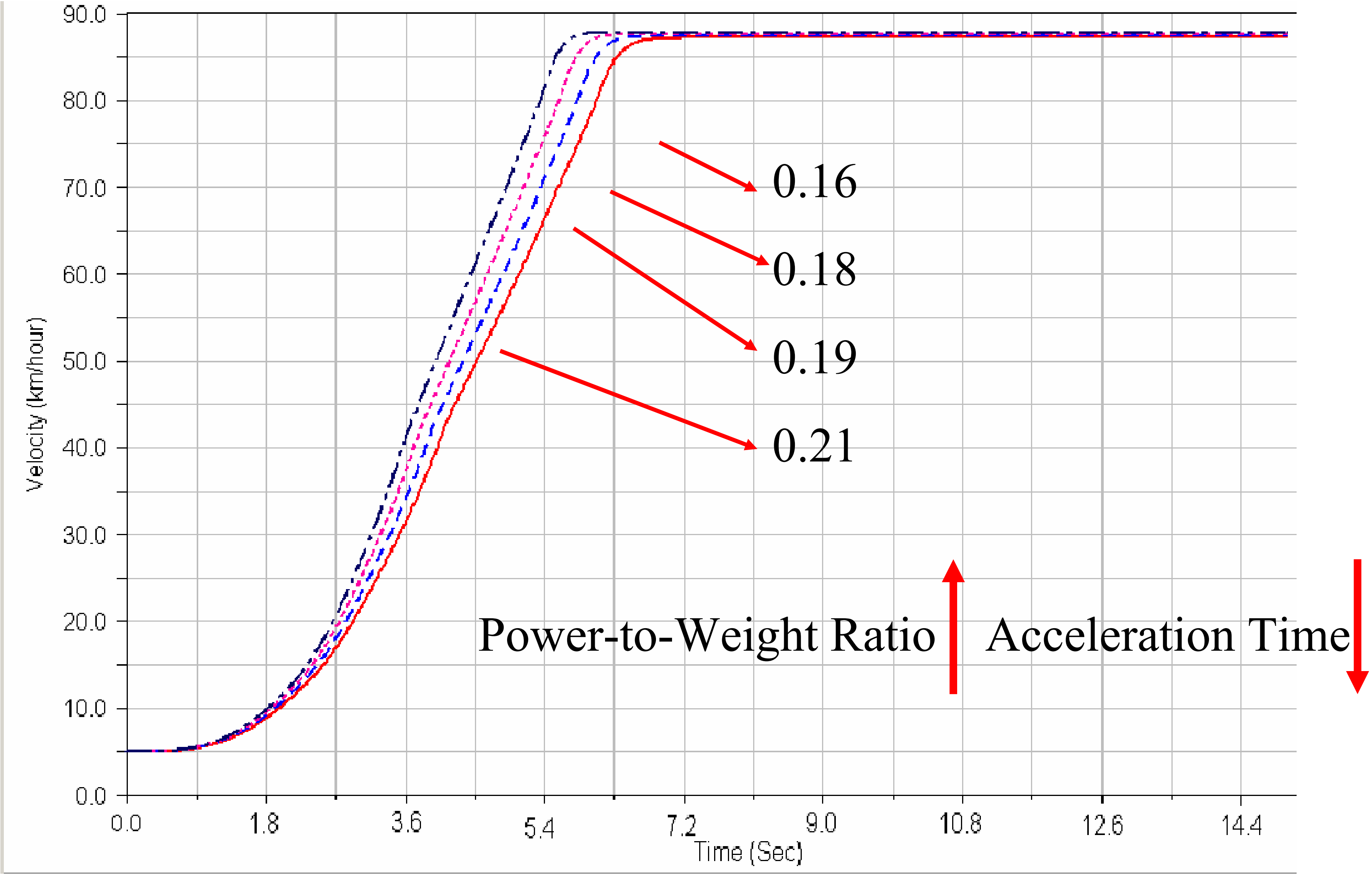
$$P = Engine \quad Power \quad in \quad kW$$

$$W = Weight\ of\ the\ Vehicle\ in\ N$$



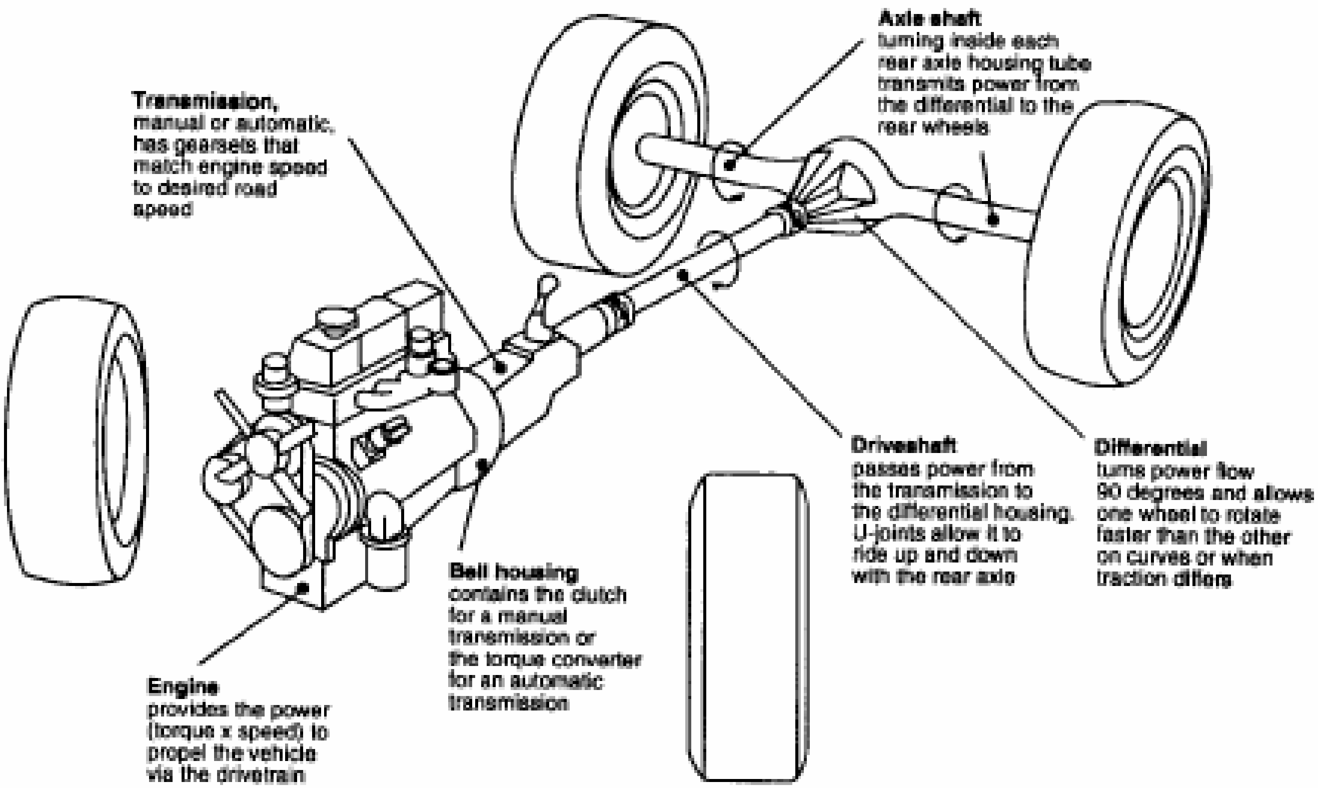
- Acceleration capability decreases with increasing vehicle speed.
- Heavy trucks will have much lower performance levels than cars because of the less favorable power-to-weight ratio

Velocity graph for different Power-to-Weight Ratio



Effect of Drive Train on Acceleration

- Estimation of acceleration performance requires modeling the mechanical systems by which engine power is transmitted to the ground.



Effect of Drive Train on Acceleration

$$F_x = \frac{T_e N_{tf} \eta_{tf}}{r} - \{(I_e + I_t) N_{tf}^2 + I_d N_f^2 + I_w\} \frac{a_x}{r^2}$$

$$a_x = \frac{g}{W}[F_x - R_x - D_A - W \sin\theta - R_{hx}]$$

$$Ma_x = [\frac{T_e N_{tf} \eta_{tf}}{r} - \{(I_e + I_t) N_{tf}^2 + I_d N_f^2 + I_w\} \frac{a_x}{r^2} - R_x - D_A - W \sin\theta - R_{hx}]$$

$$Ma_x + \{(I_e + I_t) N_{tf}^2 + I_d N_f^2 + I_w\} \frac{a_x}{r^2} = [\frac{T_e N_{tf} \eta_{tf}}{r} - R_x - D_A - W \sin\theta - R_{hx}]$$

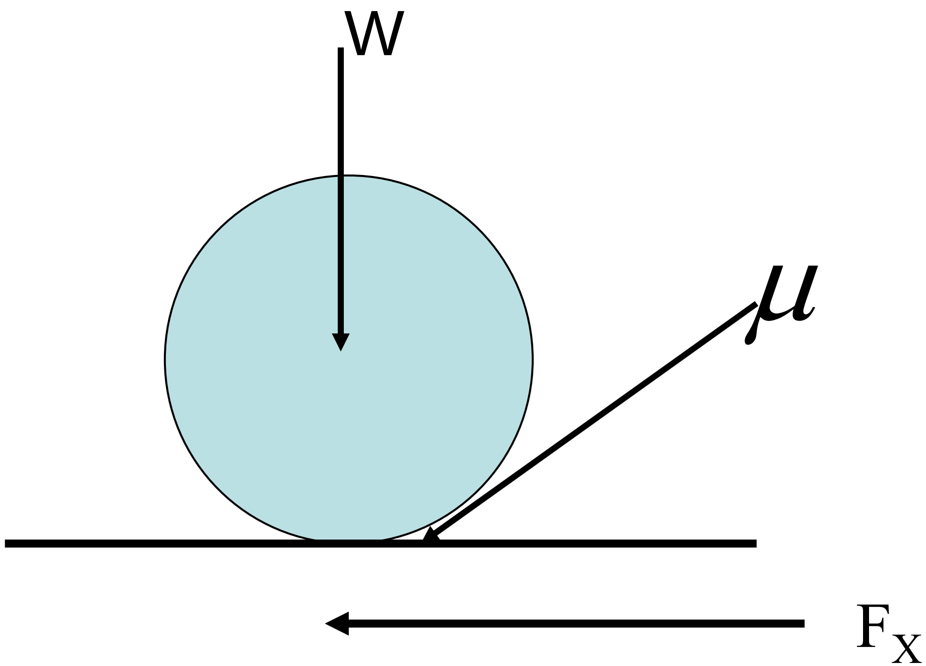
$$a_x = [\frac{T_e N_{tf} \eta_{tf}}{r} - R_x - D_A - W \sin\theta - R_{hx}]/(M + M_r)$$

T_a = Torque on the axles
F_x = Tractive force at the ground
r = Radius of the wheels
I_w = Rotational inertial of the wheels and axles shafts
α_w = Rotational acceleration of the wheels
I_d = Rotational inertia of the drive shaft
α_d = Rotational acceleration of the drive shaft
N_f = Numerical ratio of the final drive

Tractive Force

$$Tractive\ Effort = \frac{T_e N_{tf} \eta_{tf}}{r}$$

$$W = W_{static} + W_{dynamic\ longitudinal} + W_{dynamic\ transverse}$$



Tractive forces acting on a wheel.

Traction Limited Acceleration

- Assume there is adequate power from the engine, the acceleration may be limited by the coefficient of friction between the tire and road.
- In that case F_x is limited by:

$$F_x = \mu W$$

$$\mu = Peak\ coefficient\ of\ \ Friction$$

$$W\ = Weight\ on\ drive\ wheels$$

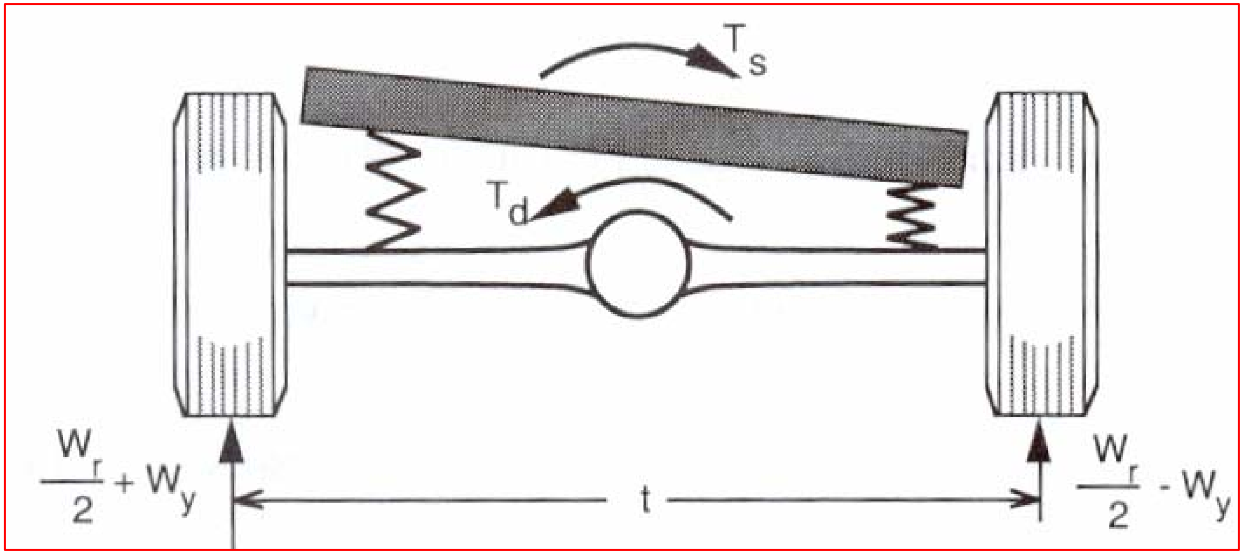
- The weight on a drive wheel then depends on the static plus the dynamic load due to acceleration, and on any transverse shift of load due to drive torque

Transverse Weight Shift due to Drive Torque

- Transverse weight transfer occurs because the driveshaft torque (T_d) reacts between the frame mounted engine and the axle. The engine, which is a part of the sprung weight, produces the torque through the transmission. The rear axle has to resist that torque at the rear tire patch.
  - Transverse weight transfer adds cross weight under acceleration and removes cross weight during deceleration.
  - The magnitude of the transverse weight shift is a function of the instantaneous engine torque and the roll stiffness (K_φ).

Transverse Weight Shift due to Drive Torque

- The driveshaft imposes a torque Td on the axle
- As the chassis roll compressing and extending springs on opposite sides of the vehicle such that a torque due to suspension roll stiffness Ts is produced



$$\Sigma T_o = (W_r/2 + W_y - W_r/2 + W_y)\, t/2 + T_s - T_d = 0$$

or $$W_y = (T_d - T_s)/t$$

Now Td can be determined by the following equation

$$T_d = F_x\, r/N_f$$

where:

F_x = Total drive force from the two rea

r = Tire radius

N_f = Final drive ratio

To find Ts let us consider the relations

$$T_{sf} = K_{\phi f}\, \phi$$

$$T_{sr} = K_{\phi r}\, \phi$$

$$K_\phi = K_{\phi f} + K_{\phi r}$$

where:

T_{sf} = Roll torque on the front suspension

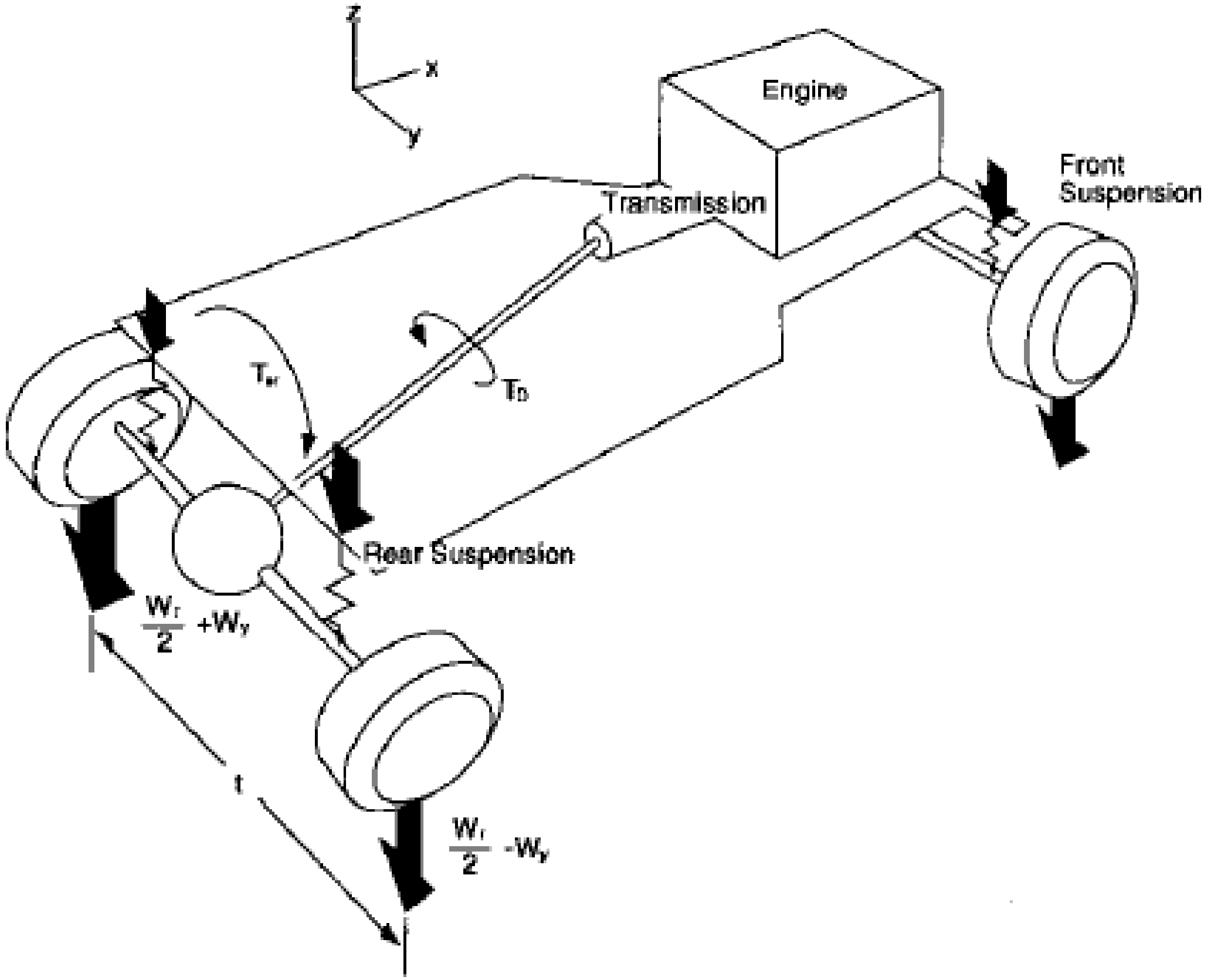
T_{sr} = Roll torque on the rear suspension

$K_{\phi f}$ = Front suspension roll stiffness

$K_{\phi r}$ = Rear suspension roll stiffness

K_ϕ = Total roll stiffness

Drive Torque Reactions



$$\phi = T_d / K_\phi = T_d / (K_{\phi f} + K_{\phi r})$$

$$T_{sr} = K_{\phi r} T_d / (K_{\phi f} + K_{\phi r})$$

$$\Sigma T_o = (W_r/2 + W_y - W_r/2 + W_y)\, t/2 + T_s - T_d = 0$$

$$\text{or} \quad W_y = (T_d - T_s)/t$$

Substituting Ts and Td values in the above equation

$$W_y = \frac{F_x r}{N_f t}\left[1 - \frac{K_{\phi r}}{K_{\phi r} + K_{\phi f}}\right]$$

$$W_y = \frac{F_x r}{N_f t} \frac{K_{\phi f}}{K_\phi}$$

During Acceleration

$$W_r = W\left(\frac{b}{L} + \frac{a_x}{g}\frac{h}{L}\right)$$

Substitute for a_x

$$W_r = W\left(\frac{b}{L} + \frac{F_x}{M\,g}\frac{h}{L}\right)$$

Then the weight on the right rear wheel, W_{rr}, will be $W_r/2 - W_y$, or:

$$W_{rr} = \frac{W\,b}{2\,L} + \frac{F_x}{2}\frac{h}{L} - \frac{F_x\,r}{N_f\,t}\frac{K_{\phi f}}{K_\phi}$$

Solving for Fx

$$F_x = 2\,\mu\,W_{rr} = 2\,\mu\left(\frac{W\,b}{2\,L} + \frac{F_x\,h}{2\,L} - \frac{F_x\,r}{N_f\,t}\frac{K_{\phi f}}{K_\phi}\right)$$

Traction Limits

- The maximum tractive force that can be developed by a solid rear axle with a non-locking differential:

$$F_{x\max} = \frac{\mu \dfrac{Wb}{L}}{1 - \dfrac{h}{L}\mu + \dfrac{2\mu r}{N_f t}\dfrac{K_{\phi f}}{K_\phi}}$$

- For a solid rear axle with a locking differential, additional tractive force can be obtained from the other wheel up to its traction limits such that the last term in the denominator of the above equation drops out.

$$F_{x\max} = \frac{\mu \dfrac{Wb}{L}}{1 - \dfrac{h}{L}\mu}$$

- The above equation holds good for independent rear suspension

Traction Limited Acceleration

- The maximum tractive force that can be developed by a solid front drive axle with a non-locking differential:

$$F_{x\max} = \frac{\mu \frac{Wc}{L}}{1 + \frac{h}{L}\mu + \frac{2\mu r}{N_f t}\frac{K_{\phi f}}{K_{\phi}}}$$

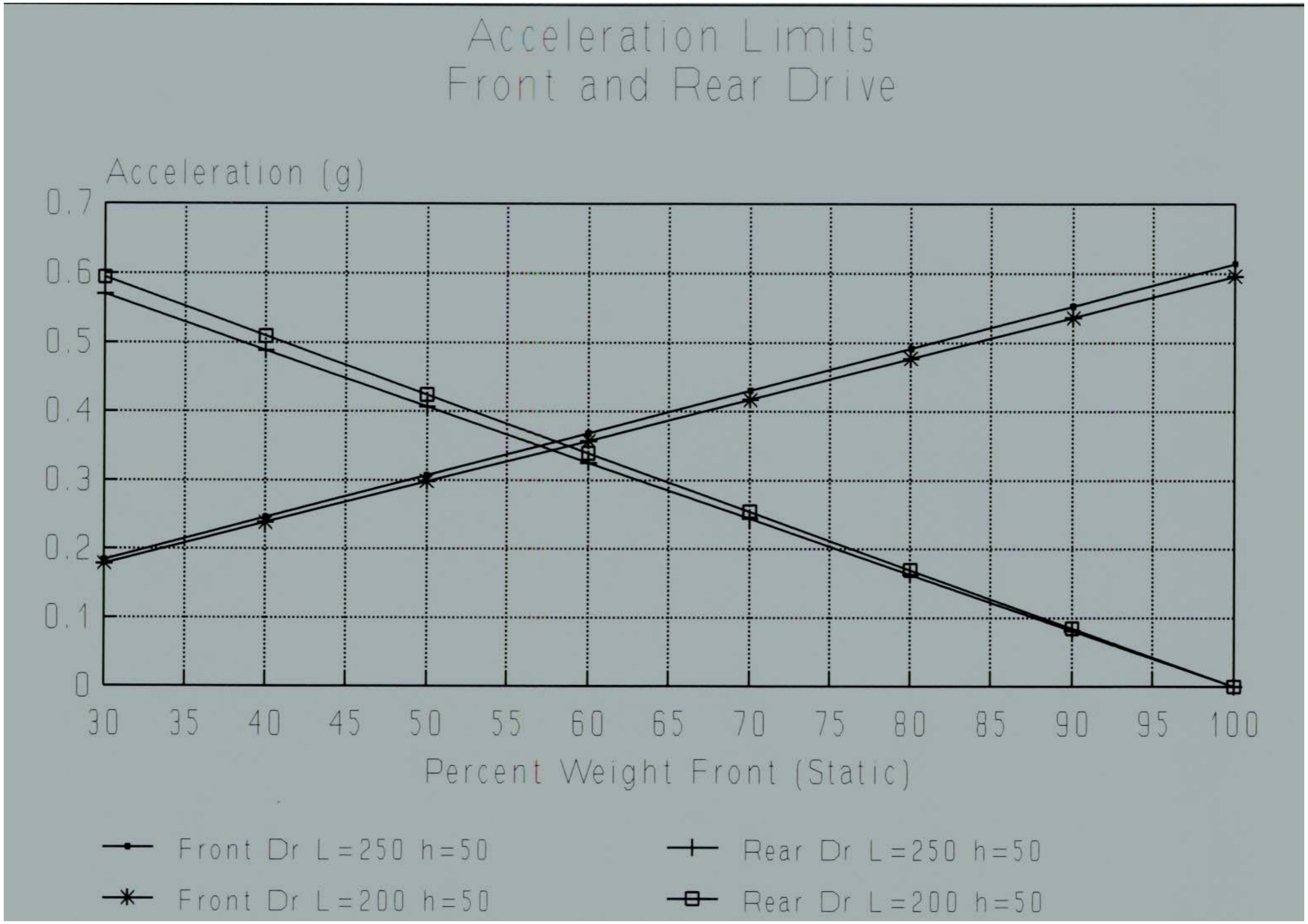
- For a solid front drive axle with a locking differential, or independent front suspension

$$F_{x\max} = \frac{\mu \frac{Wc}{L}}{1 + \frac{h}{L}\mu}$$

- The load on the front axle will be higher than rear axle, however,the load gets transferred during acceleration.

- The acceleration performance of front wheel drive vehicle will not be proportionately better compared to rear wheel drive vehicles, though numerical values of performance is higher

Front and Rear Drive Acceleration Performance

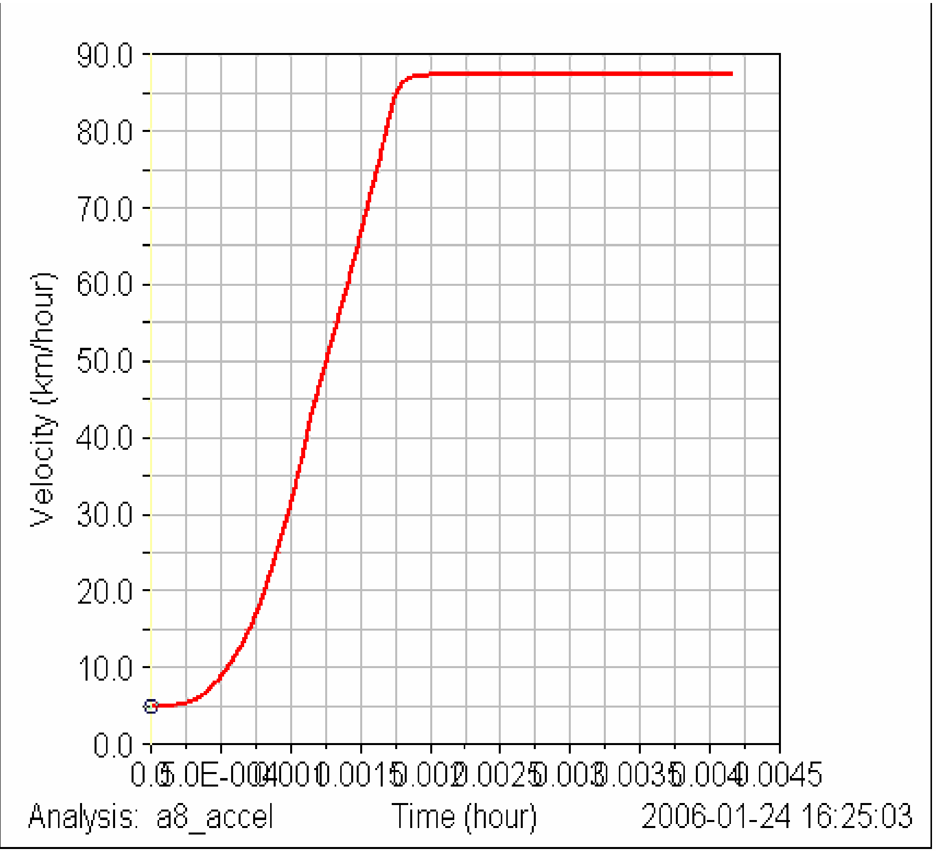


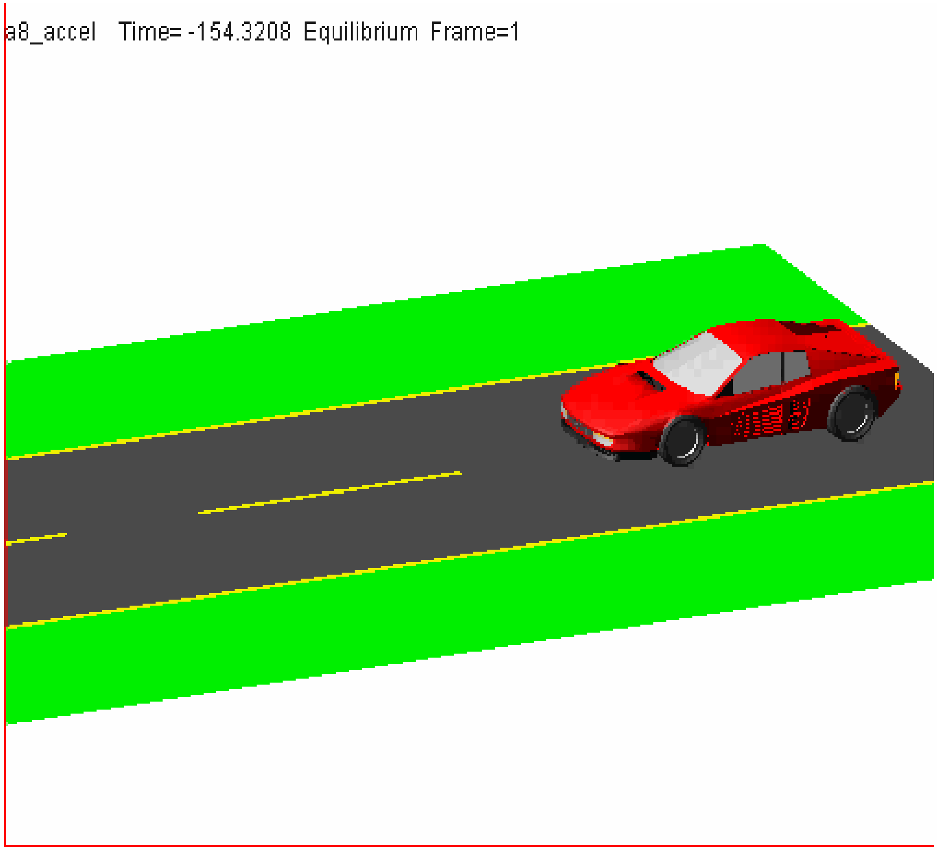
Locking Differential

- A locking differential is designed to overcome the chief limitation of a standard open differential by essentially "locking" both wheels on an axle together as if on a common shaft. This forces both wheels to turn in unison, regardless of the traction (or lack thereof) available to either wheel individually.
- A locked differential forces both left and right wheels on the same axle to rotate at the same speed under nearly all circumstances, without regard to tractional differences seen at either wheel. Therefore, each wheel can apply as much rotational force as the traction under it will allow, and the torques on each side-shaft will be unequal.(Unequal torque, equal rotational speeds)

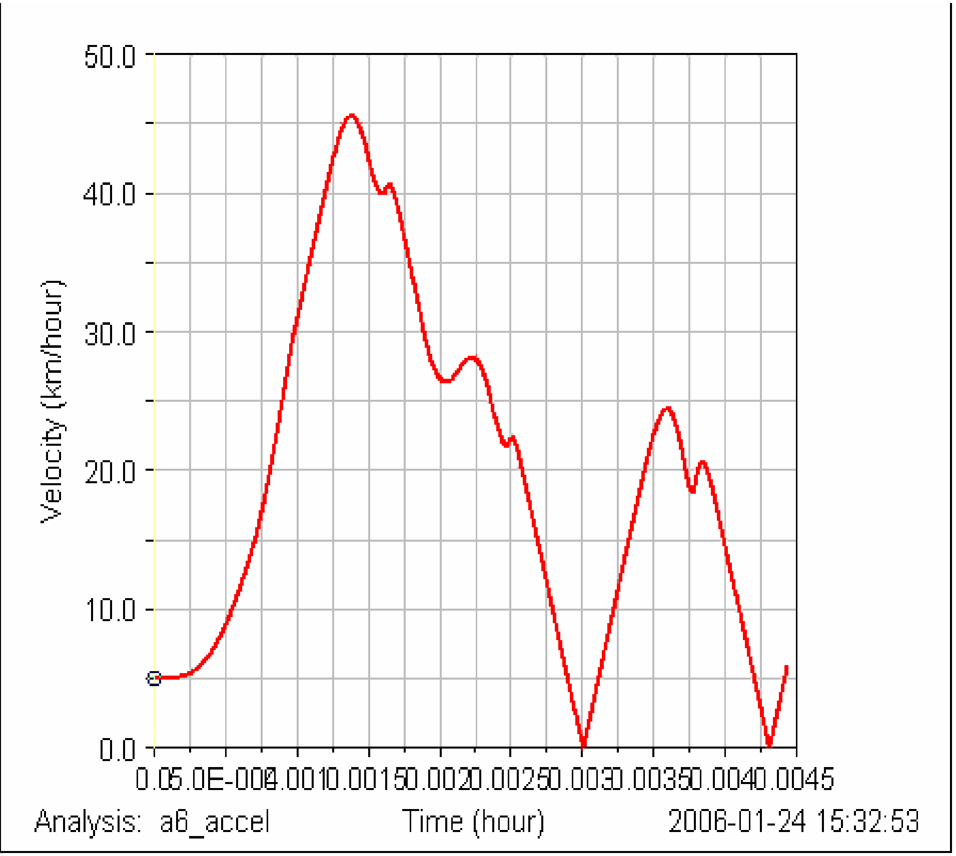
Locking Differential

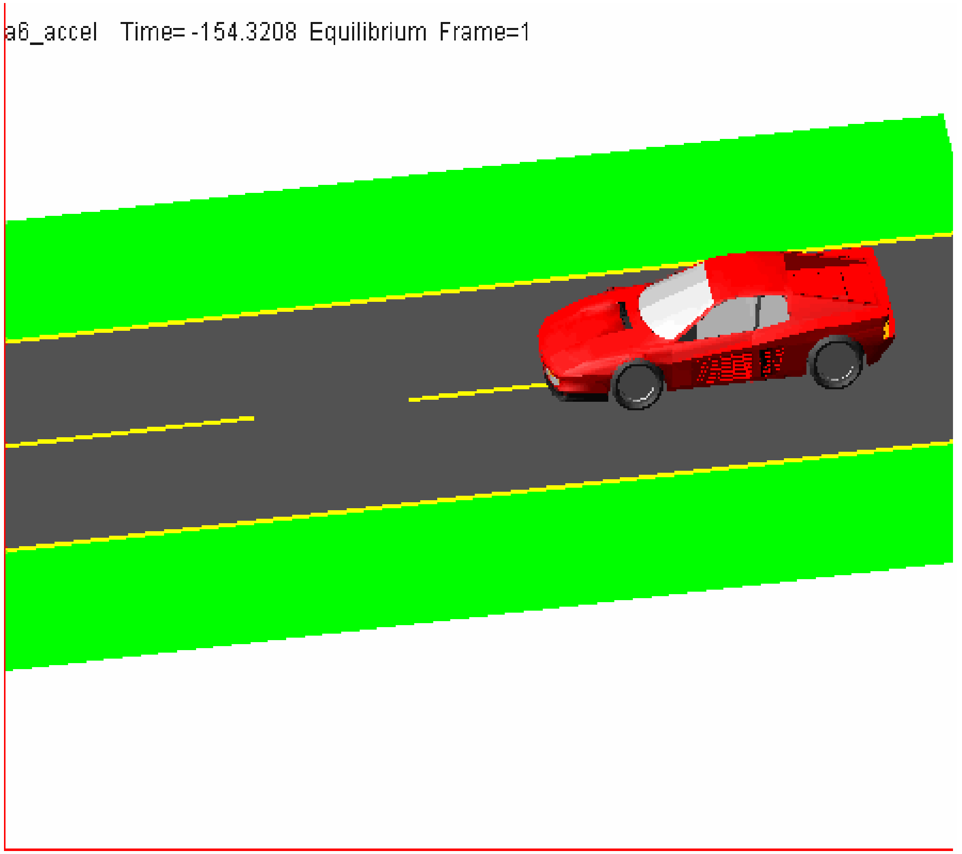
With Road μ = 0.8



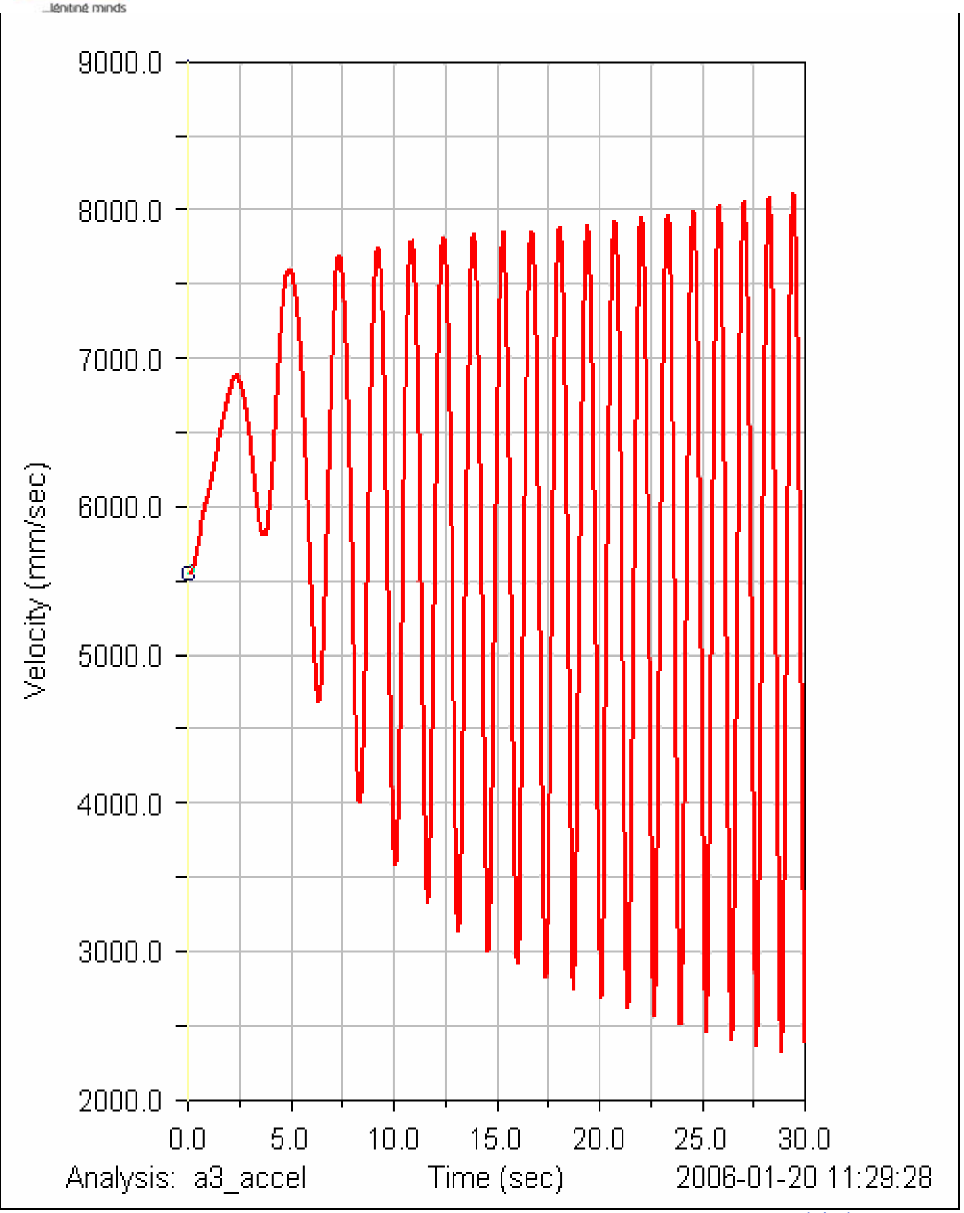


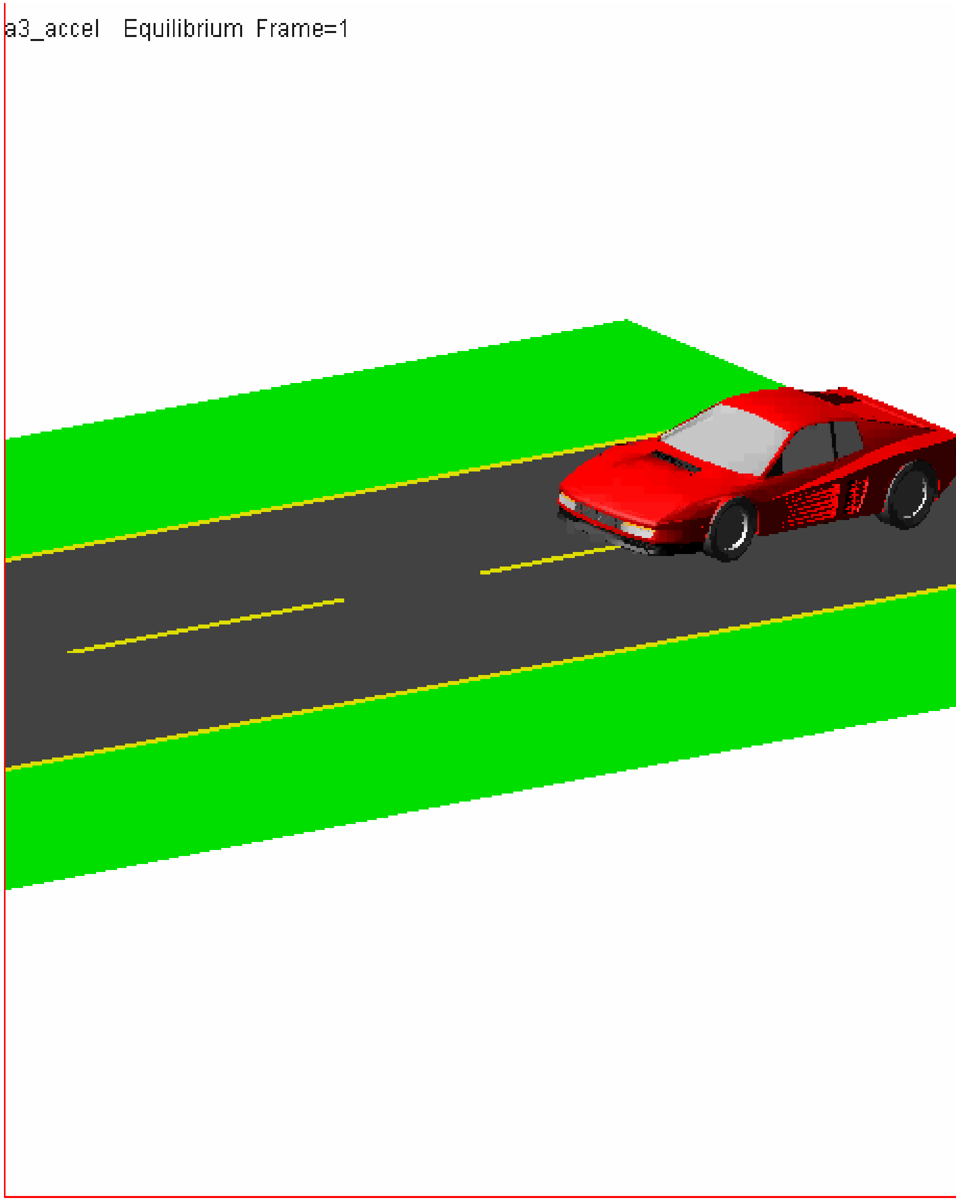
With Road μ = 0.6



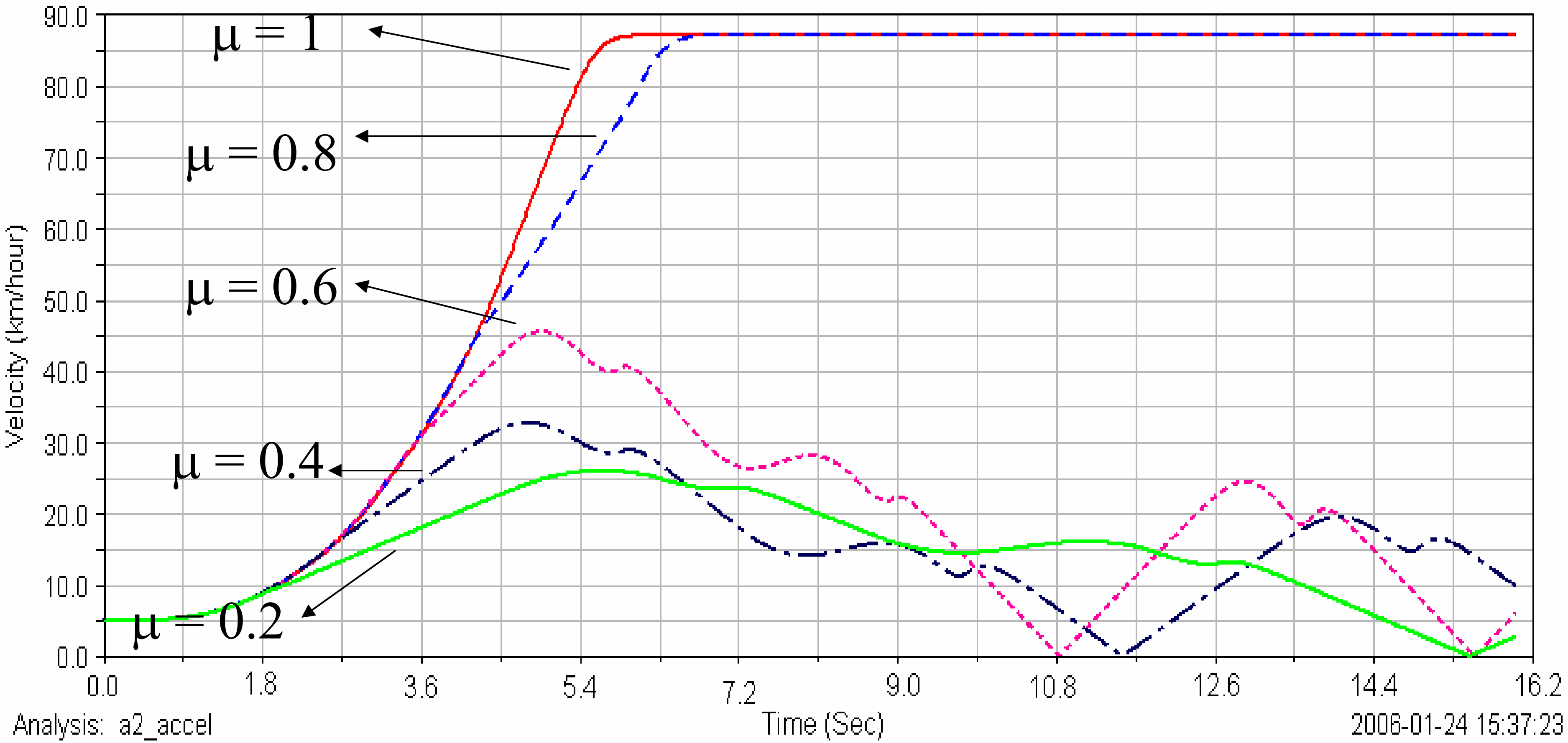


With Road μ = 0.05

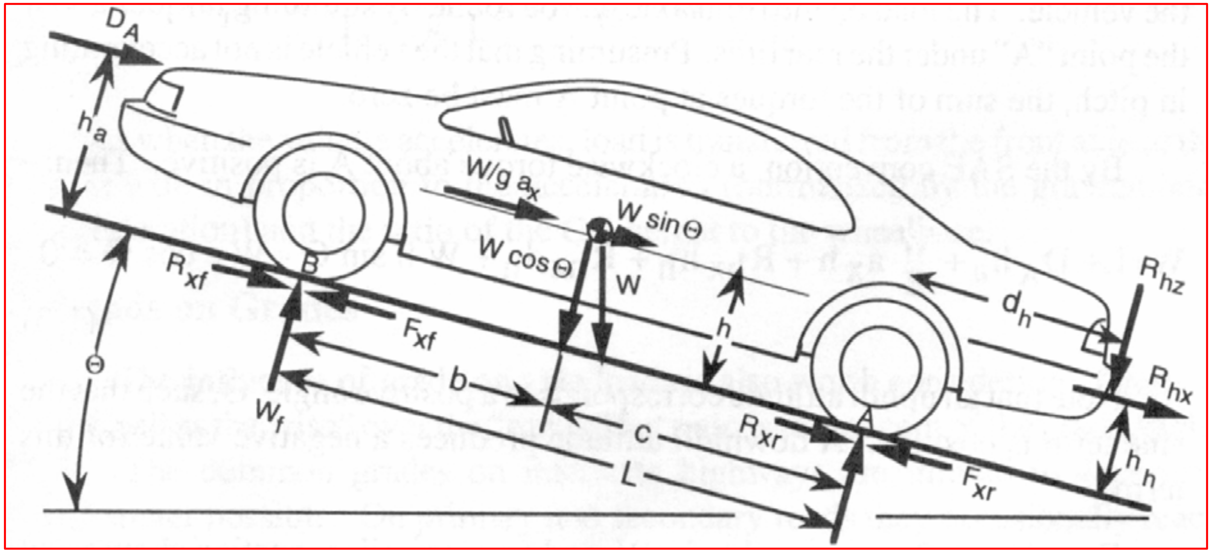




Acceleration Performance



General Equation for Braking



Arbitrary forces acting on a vehicle.

- The general equation for braking performance may be obtained from Newton's Second Law written for the x-direction.

$$D_x = (F_{xf} + F_{xr} + D_A + W \sin\theta) / M = \frac{F_{xt}}{M}$$

Constant Deceleration

- Assuming that the forces acting on the vehicle will be constant throughout a brake application.

$$D_x = \frac{F_{xt}}{M} = -\frac{dV}{dt}$$

$$F_{xt} = \text{The Total of all longitudinal acceleartion forces}$$

$$V = \text{Forward velocity}$$

$$\text{This equation can be integrated for deceleration}$$

$$\int_{V_o}^{V_f} dV = -\frac{F_{xt}}{M}\int_0^{t_s} dt$$

$$V_0 - V_f = \frac{F_{xt}}{M} t_s$$

V_0= Initial Velocity

V_f = Final Velocity

t_s =Time for the Velocity Change

Time to Stop

The following equation gives the time required to bring the vehicle from initial velocity to final velocity

$$D_x = \frac{F_{xt}}{M} = -\frac{dV}{dt}$$

$$F_{xt} = The\ Total\ of\ all\ longitudin\ al\ accelearti\ on\ forces$$

$$V = Forward\ velocity$$

$$This\ equation\ can\ be\ \text{int}\ egrated\ for\ decelerati\ on$$

$$\int_{V_o}^{V_f} dV = -\frac{F_{xt}}{M}\int_0^{t_s} dt$$

$$V_0 - V_f = \frac{F_{xt}}{M} t_s$$

$$t_s = (V_0 - V_f) / \frac{F_{xt}}{M} = (V_0 - V_f) / D_x$$

$$if\quad V_f = 0, then$$

$$t_s = \frac{V_0}{D_x}$$

Stopping Distance

$$D_x = \frac{F_{xt}}{M} = -\frac{dV}{dt}$$

$$F_{xt} = The\,Total\ of\ all\ longitudinal\ acceleartion\ forces$$

$$V = Forward\ velocity$$

$$This\ equation\ can\,be\,\text{int}\,egrated\ \ for\ deceleration$$

$$\int_{V_o}^{V_f} dV = -\frac{F_{xt}}{M}\int_0^{t_s} dt$$

$$V = \frac{dx}{dt}$$

$$dt = \frac{dx}{V}$$

$$\int_{V_0}^{V_f} dV = -\frac{F_{xt}}{M}\int_0^{X} \frac{dx}{V}$$

$$\frac{V_0^2 - V_f^2}{2} = \frac{F_{xt}}{M}x$$

$$x = (\frac{V_0^2 - V_f^2}{2}) / \frac{F_{xt}}{M}$$

In the case where the deceleration is a full stop, then Vf is zero, and X is the stopping distance, SD. Then:

$$SD = \frac{V_0^{\ 2}}{2\,\frac{F_{xt}}{M}} = \frac{V_0^{\ 2}}{2D_x}$$

Energy Absorbed by Brake System

- The energy and/or power absorbed by a brake system can be substantial during a typical maximum-effort stop.
- The energy absorbed is the kinetic energy of motion for the vehicle, and is thus dependent on the mass.

$$Energy = \frac{M}{2}\left(V_0^2 - V_f^2\right)$$

Power Absorbed by Brake System

- The power absorption will vary with the speed, being equivalent to the braking force times the speed at any instant of time.
- Thus, the power dissipation is greatest at the beginning of the stop when the speed is highest. Over the entire stop, the average power absorption will be the energy divided by the time to stop. Thus

$$Power = \frac{M}{2}\frac{V_0^2}{t_s}$$

Other Braking Forces

Rolling Resistance

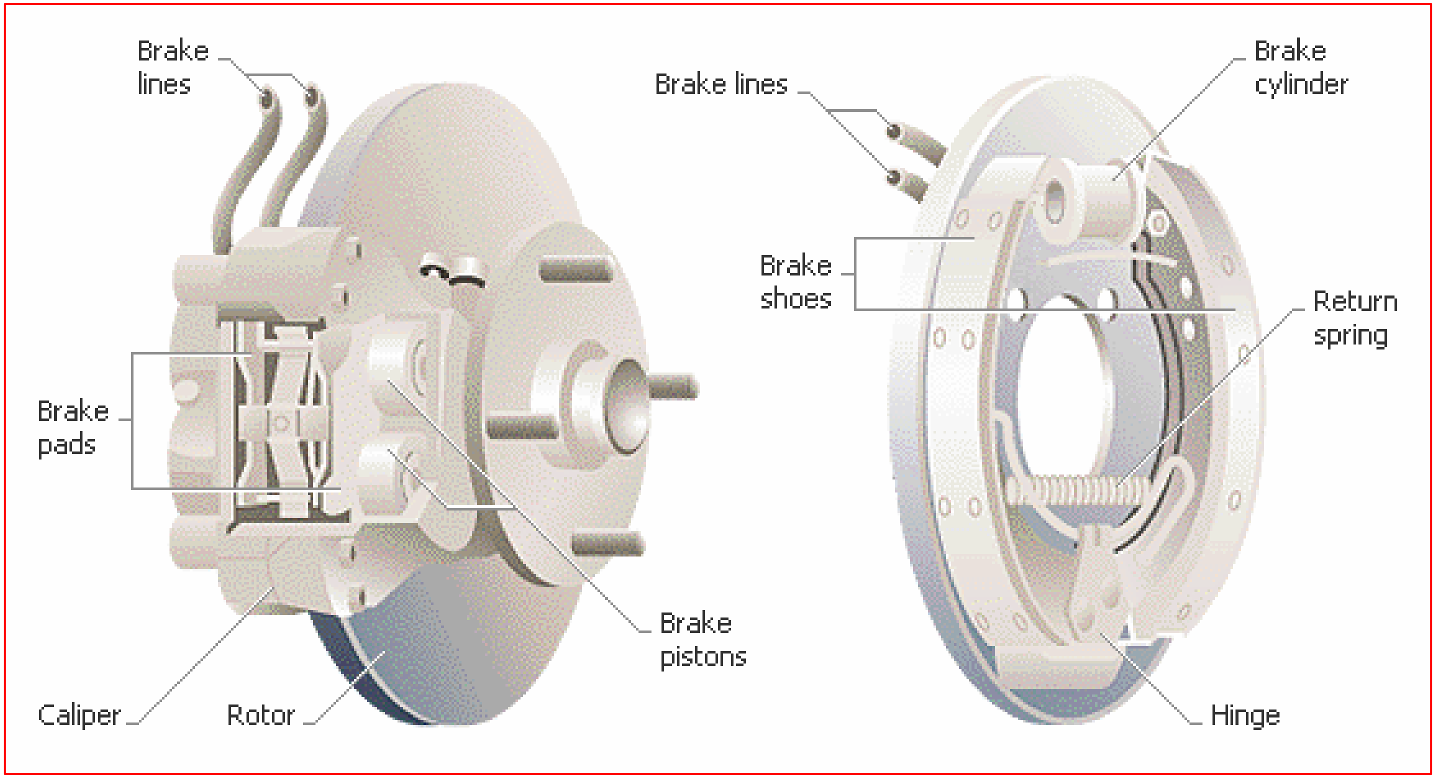
Aerodynamic Drag

Driveline Drag

Engine Drag- not much an effect

Grade

Brakes



Disc Brake

Drum Brake

Drum Brakes Vs Disc Brakes

- Drum brakes have high brake factor and the easy incorporation of parking brake features.
- On the negative side, drum brakes may not be as consistent in torque performance as disc brakes.
- Disc brakes have lower brake factors, require higher actuation effort, and development of integral parking brake features has been required before disc brakes could be used at all wheel positions.
- Disc brakes have better torque performance

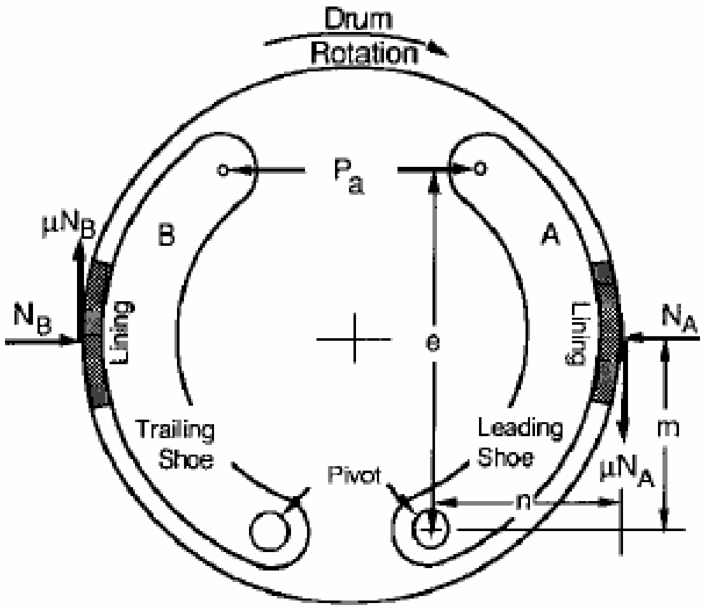
Brake Factor

Brake Factor is a mechanical advantage that can be utilized in drum brakes to minimize the actuation effort required

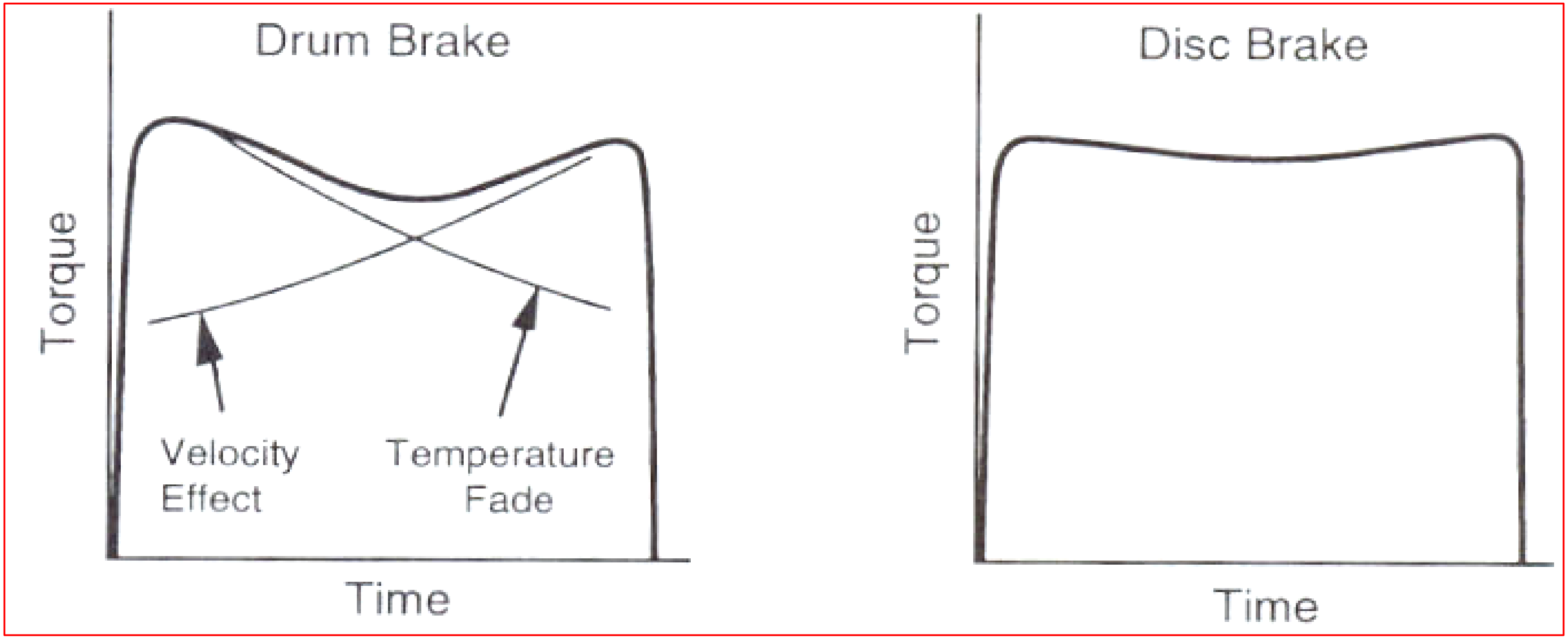
The friction force developed by each brake shoe is:

$$F_A = \mu N_A \quad \text{and} \quad F_B = \mu N_B$$

$$\frac{F_A}{P_a} = \frac{\mu e}{(m - \mu n)} \quad \text{and} \quad \frac{F_B}{P_a} = \frac{\mu e}{(m + \mu n)}$$



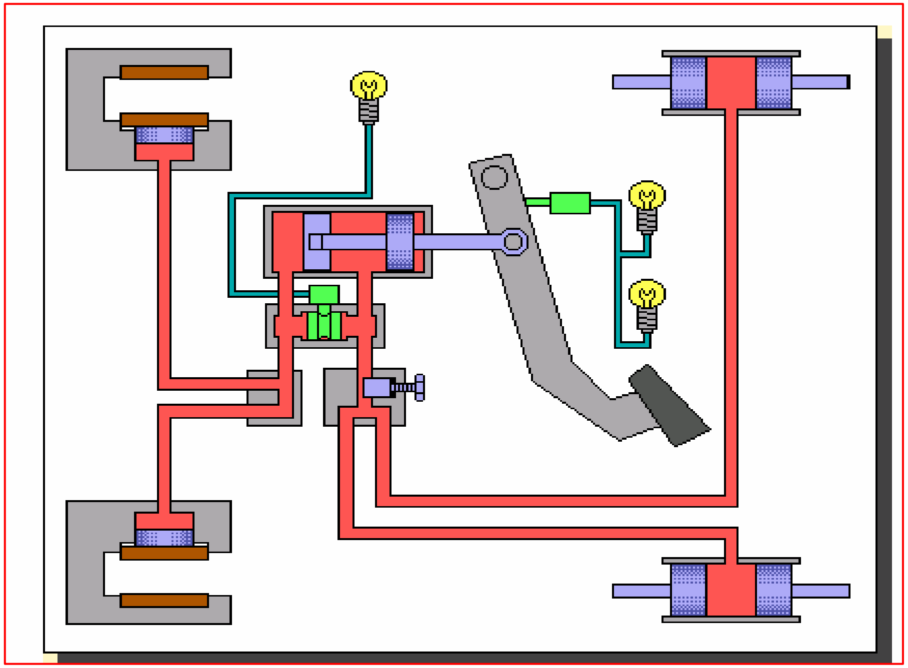
Brake Fading

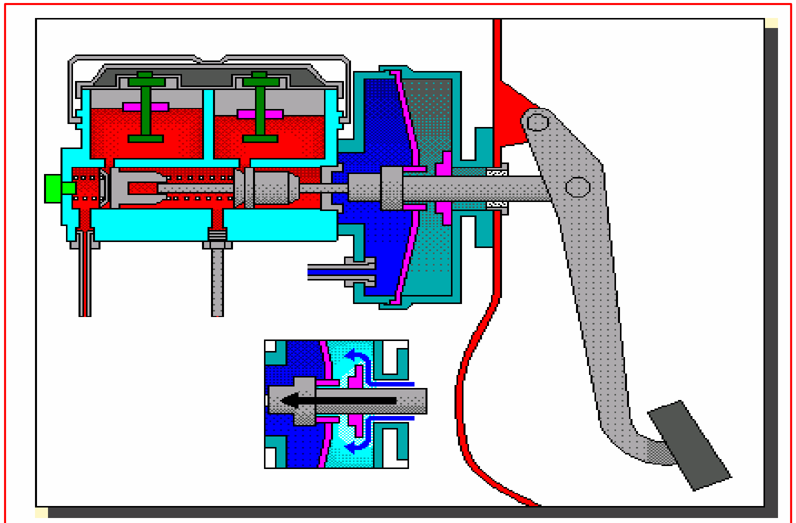


Torque Vs Time.

The reduction of friction termed brake fade is caused when the temperature reaches the "kneepoint" on the temperature-friction curve

Braking System

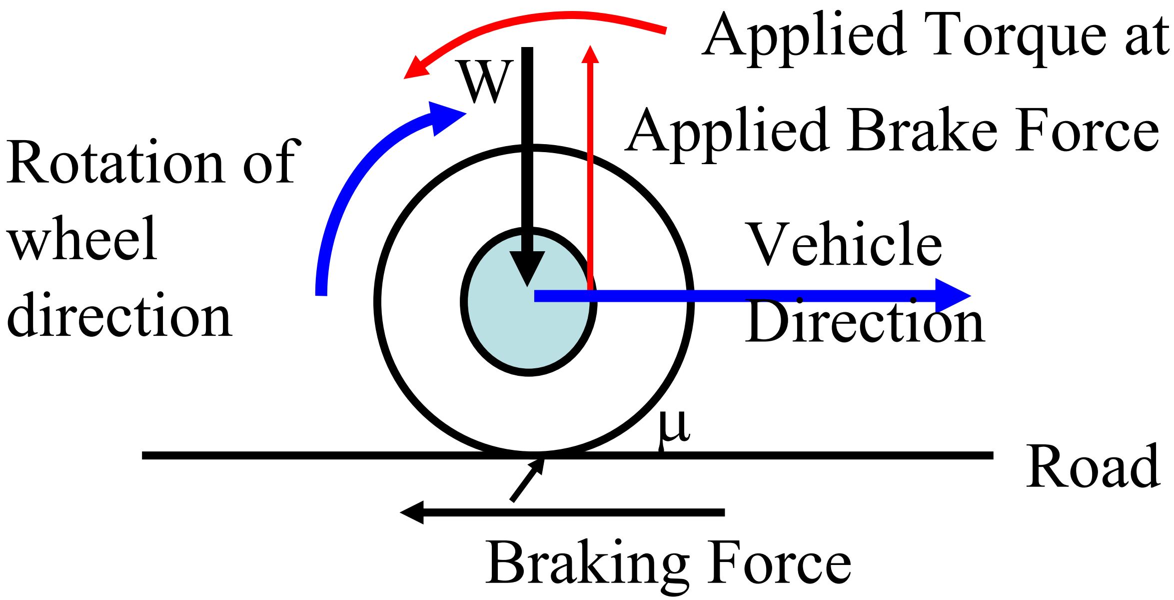




Master Cylinder and Booster

Force on Brake

- Applied Brake force-the force that exists between brake shoe and the brake drum, it acts tangentially to the brake drum in a direction opposite to the direction of rotation of the wheel.
- The brake force magnitude can be increased by applying a greater pressure on the brake shoe. However, there is a limit on the brake force.Its maximum magnitude can be equal to that of the frictional coupling between the tire and road-braking force.



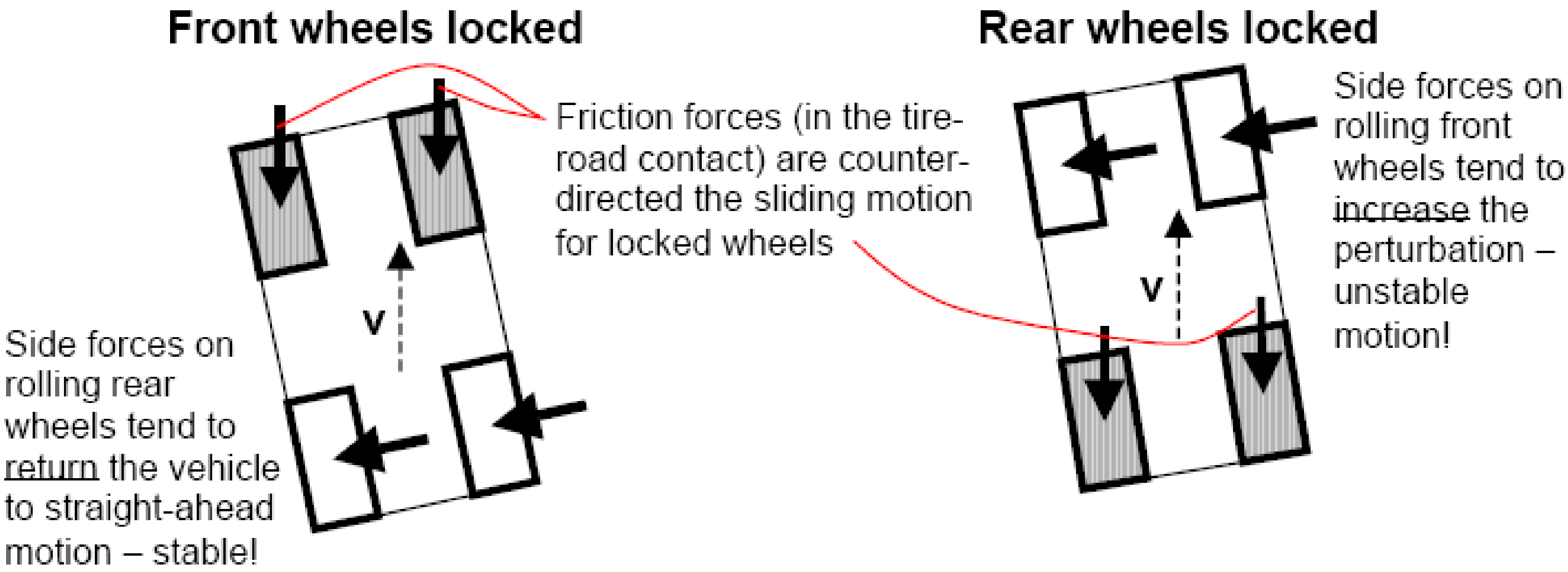
Braking Force =μW, (coefficient of friction and weight on the wheel

Wheel Lockup

- When brake force is greater than braking force, wheel lock up occurs
- Once wheels are locked in a panic braking situation vehicle skids
- Driver looses steering control

Wheel Lockup

Wheel Lockup



- A vehicle with locked front wheels will have a stable straight-ahead motion, however, the steerability is lost
- A vehicle with locked rear wheels will be unstable; it turns around and ends up in stable sliding
- Usually, it is preferred that the front wheels lock first.

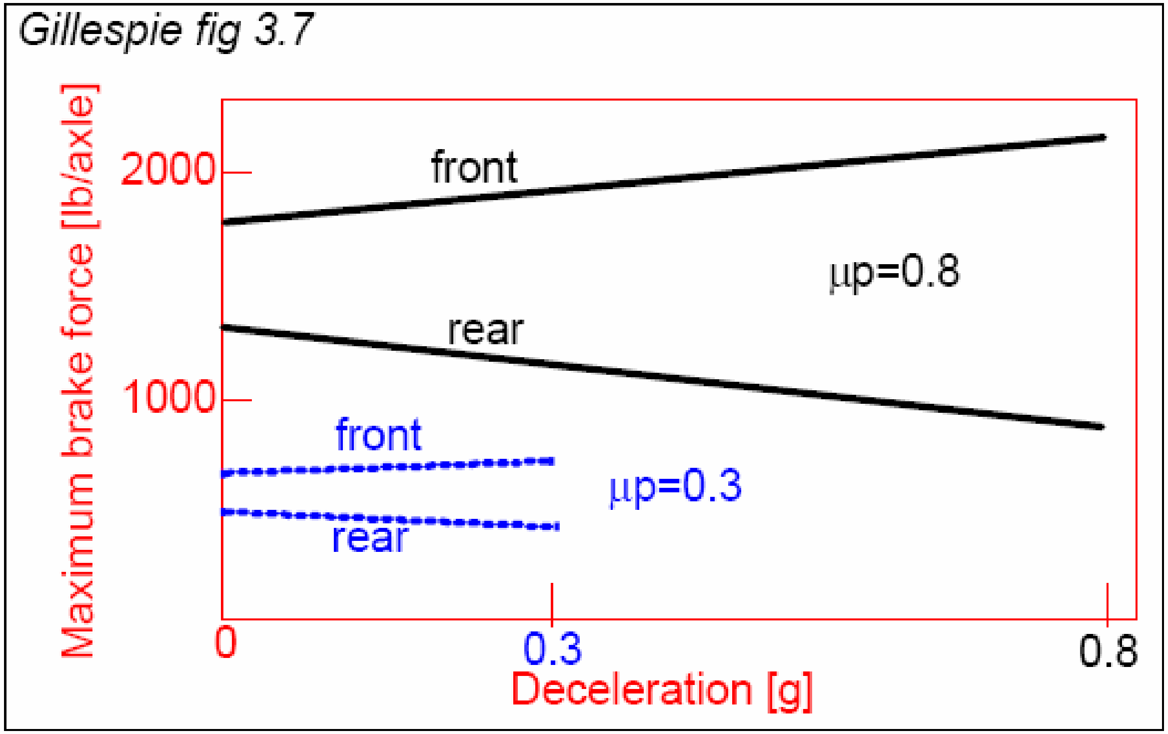
How to Avoid Wheel Lockup

- Apply right brake force to the given wheel (Brake proportioning)
- Have a control system which can control wheel lockup (ABS)

Brake Proportioning

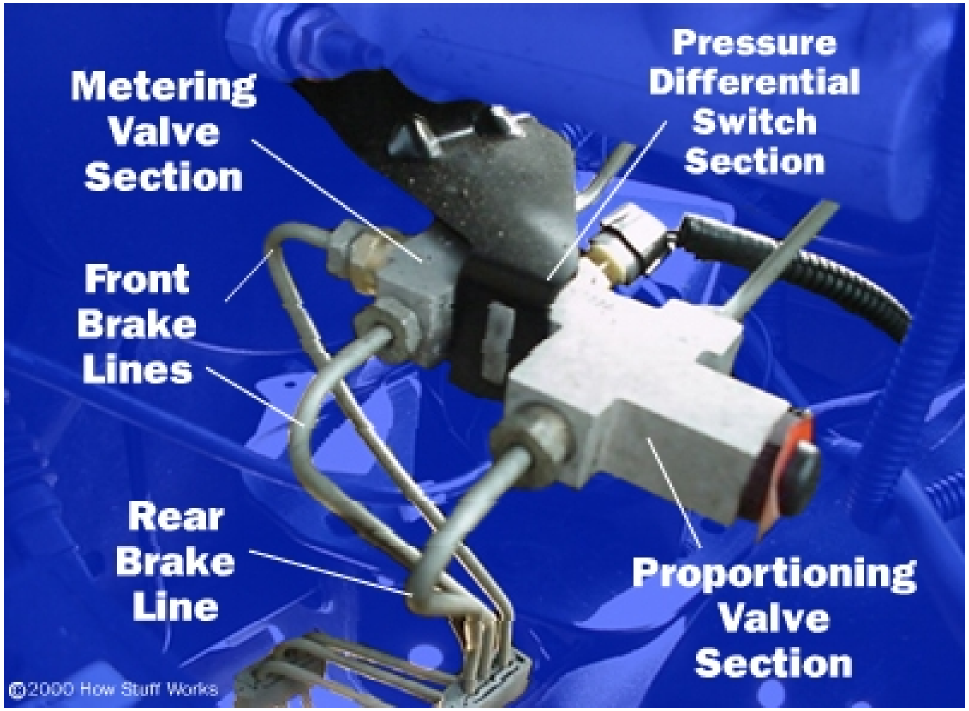
- Due to dynamic load transferring load acting on the axles change and some times load acting on each of the wheels is different
- Brake force applied to each one of the wheels must be proportionate to the vertical load acting on wheel
- Distribution of the brake force at each of the wheels based on the load acting on the wheels is called proportioning
- If proper proportioning is not done, there is a chance of wheels getting locked up due to brake-forces
- The variation of forces on the front and rear axle during deceleration and for different friction coefficient is given below

Load Variation on Axles

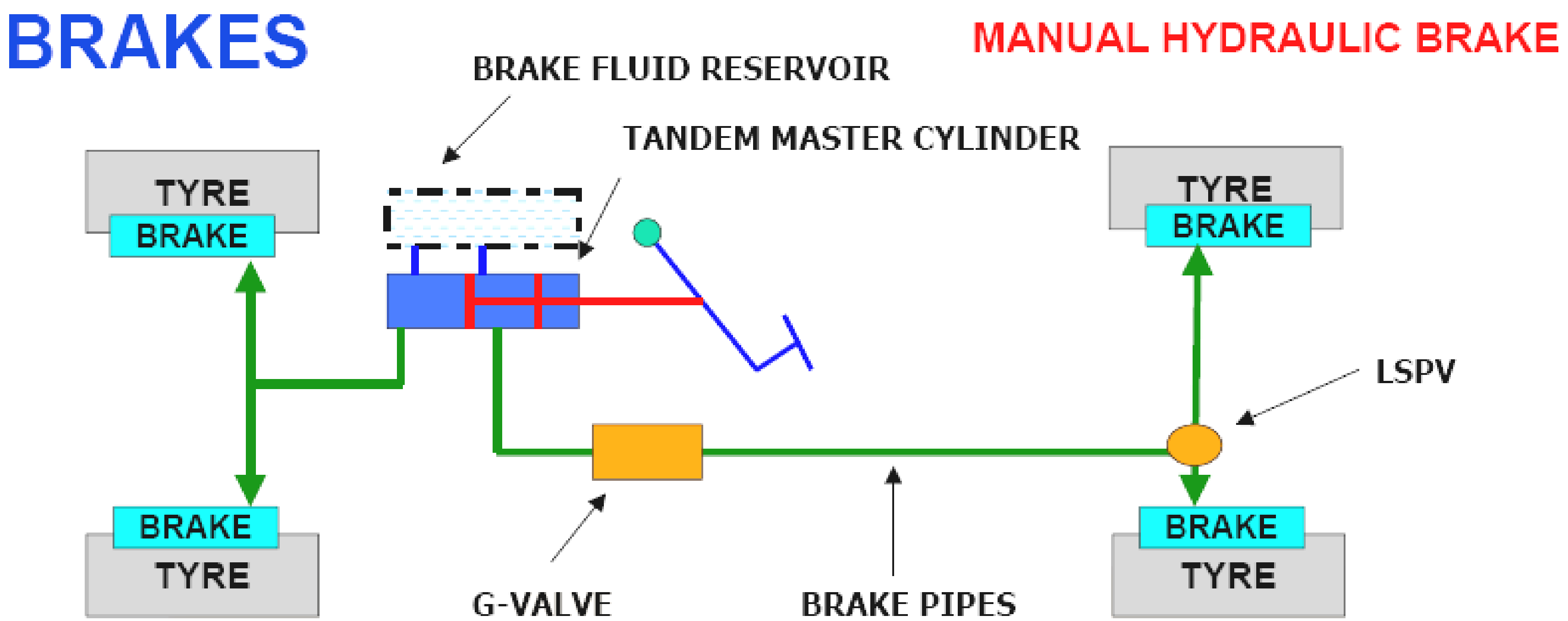


- Variation of load on the axle during braking also with respect to road friction

Proportioning and Other Valves



Brake Circuit with Proportioning Valves



LSPV-Load Sensing Proportioning Valve

G-Valve: Load Sensing Valve (Deceleration)

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Proportioning Valve

- The proportioning valve is designed to prevent rear wheel lockup during panic braking.
- It is needed for two main reasons - most vehicles use drum brakes in the rear which are hydraulically operated and all vehicles experience weight transfer during a panic stop
- The most important point to understand about proportioning valves is when they work - only during panic braking. This means that a vehicle could potentially go its whole life without ever using its proportioning valve
- Proportioning Valves
  - Hydraulic Proportioning Valve
  - Mechanical Proportioning Valve (Load Sensing Proportioning Valve)

Hydraulic Proportion Valve

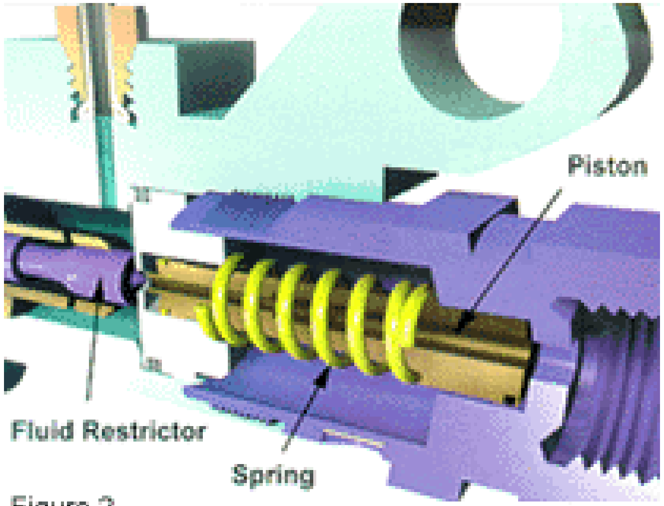


Figure 2

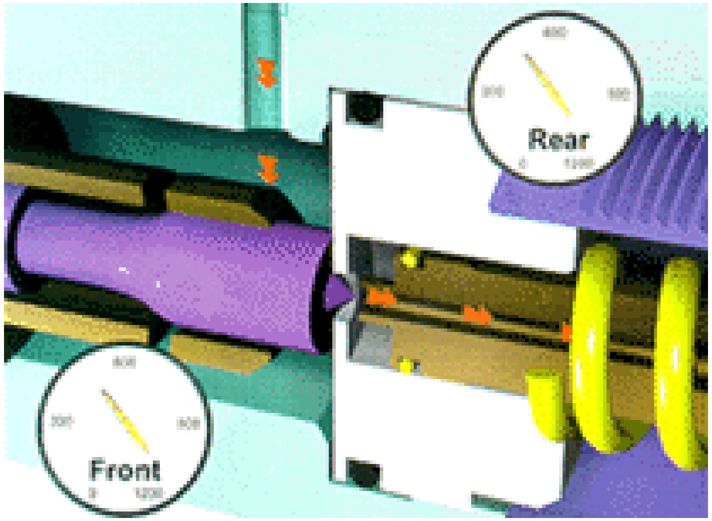


Figure 3

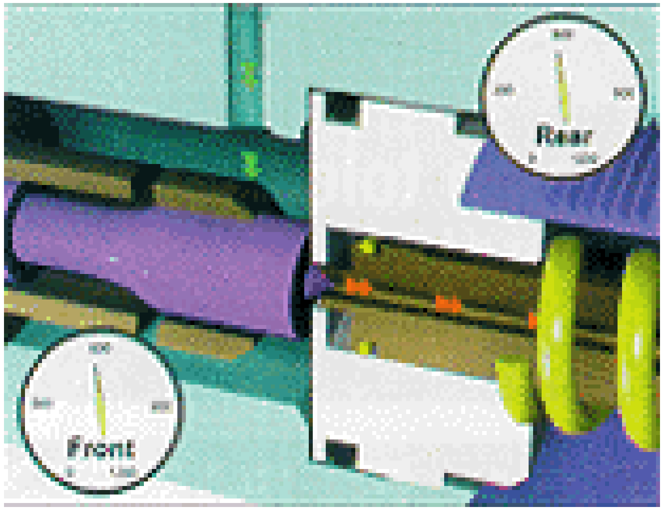


Figure 4

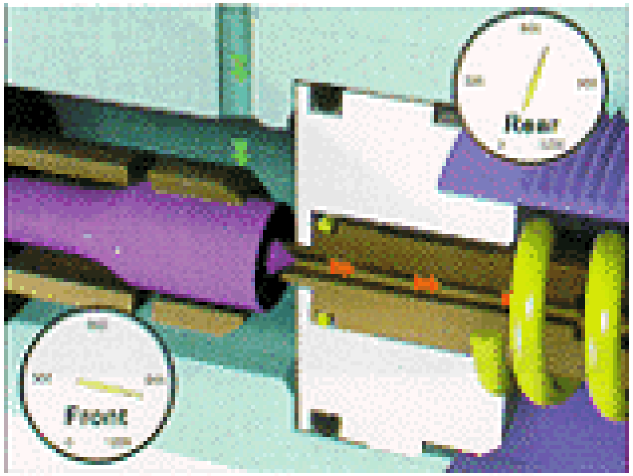


Figure 5

Mechanical Proportioning Valve

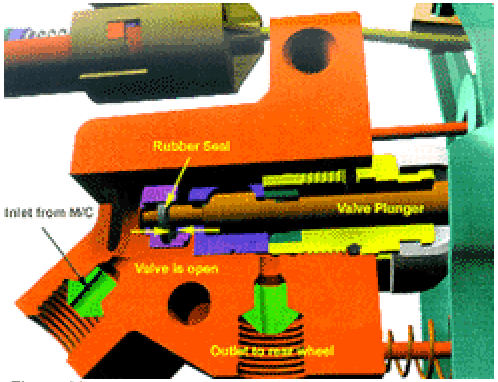


Figure 11


Figure 12

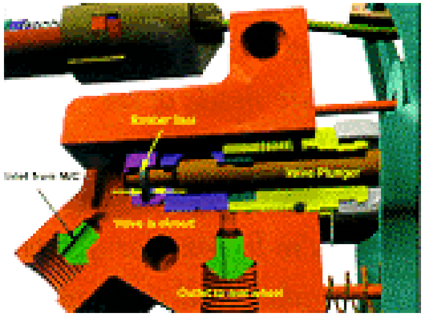
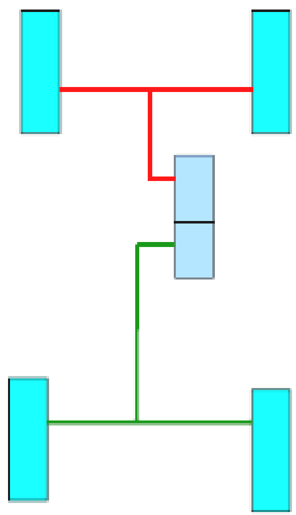
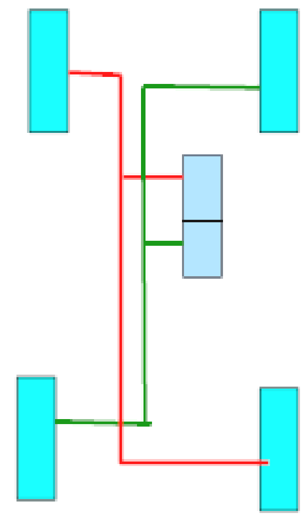


Figure 13

Brake Circuit- Split



FRONT/BACK SPLIT



X- SPLIT

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Federal Requirements for Braking Performance

- Out of the public concern for automotive safety in the 1960s, the Highway Safety Act of 1965 was passed establishing the National Highway Traffic Safety Administration charged with promulgating performance standards for new vehicles which would increase safety on the highways.
- Among the many standards that have been imposed are Federal Motor Vehicle Safety Standard (FMVSS)
- FMVSS 105, establishing braking performance requirements for vehicles with hydraulic brake systems,
- FMVSS 121, establishing braking performance requirements for vehicles with air brake systems.

Federal Requirements for Braking Performance

Although the standard is quite detailed and complex, the requirements for stopping distance performance can be summarized into tests:

1) First effectiveness – A fully loaded passenger car with new, unburnished brakes must be able to stop from speeds of 30 and 60 mph in distances that correspond to average deceleration of 17 and 18 ft/sec^2, respectively.
2) Second effectiveness – A fully loaded passenger car with burnished brakes must be able to stop from 30, 60 and 80 mph in distances that correspond to average decelerations of 17, 19 and 18 ft/sec^2.
3) Third effectiveness – A lightly loaded passenger car with burnished brakes must be able to stop from 60 mph in a distance that corresponds to an average deceleration of 20 ft/sec^2.
4) Fourth effectiveness – A fully loaded passenger car with burnished brakes must be able to stop from 30, 60, 80 and 100 mph in distances that correspond to average decelerations of 17, 18, 17 and 16 ft/sec^2, respectively.
5) Partial Failure – A lightly loaded and fully loaded passenger car with a failure in the brake system must of able to stop from 60 mph in a distance that corresponds to an average deceleration of 8.5 ft/sec^2.

Load on Front and Rear Axles During Deceleration

$$W_f = \frac{c}{L}W + \frac{h}{L}\frac{W}{g}D_x = W_{fs} + W_d$$

$$W_r = \frac{b}{L}W - \frac{h}{L}\frac{W}{g}D_x = W_{rs} - W_d$$

$$W_{fs} = Front\ axle\ static\ load$$

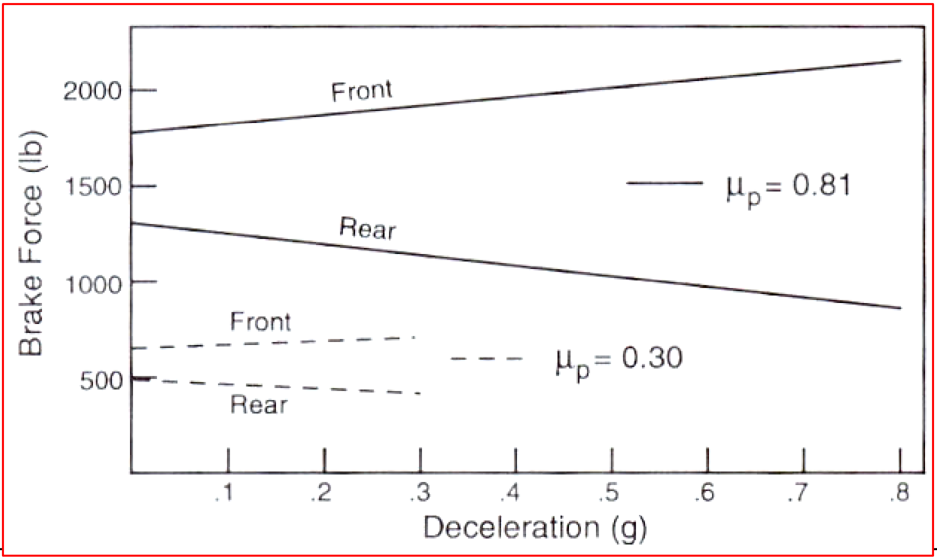
$$W_{rs} = Rear\ axle\ static\ load$$

$$W_d = \left(\frac{h}{L}\right)\left(\frac{W}{g}\right)D_x = Dynamic\ load\ transfer$$

$$F_{xmf} = \mu_p W_f = \mu_p (W_{fs} + \frac{h}{L}\frac{W}{g}D_x)$$

$$F_{xmr} = \mu_p W_r = \mu_p (W_{rs} - \frac{h}{L}\frac{W}{g}D_x)$$

$$\mu_p = Peak\ coefficient\ of\ \ friction$$



Proportioning Line

$$D_x = \frac{(F_{xmf} + F_{xr})}{M}$$

for F_{xmr}

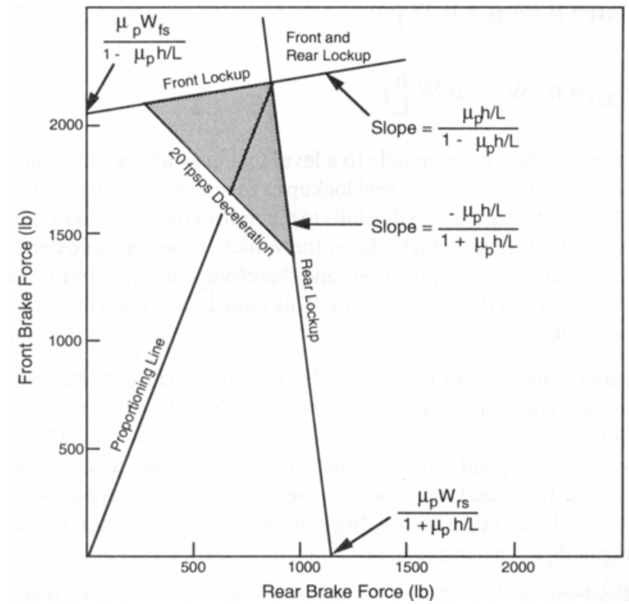
$$D_x = \frac{(F_{xmr} + F_{xf})}{M}$$

$$F_{xmf} = \frac{\mu_p W_{fs}}{1 - \mu_p \frac{h}{L}} + \frac{\mu_p}{1 - \mu_p \frac{h}{L}} \frac{h}{L} F_{xr}$$

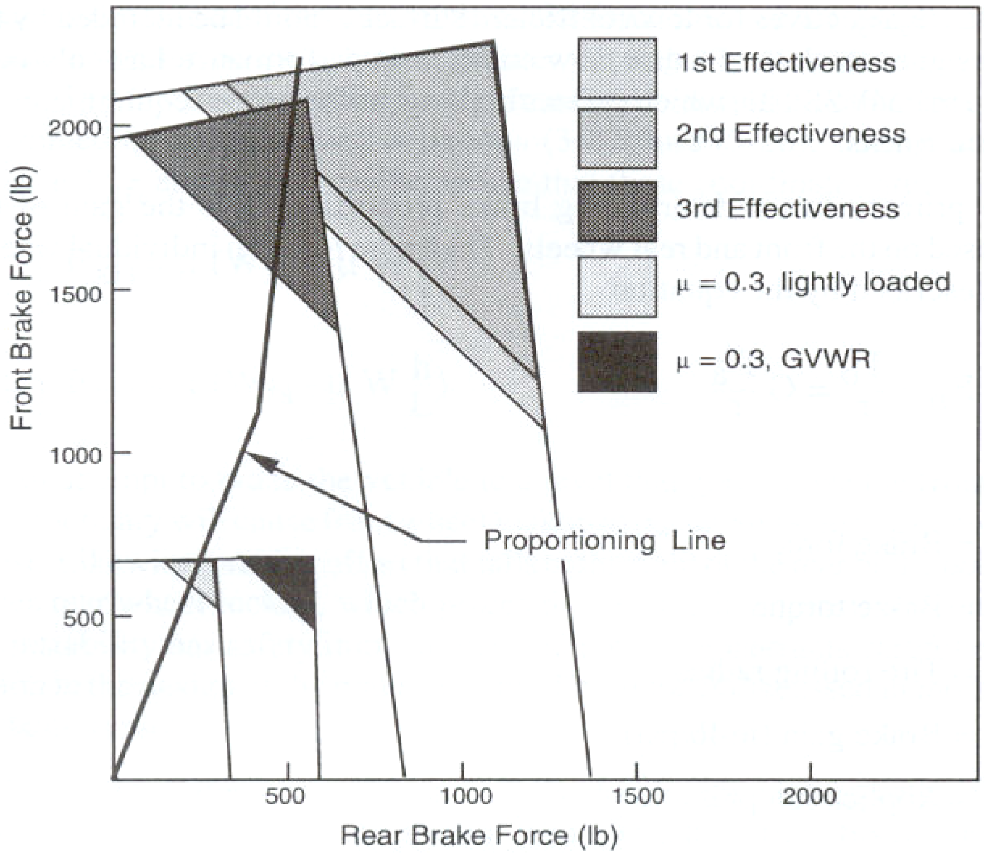
$$F_{xmr} = \frac{\mu_p W_{rs}}{1 + \mu_p \frac{h}{L}} - \frac{\mu_p}{1 + \mu_p \frac{h}{L}} \frac{h}{L} F_{xf}$$

$$F_{xmf} = \frac{\mu_p (W_{fs} + \frac{h}{L} F_{xr})}{1 - \mu_p \frac{h}{L}}$$

$$F_{xmr} = \frac{\mu_p (W_{rs} - \frac{h}{L} F_{xf})}{1 + \mu_p \frac{h}{L}}$$



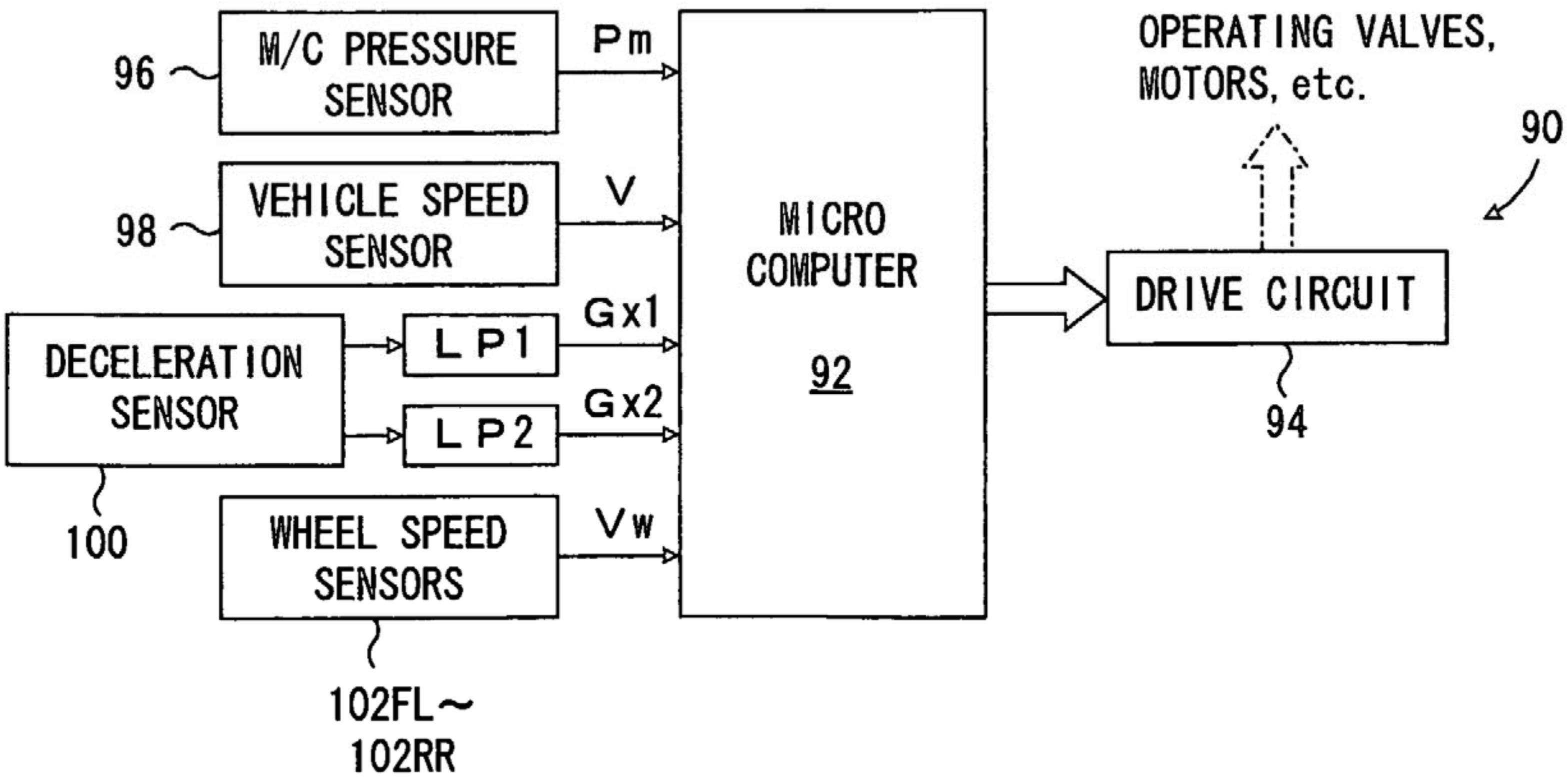
Proportioning line for Different Mu and FMVSS Conditions



Electronic Brake Force Distribution-EBD

- Proportioning can be done by using mechanical brake proportioning valves
- Modern practice is to use Electronic Brake Force Distribution (EBFD) technology
- EBFD is an automobile brake technology that automatically varies the amount of force applied to each of a vehicle's brakes, based on road conditions, speed, loading, etc.
- EBD can apply more or less braking pressure to each wheel in order to maximize stopping power

Electronic Brake Force Distribution



Slip

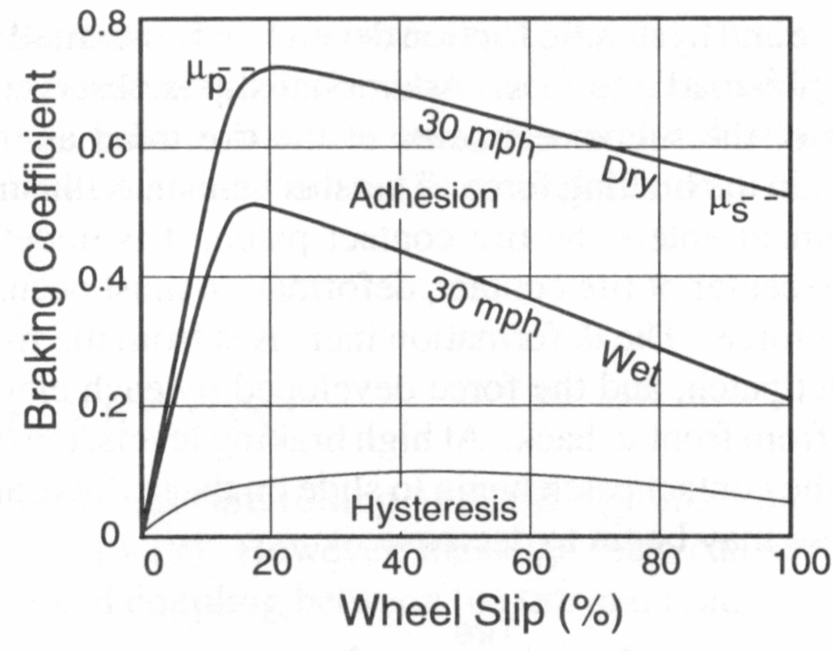
- Wheel locking condition is expressed by 100% slip
- Slip is defined as =

$$\frac{V - \omega r}{V}$$

  – V: vehicle Velocity, ω: Tire rotational speed

Braking Coefficient

- Braking Coefficient = Braking Force/Tire load



- Braking force will be large if braking coefficient is high which can happen at 20% wheel slip for all types of road
- Braking coefficient is very low at 100% slip, wheels are not spinning, means vehicle skids

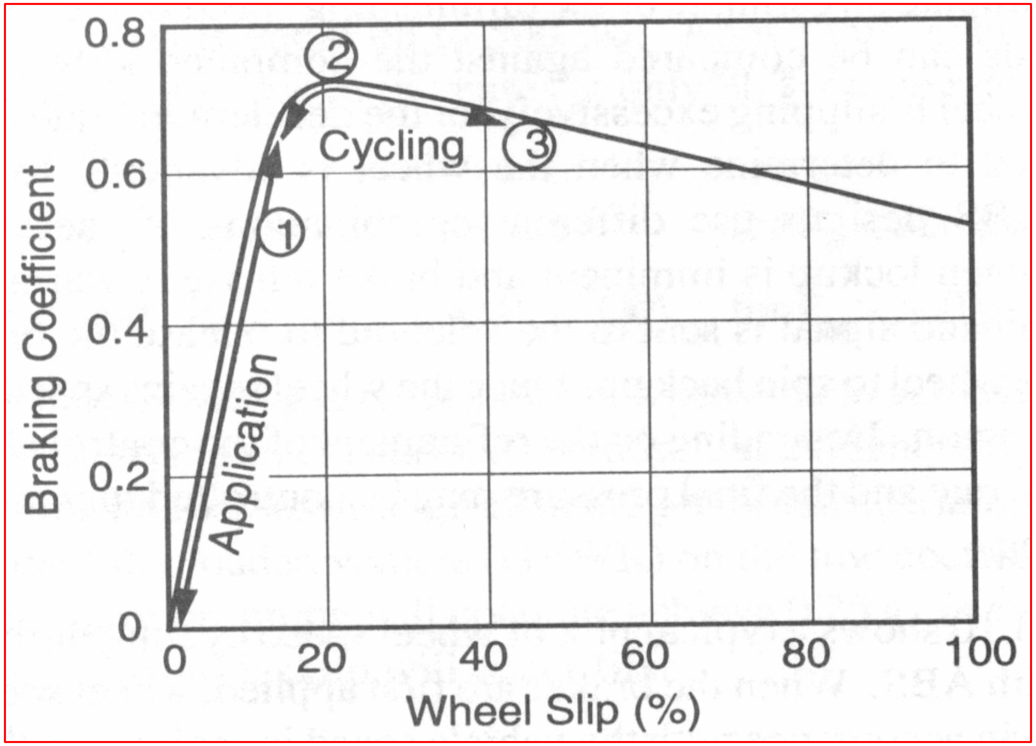
Effect of Slip

- The increased pressure on the brake pedal increases the slip because wheel spinning speed decreases-the increased pressure on the brake pedal produces undesirable effects
- Lateral force is the force keeping a tire from sliding in a direction normal to the direction of the vehicle. The equation for lateral force is

$$F_y = \mu_{lateral} W_{wh}$$

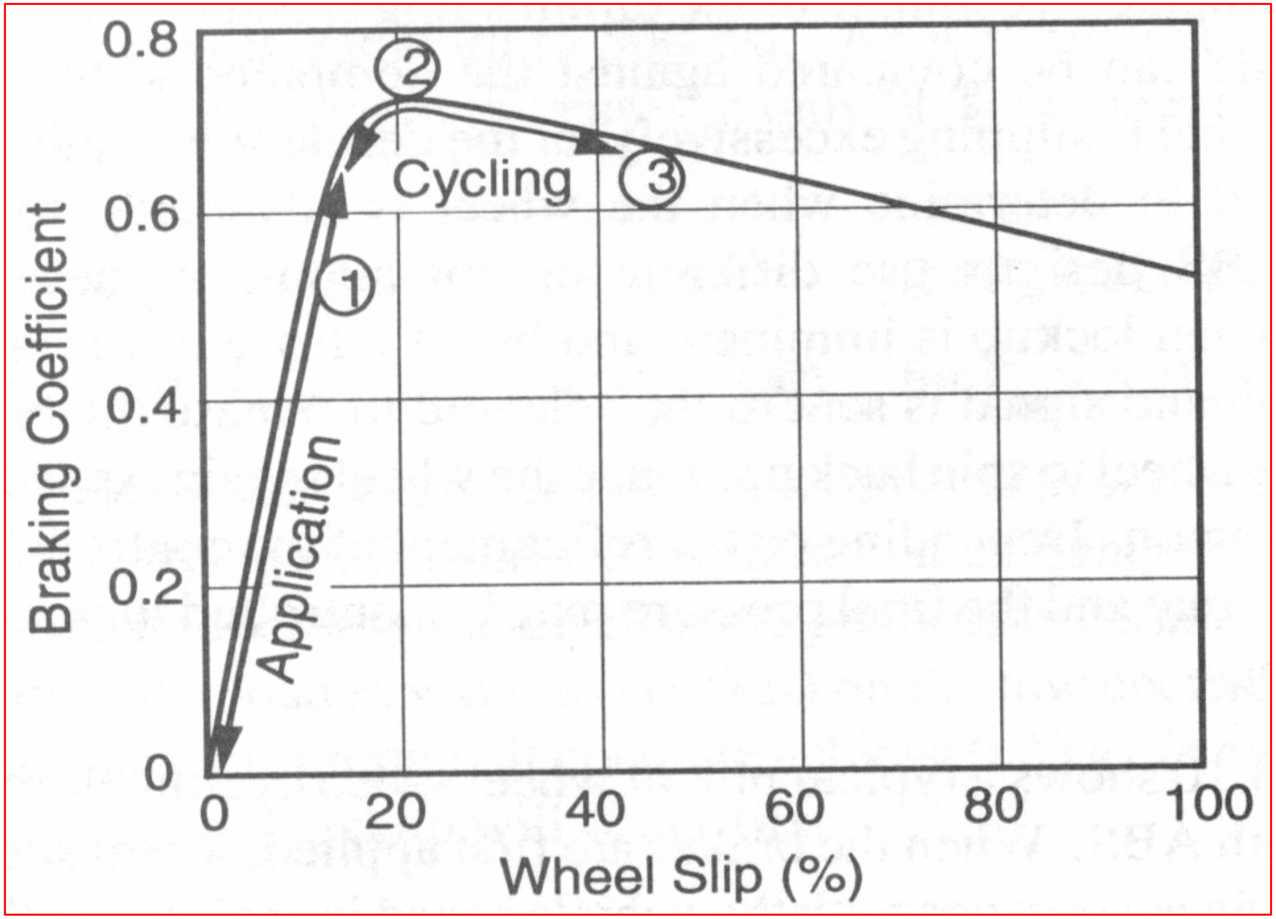
- The lateral coefficient of friction drops off quickly once a wheel begins to slip longitudinally, as can happen during braking.
- Excessive wheel slip at the rear wheels of a vehicle and the resulting loss of lateral frictional force will contribute to instability as the rear of the vehicle tends to slide sideways with relatively small lateral forces on the vehicle.
- Excessive wheel slip and the resulting loss of lateral friction on the front wheels of a vehicle will contribute to the loss of steerability; this loss of steering phenomenon is common during panic stops on low coefficient surfaces such as ice, as a hard apply of the brakes puts the tires in a 100% slip situation

Improving Braking Force

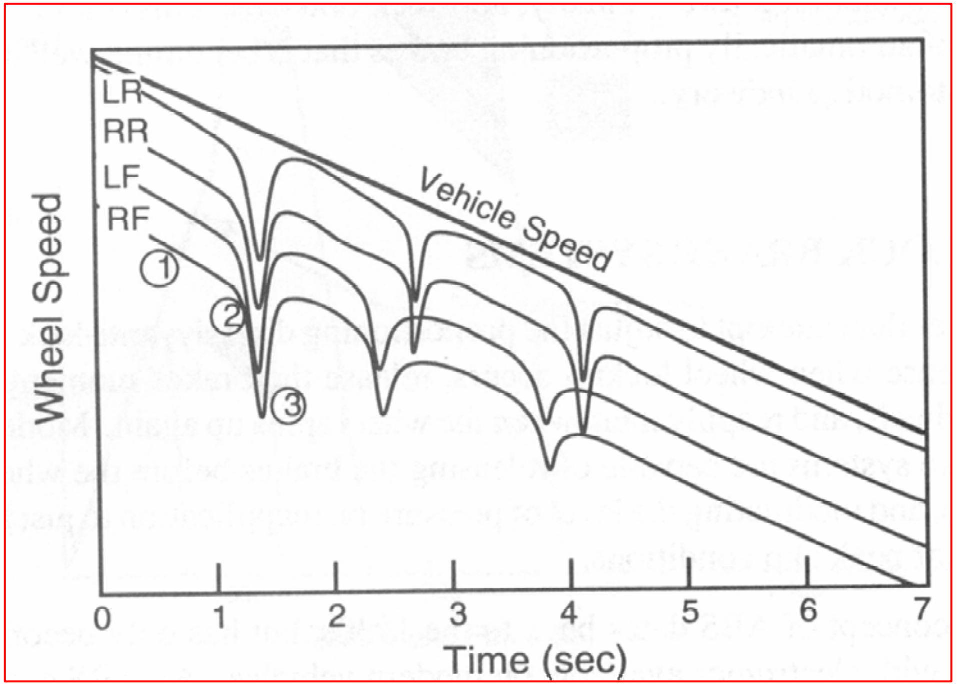


- To have better braking the wheel speed should be cyclically altered between point 2 and 3

Braking Coefficient & Wheel Slip



Wheel Speed Cycling



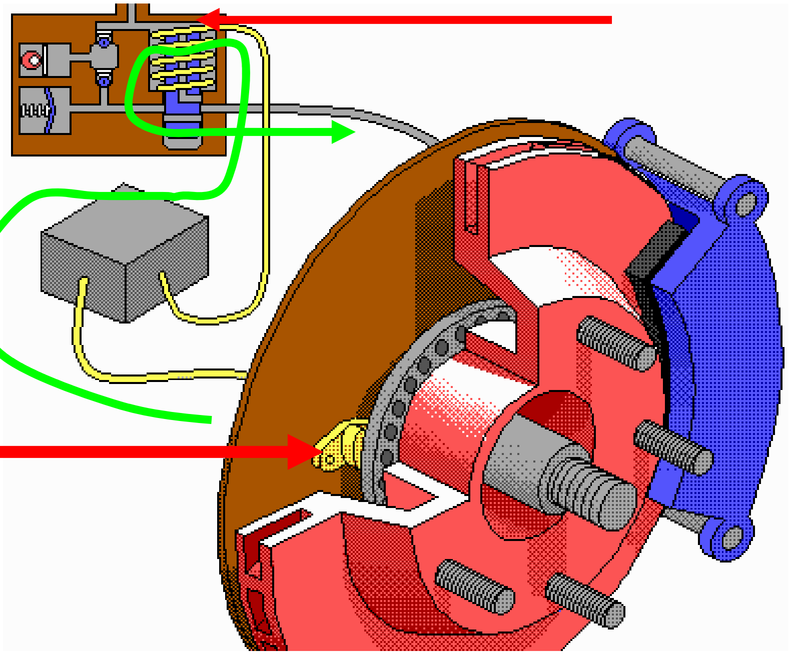
- Figure shows wheel speed with respect to time when brake is applied
- When the brakes are first applied, wheel speeds diminish more or less in accordance with the vehicle speed in region 1 in the plot

Pressure Modulation at Wheels

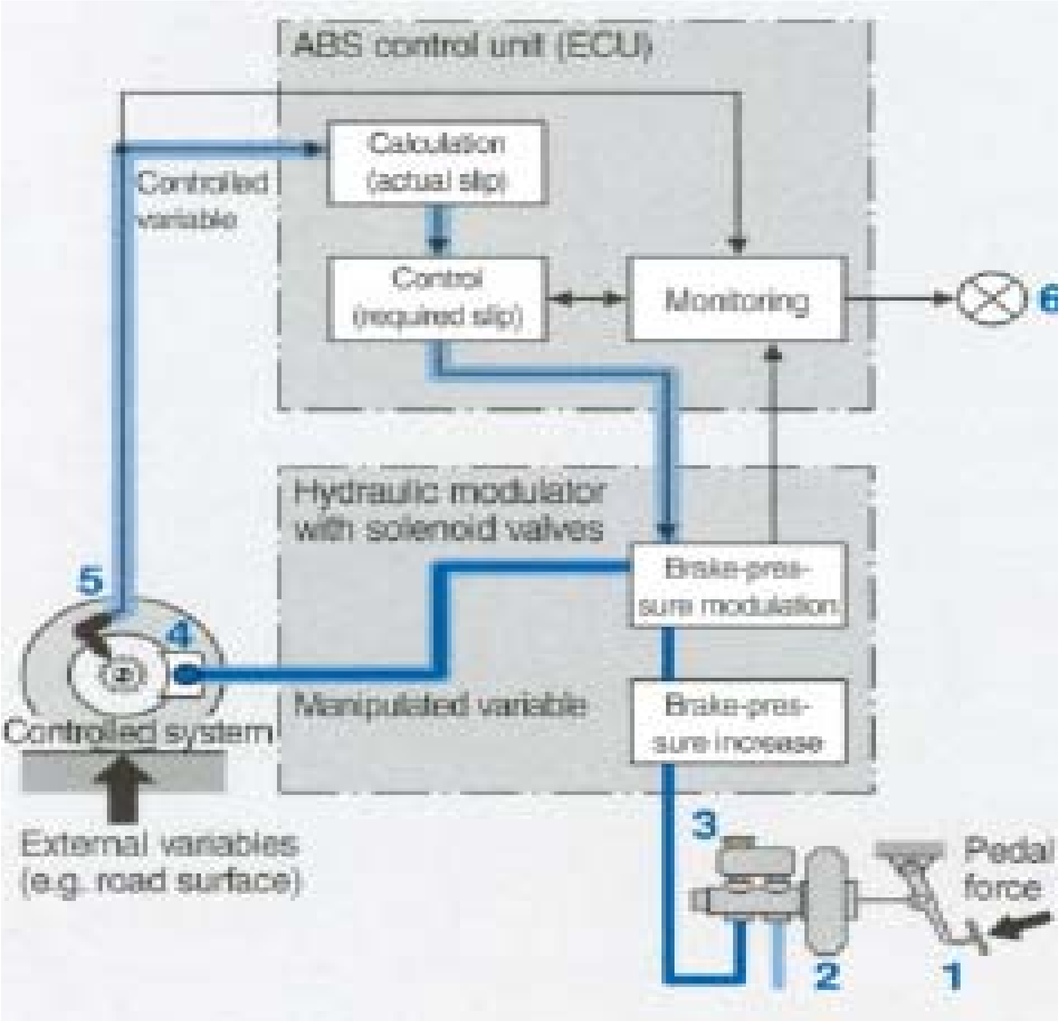
Solenoid Valve

Micro Controller

Wheel Speed Sensor

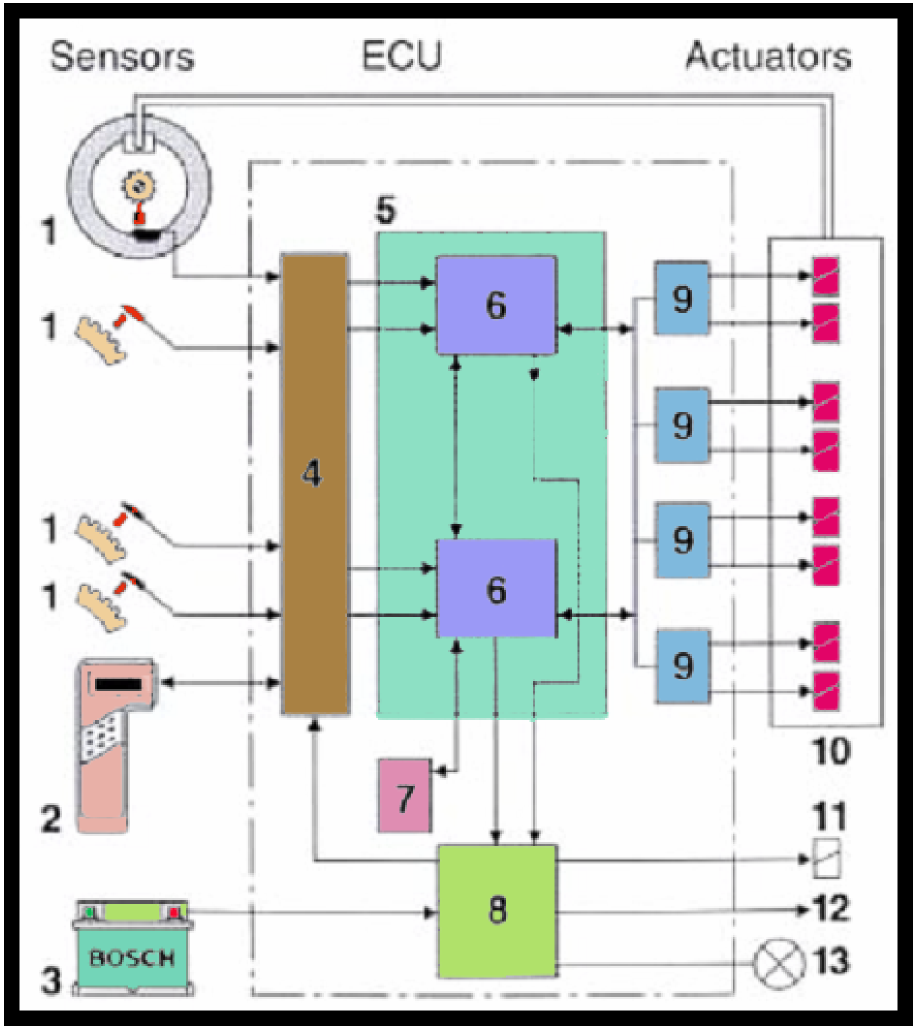


Algorithm for Pressure Modulation



1. Brake pedal
2. Brake servo unit
3. Master cylinder with brake-fluid reservoir
4. Brake
5. Wheel-speed sensor
6. Warning lamp

Complete ABS System

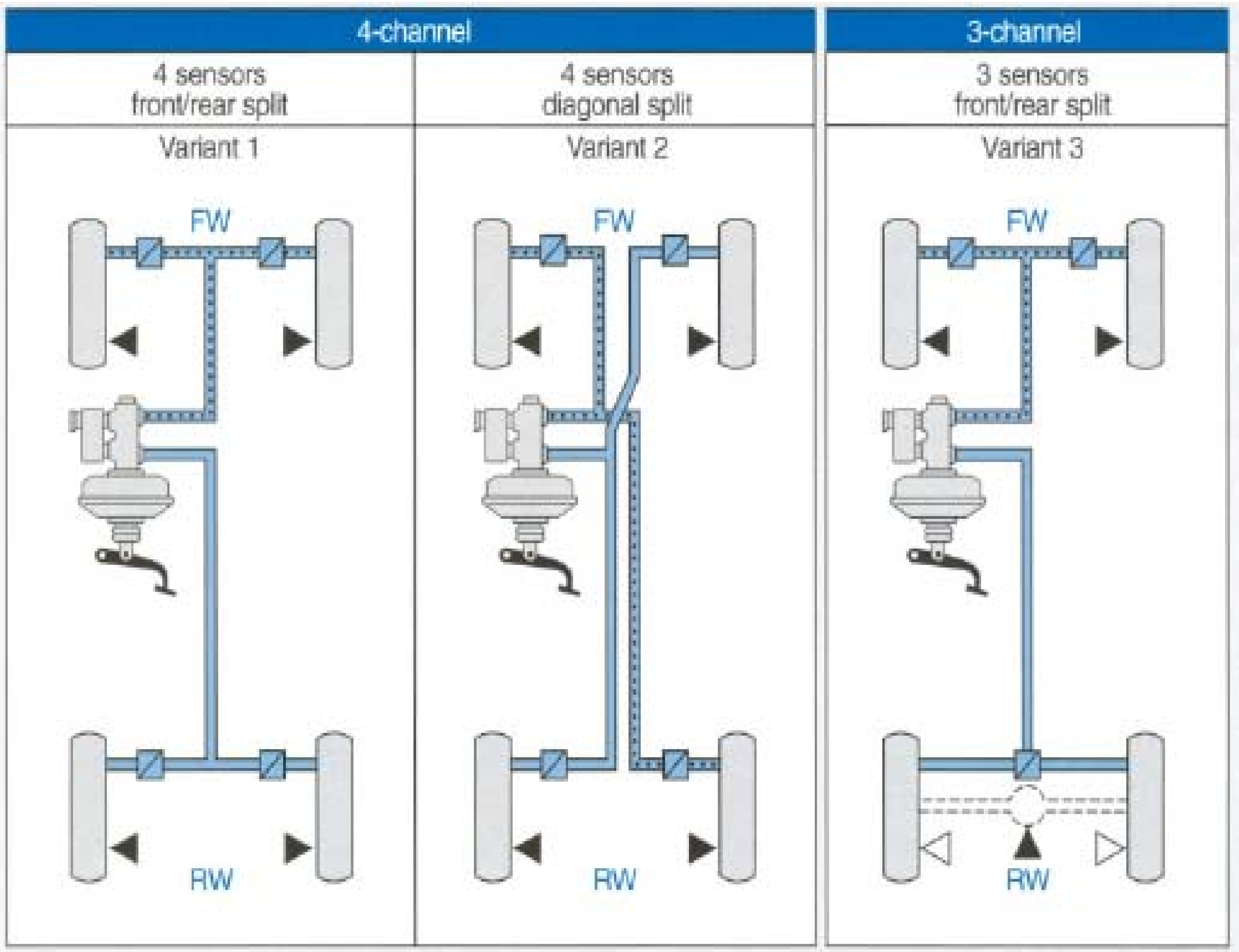


ECU (4-channel installation)

1 Wheel-speed sensors,
2 Diagnosis connection,
3 Battery,
4 Input circuit,
5 Digital electronic controller,
6 Microcontroller,
7 Non-volatile memory,
8 Voltage stabilizer/Error store,
9 Output circuits with driver stages,
10 Solenoid-valve pairs

11 Relay,
12 Stabilized battery voltage,
13 Check lamp.

ABS Variants



Control channel

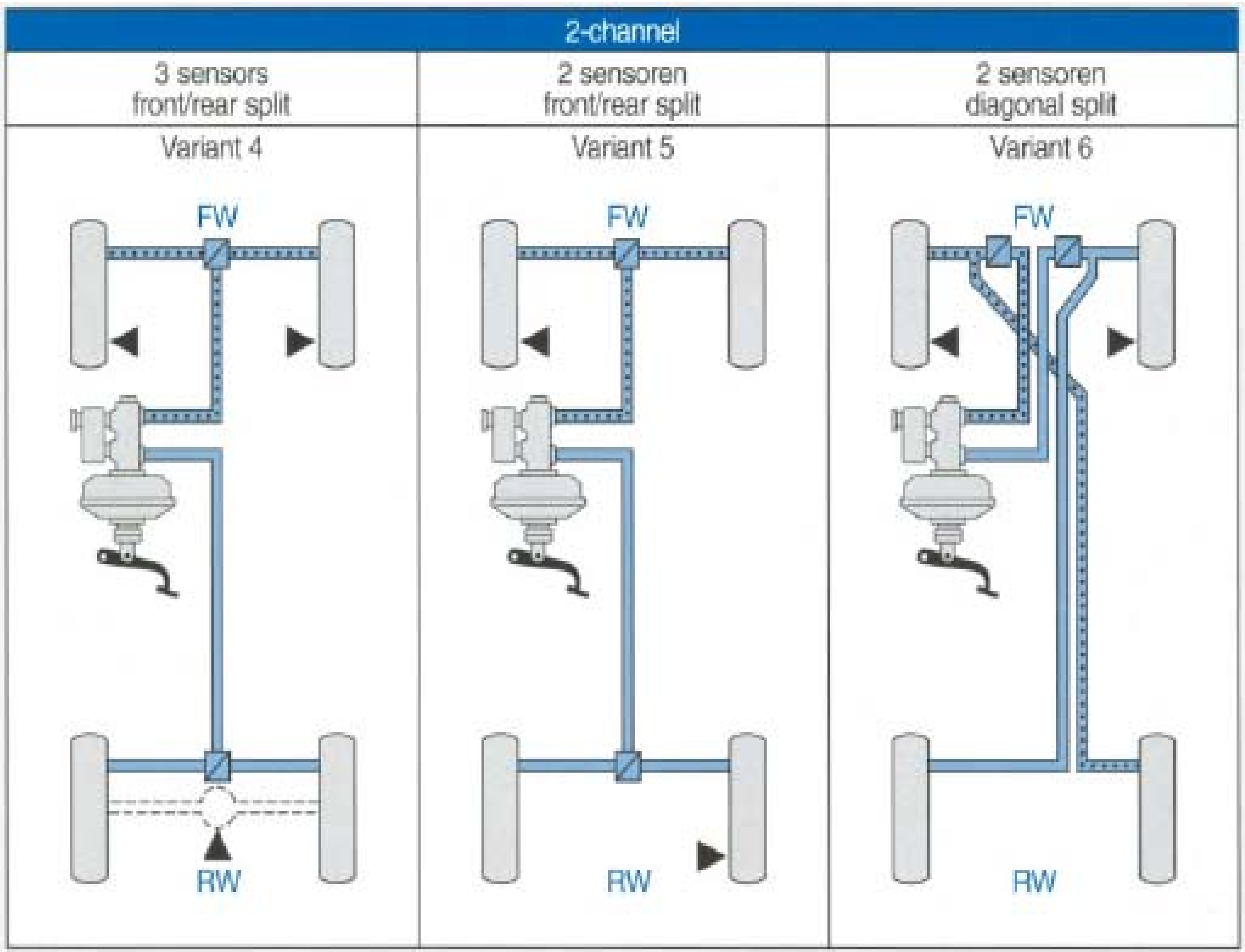
Wheel-speed sensor

Wheel-speed sensor (alternative too differential speed sensor)

FW Front wheels

RW Rear wheels

ABS Variants



Control channel

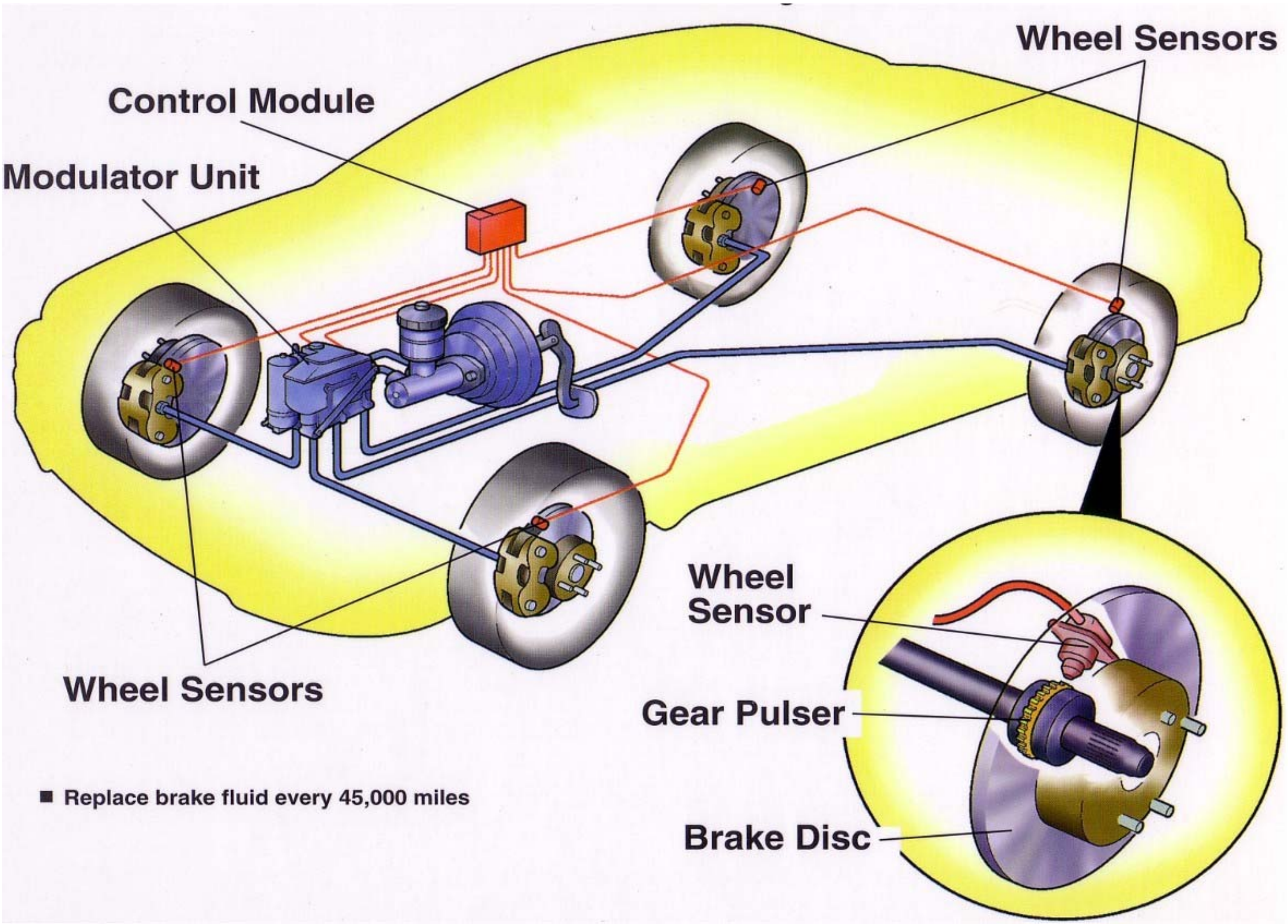
Wheel-speed sensor

Wheel-speed sensor (alternative too differential speed sensor)

FW Front wheels

RW Rear wheels

Braking System with ABS



Braking Efficiency

- **Braking efficiency** = a property defined for a complete vehicle
- Braking efficiency = deceleration/(g*max(braking coefficient))
- It can be seen as totally used friction (deceleration/g) in relation to how well the best used axle (or wheel) uses the friction if 100%, the distribution of braking is optimal.

$$\eta_b = \frac{D_{act}}{\mu_p}$$

- The braking efficiency concept is useful as a design tool for the designer to assess success in optimizing the vehicle braking system.

Braking Efficiency