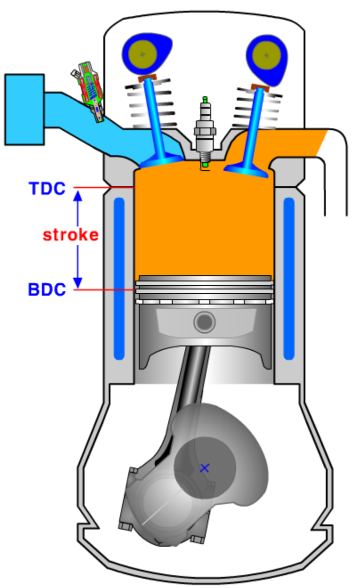
Contents

- Power Source : Engine/Motor
- Power Transfer : Clutch/Transmission
- Power Storage : Battery
- Driving Resistance
- Driver Controller

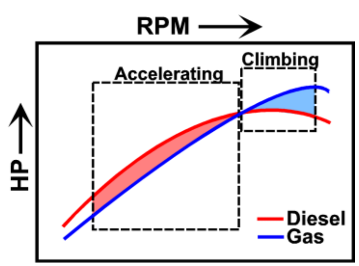
Engine

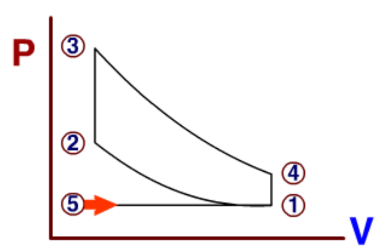
- Generation of the power to drive a vehicle
- Operating principle
  - Force generation by fuel injection and ignition in the cylinder
  - Torque generation on a crank shaft from the force through the mechanical linkage

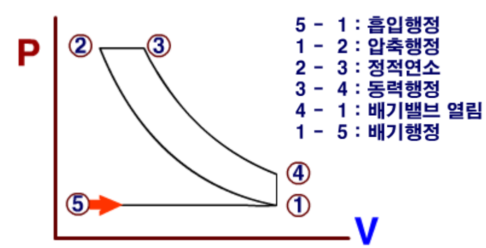


[작동원리 Link]

Specification	Gasoline Engine (Otto)	Diesel Engine
Ignition Type	Spark Ignition	Compression Ignition
Compression Ratio	Between 8:1 and 12:1	Between 16:1 and 22:1
Efficiency	25-30%	36-45%
Maximum Engine Speed	7000-8250 RPM	up to 5250 RPM
Exhaust Temperature (under full load)	700-1200 Degrees Celsius	300-900 Degree Celsius







Mean Value Model

- Input : fuel mass flow rate
- Output : engine torque

1. Engine dynamic equation

$$J_e \dot{\omega}_e = T_e = T_{ind} - T_{loss}$$

J_e : engine equivalent inertia [kgm^2]

ω_e :engine angular velocity [rad/s]

T_e :engine output torque [Nm]

T_{ind} :indicated combustion torque [Nm]

T_{loss} :pumping and friction losses [Nm]

2. Indicated combustion torque

$$\dot{m}_f = \frac{\dot{m}_{ao}}{L_{th}} \qquad T_{ind} = \frac{H_u \eta_i \dot{m}_f}{\omega_e}$$

$\dot{m}_f$:air mass flow rate [kg/s]

$\dot{m}_{ao}$:fuel mass flow rate into cylinder [kg/s]

L_{th} :stoichiometric air/fuel mass ratio

T_{ind} :indicated combustion torque [Nm]

H_u : fuel energy constant [J/kg]

η_i :indicated efficiency

3. Pumping and friction losses

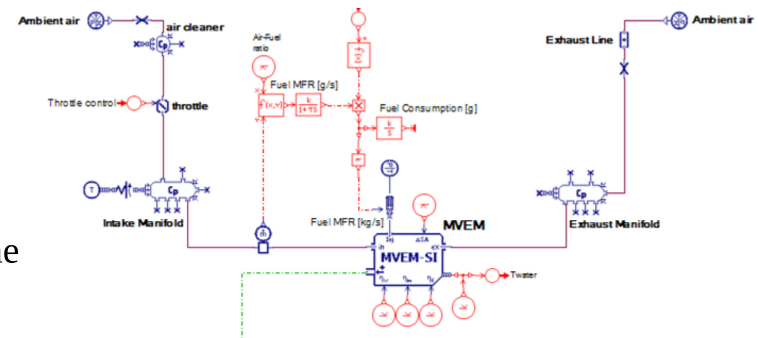
$$T_{loss} = T_{fric} + T_{pump}$$

$$T_{fric} = a_0 \omega_e^2 + a_1 \omega_e + a_2$$

$$T_{pump} = b_0 \omega_e p_{man} + b_1 p_{man}$$

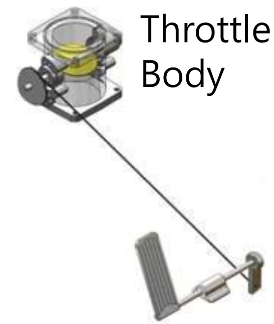
a_0, a_1, a_2, b_0, b_1 :parameters dependent on specific engine

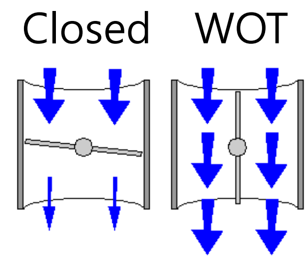
p_{man} :manifold air pressure [bar]



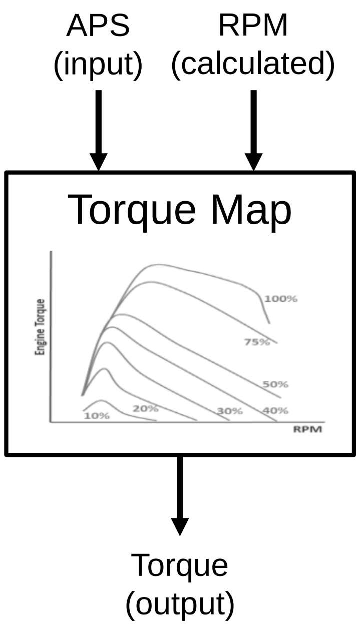
Torque Map Model

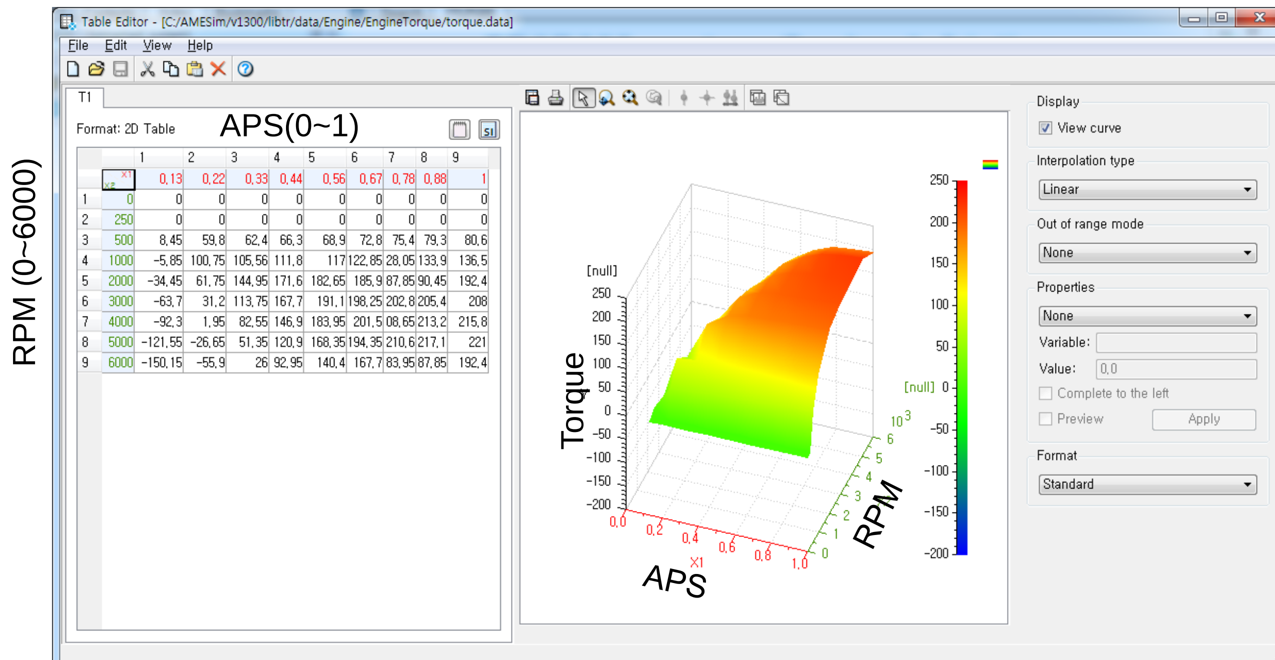
- Input : APS (accelerator pedal sensor)
- Output : engine torque
- Calculation of the engine torque from the experimental torque map





$$T_e = f(APS, RPM)$$

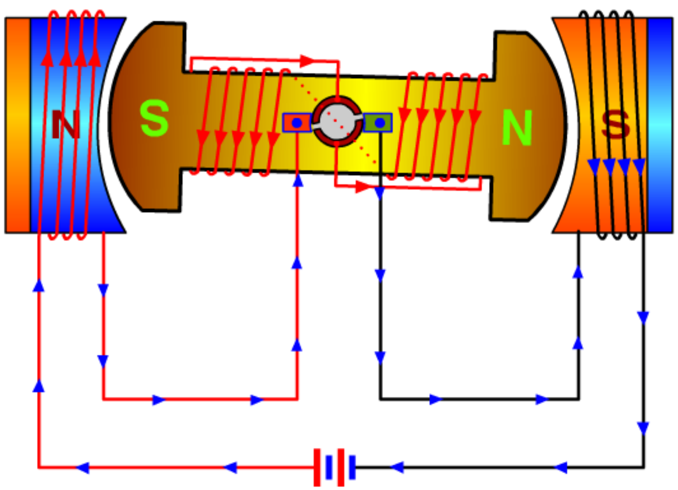




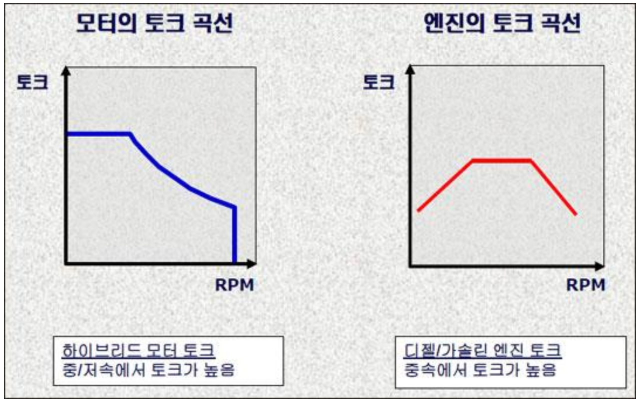
	X2 \ X1	0,13	0,22	0,33	0,44	0,56	0,67	0,78	0,88	1
1	0	0	0	0	0	0	0	0	0	0
2	250	0	0	0	0	0	0	0	0	0
3	500	8,45	59,8	62,4	66,3	68,9	72,8	75,4	79,3	80,6
4	1000	-5,85	100,75	105,56	111,8	117	122,85	28,05	133,9	136,5
5	2000	-34,45	61,75	144,95	171,6	182,65	185,9	87,85	90,45	192,4
6	3000	-63,7	31,2	113,75	167,7	191,1	198,25	202,8	205,4	208
7	4000	-92,3	1,95	82,55	146,9	183,95	201,5	08,65	213,2	215,8
8	5000	-121,55	-26,65	51,35	120,9	168,35	194,35	210,6	217,1	221
9	6000	-150,15	-55,9	26	92,95	140,4	167,7	83,95	87,85	192,4

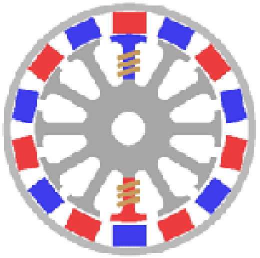
Motor

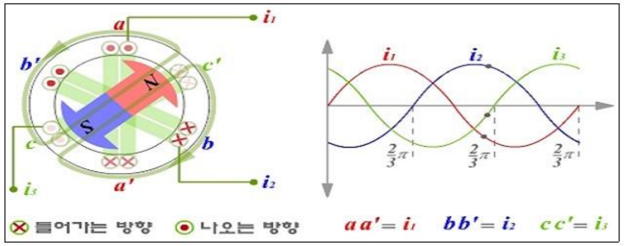
- Generation of the power to drive a vehicle
- Operating principle
  - Generation of a rotating magnetic field from an electric current
  - Mechanical torque generation on a rotating shaft from the magnetic force



[작동원리 Link]

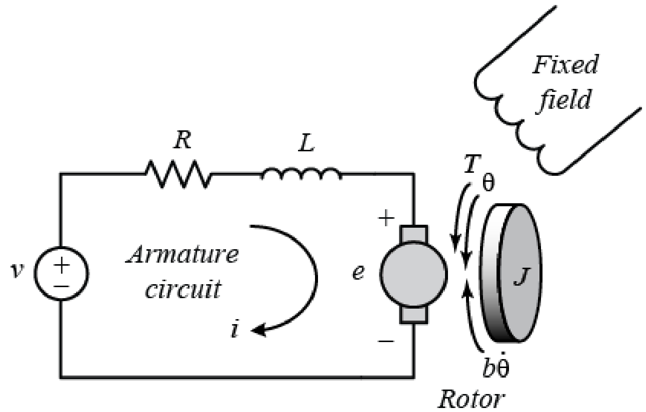


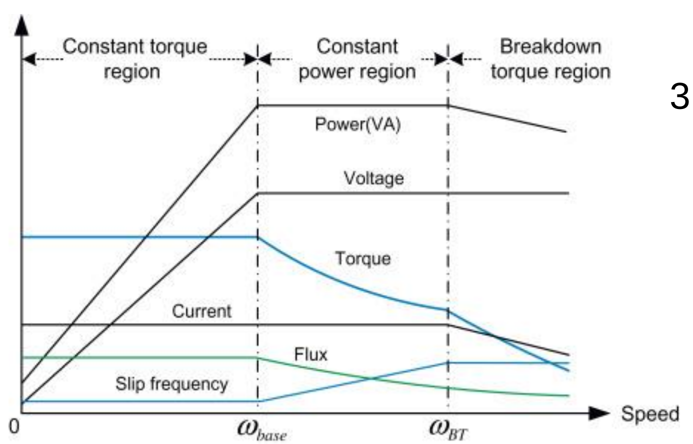




Electric Circuit Model

- Input : circuit voltage
- Output : motor torque





1. Equivalent circuit

$$V = L\frac{di}{dt} + RI + E_b$$

V : circuit voltage [V]

L : electric inductance [H]

I : electric current [A]

R : electric resistance [Ω]

E_b : back electro motive force [V]

2. Motor torque

$$E_b = K_e \omega_m$$

$$T_m = K_t I$$

K_e : back-EMF constant [Vs]

ω_m : motor shaft speed [rad/s]

T_m : motor torque [Nm]

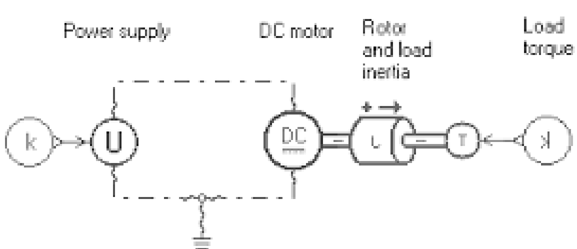
K_t : torque constant [Nm/A]

3. Motor dynamic equation

$$T_m - T_{loss} = J\dot{\omega}_m$$

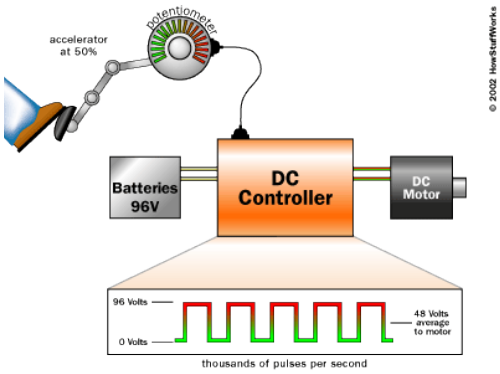
T_{loss} : total loss torque [Nm]

J : motor inertia [kgm^2]

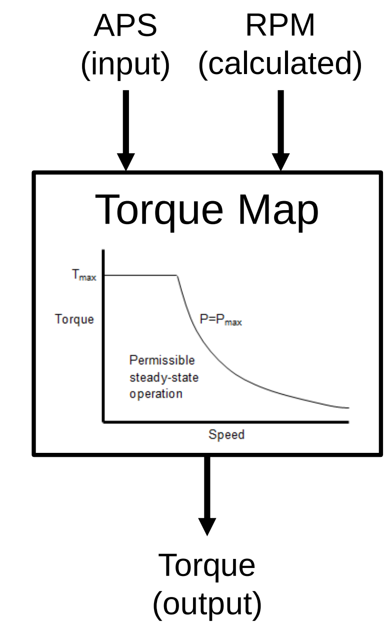


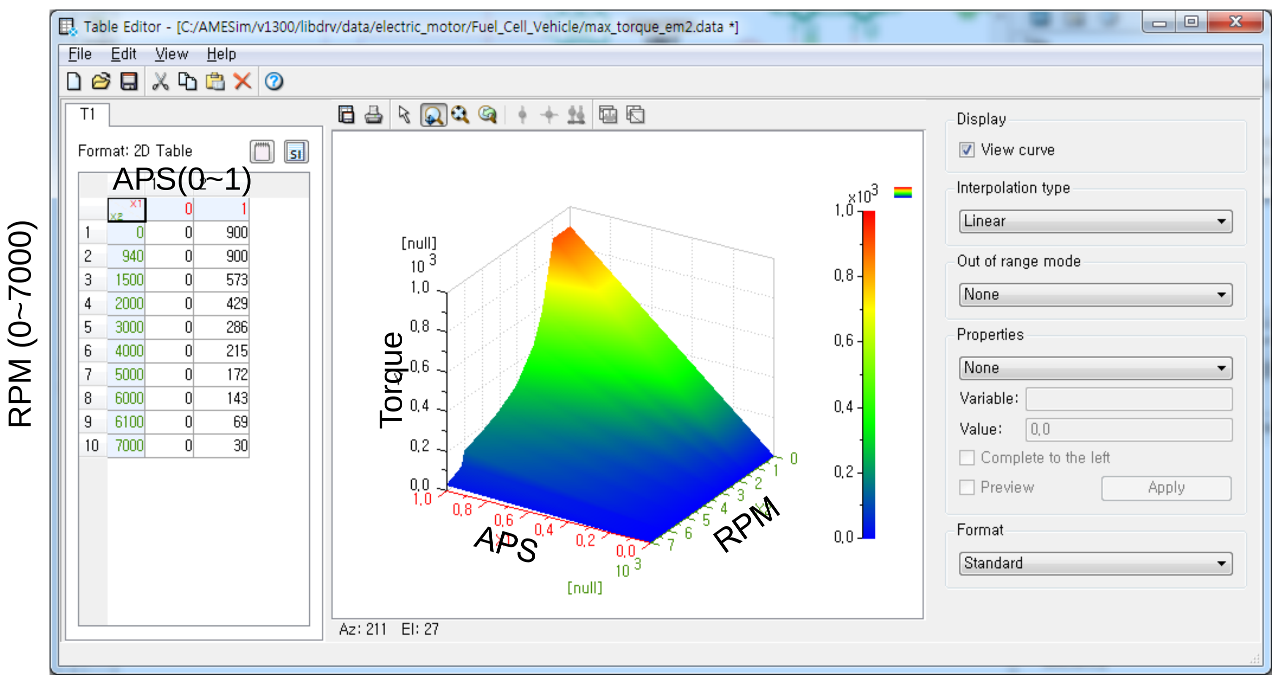
Torque Map Model

- Input : APS (accelerator pedal sensor)
- Output : motor torque
- Calculation of the motor torque from the experimental torque map



$$T_m = f(APS, RPM)$$



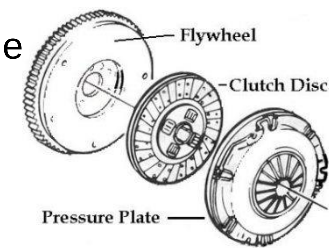


	RPM \ APS	0	1
1	0	0	900
2	940	0	900
3	1500	0	573
4	2000	0	429
5	3000	0	286
6	4000	0	215
7	5000	0	172
8	6000	0	143
9	6100	0	69
10	7000	0	30

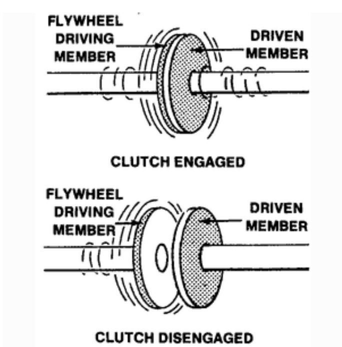
Clutch

- Torque transfer or cut-off between input and output shaft
- Operating principle
  - Generation of the friction torque on a clutch disk by the clutch engaging or disengaging
  - Synchronization of both shaft speeds

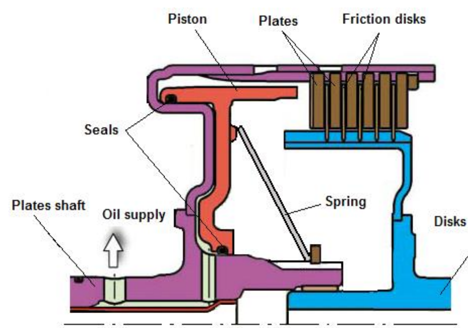
Engine side



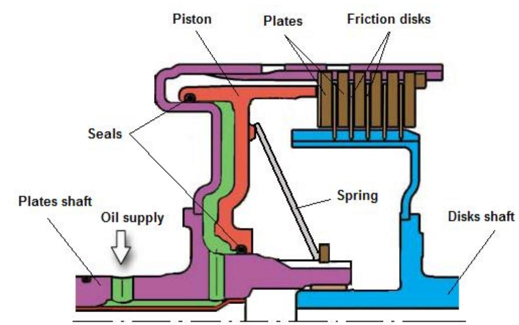
TM side



< Single Disk >



Disengaged

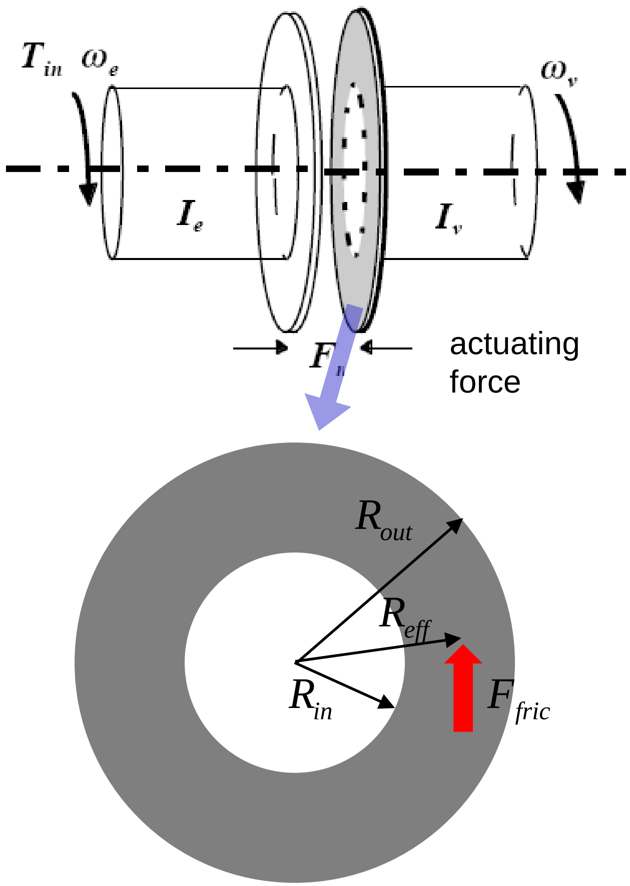


Engaged

< Multi Disk >

Friction Torque Model

- Input : clutch actuating force
- Output : output shaft torque



1. Output torque equation

$$T_{out} = \begin{cases} F_{fric} R_{eff} & (\omega_{rel} \neq 0) \\ T_{in} & (\omega_{rel} = 0) \end{cases}$$

F_{fric} :friction force [N]

R_{eff} :effective firction radius [m]

ω_{rel} :relative speed of shafts [rad/s]

2. Friction equation

$$F_{fric} = \mu_{disk} F_n$$

$$F_n = F_{act} \tanh\left(2 \frac{\omega_{rel}}{d\omega}\right)$$

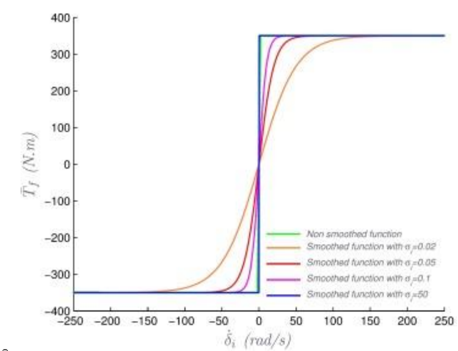
$$\omega_{rel} = \omega_e - \omega_v$$

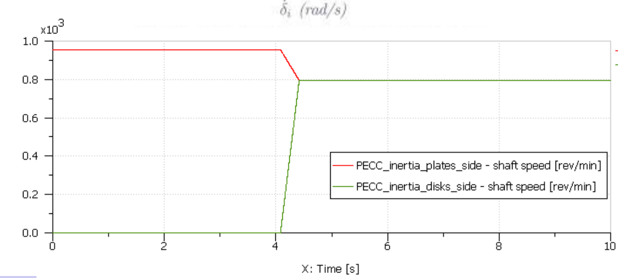
$$R_{eff} = \frac{2(r_{out}^3 - r_{in}^3)}{3(r_{out}^2 - r_{in}^2)}$$

μ_{disk} :friction coefficient

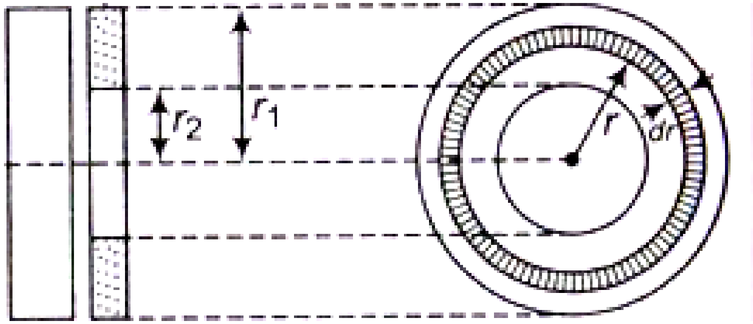
F_n :normal force on disk [N]

F_{act} :clutch actuating force [N]





Effective Friction Radius



$$dA = 2\pi r \times dr$$

P : normal pressure

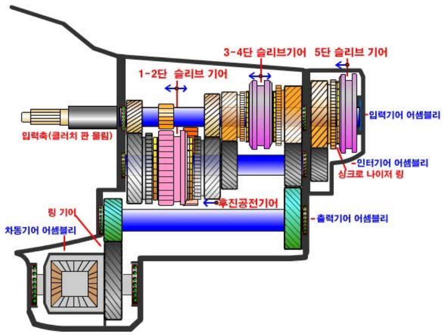
$$F_n = P\int_{r_2}^{r_1} 2\pi r \ dr \qquad P = \frac{F_n}{\pi(r_1^2 - r_2^2)}$$

$$T = \mu P\int_{r_2}^{r_1} 2\pi r^2 \ dr = 2\mu\pi \frac{F_n}{\pi(r_1^2 - r_2^2)} \times \frac{r_1^3 - r_2^3}{3}$$

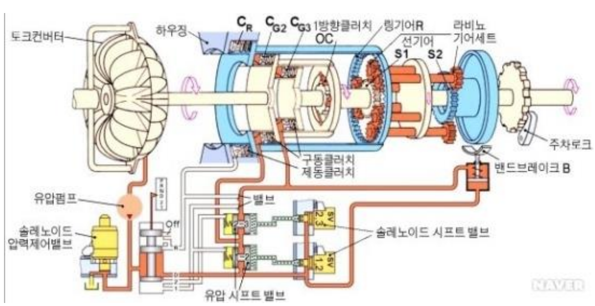
$$T = \mu F_n R_{eff} \qquad \therefore \ R_{eff} = \frac{2(r_1^3 - r_2^3)}{3(r_1^2 - r_2^2)}$$

Transmission

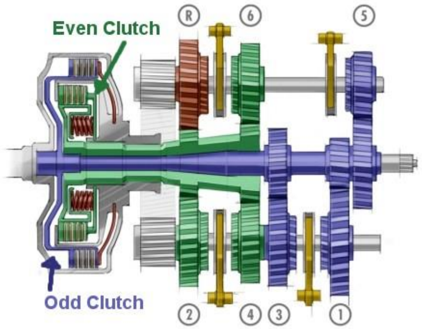
- Conversion of the torque and speed from input shaft to the proper torque and speed on output shaft
- Operating principle
  - Selection of a proper gear by operating a clutch
  - Increasing or decreasing of the torque and speed from input shaft



< Manual Transmission(MT) >

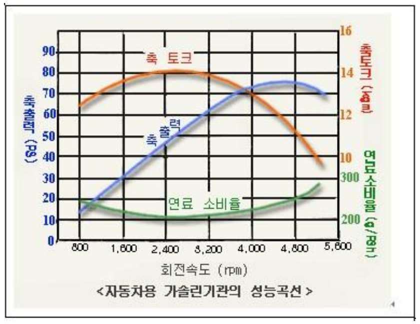


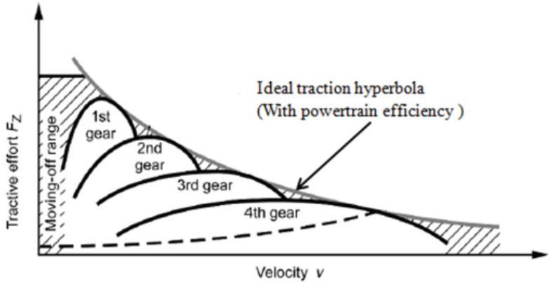
< Automatic Transmission(AT) >



< Dual Clutch Transmission(DCT) >

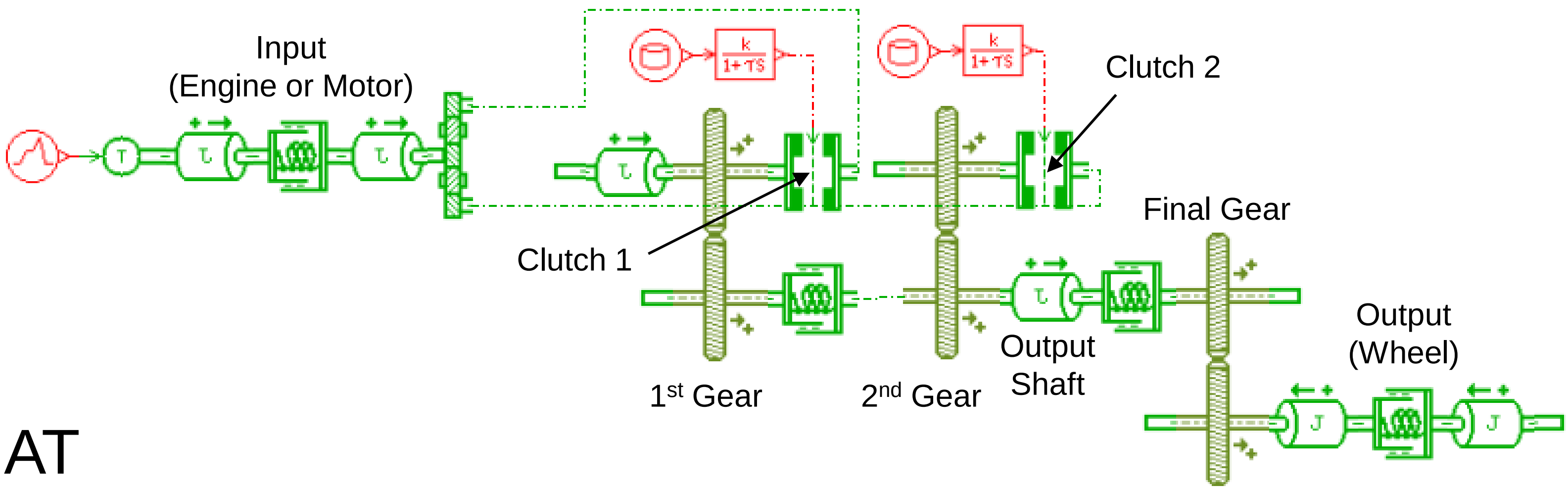
구분	MT	AT	DCT
Efficiency	↑	↓	↑
Drivability	↓	↑	↑
Cost	↓	-	↑



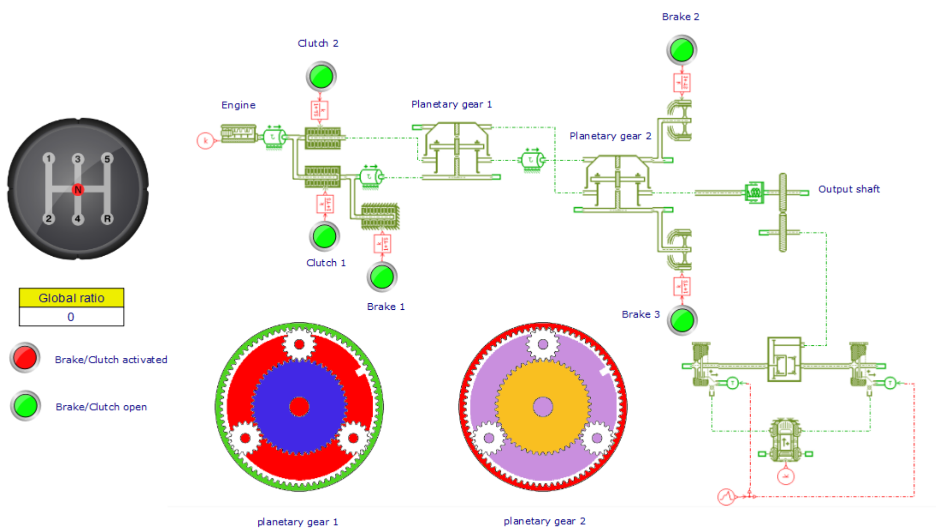


Geartrain

- MT/DCT



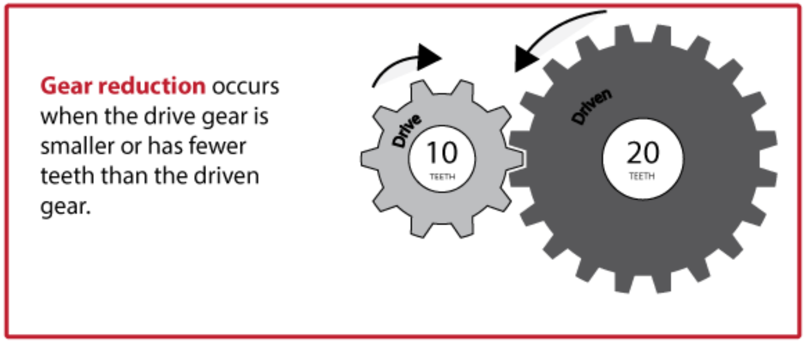
- AT

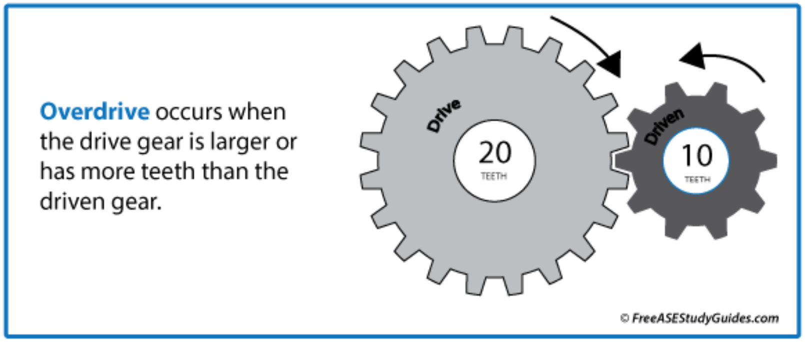


	Clutch 1	Clutch 2	Brake 1	Brake 2	Brake 3
Neutral					
Reverse	●			●	
1th Gear	●				●
2nd Gear		●			●
3rd Gear	●	●			
4th Gear		●	●		

Parallel Gear Model (MT/DCT)

- Input : input torque/speed
- Output : output torque/speed





1. Gear ratio

$$GR = \frac{\text{\# of driven gear teeth}}{\text{\# of drive gear teeth}}$$

2. Output torque & speed

$$T_{out} = T_{in} \times GR$$

$$\omega_{out} = \frac{\omega_{in}}{GR}$$

※ Example : $T_{in} = 100 \text{ Nm}, \ \omega_{in} = 3000 \text{ RPM}$

1) $GR = 2$ (reduction)

$$T_{out} = 100 \times 2 = 200 \text{ Nm}$$

$$\omega_{out} = \frac{3000}{2} = 1500 \text{ RPM}$$

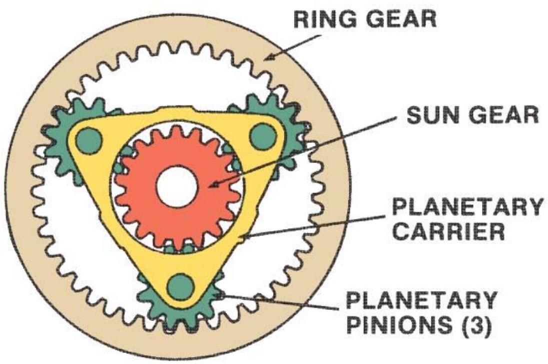
2) $GR = 0.75$ (overdrive)

$$T_{out} = 100 \times 0.75 = 75 \text{ Nm}$$

$$\omega_{out} = \frac{3000}{0.75} = 4000 \text{ RPM}$$

Coaxial Gear Model (AT)

- Input : input torque/speed
- Output : output torque/speed



Ring	Carrier	Sun	Gear Ratio	
driven	drive	fixed	$Z_r/(Z_s+Z_r)$	
drive	driven	fixed	$(Z_s+Z_r)/Z_r$	
fixed	drive	driven	$Z_s/(Z_s+Z_r)$	
fixed	driven	drive	$(Z_s+Z_r)/Z_s$	
driven	fixed	drive	$-Z_r/Z_s$	reverse

1. Motion equation

$$\omega_s + \frac{Z_r}{Z_s}\omega_r - \frac{Z_s+Z_r}{Z_s}\omega_c = 0$$

Z_r : # of ring gear teeth

Z_s : # of ring gear teeth

$Z_s + Z_r$: # of carrier equivalent teeth

2. Output torque & speed

$$T_{out} = T_{in} \times GR$$

$$\omega_{out} = \frac{\omega_{in}}{GR}$$

※ Example : $T_{in} = 100\ \text{Nm},\ \omega_{in} = 3000\ \text{RPM},\ Z_r = 80,\ Z_s = 40$

ring(drive), sun(fixed)

$$GR = \frac{Z_s + Z_r}{Z_s} = \frac{40+80}{40} = 3$$

$$T_{out} = 100 \times 3 = 300\ \text{Nm}$$

$$\omega_{out} = \frac{3000}{3} = 1000\ \text{RPM}$$

Coaxial Gear Model (AT)

- Motion equation

각 기어 별 접촉점에서의 속도는

$$V_s = \omega_s r_s \quad V_r = \omega_r r_r \quad V_c = \omega_c r_c$$

여기서 캐리어의 속도와 반지름은

$$V_c = \frac{V_s + V_r}{2} = \omega_c r_c = \omega_c \frac{r_s + r_r}{2}$$

$V_s = \omega_s r_s$ 이고, $V_r = \omega_r r_r$ 이므로

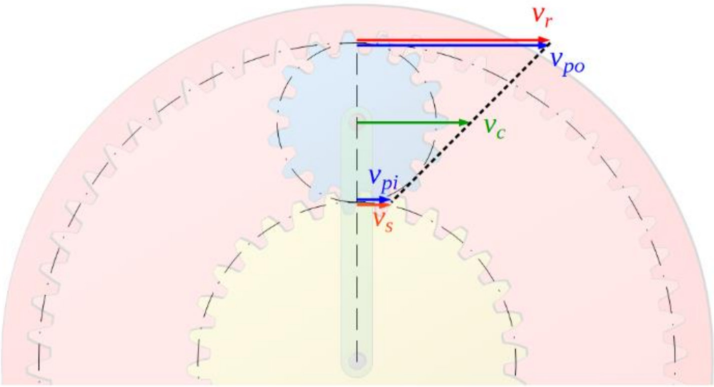
$$\frac{\omega_s r_s + \omega_r r_r}{2} = \omega_c \frac{r_s + r_r}{2}$$

정리하면

$$\omega_s r_s + \omega_r r_r - \omega_c (r_s + r_r) = 0$$

각 기어의 반지름은 잇수에 비례하므로

$$\omega_s Z_s + \omega_r Z_r - \omega_c (Z_s + Z_r) = 0$$



선기어 잇수로 나눠주면

$$\therefore \ \omega_s + \omega_r \frac{Z_r}{Z_s} - \omega_c \frac{Z_s + Z_r}{Z_s} = 0$$

Example: Ring(driven), Carrier(drive), Sun(fixed)

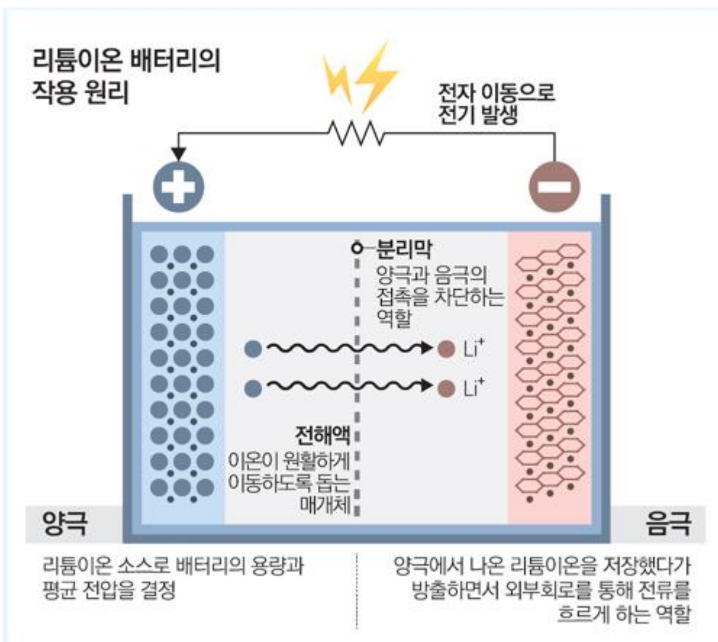
0 out in

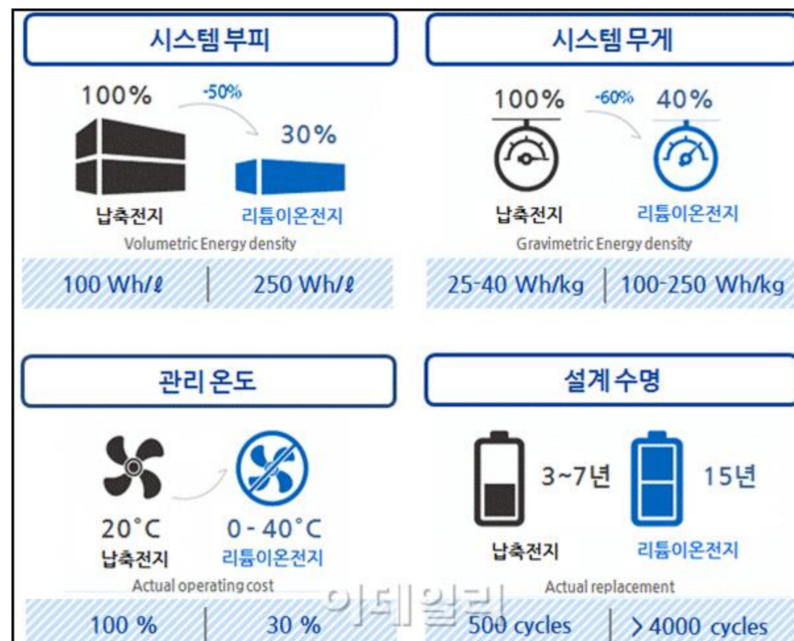
$$\omega_s + \omega_r \frac{Z_r}{Z_s} - \omega_c \frac{Z_s + Z_r}{Z_s} = 0$$

$$GR = \frac{\omega_{in}}{\omega_{out}} = \frac{\omega_c}{\omega_r} = \frac{Z_s}{Z_s + Z_r}\frac{Z_r}{Z_s} = \frac{Z_r}{Z_s + Z_r}$$

Battery

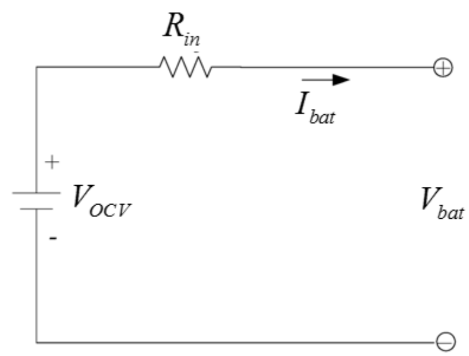
- Providing the current to generate the mechanical torque from a motor
- Operating principle
  - Conversion of the electric energy in a capacitor to the current by the battery voltage and resistance

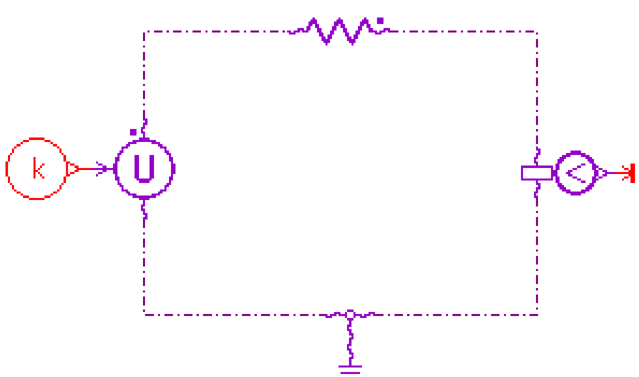




Equivalent Circuit Model

- Input : motor power (torque and speed)
- Output : state of charge (SOC)





1. Equivalent circuit equation

$$V_{bat} = V_{OCV} - R_{in} I_{bat}$$

V_{bat} : battery volatage [V]

V_{OCV} : open circuit voltage [V]

R_{in} : equivalent internal resistance [Ω]

I_{bat} : battery current [A]

2. SOC calculation

Mechanical Power = Electrical Power

$$T_{mot}\omega_{mot} = \eta V_{bat} I_{bat} \text{ (discharging)}$$

$$\eta T_{mot}\omega_{mot} = V_{bat} I_{bat} \text{ (charging)}$$

$$\frac{dSOC}{dt} = -I_{bat}\frac{100}{C_{nom}}$$

$$SOC = SOC_{ini} - \frac{100}{C_{nom}}\int I_{bat}\, dt$$

η : motor efficiency

SOC_{ini} : initial SOC [%]

C_{nom} : rated capacity [As]

Equivalent Circuit Model

※ Example : when $T_{mot} = 100\ \text{Nm},\ \omega_{mot} = 955\,\text{RPM}\ (100\,\text{rad/s})$ during 2 min, final SOC?

$V_{OCV} = 300\ \text{V},\ R_{in} = 0.1\ \Omega,\ \eta = 1,\ C_{nom} = 40{,}000\ \text{As},\ SOC_{ini} = 50\ \%$

$$V_{bat} = V_{OCV} - R_{in} I_{bat} = 300 - 0.1 \times I_{bat}$$

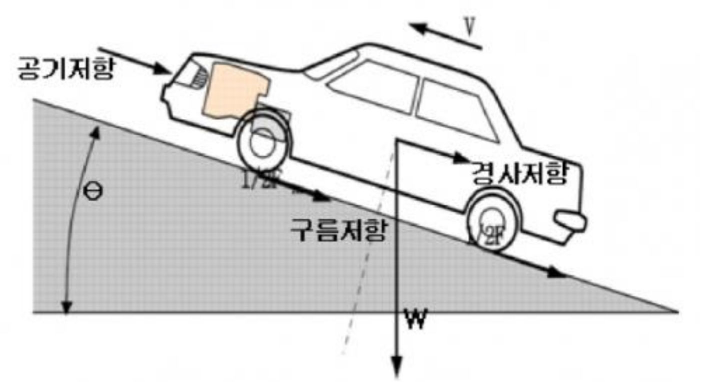
$$T_{mot}\omega_{mot} = \eta V_{bat} I_{bat} \longrightarrow 0.1 I_{bat}^2 - 300 I_{bat} + 10{,}000 = 0$$

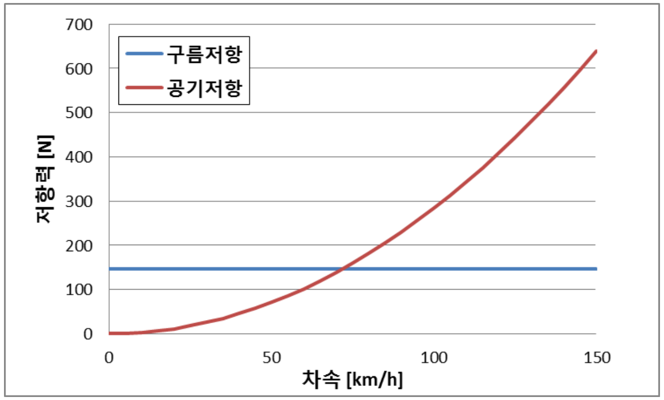
$$I_{bat} = 2966 \text{ or } 33.7\ \text{A}$$

$$SOC = SOC_{ini} - \frac{100}{C_{nom}} \int I_{bat}\, dt = 50 - 0.084 \times 120 = 39.9\ \%$$

Driving resistances

- Drag forces during the driving from the various conditions
- Air, rolling, climbing, and acceleration resistance





< Air resistance >

< Rolling resistance >

< Climbing resistance >

Resistance Calculation Model

- Input : vehicle speed, gradient
- Output : drag force

1. Air resistance

$$F_{air} = \frac{1}{2} C_d A_{fr} \rho_{air} V_{veh}^2$$

C_d : air drag coefficient

A_{fr} : frontal area [m^2]

ρ_{air} : air density [kg/m^3]

V_{veh} : vehicle speed [m/s^2]

2. Rolling resistance

$$F_{roll} = \mu_r m_b g$$

μ_r : rolling friction coefficient

m_b : body mass[kg]

3. Climbing resistance

$$F_c = m_b g \sin \theta_{grad}$$

θ_{grad} : gradient [rad]

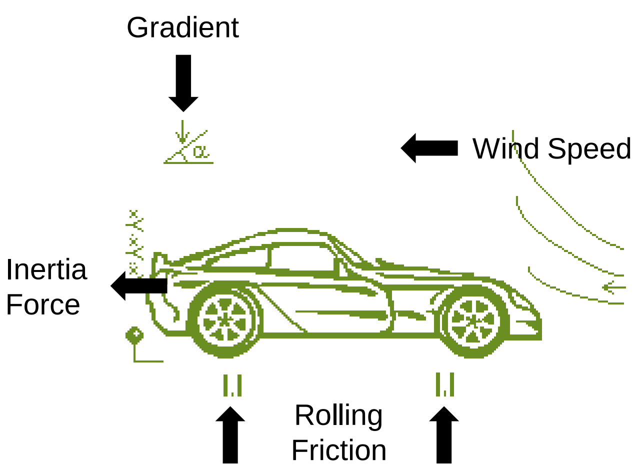
4. Acceleration resistance

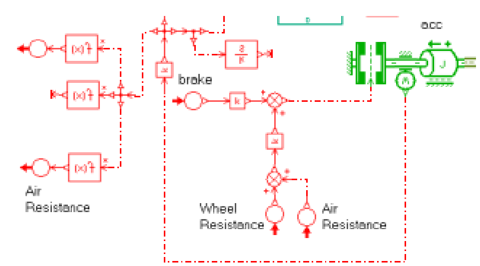
$$F_{acc} = ma = J_{eq} \alpha_{whl} R_{tire}$$

J_{eq} : vehicle equivalent inertia at wheel [kgm^2]

α_{whl} : wheel rotational acceleration [rad/s^2]

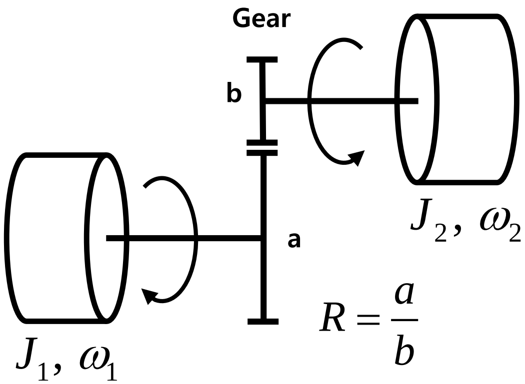
R_{tire} : effective tire radius [m]





Equivalent Inertia

- Calculation of an equivalent inertia from each inertias



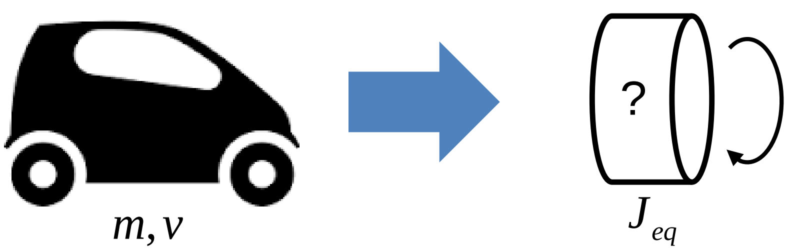
$$E_1 + E_2 = E_{eq} \quad \text{(energy conservation)}$$

$$\frac{1}{2}J_1\omega_1^2 + \frac{1}{2}J_2\omega_2^2 = \frac{1}{2}J_{eq,1}\omega_1^2$$

$$J_1\omega_1^2 + J_2R^2\omega_1^2 = J_{eq,1}\omega_1^2 \quad (\omega_2 = R\omega_1)$$

$$J_{eq,1} = J_1 + J_2R^2 \longleftrightarrow J_{eq,2} = \frac{J_1}{R^2} + J_2$$

Equivalent inertia at wheel w.r.t vehicle mass



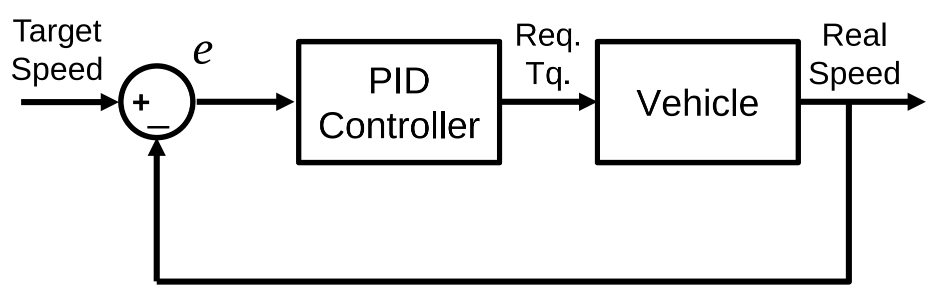
$$E_v = E_w$$

$$\frac{1}{2}m_bV_{veh}^2 = \frac{1}{2}J_{eq}\omega_{whl}^2 \quad (V_{veh} = R_{tire}\omega_{whl})$$

$$J_{eq} = m_bR_{tire}^2$$

Driver Controller

- Torque control to match a target vehicle speed from the driver request
- Operating principle
  - Reducing an error between the target speed and the real speed



$$T_{req} = K_p e(t) + K_i \int e(t)\,dt + K_d \frac{de(t)}{dt} \qquad \begin{cases} e(t) \geq 0 : \text{accelation} \\ e(t) < 0 : \text{braking} \end{cases}$$

$$(\, e(t) = V_{\text{target}} - V_{\text{real}} \,)$$

K_p : proportional gain

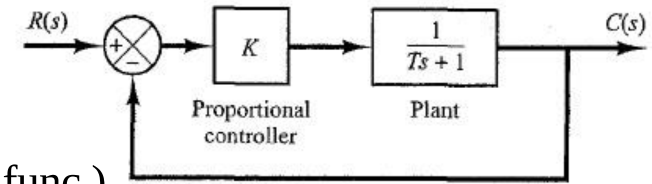
K_i : integral gain

K_d : differential gain

PI control

- Proportional control

$$G(s)=\frac{K}{Ts+1} \qquad \frac{E(s)}{R(s)}=\frac{R(s)-C(s)}{R(s)}=1-\frac{C(s)}{R(s)}=\frac{1}{1+G(s)}$$

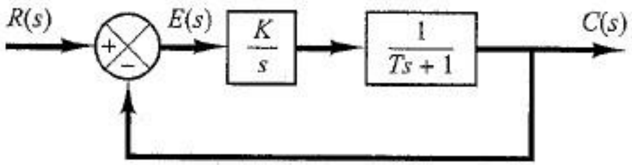


$$E(s)=\frac{1}{1+G(s)}R(s)=\frac{1}{1+\dfrac{K}{Ts+1}}R(s) \qquad R(s)=\frac{1}{s}\ \text{(unit-step func.)}$$

$$E(s)=\frac{Ts+1}{Ts+1+K}\frac{1}{s} \qquad e_{ss}=\lim_{t\to\infty}e(t)=\lim_{s\to0}sE(s)=\lim_{s\to0}\frac{Ts+1}{Ts+1+K}=\frac{1}{K+1}$$

- Integral control

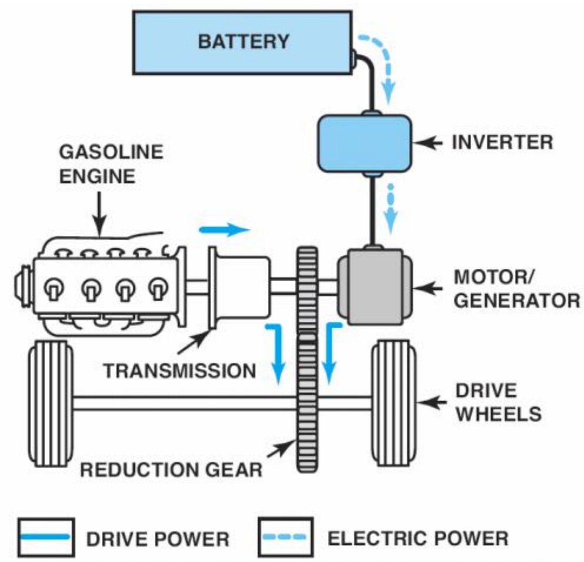
$$\frac{C(s)}{R(s)}=\frac{K}{s(Ts+1)+K} \qquad \frac{E(s)}{R(s)}=\frac{R(s)-C(s)}{R(s)}=\frac{s(Ts+1)}{s(Ts+1)+K}$$



$$E(s)=\frac{s(Ts+1)}{s(Ts+1)+K}\frac{1}{s} \qquad R(s)=\frac{1}{s}\ \text{(unit-step func.)}$$

$$e_{ss}=\lim_{t\to\infty}e(t)=\lim_{s\to0}sE(s)=\lim_{s\to0}\frac{s^2(Ts+1)}{Ts^2+s+K}\frac{1}{s}=0$$

Assignment



Vehicle Parameters

$$J_{eng} = 0.2\,\mathrm{kgm}^2,\ J_{motor} = 0.05\,\mathrm{kgm}^2$$

$$GR_{TM} = 2,\ GR_F = 4$$

$$M_{veh} = 1500\,kg,\ R_{tire} = 0.3$$

$$T_{eng} = 80\,Nm,\ T_{mot} = 50\,Nm$$

Resistance Parameters

$$A = 2\,m^2,\ C_d = 0.3,\ \rho = 1.2\,\mathrm{kg/m}^3,\ V = 15\ \mathrm{m/s}$$

$$\mu_{roll} = 0.01,\ g = 9.81\mathrm{m/s}^2$$

Problems

1. Equivalent inertia at wheel
2. Driving torque at wheel
3. Drag torque at wheel (air, rolling)
4. Vehicle acceleration speed

   (Driving torque – Drag torque = Eq. Inertia X Acceleration rotational speed)

```
Eq. Inertia : 148.6 [kgm^2]
Driving Torque : 840 [Nm]
Drag Torque : 68.44 [Nm]
Vehicle Acc. : 1.558 [m/s^2]
```