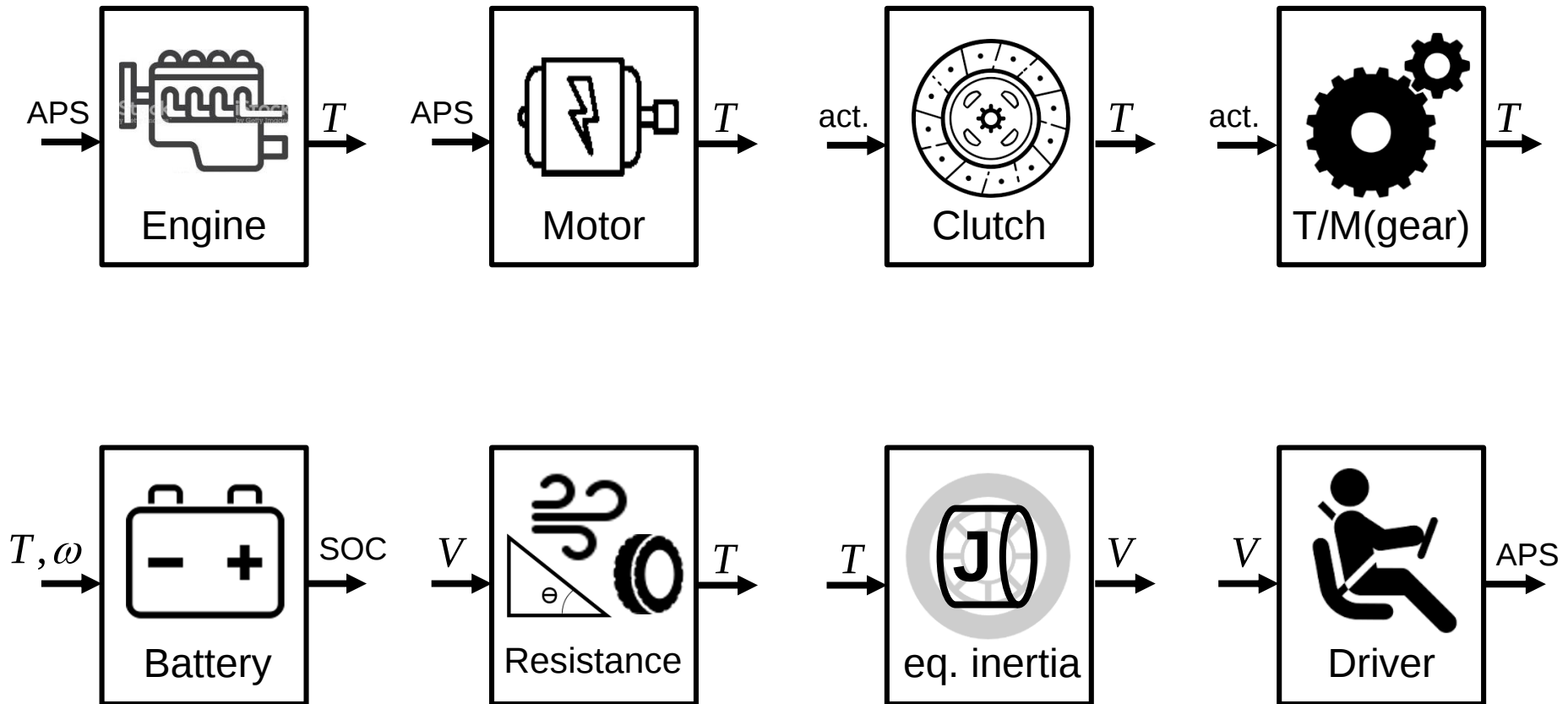


Contents

- Powertrain system model : HEV/EV
- Efficiency analysis
- Performance analysis
- Example: Chevrolet Bolt EV

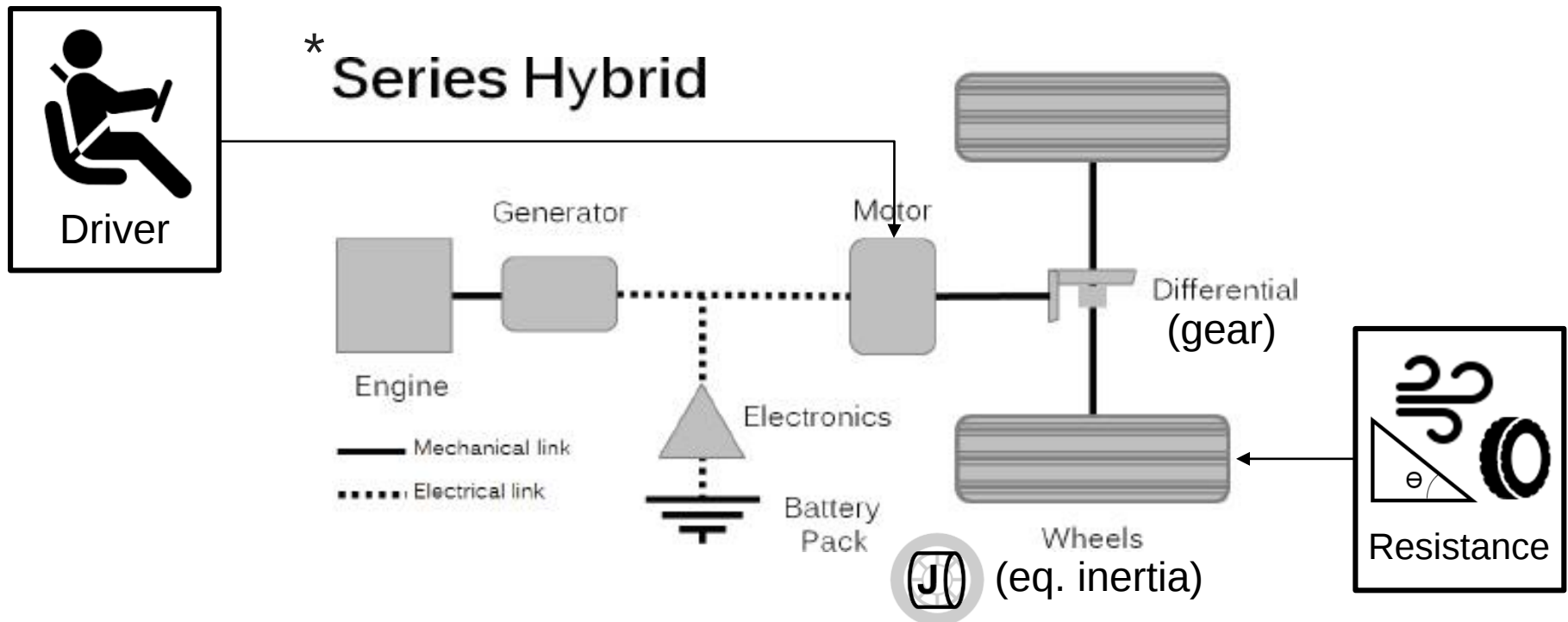
Powertrain system model

- Modeling components



Powertrain system model: HEV(1)

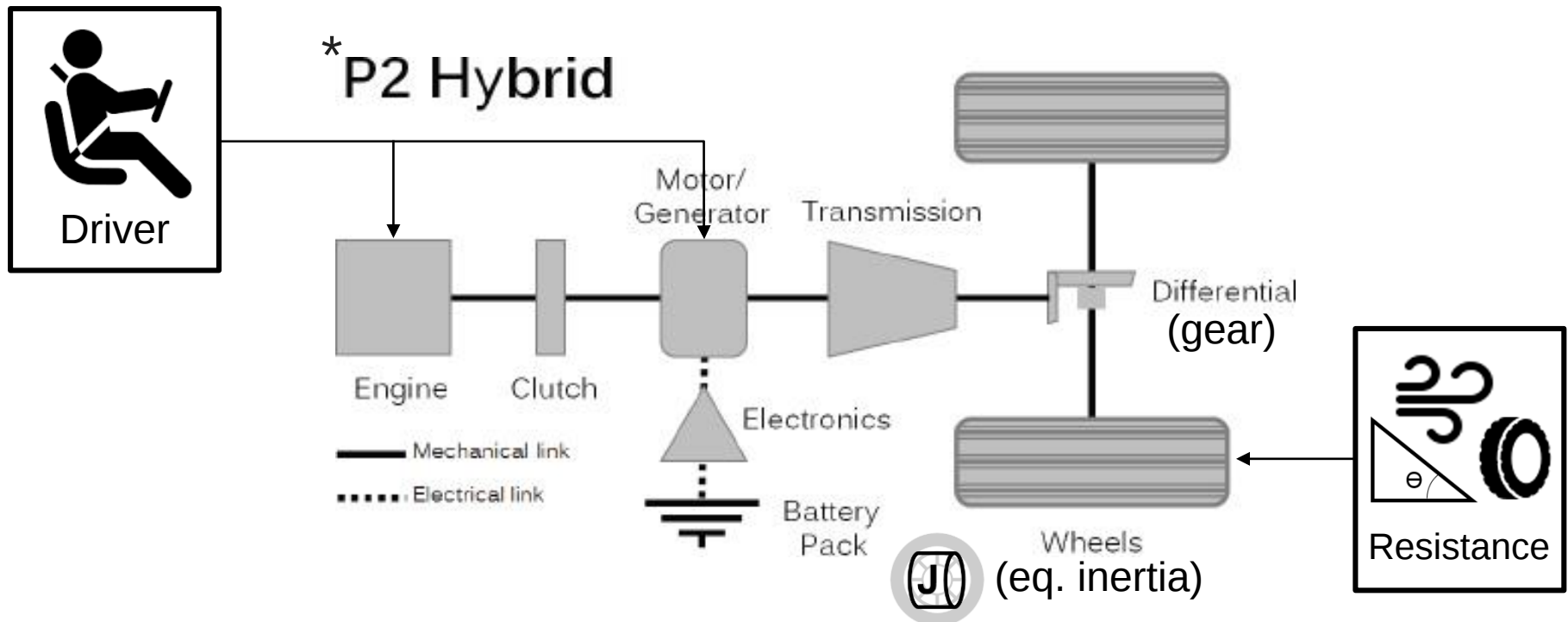
- Series HEV
 - Powertrain: Engine, Generator, Motor, Battery, Gear
 - Others: Driver, Equivalent inertia, Resistance



*National Research Council. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. National Academies Press, 2015.

Powertrain system model: HEV(2)

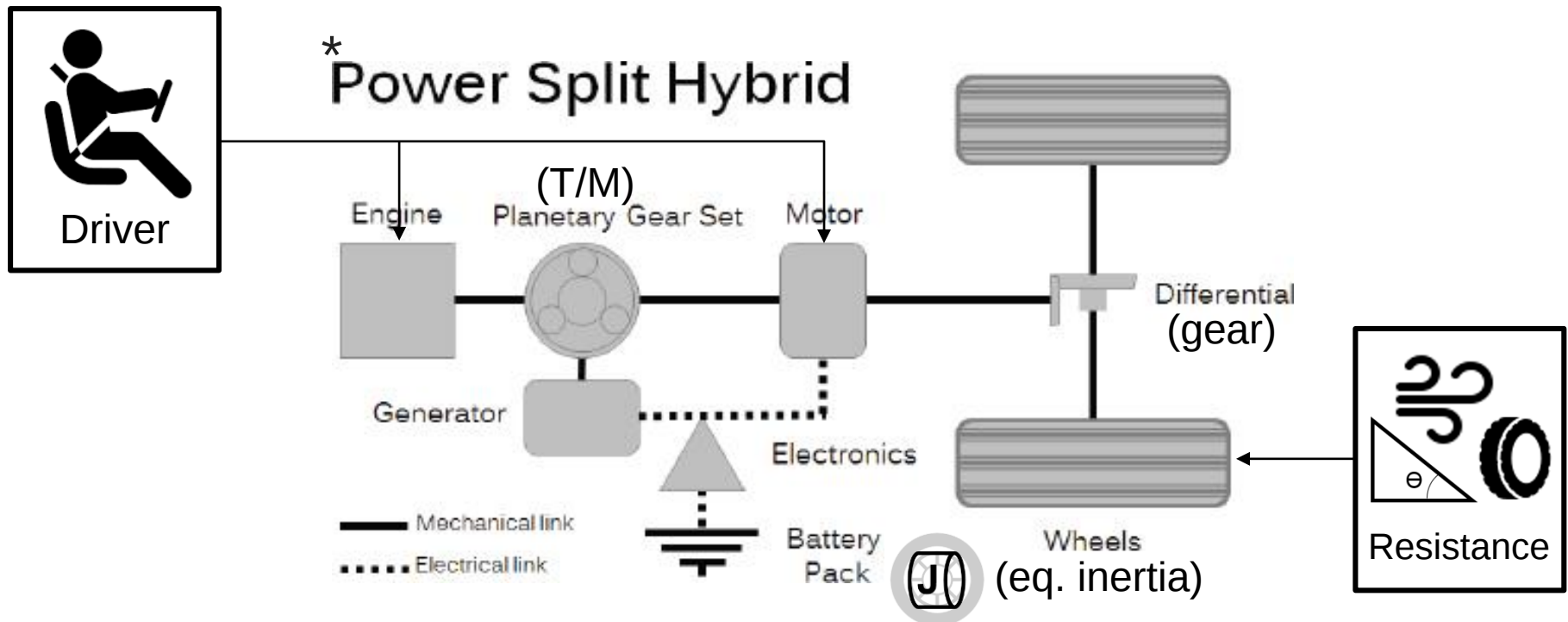
- Parallel HEV
 - Powertrain: Engine, Clutch, Motor, Battery, T/M, Gear
 - Others: Driver, Equivalent inertia, Resistance



*National Research Council. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. National Academies Press, 2015.

Powertrain system model: HEV(3)

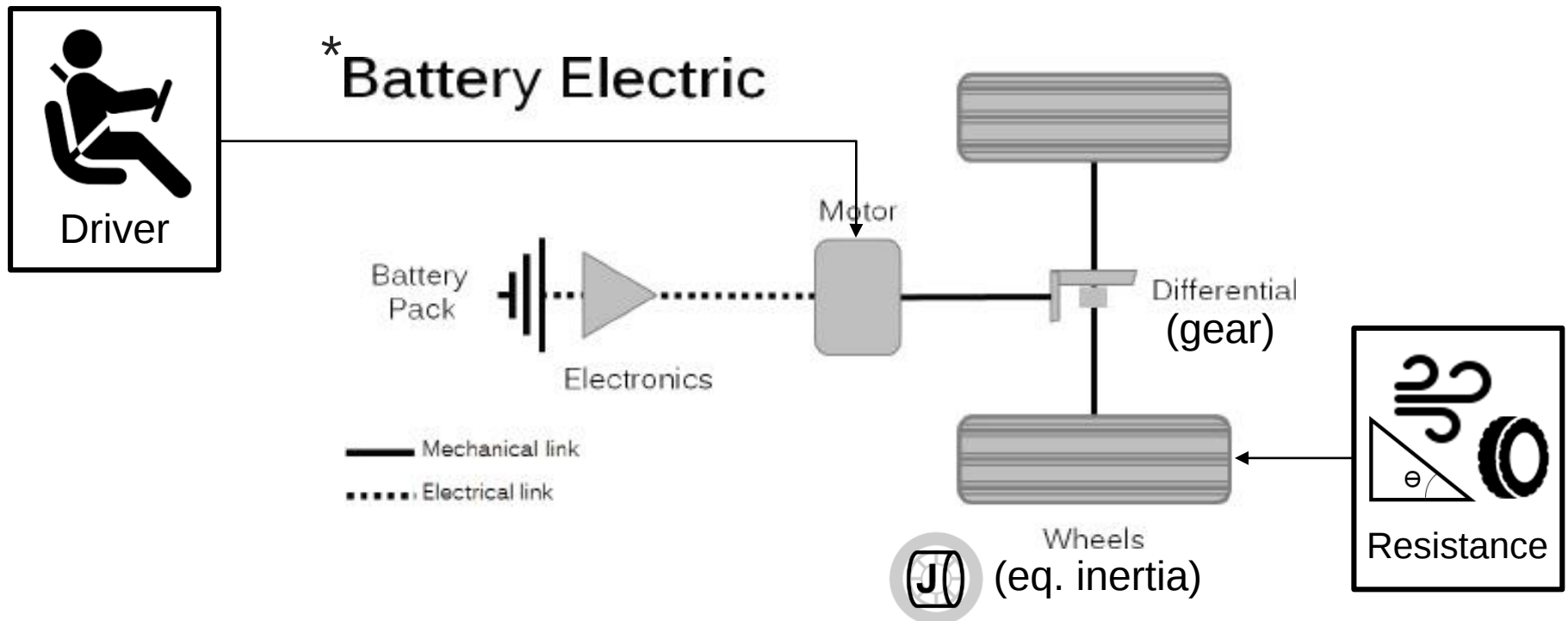
- Power Split HEV
 - Powertrain: Engine, Generator, Motor, Battery, T/M(Power split), Gear
 - Others: Driver, Equivalent inertia, Resistance



*National Research Council. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. National Academies Press, 2015.

Powertrain system model: EV

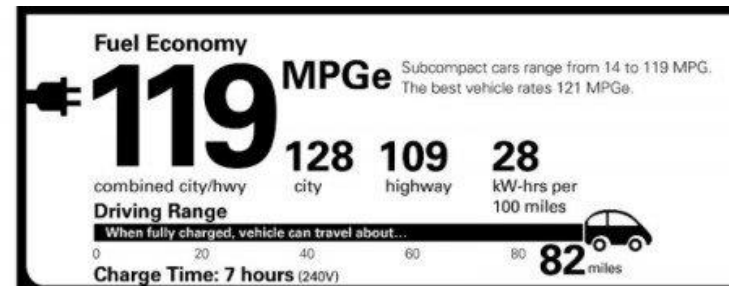
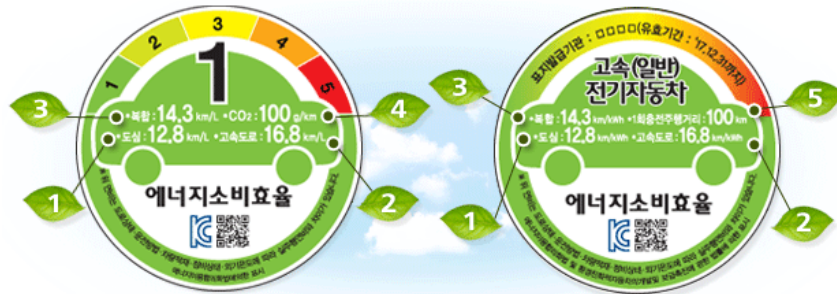
- Battery EV
 - Powertrain: Motor, Battery, Gear
 - Others: Driver, Equivalent inertia, Resistance



*National Research Council. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. National Academies Press, 2015.

Efficiency analysis (1)

- Measurements
 - HEV: Fuel efficiency (km/L, MPG, L/100km)
 - EV: Energy efficiency (km/kWh, MPGe, kWh/100km)



1) Fuel efficiency (HEV)

$$\text{km/L} = \frac{\text{Driving distance [km]}}{\text{Fuel consumption [L]}}$$

$$1 \text{ km/L} = \frac{\text{mile}}{\text{gallon}} \frac{3.785}{1.609} = 2.352 \text{ MPG}$$

2) Energy efficiency (EV)

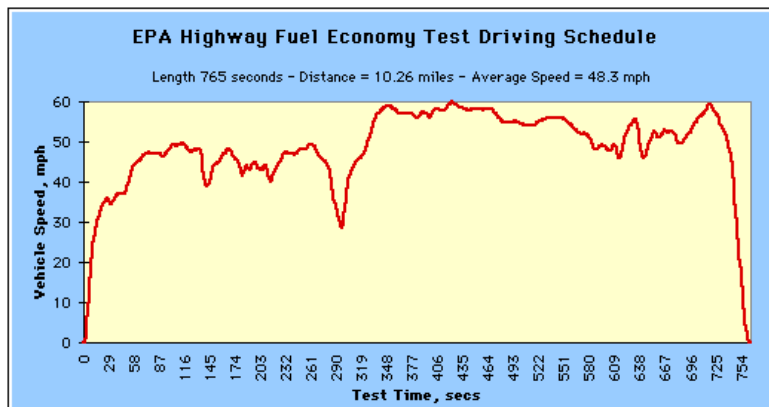
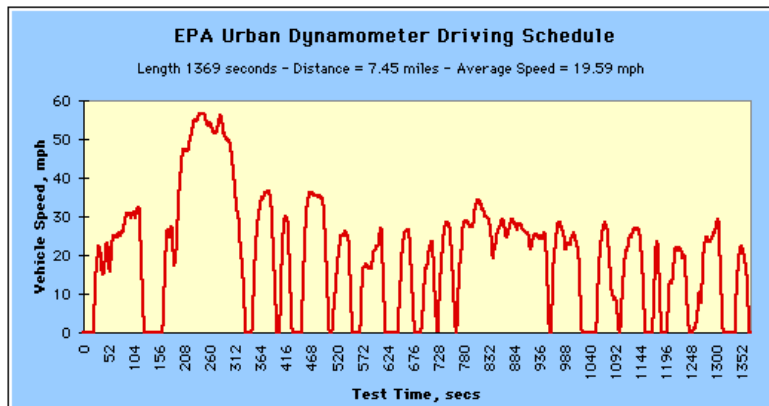
$$\text{km/kWh} = \frac{\text{Driving distance [km]}}{\text{Energy consumption [kWh]}}$$

$$1 \text{ km/kWh} = \frac{\text{mile}}{\text{eq. gallon}} \frac{33.705}{1.609} = 20.95 \text{ MPGe}$$

Efficiency analysis (2)

- Driving cycles
 - UDDS+HWFET(Korea, US), NEDC (Europe), JP 10-15 (Japan)

UDDS / HWFET



NEDC

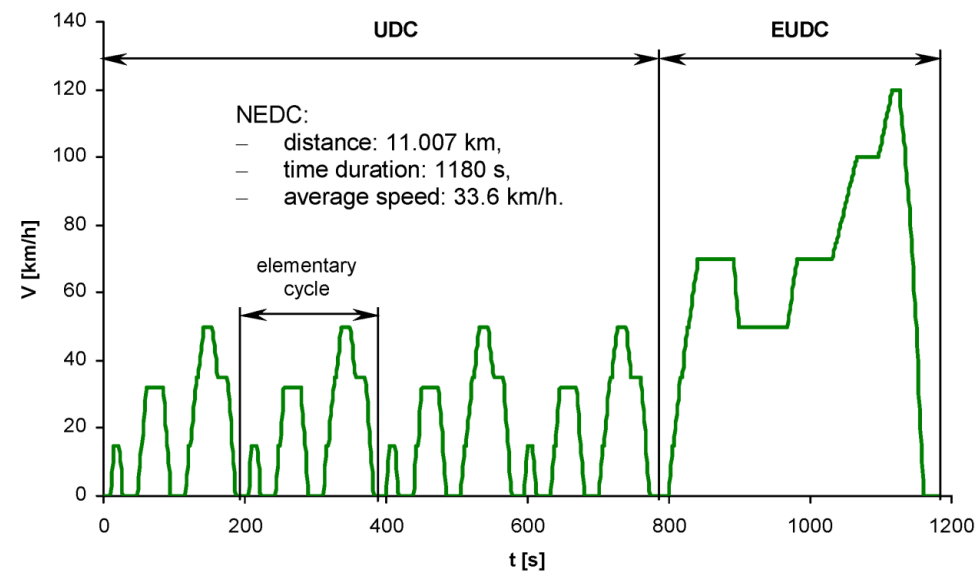
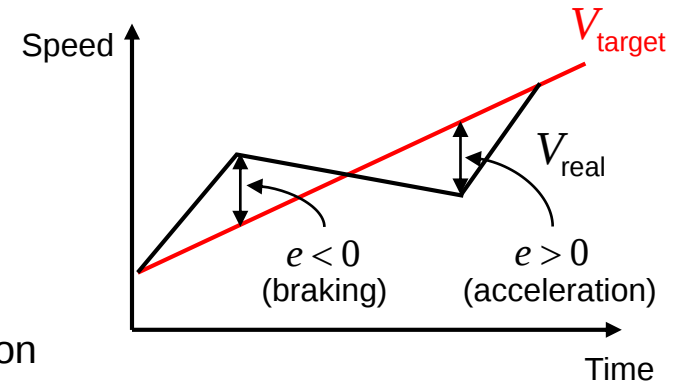
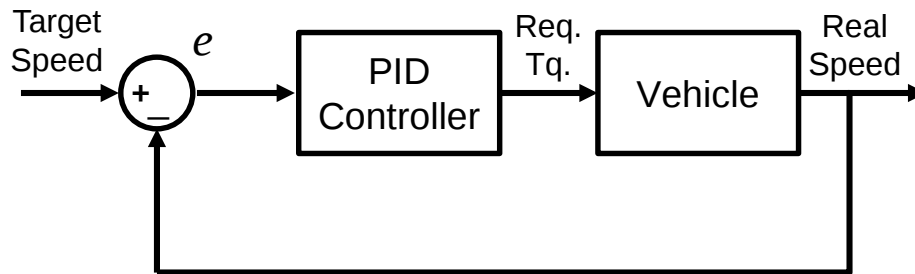


Figure 1, viewing NEDC cycle. Divided in two parts; urban and extra urban driving cycle [4].

NORALM, Zeerak. Implementing method for conducting Real Driving Emission (RDE). 2018.

Efficiency analysis (3)

- Concept for tracking vehicle speed of driving cycle



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

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

$$C_{brk} \leq T_{req} \leq T_{max}(\omega)$$

C_{brk} : Brake capacity [Nm]

T_{max} : Maximum torque of engine/motor [Nm]

Example

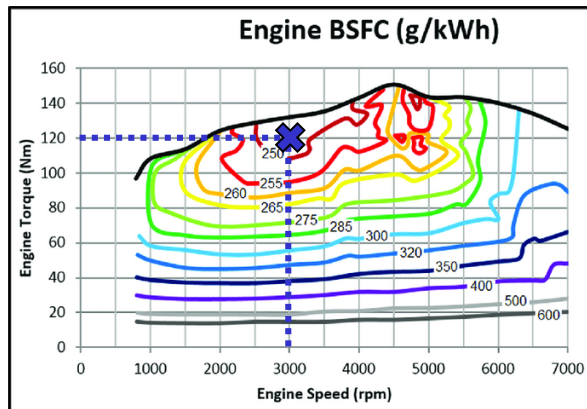
Target speed = 30 km/h, Real speed = 28 km/h

Proportional gain = 100

Request torque of driver?

Efficiency analysis (4)

- Efficiency map (Engine)
 - Brake specific fuel consumption (BSFC)



Example

Engine: torque = 120 Nm, RPM = 3000

Fuel consumption per second? (L/s)

BSFC(120 Nm, 3000 RPM) = 250 g/kWh

$$\frac{250 \text{ g}}{\text{kWh}} \times \frac{120 \times 3000}{1000} \frac{\pi}{30} \times \frac{1 \text{ h}}{3600 \text{ s}} \times \frac{1 \text{ L}}{860 \text{ g}} = 0.003 \text{ L/s}$$

BSFC Engine power [kW] Fuel density

When a vehicle is driving during 5 min with this condition, fuel efficiency?
(Total gear ratio: 4, Tire radius: 0.3 m)

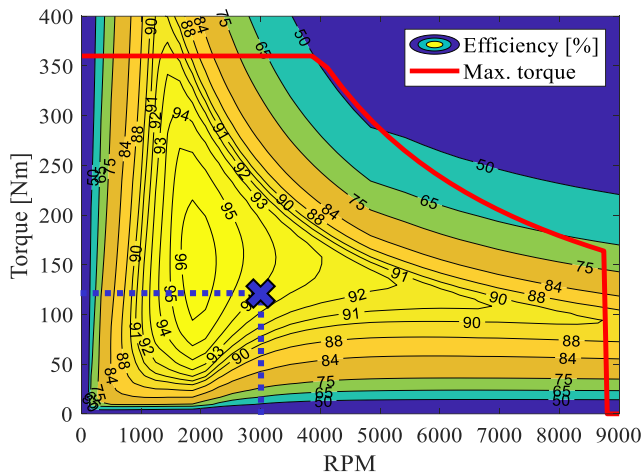
$$\text{Driving distance: } \int_0^{5 \text{ min}} V \, dt = \int_0^{5 \text{ min}} \frac{\omega}{GR} R_{\text{tire}} \, dt = \left(\frac{3000}{4} \frac{\pi}{30} \times 0.3 \right) \times 300 \text{ s} = 7,068 \text{ m}$$

$$\text{Fuel consumption: } \int_0^{5 \text{ min}} 0.003 \text{ L/s} \, dt = 300 \text{ s} \times 0.003 \text{ L/s} = 0.9 \text{ L}$$

$$\text{Fuel efficiency: } \frac{7.068 \text{ km}}{0.9 \text{ L}} = 7.85 \text{ km/L}$$

Efficiency analysis (5)

- Efficiency map (Motor)
 - Electric efficiency



Example

Motor: torque = 120 Nm, RPM = 3000

Battery: voltage = 350 V, capacity = 60 kWh

SOC consumption per second? (%/s)

Motor efficiency = 94%

$$120 \times 3000 \frac{\pi}{30} = 0.94 \times 350 \times I \quad I = 114.59 \text{ A}$$

Motor power Eff. Voltage

$$-114.59 \text{ A} \frac{100\% \times 350 \text{ V}}{60,000 \text{ Wh}} \times \frac{1 \text{ h}}{3600 \text{ s}} = -0.019 \text{ \%/s}$$

When a vehicle is driving during 5 min with this condition, energy efficiency?

(Total gear ratio: 4, Tire radius: 0.3 m)

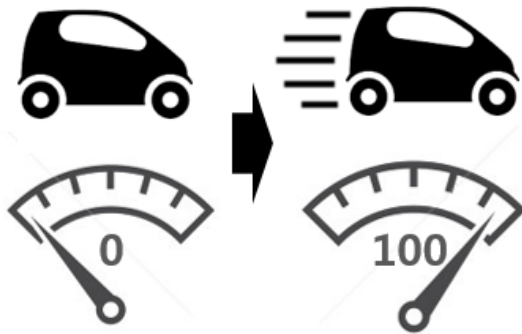
$$\text{Energy consumption: } \Delta \text{SOC} = \int_0^{5 \text{ min}} -0.019 \text{ \%/s} \, dt = 300 \text{ s} \times 0.019 \text{ \%/s} = -5.7 \%$$

$$60 \text{ kWh} \times 5.7\% = 3.42 \text{ kWh}$$

$$\text{Energy efficiency: } \frac{7.068 \text{ km}}{2.88 \text{ kWh}} = 2.07 \text{ km/kWh}$$

Performance analysis (1)

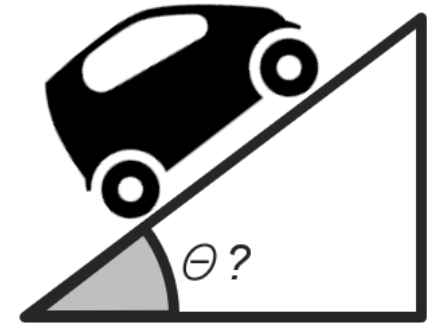
- Measurements
 - 0-100 km/h acceleration time, maximum speed, ascendable slope



$V = 100 \text{ km/h}$



$V = \text{maximum}$



$V > 0$

$$V = \int \frac{(T_{drv} - T_{res})}{J_{eq}} dt \times R_{tire}$$

Driving torque at wheel Resistance torque at wheel

Performance analysis (2)

- Acceleration time

$$V = \int_0^{t_a} \frac{(T_{drv} - T_{res})}{J_{eq}} dt \times R_{tire} = 100 \text{ km/h}$$

Parallel HEV

$$J_{eq} = (J_{eng} + J_{mot}) \times GR(t)^2 + m_b R_{tire}^2$$

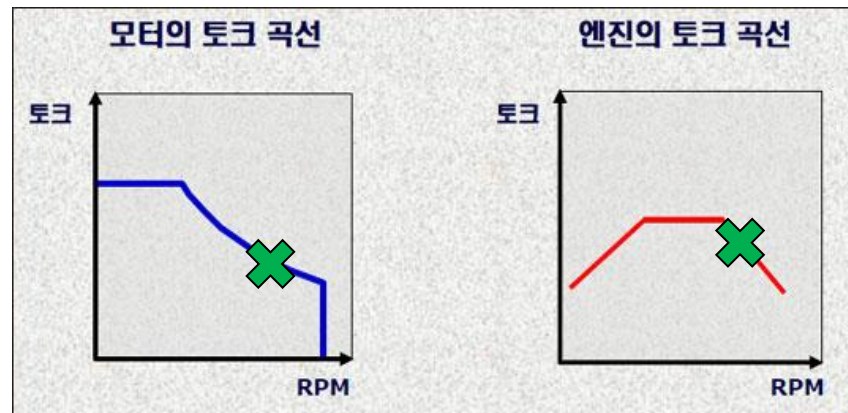
$$T_{drv} = (T_{eng}(t) + T_{mot}(t)) \times GR(t)$$

Series HEV / Battery EV

$$J_{eq} = J_{mot} \times GR^2 + m_b R_{tire}^2$$

$$T_{drv} = T_{mot}(t) \times GR$$

$$T_{res} = \left(\frac{1}{2} C_d A_{fr} \rho_{air} V^2(t) + \mu_r m_b g \right) \times R_{tire}$$



Performance analysis (3)

- Maximum speed

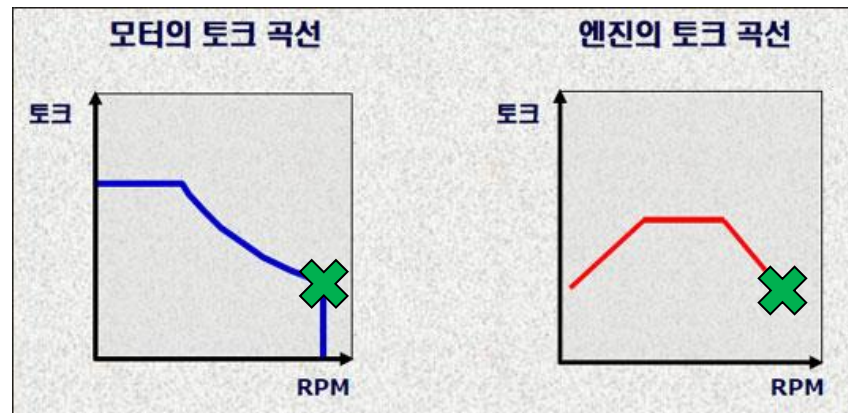
$$V_{\max} = \int \frac{(T_{drv} - T_{res})}{J_{eq}} dt \times R_{tire} = \frac{R_{tire}}{J_{eq}} (T_{drv}(V_{\max}) - T_{res}(V_{\max})) > 0$$

Constant

therefore $T_{drv}(V_{\max}) - T_{res}(V_{\max}) > 0$

$$V_{\max} = \frac{\omega_{\max}}{GR_h} \times R_{tire} \quad \text{GR is minimum ratio at highest speed (ex: 6th speed)}$$

$$T_{drv} - T_{res} = (T_{eng}(\omega_{\max}) + T_{mot}(\omega_{\max})) \times GR_h - \left(\frac{1}{2} C_d A_{fr} \rho_{air} V_{\max}^2 + \mu_r m_b g \right) \times R_{tire} > 0$$



Performance analysis (4)

- Ascendable slope

$$V = \int \frac{(T_{drv} - T_{res})}{J_{eq}} dt \times R_{tire} = \boxed{\frac{R_{tire}}{J_{eq}}} (T_{drv}(0) - T_{res}(0)) = 0$$

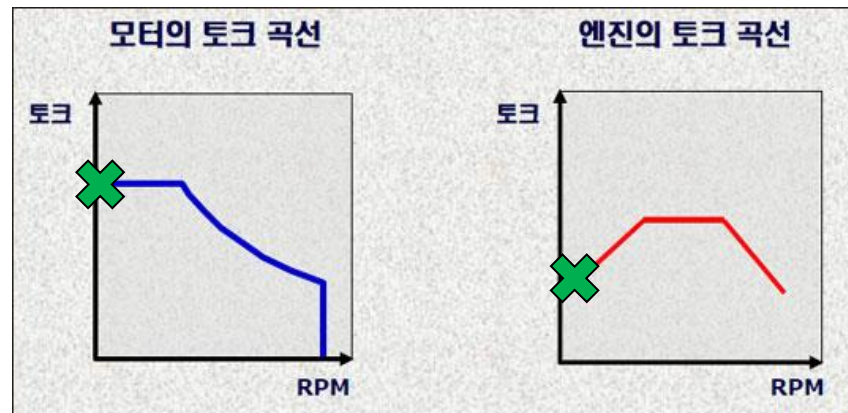
Constant

therefore $T_{drv}(0) = T_{res}(0)$

$T_{drv} = (T_{eng}(0) + T_{mot}(0)) \times GR_l$ GR is maximum ratio at lowest speed (1st speed)

$T_{res} = (\mu_r m_b g \cos \theta + m_b g \sin \theta) \times R_{tire} \approx m_b g \sin \theta \times R_{tire}$ (if theta is large value)

$$\theta = \sin^{-1} \left[\frac{(T_{eng}(0) + T_{mot}(0)) \times GR_l}{m_b g \times R_{tire}} \right]$$



Example (1)

- 2017 Chevrolet Bolt EV

Battery Electric

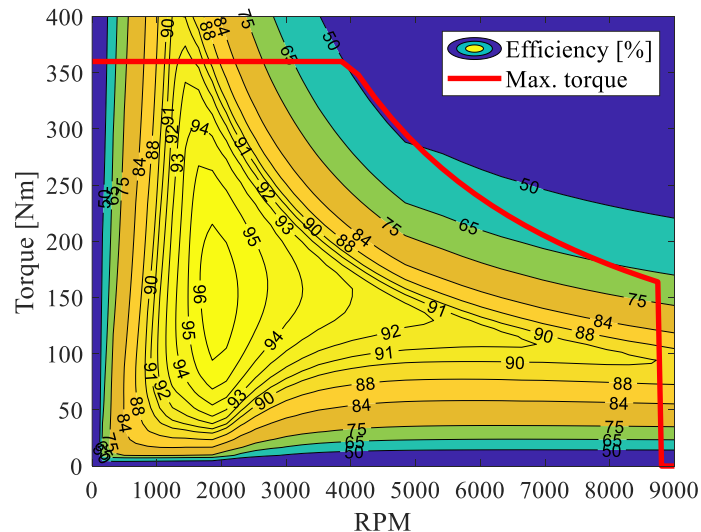
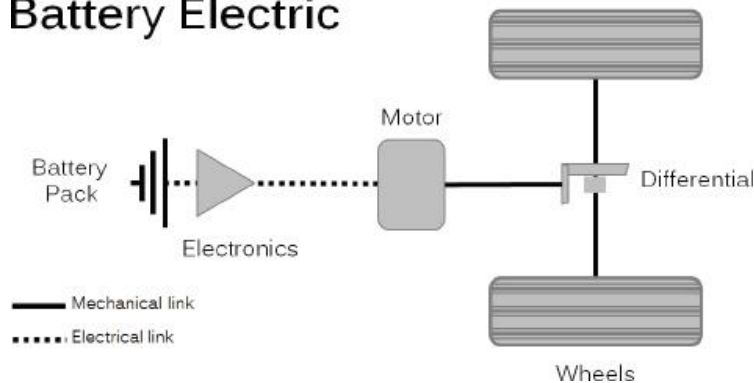


Table 2: Specification of reference vehicle.

Item	Specification	
Vehicle mass	1,625 kg	
Frontal area	2.397 m ²	
Drag coefficient	0.308	
Tire	215/50 R17	
Final gear ratio	7.050	
Motor	Maximum torque	360 Nm
	Maximum power	150 kW
	Maximum speed	8,800 RPM
Battery	Voltage	350 V
	Capacity	60 kWh

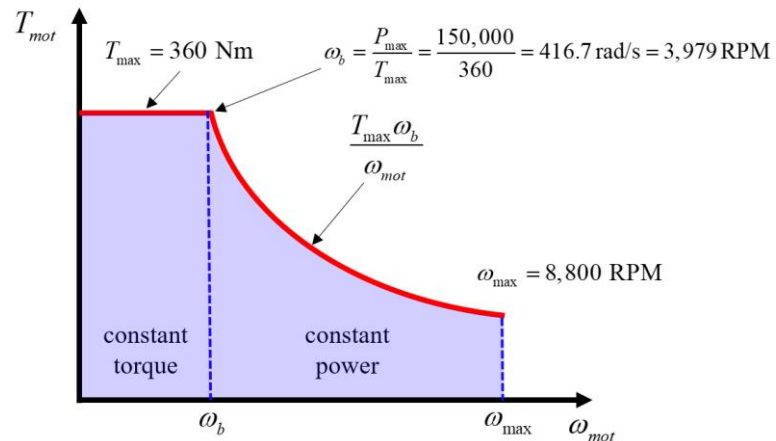
BASE BATTERY MEASUREMENTS

	Chevrolet Bolt EV	
Capacity (kWh)	60	
Output (hp)	200	
Output (lb-ft)	266	
Range (mi)	238	
Max Charging Rate	DC Fast (90 mi / 30 min)	
0-60 mph (sec)	6.5	
Top Speed (mph)	93	150 km/h
Pre-Incentive Base Price (USD)	\$37,495	

Example (2)

- Maximum motor torque curve

	Maximum torque	360 Nm
Motor	Maximum power	150 kW
	Maximum speed	8,800 RPM



- Maximum speed

$$V_{max} = \frac{\omega_{max}}{GR_h} \times R_{tire} \quad \text{Tire 215/50 R17} \longrightarrow R_{tire} = 215 \times \frac{50}{100} + \frac{17 \times 25.4}{2} = 323 \text{ mm}$$

$$V_{max} = \frac{8800}{7.05} \times \frac{\pi}{30} \times 0.323 = 42.22 \text{ m/s} = 42.22 \times \frac{3600 \text{ h}}{1000 \text{ km}} = 152 \text{ km/h}$$

- Ascendable slope

$$\theta = \sin^{-1} \left[\frac{360 \times 7.05}{1625 \times 9.81 \times 0.323} \right] = 0.515 \text{ rad} \quad \% \text{ slope} = \tan^{-1} \theta = 47.6 \%$$