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 2 – Accelerating Performance

Class Lecture

- ***CONTENTS:***

Vehicle Acceleration

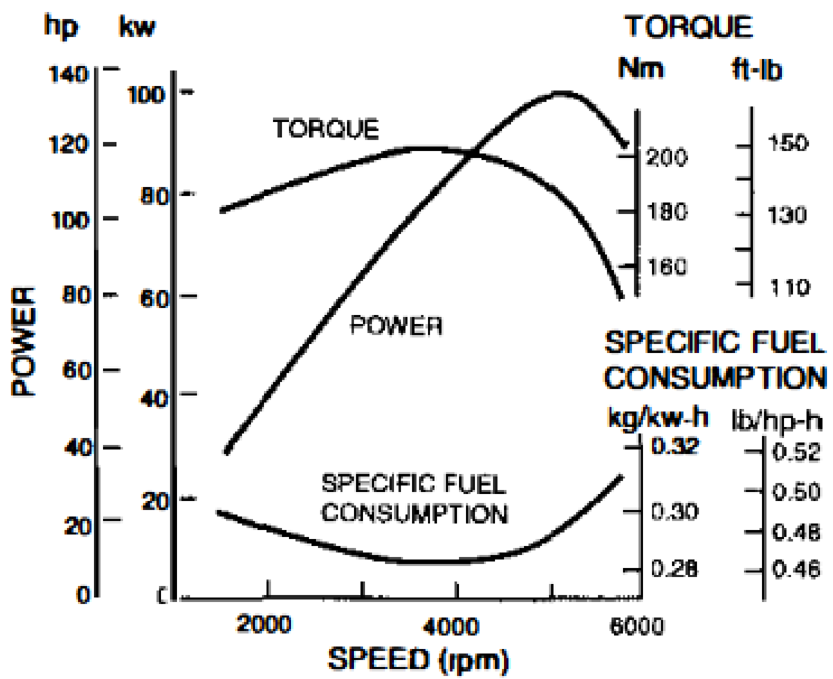
Maximum performance in longitudinal acceleration is determined by one of two limits:

- Engine power
- Traction limits
  - At low speeds tire traction may be the limiting factor, whereas at high speeds engine power may account for the limits

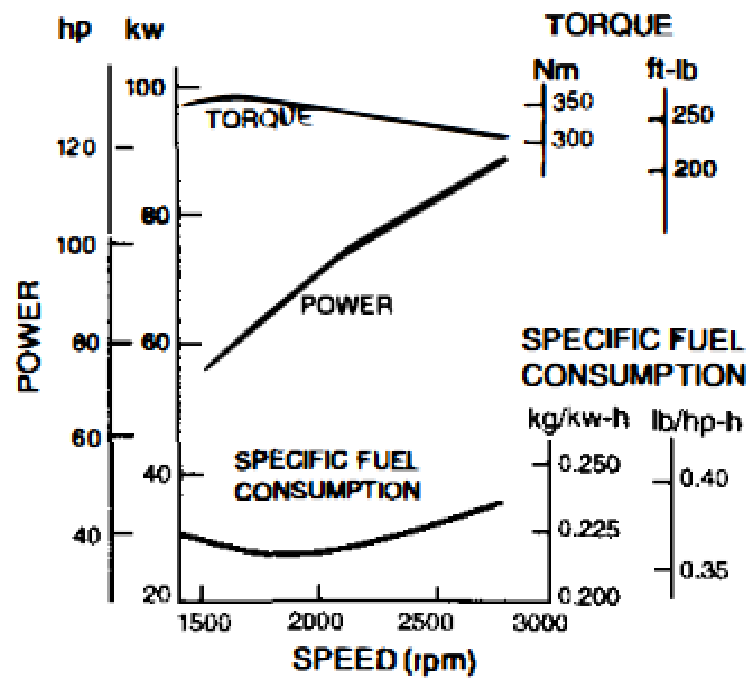
- Power-limited Acceleration
  - Engine characteristics and power train
- Traction-limited Acceleration
  - Coefficient of friction between the tire and road.

POWER-LIMITED ACCELERATION

- **Engines:** The source of propulsive power is the engine.
- Engines may be characterized by their torque and power curves as a function of speed.



Gasoline



Diesel

POWER-LIMITED ACCELERATION

- Power, torque and speed relation:

Power (ft-lb/sec) = Torque (ft-lb) x speed (radians/sec)

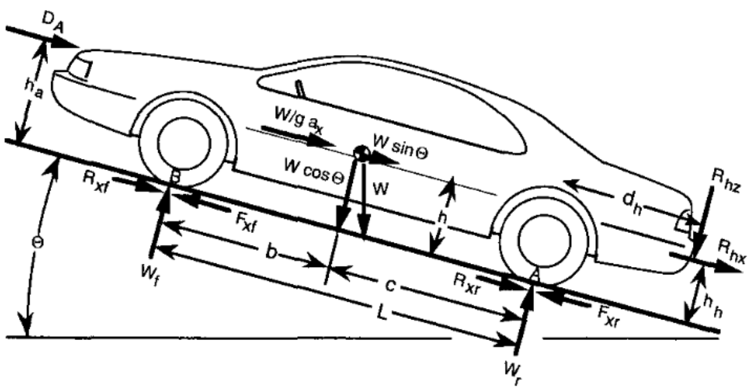
Horsepower = T (ft-lb) x ω_e (rad/sec) / 550 = T (ft-lb) x RPM / 5252

Power (kw) = 0.746 x HP   1 hp = 550 ft-lb/sec

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

Power-Limited Acceleration

- At low to moderate speeds (by neglecting all resistance forces):
  - Newton’s Second Law



$$M\,a_x = F_x$$

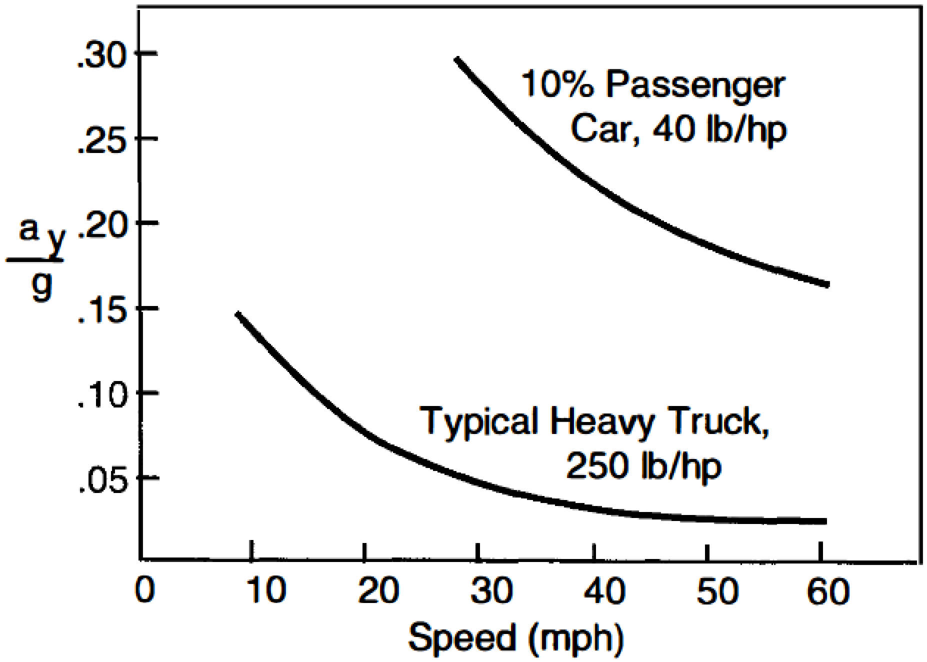
$$a_x = \frac{1}{M} F_x = 550\,\frac{g}{V}\,\frac{HP}{W} \quad (\text{ft/sec}^2)$$

g = Gravitational constant (32.2 ft/sec^2)
V = Forward speed (ft/sec)
HP = Engine horsepower
W = Weight of the vehicle (lb)

POWER-LIMITED ACCELERATION

- Acceleration vs. Speed diagram:
  - Because of the velocity term in the denominator, acceleration capability must decrease with increasing speed

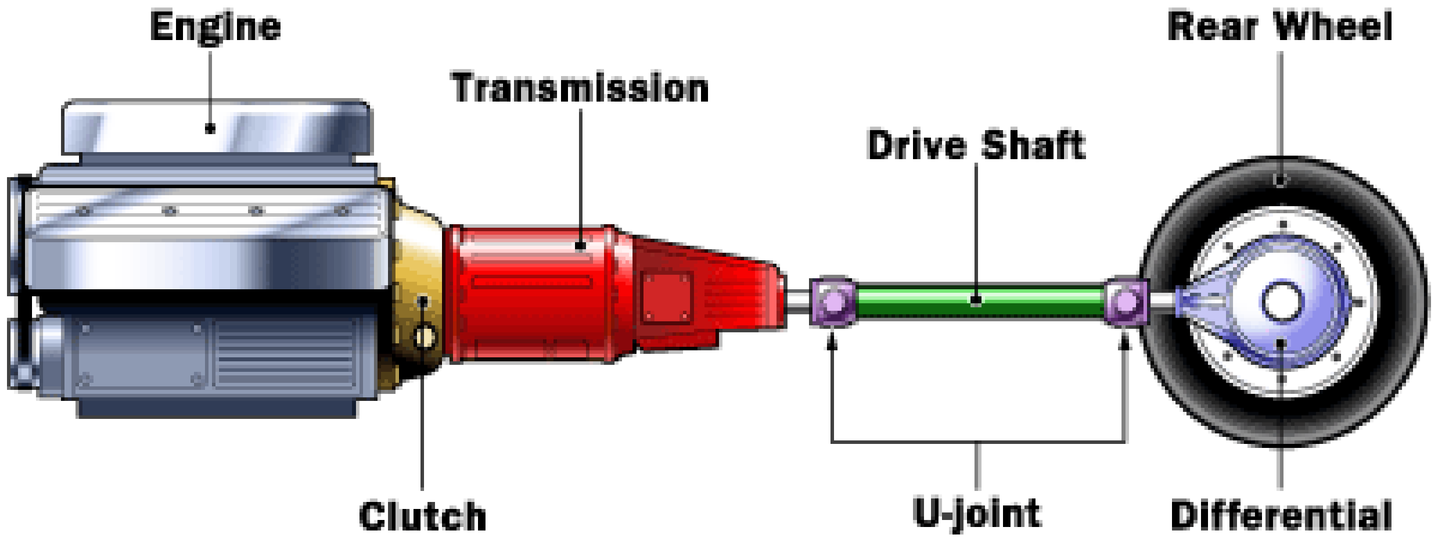
$$a_x = \frac{1}{M} F_x = 550 \frac{g}{V} \frac{HP}{W} \quad (ft/sec^2)$$

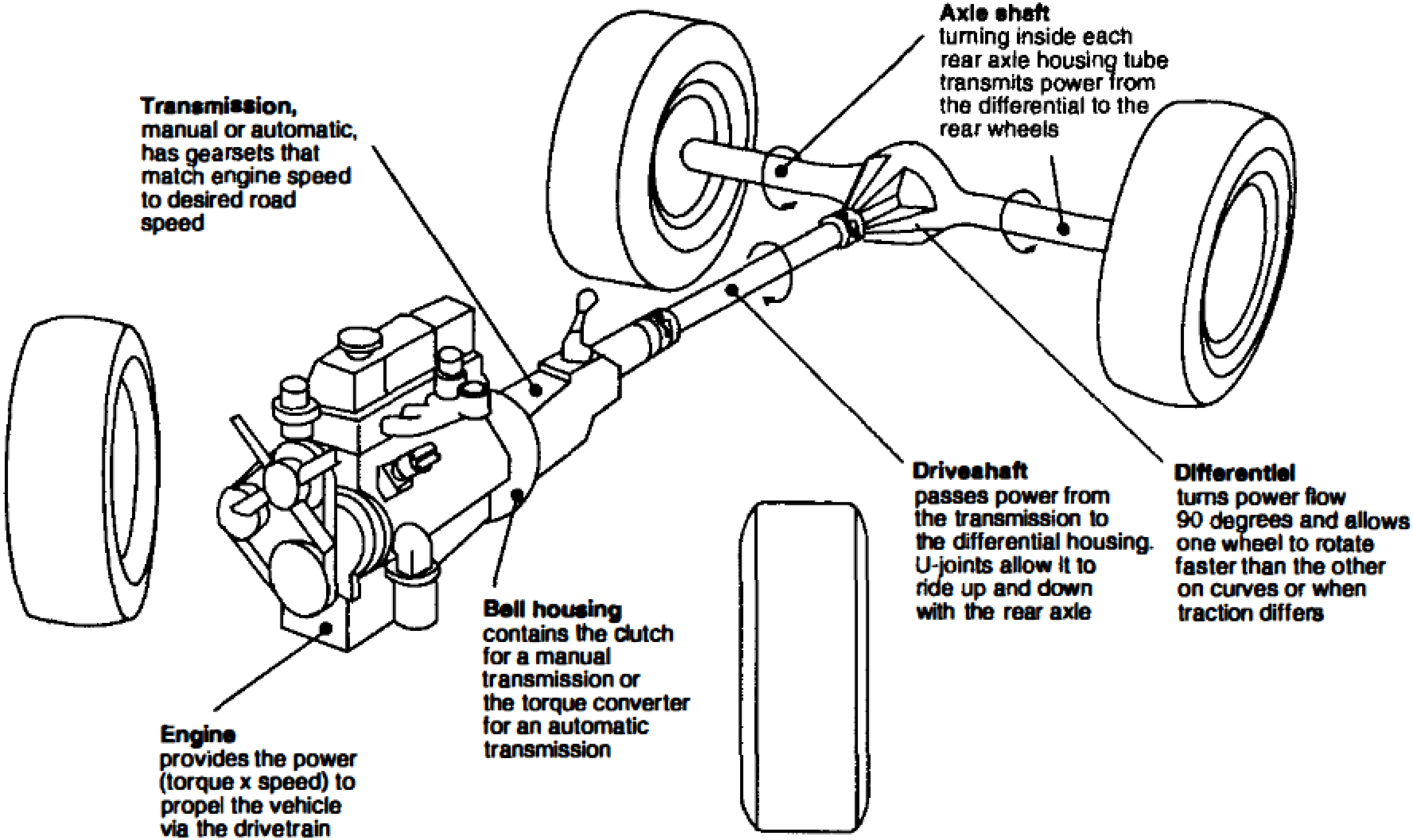


Power-Limited Acceleration

❑ Power Train

❖ More exact estimation of acceleration performance requires modeling the mechanical systems by which engine power is transmitted to the ground.




Axle shaft
turning inside each rear axle housing tube transmits power from the differential to the rear wheels
Transmission,
manual or automatic, has gearsets that match engine speed to desired road speed
Driveshaft
passes power from the transmission to the differential housing. U-joints allow it to ride up and down with the rear axle
Differential
turns power flow 90 degrees and allows one wheel to rotate faster than the other on curves or when traction differs
Bell housing
contains the clutch for a manual transmission or the torque converter for an automatic transmission
Engine
provides the power (torque x speed) to propel the vehicle via the drivetrain

POWER-LIMITED ACCELERATION

- Engine torque is measured at steady speed on a dynamometer.
- Thus the actual torque delivered to the drivetrain is reduced by the amount required to accelerate the inertia of the rotating components

$$T_c = T_e - I_e \alpha_e$$

T_c = Torque at the clutch (input to the transmission)
T_e = Engine torque at a given speed (from dynamometer data)
I_e = Engine rotational inertia
α_e = Engine rotational acceleration

Power-Limited Acceleration

- The torque delivered at the output of the transmission is amplified by the gear ratio of the transmission.
- It also is decreased by inertial losses in the gears and shafts

$$T_d = (T_c - I_t \alpha_e) N_t$$

T_d = Torque output to the driveshaft
N_t = Numerical ratio of the transmission
I_t = Rotational inertia of the transmission (as seen from the engine side)

Power-Limited Acceleration

- Similarly, the torque delivered to the axles to accelerate the rotating wheels is amplified by the final drive ratio with some reduction from the inertia of the driveline components between the transmission and final drive:

$$T_a = F_x r + I_w \alpha_w = (T_d - I_d \alpha_d) N_f$$

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 driveshaft
α_d = Rotational acceleration of the driveshaft
N_f = Numerical ratio of the final drive

POWER-LIMITED ACCELERATION

Rotational accelerations (engine, transmission, driveline and wheels) relation:

$$\alpha_d = N_f \alpha_w \quad \text{and} \quad \alpha_e = N_t \alpha_d = N_t N_f \alpha_w$$

- Tractive force available at the ground

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

N_{tf} = Combined ratio of transmission and final drive

Power-Limited Acceleration

- The inefficiencies (due to mechanical and viscous losses) act to reduce the engine torque in proportion to the product of the efficiencies of the individual components.
- The efficiencies vary widely with the torque level in the driveline.
- As a rule of thumb, efficiencies in the neighborhood of 80% to 90%

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

η_{tf} = Combined efficiency of transmission and final drive

Power-Limited Acceleration

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

η_{tf} = Combined efficiency of transmission and final drive

- ✓ 1) The first term on the right-hand side is the engine torque multiplied by the overall gear ratio and the efficiency of the drive system, then divided by tire radius.

- ✓ 2) The second term on the right-hand side represents the "loss" of tractive force due to the inertia of the engine and drivetrain components.

Power-Limited Acceleration

- Acceleration Performance of a Vehicle:

$$M a_x = \frac{W}{g} a_x = F_x - R_x - D_A - R_{hx} - W \sin \Theta$$

- Rotational inertias are often lumped in with the mass of the vehicle:

$$(M + M_r) a_x = \frac{W + W_r}{g} a_x = \frac{T_e N_{tf} \eta_{tf}}{r} - R_x - D_A - R_{hx} - W \sin \Theta$$

M_r = Equivalent mass of the rotating components

POWER-LIMITED ACCELERATION

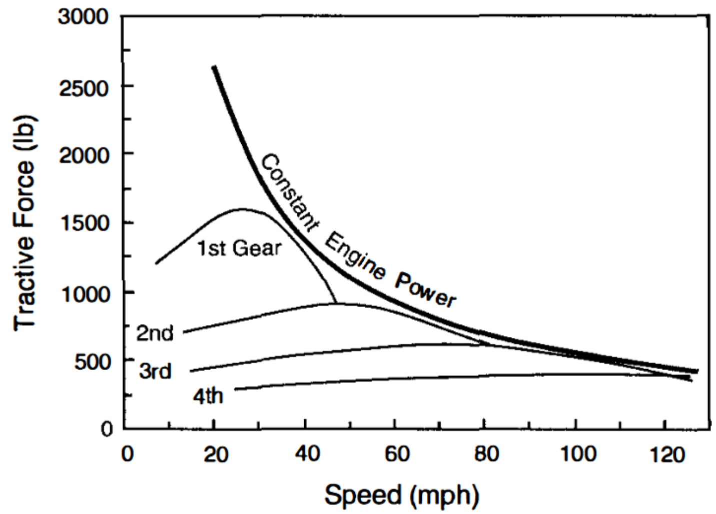
- Effective Mass: M+Mr
- Mass Factor: (M + Mr)/M
  - The mass factor will depend on the operating gear

		Mass Factor			
Vehicle	Gear:	High	Second	First	Low
Small Car		1.11	1.20	1.50	2.4
Large Car		1.09	1.14	1.30	—
Truck		1.09	1.20	1.60	2.5

$$\text{Mass Factor} = 1 + 0.04 + 0.0025\, N_{tf}^2$$

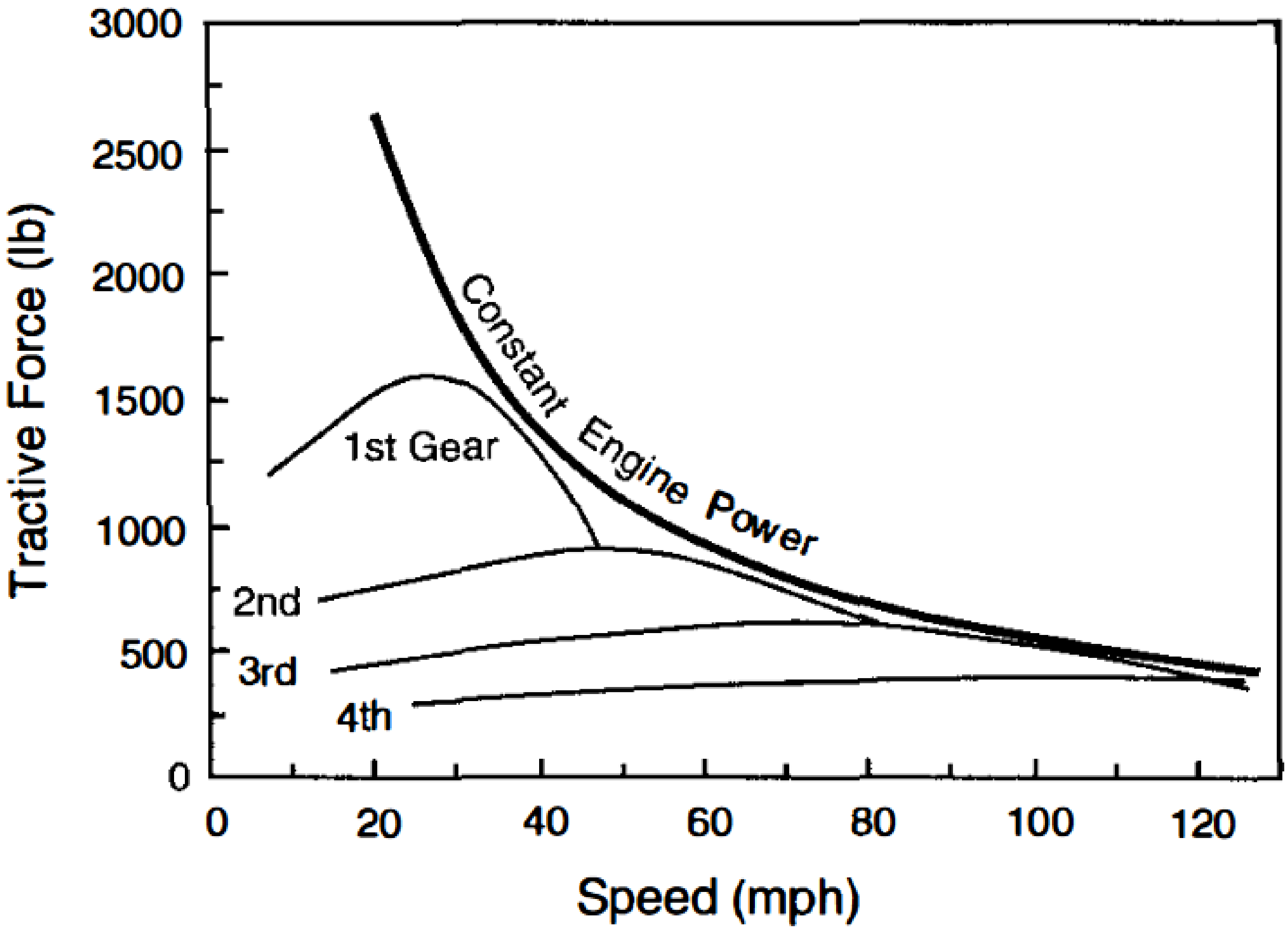
Power-Limited Acceleration

- The tractive: the effort available to overcome road load forces and accelerate the vehicle



- ✓ The "Constant Engine Power" line is equal to the maximum power of the engine.
- ✓ Optimum shift point for max. acc. performance: the point where the lines cross.

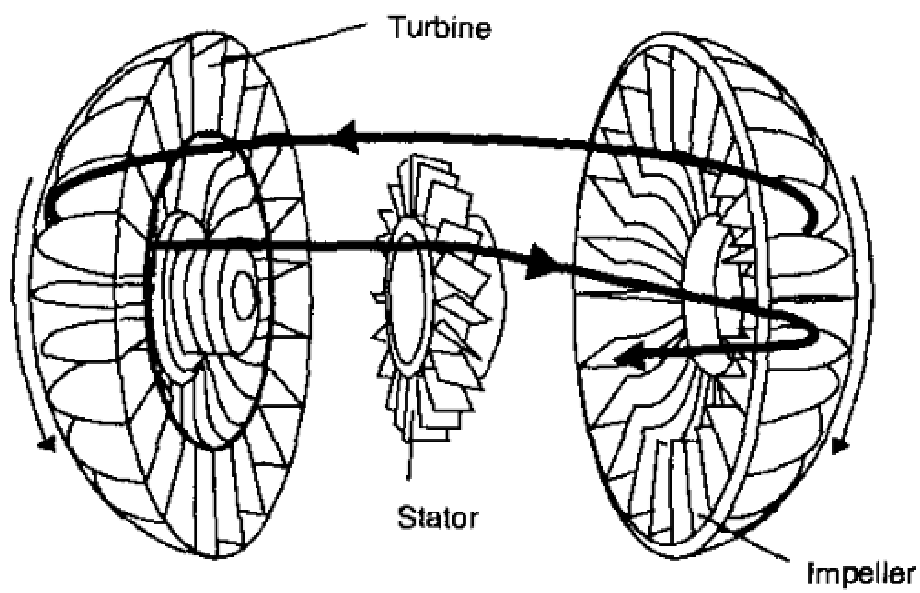
Power-Limited Acceleration



POWER-LIMITED ACCELERATION

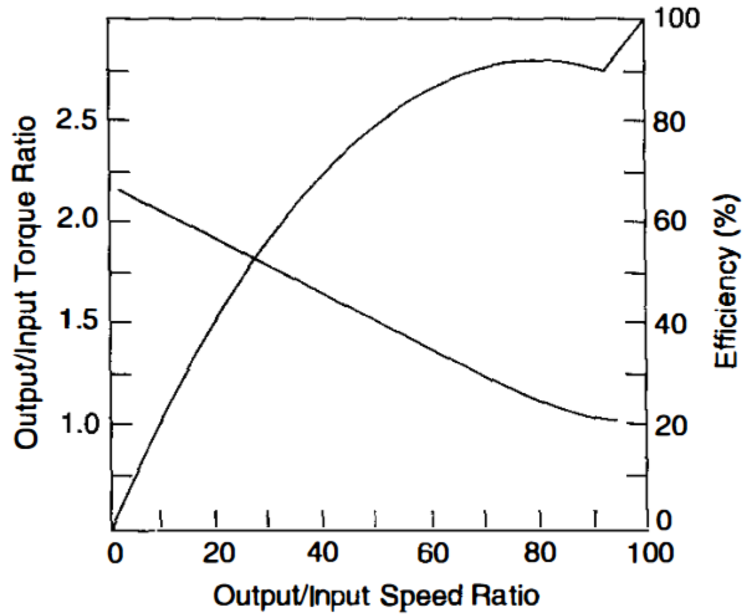
Automatic Transmissions

- Automatic transmissions provide more closely matching the ideal because of the torque converter on the input
- Torque converters are fluid couplings that utilize hydrodynamic principles to amplify the torque input to the transmission at the expense of speed.



POWER-LIMITED ACCELERATION

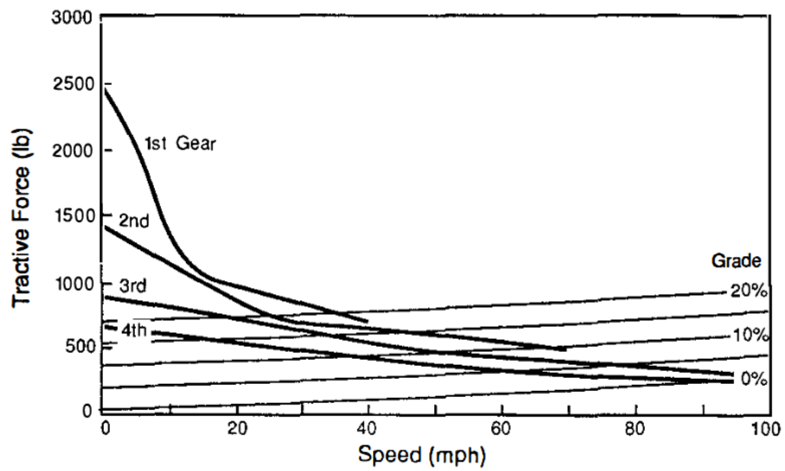
- Torque ratio and efficiency of a typical torque converter vs. speed ratio:



  - At zero output speed: the output torque will be several times that of the input.
  - As speed builds up, the torque ratio drops to unity

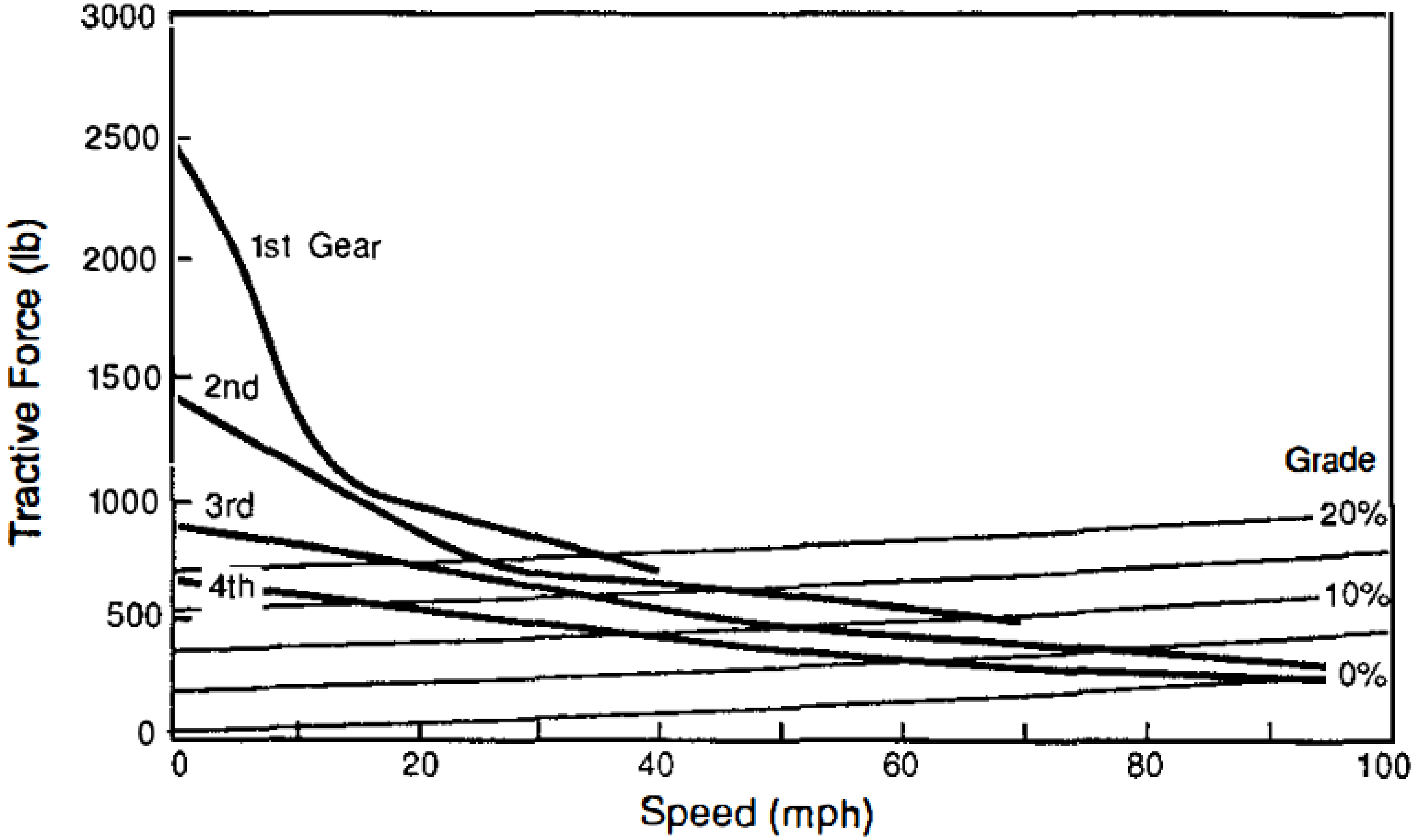
POWER-LIMITED ACCELERATION

- Tractive effort-speed performance for a automatic transmission:



  - Road load forces (rolling resistance, aerodynamic drag, and road grade are shown.
  - At a given point the difference is the tractive force available to accelerate.
  - The intersection is the maximum sustainable speed.

Power-Limited Acceleration

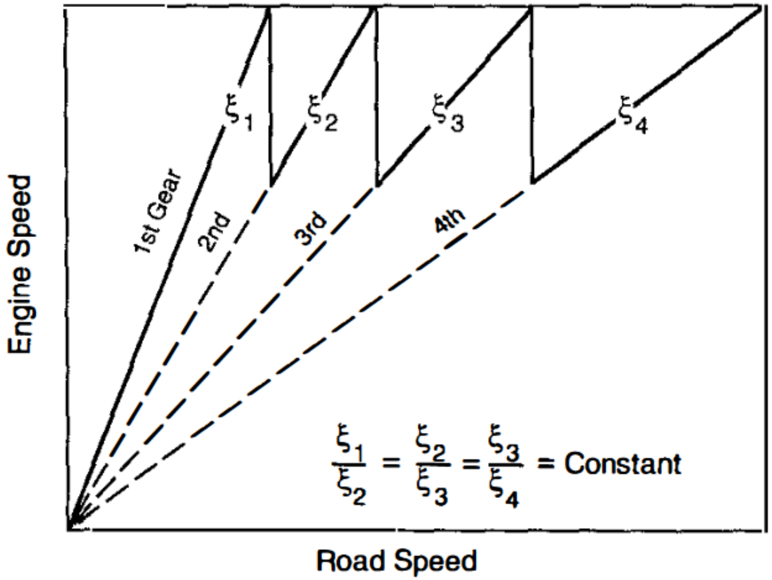


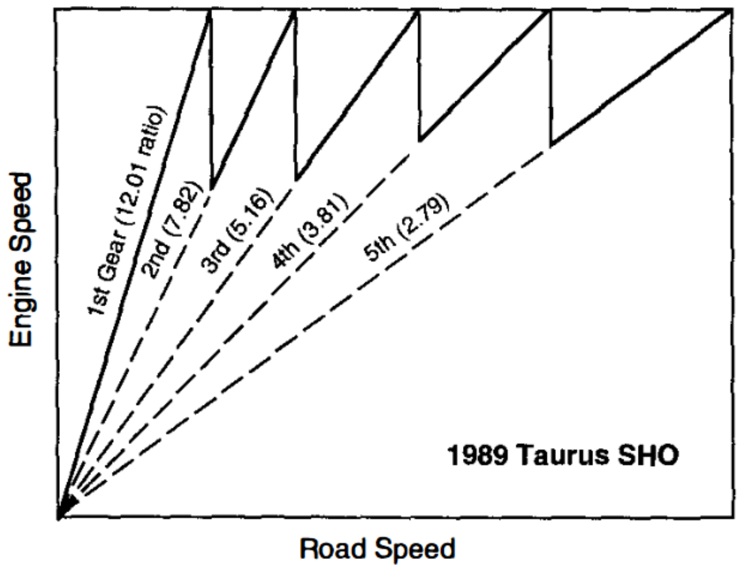
Power-Limited Acceleration

Transmission ratios selection for performance in specific modes:

- An optimal first gear for starting
- A second or third gear for passing
- A high gear for fuel economy at road speeds

- The best gear ratios usually fall close to a geometric progression.





Power-Limited Acceleration

- Other factors in selection of transmission gear ratios
  - Fuel Economy
  - Emissions

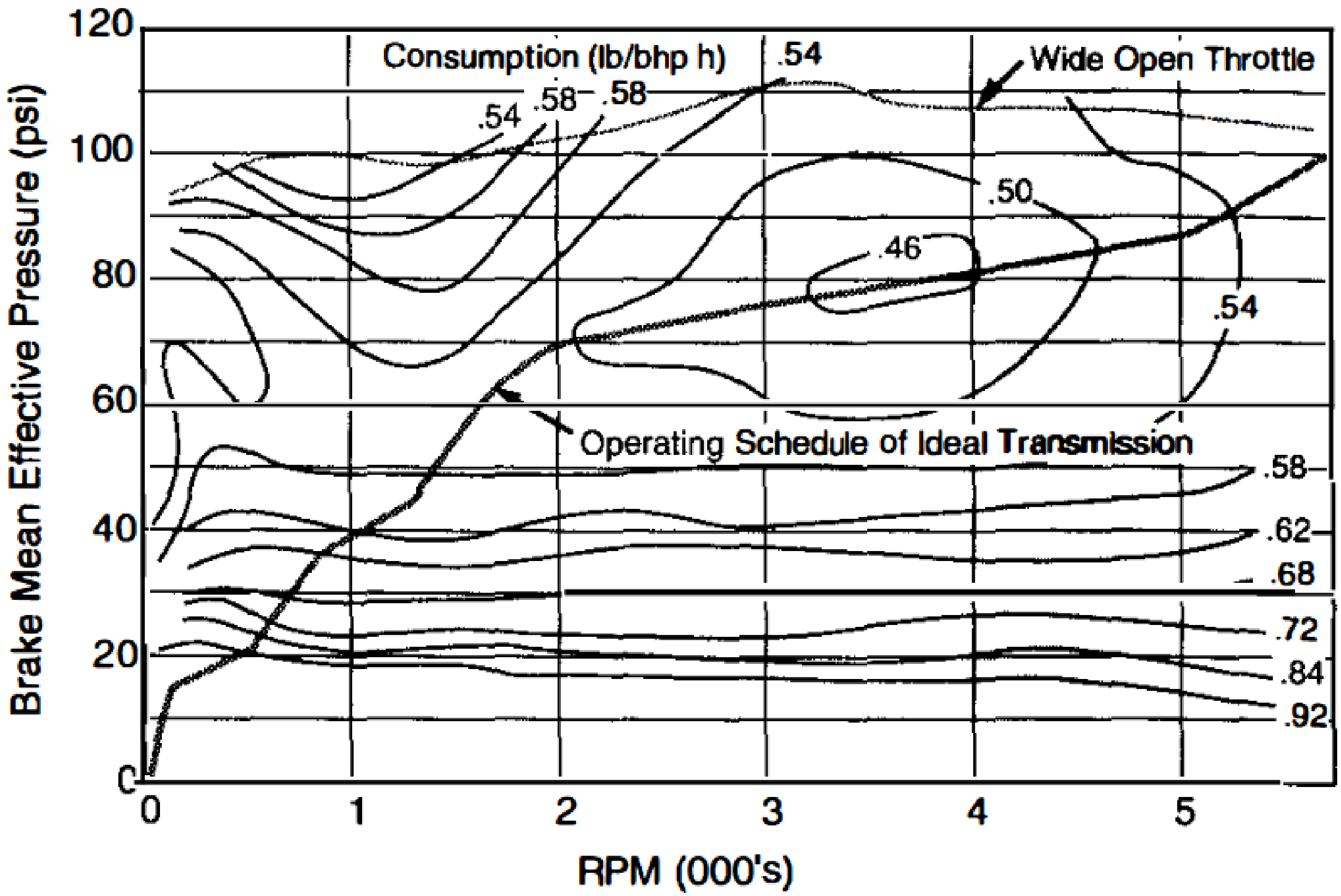
- The engine performance in both of these respects is quantified by mapping its characteristics.

Power-Limited Acceleration

- An example of a fuel consumption map (for a V -8 engine): next page
  - constant fuel consumption as a function of brake-mean-effective pressure (indicative of torque) and engine speed.
  - Near the boundaries the specific fuel consumption is highest. In the middle is a small island of minimum fuel consumption.
  - For best economy over the full driving range the transmission should be designed to operate along the bold line.
  - For emissions purposes, similar maps of engine performance can be developed to characterize the emissions properties

POWER-LIMITED ACCELERATION

- Fuel Consumption Map:



Traction-Limited Acceleration

- Presuming 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 Fx is limited by:

$$F_x = \mu W$$

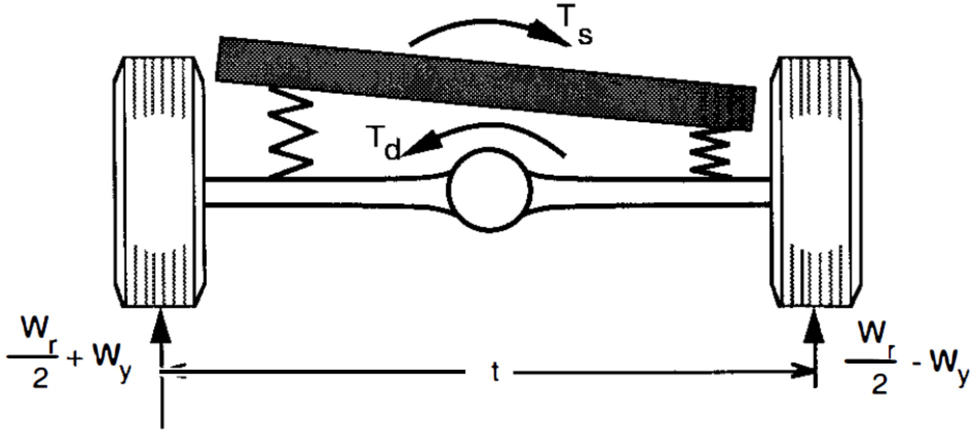
μ = Peak coefficient of friction

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

- The driveshaft into the differential imposes a torque Td on the axle.
  - Transverse weight shift occurs on all solid drive axles.
- The chassis may roll compressing and extending springs on opposite sides of the vehicle such that a torque due to suspension roll stiffness, Ts, is produced.
- The torque delivered to both wheels will be limited by the traction limit on the most lightly loaded wheel



Traction-Limited Acceleration

- Writing NSL for rotation of the axle about its center point:

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

$$W_y = (T_d - T_s)/\, t$$

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

F_x = Total drive force from the two rear wheels

r = Tire radius

N_f = Final drive ratio

TRACTION-LIMITED ACCELERATION

- Determine the roll torque produced by the suspension:
  - It is generally assumed that the roll torque produced by a suspension is proportional to roll angle (Hooke's Law) of the chassis.

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

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

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

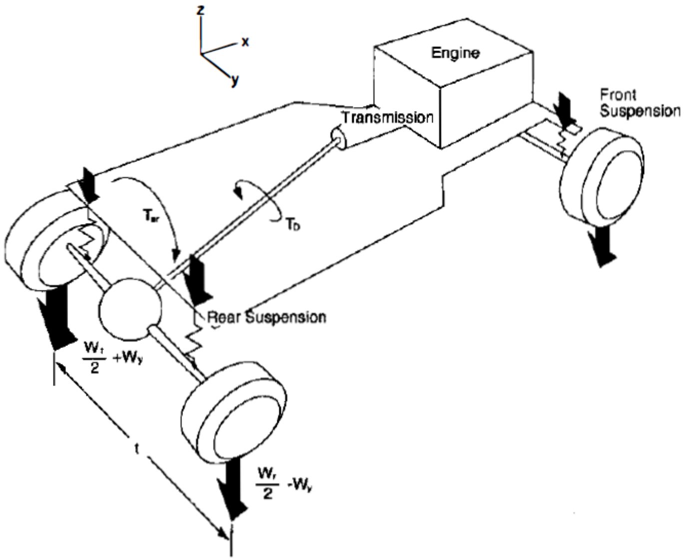
T_{sf} = Roll torque on the front suspension

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



TRACTION-LIMITED ACCELERATION

- The roll angle is simply the drive torque divided by the total roll stiffness:

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

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

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

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

  - This equation gives the magnitude of the lateral load transfer as a function of the tractive force and a number of vehicle parameters such as the final drive ratio, tread of the axle, tire radius, and suspension roll stiffnesses.

TRACTION-LIMITED ACCELERATION

- Neglecting the rolling resistance and aerodynamic drag forces:

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

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

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

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

دانشگاه سمنان

Traction Limits

- Solving for Fx gives the final expression for the maximum tractive force that can be developed by a solid rear axle with a non-locking differential:

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

- For a solid rear axle with a locking differential independent rear suspension:

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

Traction Limits

- For the solid front drive axle with non-locking differential

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

- For solid front drive axle with locking differential, or the independent front drive axle:

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