Powertrain Component Model

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CDL Computational Design Lab

목 차

- Engine / Motor
- Clutch / Transmission
- Battery
- Driving Resistance / Controller

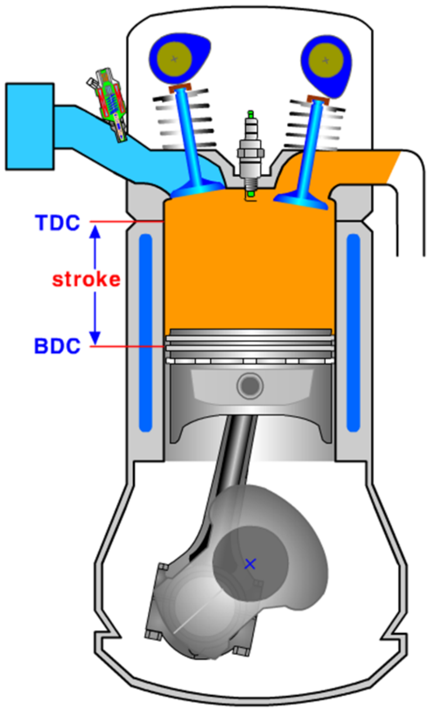
Engine

■ 목적

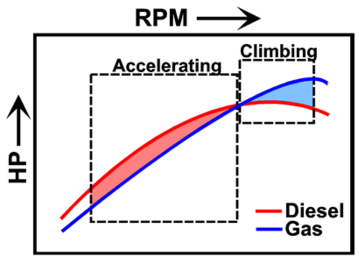
- 차량 구동을 위한 동력 발생

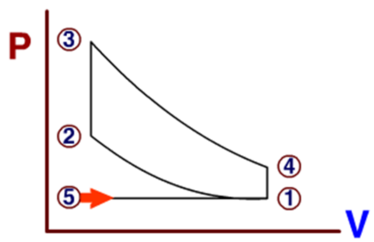
■ 원리

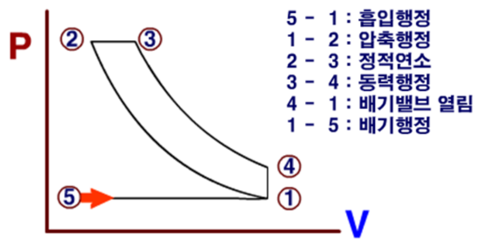
- 실린더 내 연료 분사 및 폭발을 통해 발생한 힘을 기계 링크를 통해 Crank Shaft에 토크 발생



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







작동원리 Link

Engine

■ Mean Value Model

- 입력 : air mass flow rate / 출력 : Crank Shaft Torque

Crank Shaft Torque

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

J_e : engine equivalent inertia [kgm^2]

ω_e :engine angular velocity [rad/s]

T_{ind} :indicated combustion torque [Nm]

T_{ext} :external load torque

T_{loss} :pumping and friction losses

Pumping and Friction Torque

$$T_{loss} = F_{loss} + P_{loss}$$

$$F_{loss} = a_0 \omega_e^{\,2} + a_1 \omega_e + a_2$$

$$P_{loss} = b_0 \omega_e p_{man} + b_1 p_{man}$$

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

p_{man} :manifold air pressure [bar]

Indicated Combustion Torque

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

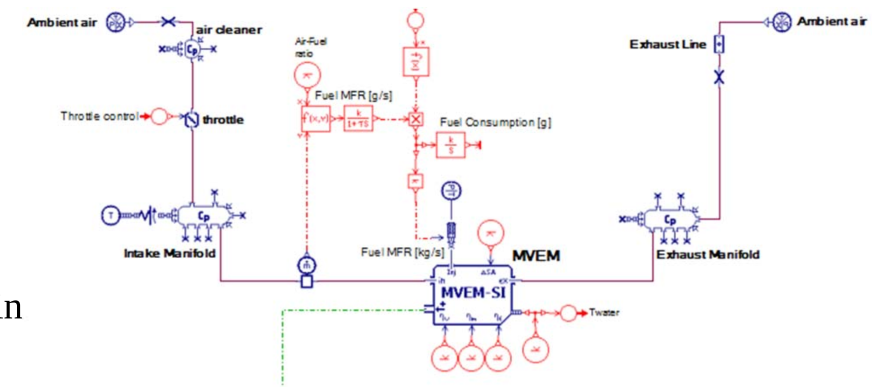
H_u : fuel energy constant [J/kg]

η_i :indicated efficiency

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

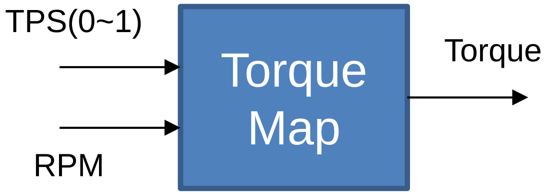
$\dot{m}_f$:air mass flow rate [kg/s]

L_{th} :stoichiometric air/fuel mass ratio



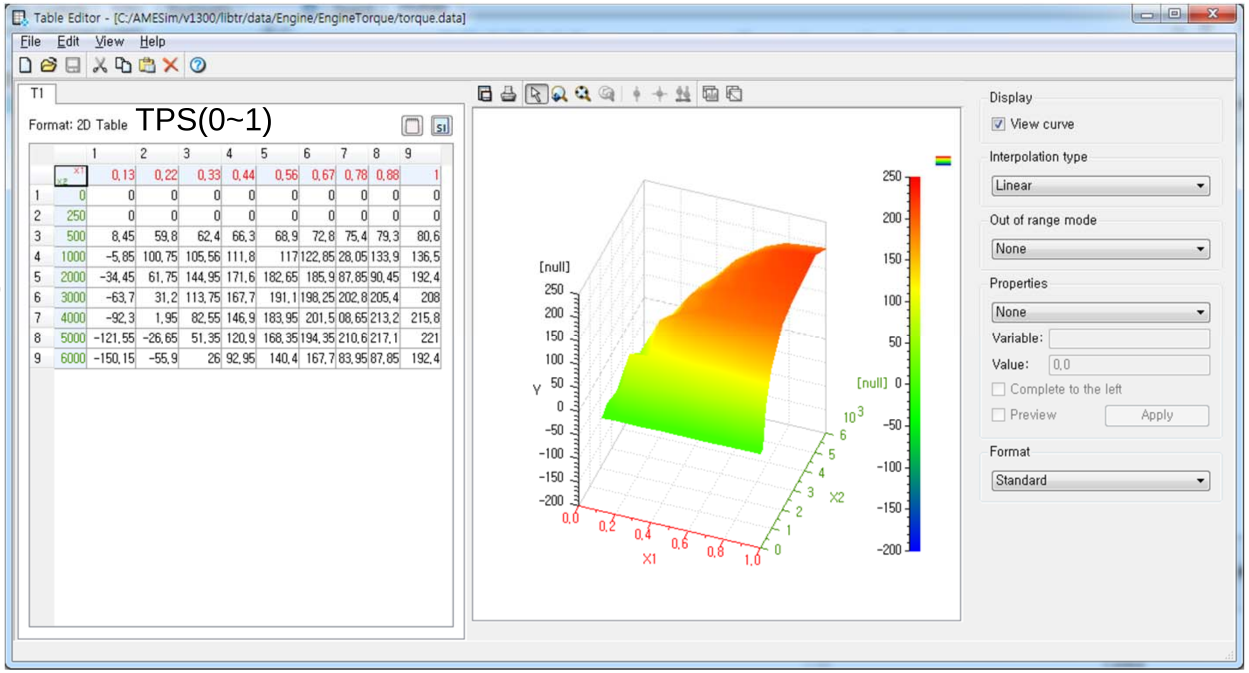
■ Torque Map Model

- 입력 : TPS(Throttle Position Sensor) / 출력 : Engine Torque
- 엔진 토크로부터 계산되는 엔진 RPM과 입력 TPS에 따라 Torque Map Table로부터 근사값 계산



$$T_{eng} = f(TPS, RPM)$$

RPM
(0~6000)



	X2 \ X1	1	2	3	4	5	6	7	8	9
		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

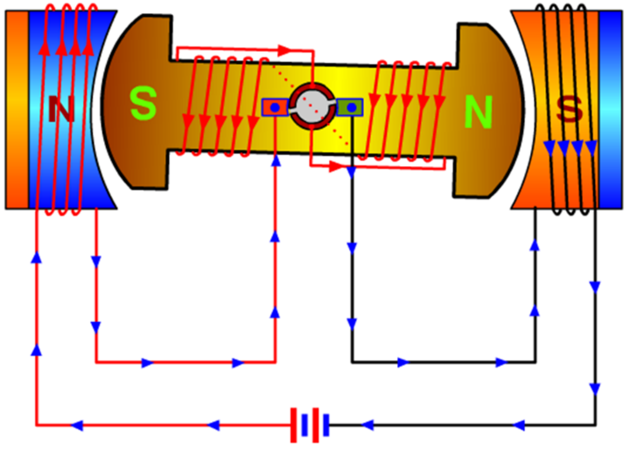
Motor

■ 목적

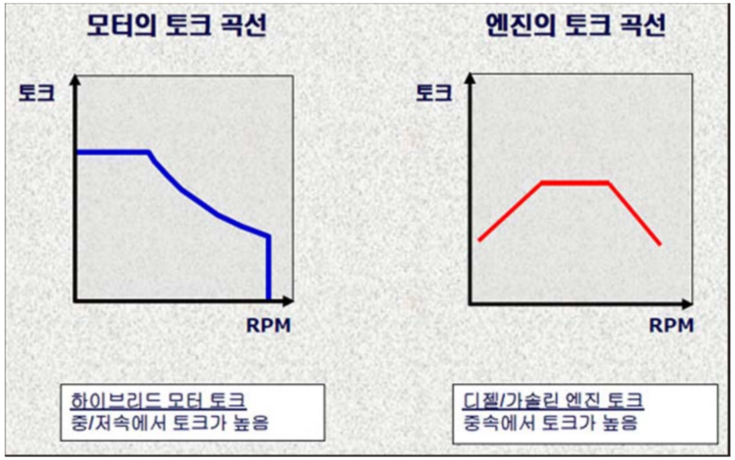
- 차량 구동을 위한 동력 발생

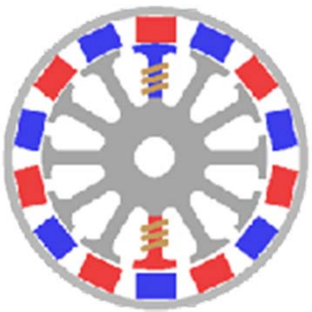
■ 원리

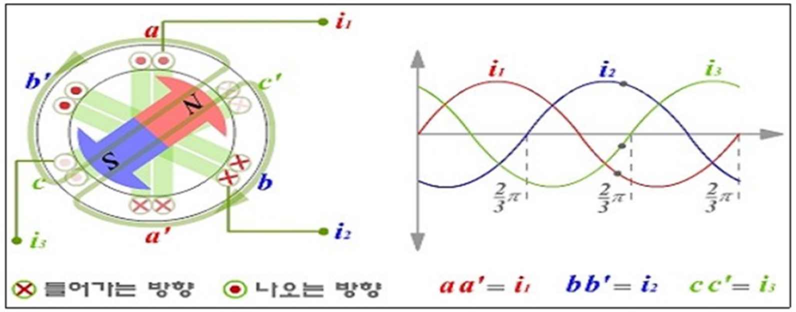
- 전류를 통해 회전자계를 형성, 모터의 회전 축에 기계적 토크를 발생



작동원리 Link



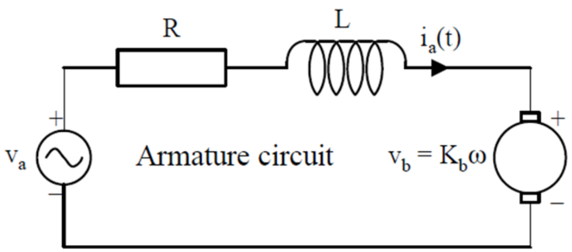


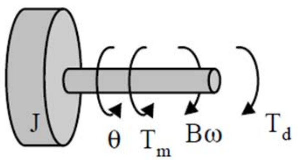


Motor

■ DC Motor Model

- 입력 : Current / 출력 : Torque





Circuit Equation

$$V = iR + L\frac{di}{dt} + V_b$$

Motor Motion

$$T_m - T_d = J\ddot{\theta} + B\dot{\theta}$$

T_d :drag torque [Nm]

B:damping coefficient [Nms]

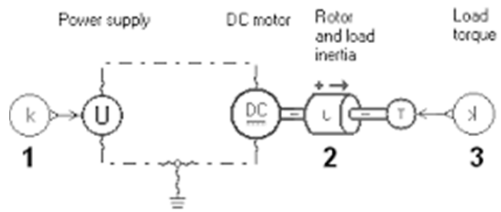
Motor Equation

$$V_b = K_b\omega \qquad T = K_t i$$

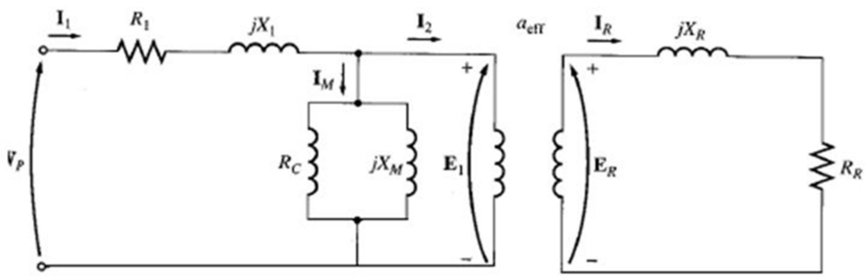
V_b :back electro motive force [V]

K_b :back-EMF constant [Vs]

K_t :torque constant [Nm/A]



AC Motor Equivalent Circuit



$$i_a = I_m \cos \omega_s t$$

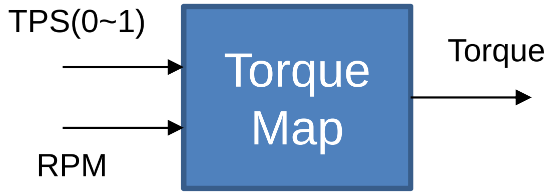
$$i_b = I_m \cos(\omega_s t - 120°)$$

$$i_c = I_m \cos(\omega_s t + 120°)$$

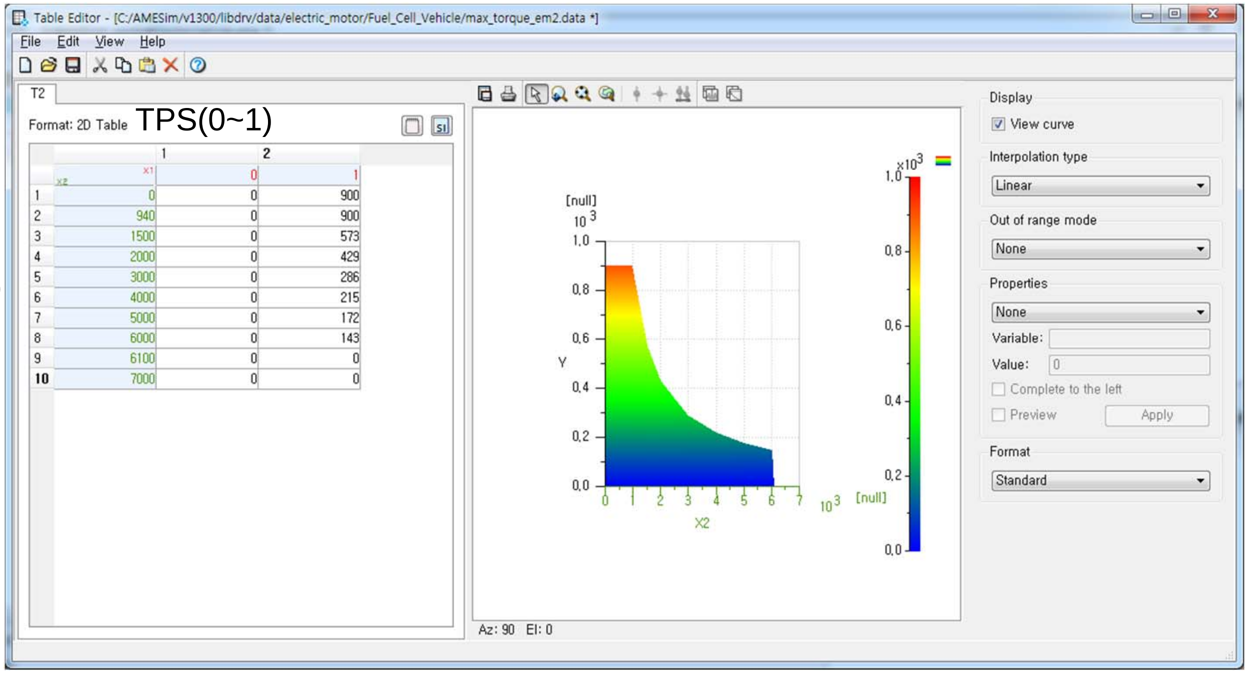
Motor

■ Torque Map Model

- 입력 : TPS(Throttle Position Sensor) / 출력 : Engine Torque
- 모터 RPM에 의해 모터 Torque Map Table로부터 최대 토크 결정, TPS(0~1)에 따라 모터 출력 토크 계산



$$T_{motor} = f(TPS, RPM)$$



	x2 \ x1	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	0
10	7000	0	0

Clutch

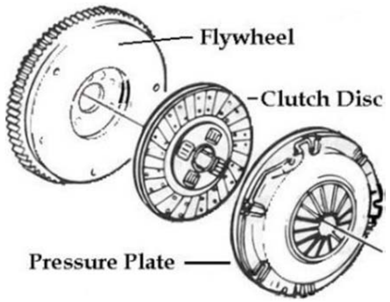
■ 목적

- 입력축으로 부터 출력축으로 동력 전달 및 차단

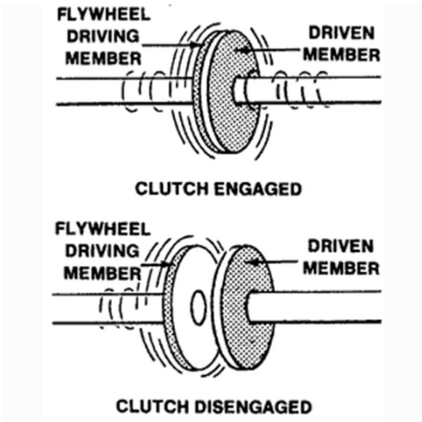
■ 원리

- 클러치의 결합/해제를 통해 디스크의 마찰 토크 생성, 양 축의 속도 동기화

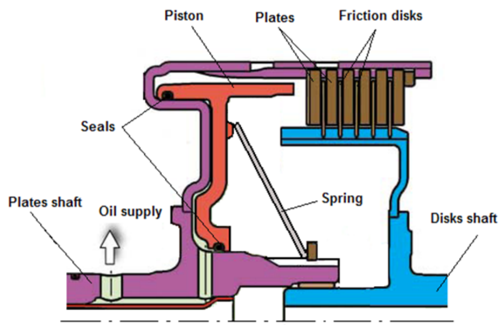
Engine side



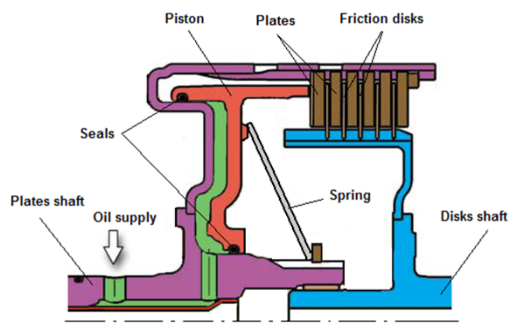
T/M side



< Single Disk >



Disengaged



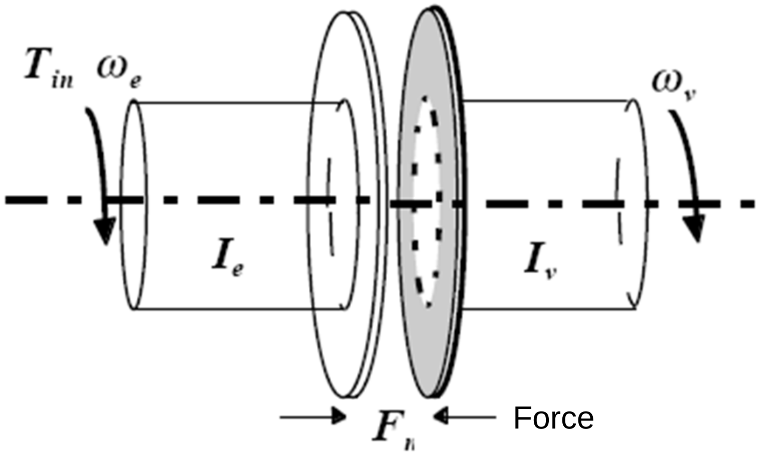
Engaged

< Multi Disk >

Clutch

■ Friction Model

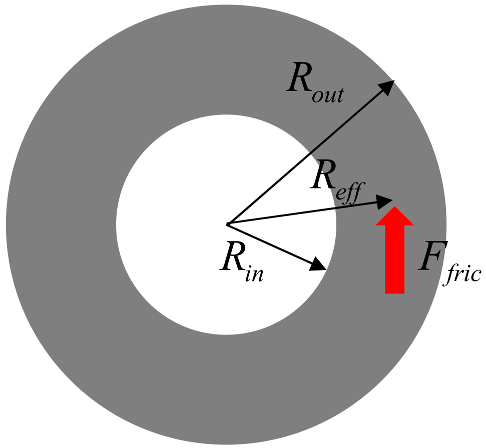
- 입력 : Actuator Force / 출력 : Torque



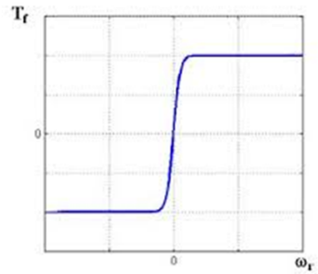
$$T_{out} = \begin{cases} F_{fric} \times R_{eff} & (\omega_{rel} \neq 0) \\ T_{in} & (\omega_{rel} = 0) \end{cases}$$

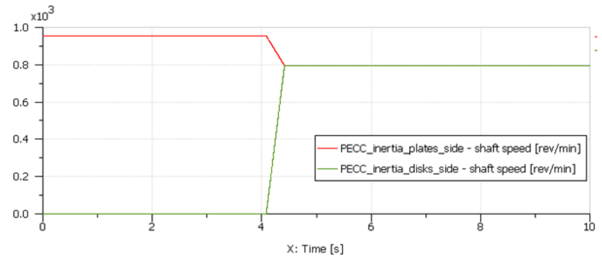
$$F_{fric} = \mu_{disk} F_n \qquad R_{eff} = \frac{2(r_{out}^3 - r_{in}^3)}{3(r_{out}^2 - r_{in}^2)}$$

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



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





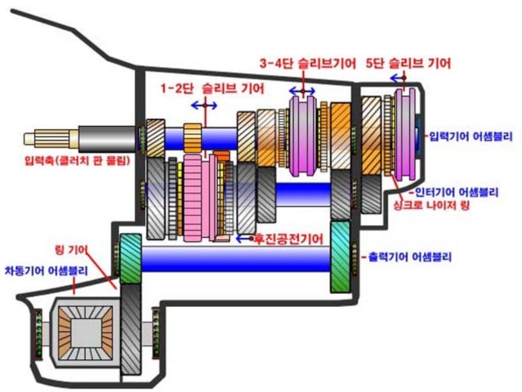
Transmission

■ 목적

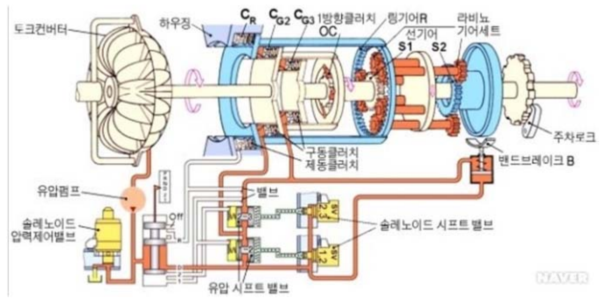
- 엔진/모터로부터의 입력축 토크, 속도를 출력축에서 필요한 적정 토크, 속도로 변환

■ 원리

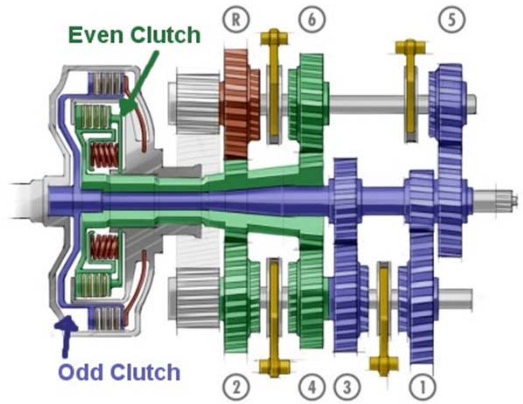
- 변속기어 단 별 클러치 등을 작동시켜, 동력 전달/해제를 통해 요구 변속 단 구현



< 수동변속기(MT) >

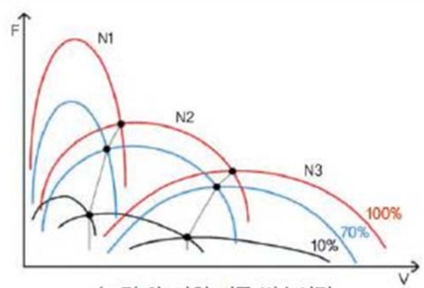


< 자동변속기(AT) >

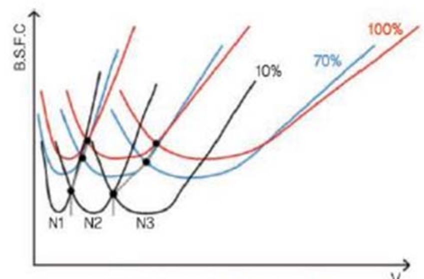


< 듀얼클러치변속기(DCT) >

	MT	AT	DCT
전달효율	좋음	나쁨	좋음
운전성	나쁨	좋음	좋음
원가	낮음	보통	비쌈



〈그림 6〉 파워 기준 변속시점

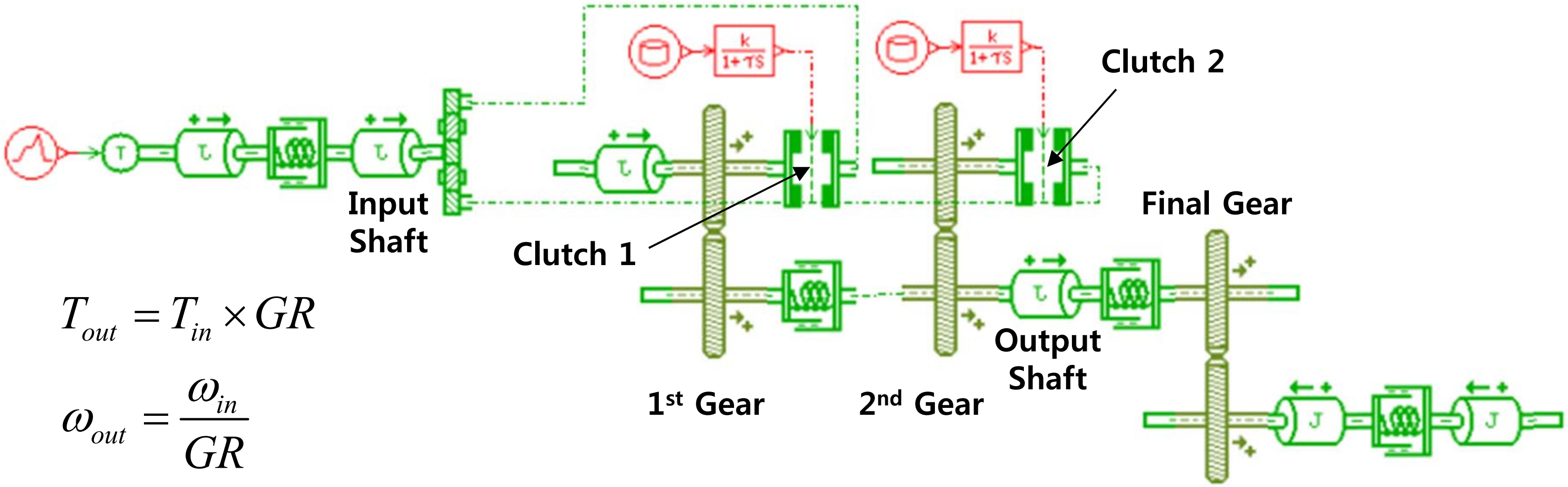


〈그림 7〉 연비 기준 변속시점

Transmission

■ Spur Gear Model

- 입력 : 변속단 클러치 Force / 출력 : 출력축 Torque



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

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

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

1) $GR = 4 \ (1st)$

$$T_{out} = 100 \times 4 = 400 \text{ Nm}$$

$$\omega_{out} = \frac{3000}{4} = 750 \text{ RPM}$$

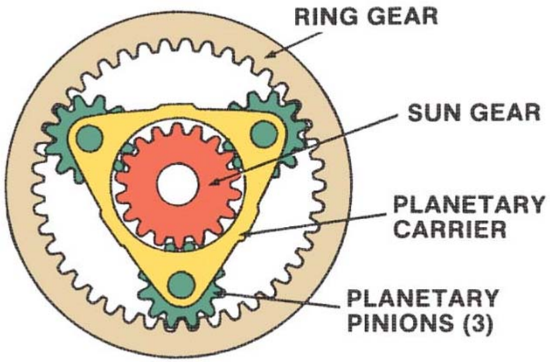
2) $GR = 2 \ (2nd)$

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

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

■ Planetary Gear Model

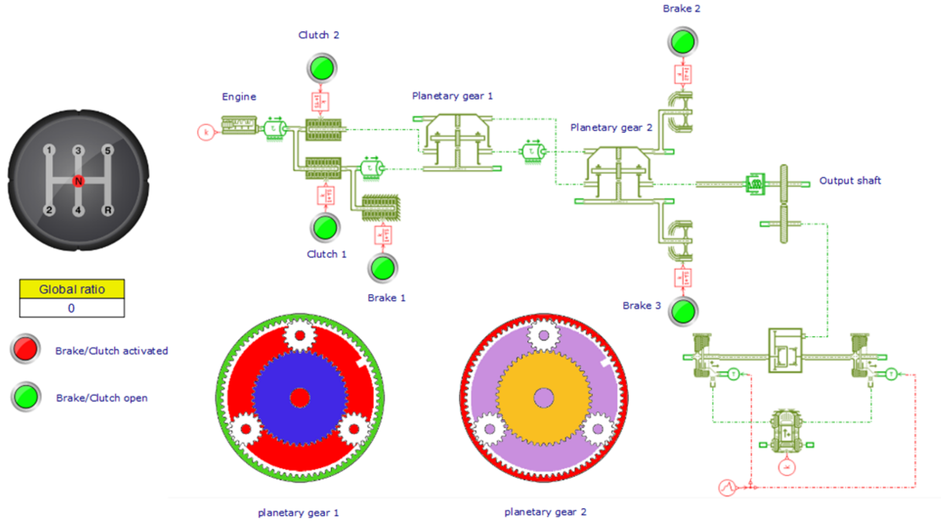
- 입력 : 클러치/브레이크 Force / 출력 : 출력축 Torque



Ring	Carrier	Sun	Ratio
driven	drive	fix	Zr/(Zs+Zr)
drive	driven	Fix	(Zs+Zr)/Zr
fix	drive	driven	Zs/(Zs+Zr)
fix	driven	drive	(Zs+Zr)/Zs
driven	fix	drive	-Zr/Zs

Zr : 링기어 잇수
Zs : 선기어 잇수
Zs+Zr : 캐리어 상당 잇수

Ex) Zr=80, Zs=40
링고정, 캐리어구동
기어비? 증속?감속?



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

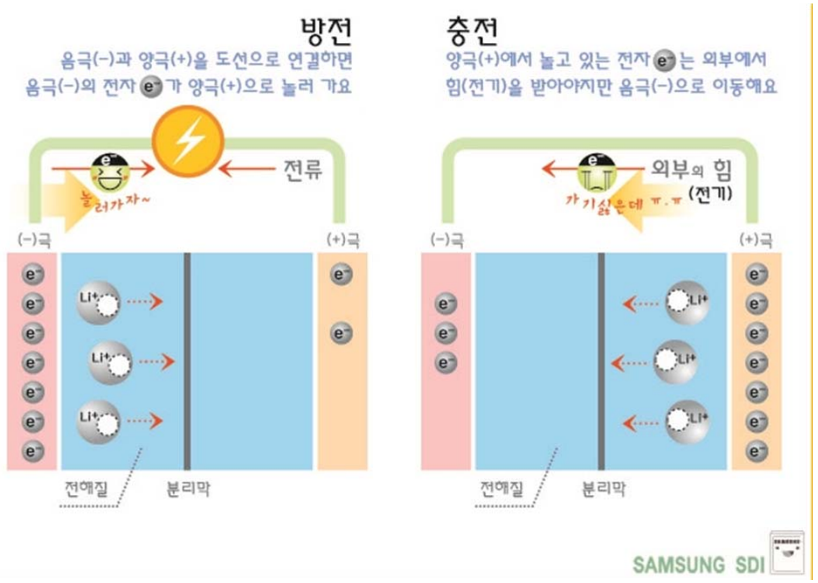
Battery

■ 목적

- 모터에서 기계적 토크를 출력하기 위한 전류 공급

■ 원리

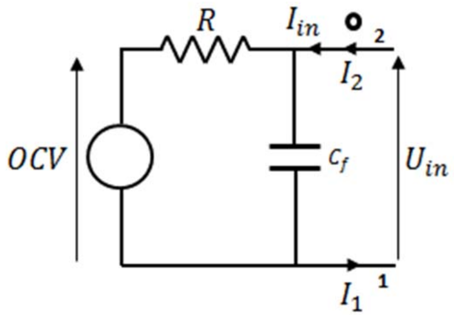
- 캐패시터 내 저장되어 있는 전기에너지를 전압, 저항에 의해 전류로 변환, 모터에 공급

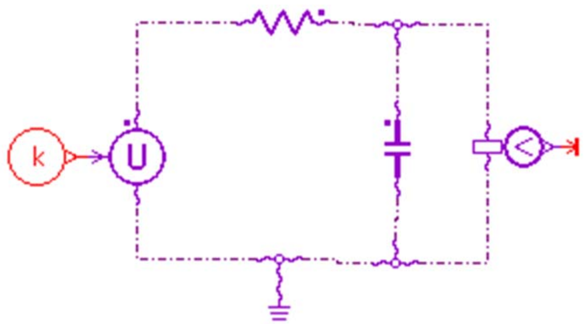


Battery

■ Circuit Model

- 입력 : 모터 소모 전력 / 출력 : SOC
- 모터 소모 전류 계산을 통해 배터리 SOC 사용량 계산





※ 배터리 모델 방정식

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

V_{bat} : output volatage [V]

V_{OCV} : open circuit voltage [V]

R_{in} : equivalent internal resistance [Ohm]

I_{bat} : battery current [A]

※ SOC 계산

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

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

기계에너지 전기에너지

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

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

SOC : state of charge [%]

C_{nom} : rated capacity [As]

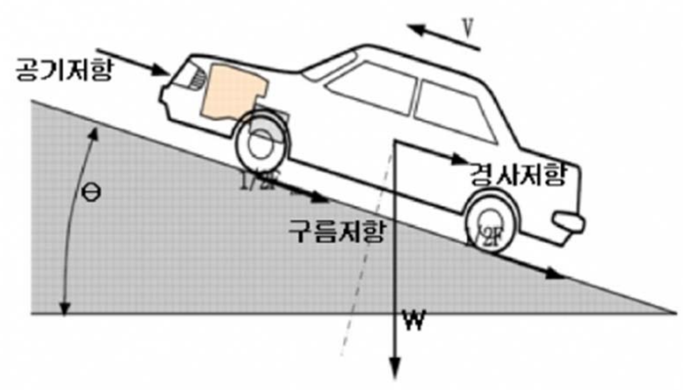
Driving Resistances

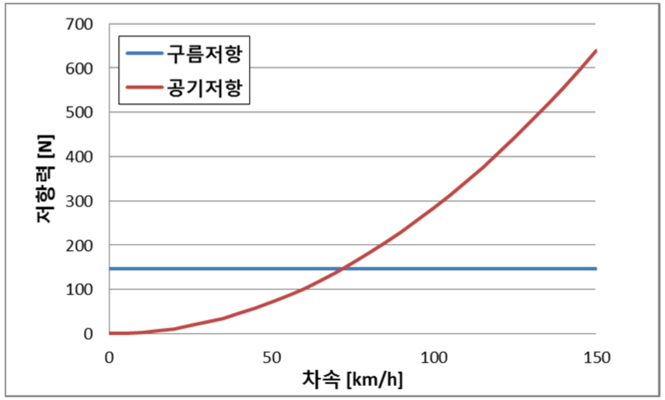
■ 정의

- 차량 주행 시, 외부 환경으로부터 발생하는 주행을 방해하는 저항력

■ 구성

- 공기저항, 구름저항, 구배저항, 가속저항 등





< 공기저항 >

< 구름저항 >

< 구배저항 >

Driving Resistances

■ Resistance Model

- 입력 : 차속,구배 / 출력 : 저항력

1) 공기저항

$$R_d = \frac{1}{2} C_d A_{front} \rho_{air} V_{car}^2$$

C_d : 항력계수

A_{front} : 전면 투영면적 [m^2]

ρ_{air} : 공기밀도 [kg/m^3]

V_{car} : 차속 [m/s]

2) 구름저항

$$R_r = \mu_r \times w$$

μ_r : 구름 마찰계수

w : 차량 무게 [N]

3) 구배저항

$$R_g = w \sin \theta_{grad}$$

θ_{grad} : 경사각 [rad]

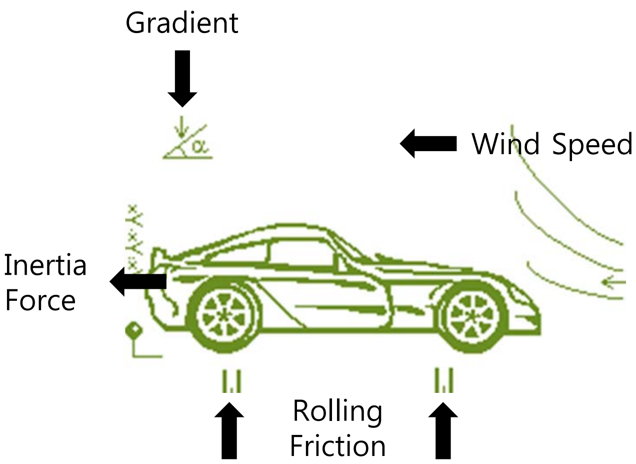
4) 가속저항

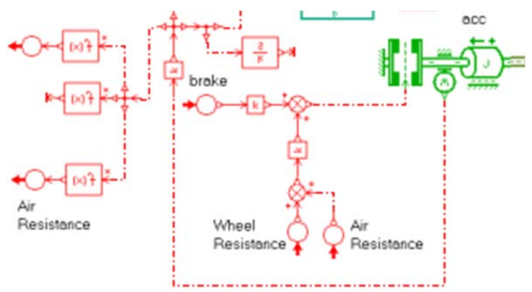
$$R_a = ma = J_{eq} \alpha_{whl} R_{tire}$$

J_{eq} : 차량 등가 관성

α_{whl} : 휠 회전가속도 [rad/s^2]

R_{tire} : 타이어 유효반경

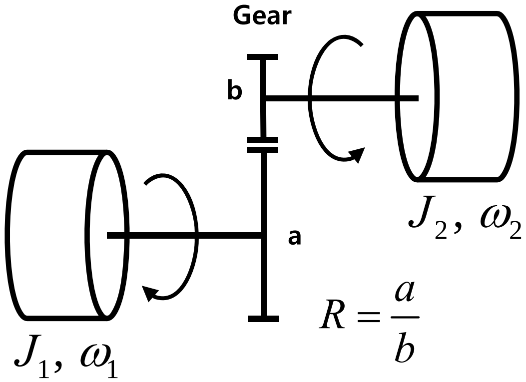




Driving Resistances

■ Equivalent Inertia

- 서로 다른 축에서 다른 속도로 회전하는 관성을 하나의 등가 관성으로 계산



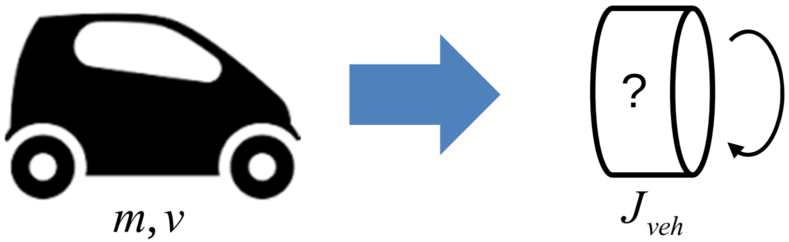
$$E_1 + E_2 = E_{eq}$$

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

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

$$J_{eq,1} = J_1(1+R^2)$$

차량 등가 관성 계산



$$E_v = E_w$$

$$\frac{1}{2}mv^2 = \frac{1}{2}J_{veh}\omega^2$$

$$J_{veh} = mR_{tire}^2$$

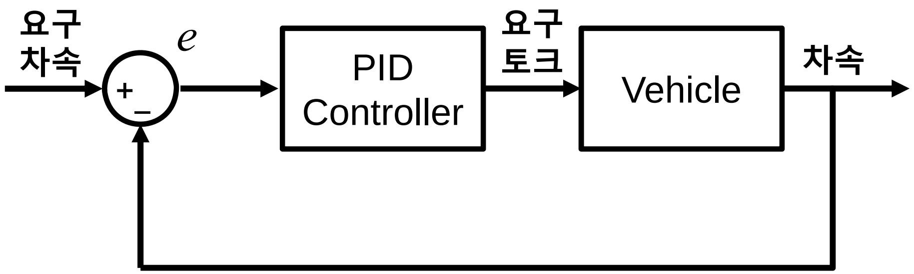
Driving Controller

■ 목적

- 차량 주행 시, 운전자가 요구하는 주행 시나리오(차속)에 맞는 구동력(엔진 or 모터) 제어

■ 원리

- 운전자 요구 차속과 실제 차속과의 에러를 감소시키도록 제어(ex : PID control)



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

$$(e(t) = V_{req.} - V_{real})$$

K_p : proportional gain

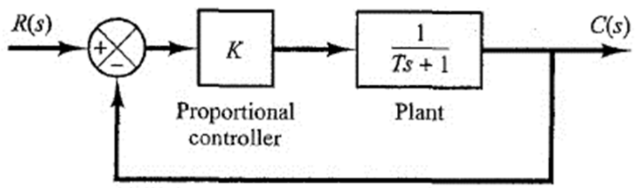
K_i : integral gain

K_d : differential gain

Driving Controller

■ Proportional Control

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

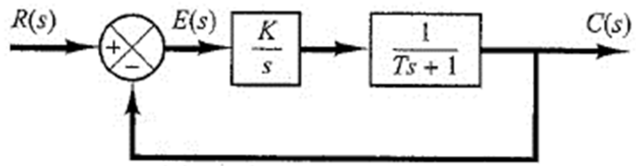


$$E(s)=\frac{1}{1+G(s)}R(s)=\frac{1}{1+\frac{K}{Ts+1}}R(s)\qquad R(s)=\frac{1}{s}\ \text{(unit-step func.)}$$

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

■ Integral Control

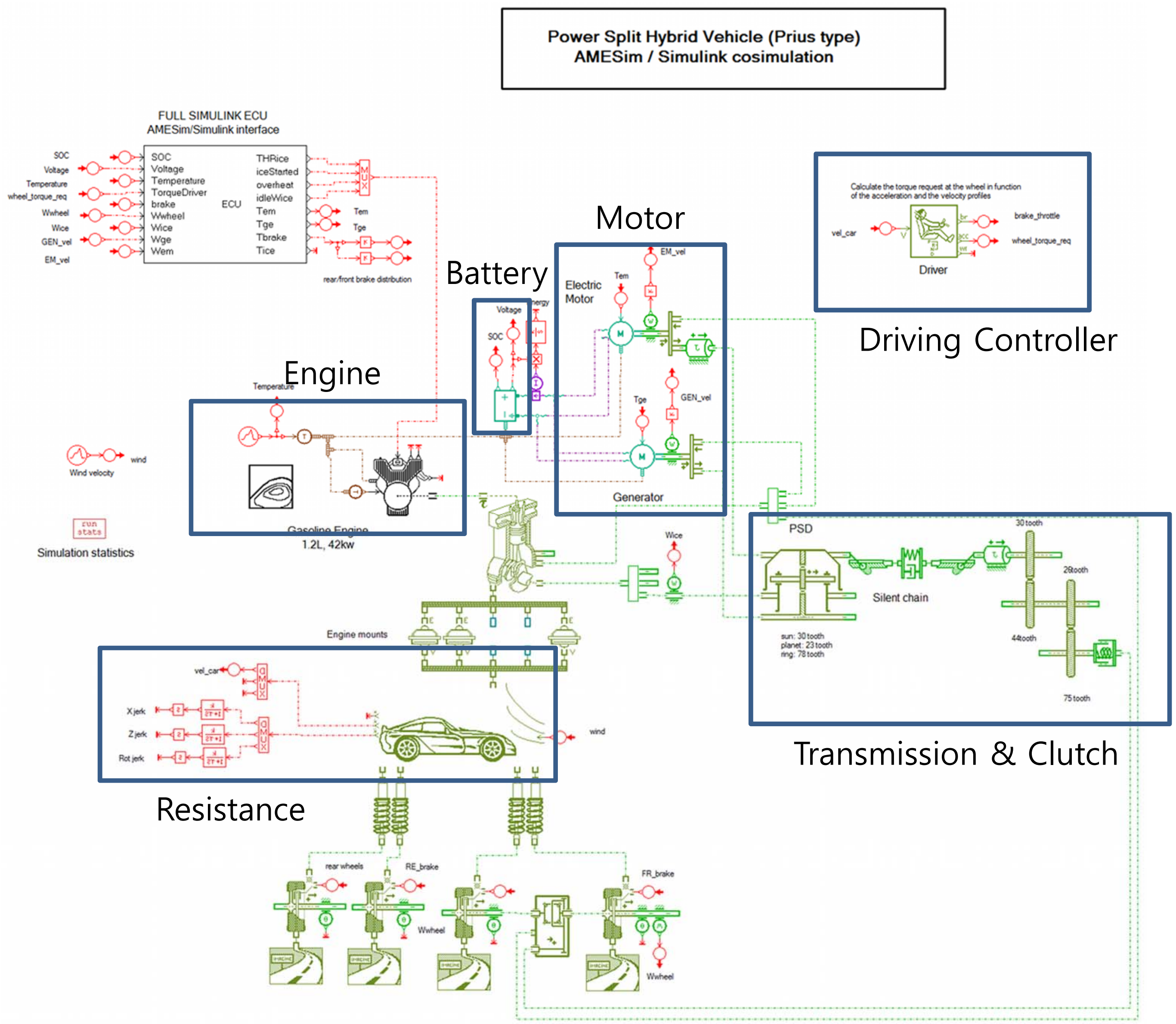
$$\frac{C(s)}{R(s)}=\frac{K}{s(Ts+1)+K}\qquad \frac{E(s)}{R(s)}=\frac{R(s)-C(s)}{R(s)}=\frac{s(Ts+1)}{s(Ts+1)+K}$$



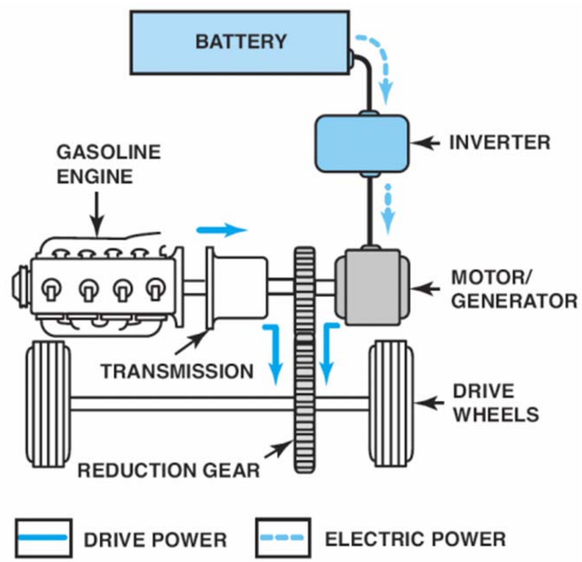
$$E(s)=\frac{s(Ts+1)}{s(Ts+1)+K}\frac{1}{s}\qquad R(s)=\frac{1}{s}\ \text{(unit-step func.)}$$

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

HEV Model


Power Split Hybrid Vehicle (Prius type)
AMESim / Simulink cosimulation
FULL SIMULINK ECU
AMESim/Simulink interface
Motor
Battery
Engine
Driving Controller
Driver
Electric Motor
Generator
Gasoline Engine
1.2L, 42kw
Wind velocity
Simulation statistics
Engine mounts
PSD
Silent chain
Transmission & Clutch
Resistance

Assignment



Vehicle Parameters

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

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

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

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

Drag Parameter

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

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

Problem

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

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