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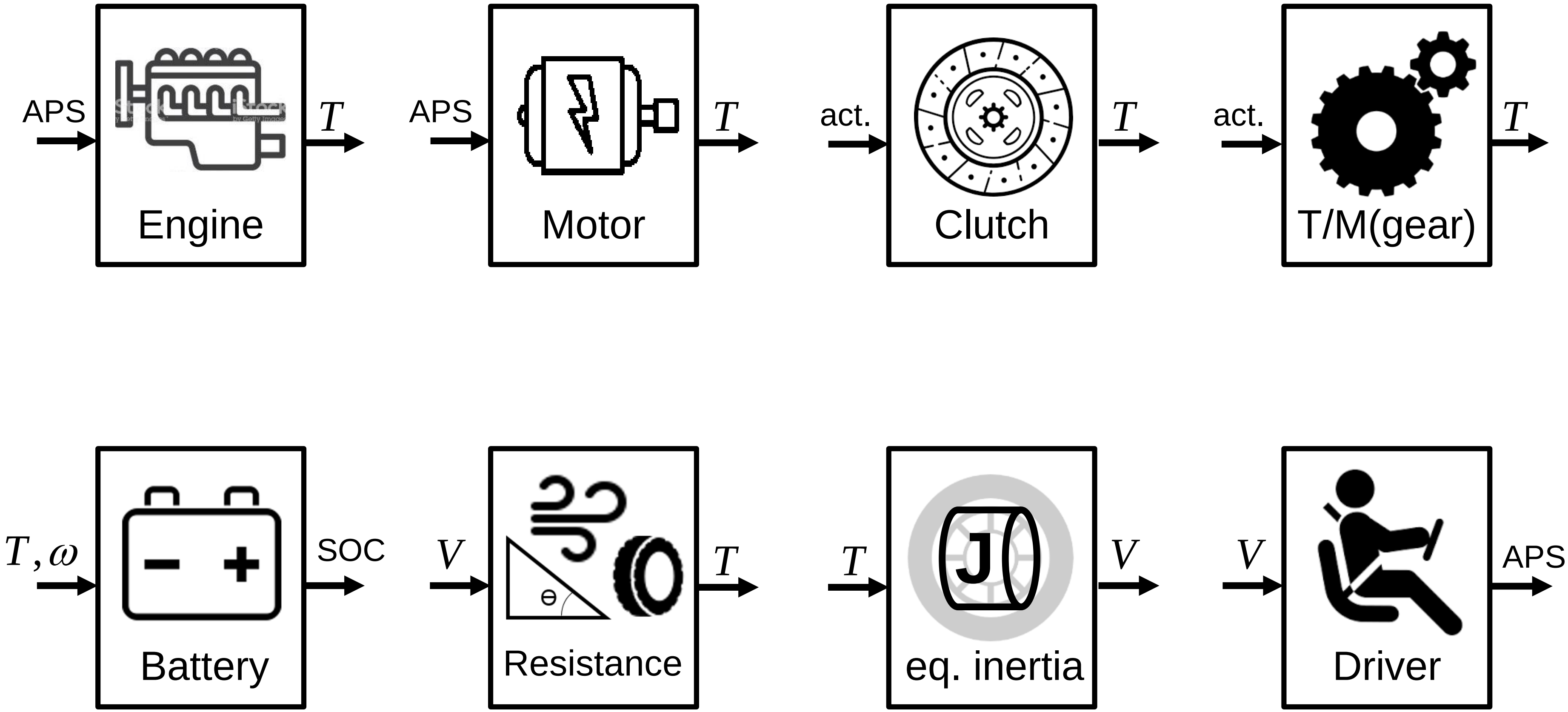
- Efficiency analysis
- Performance analysis
- Example: Chevrolet Bolt EV

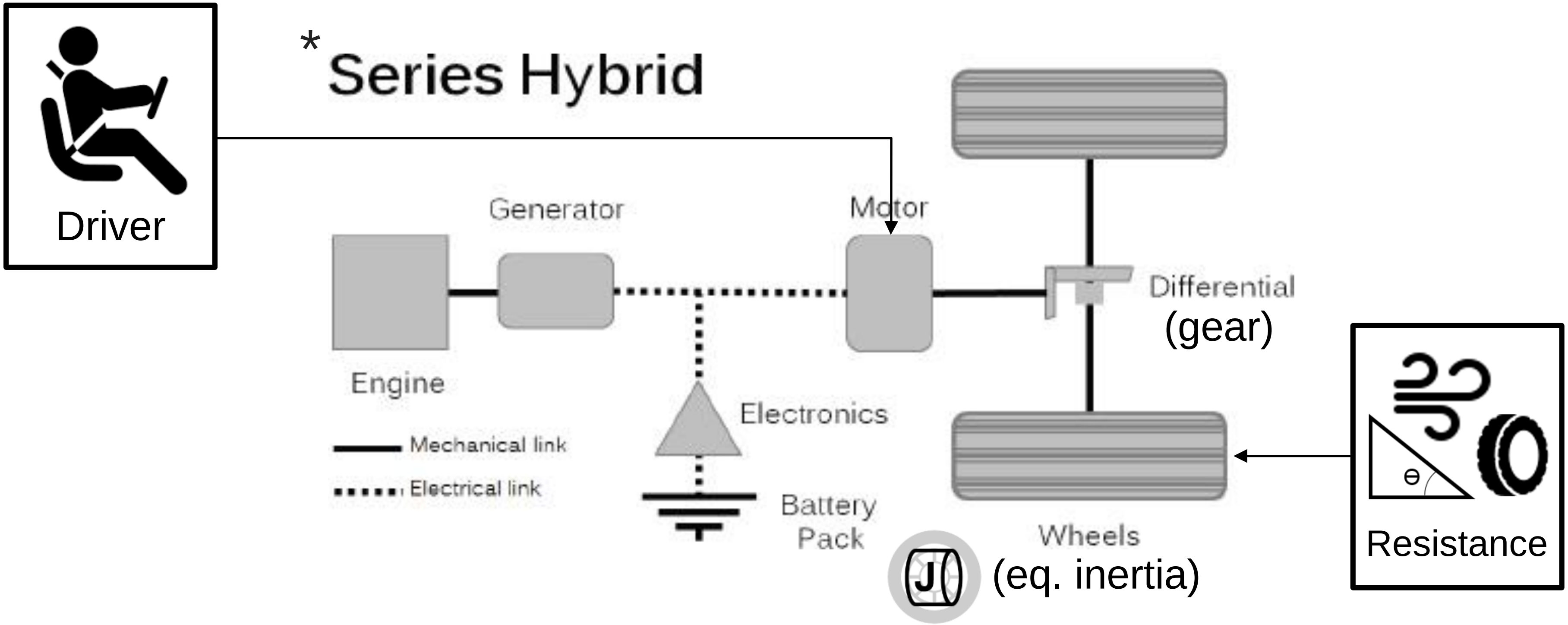
Powertrain system model

- Modeling components



Powertrain system model: HEV(1)

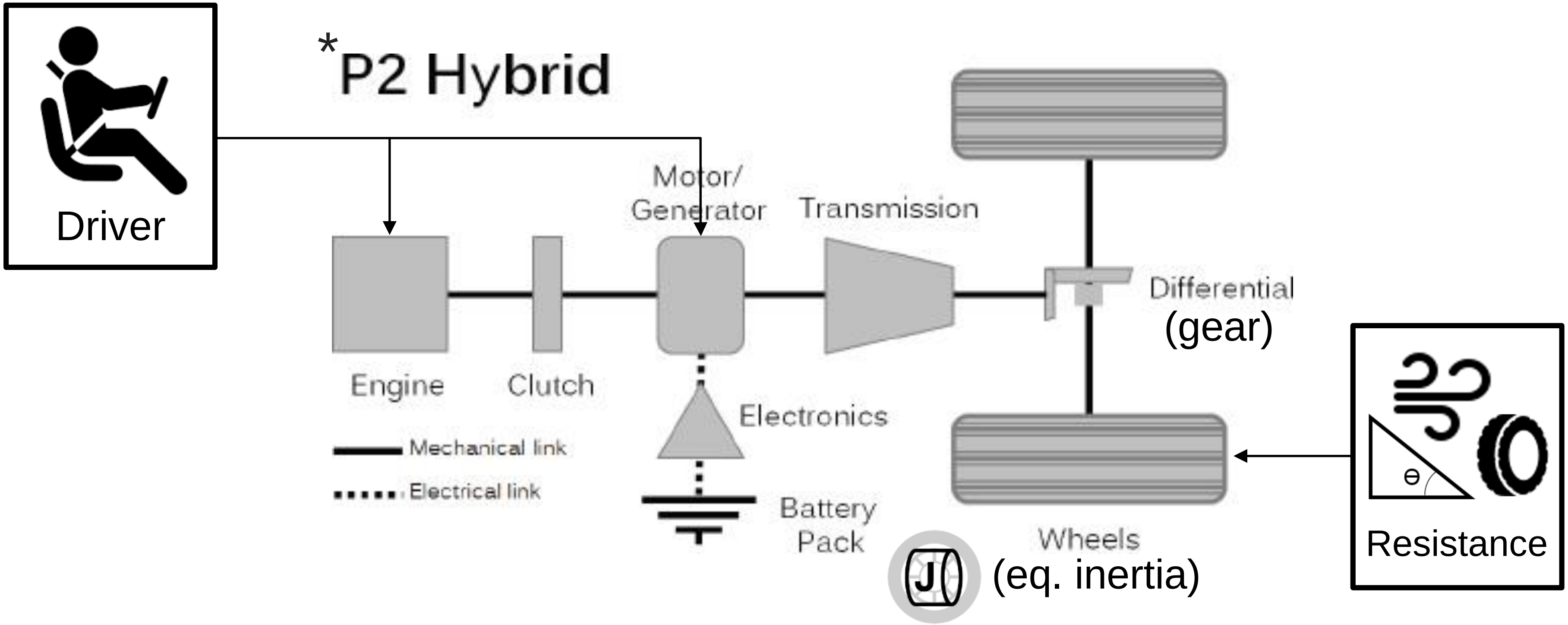
- Series HEV
  - Powertrain: Engine, Generator, Motor, Battery, Gear
  - Others: Driver, Equivalent inertia, Resistance



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

Powertrain system model: HEV(2)

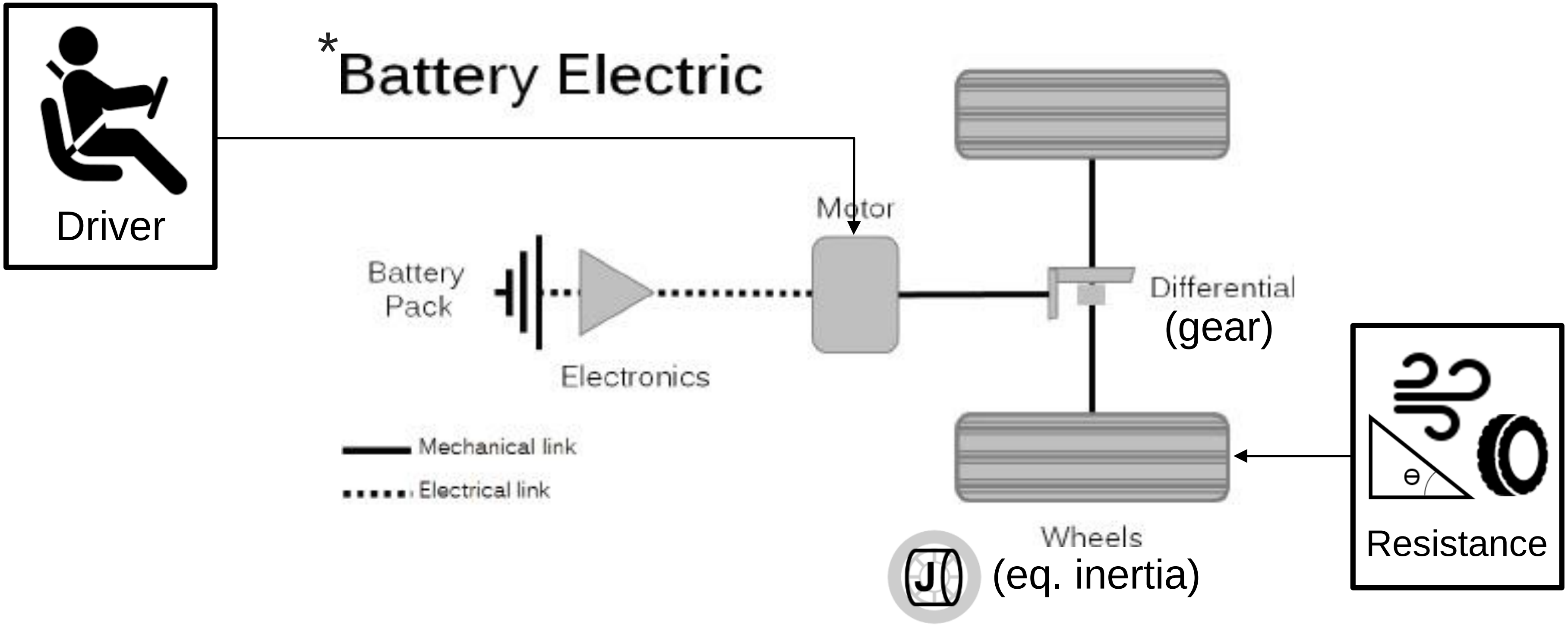
- Parallel HEV
  - Powertrain: Engine, Clutch, Motor, Battery, T/M, Gear
  - Others: Driver, Equivalent inertia, Resistance



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

Powertrain system model: EV

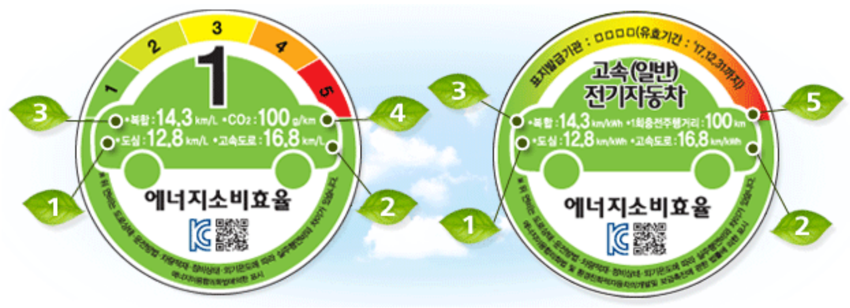
- Battery EV
  - Powertrain: Motor, Battery, Gear
  - Others: Driver, Equivalent inertia, Resistance

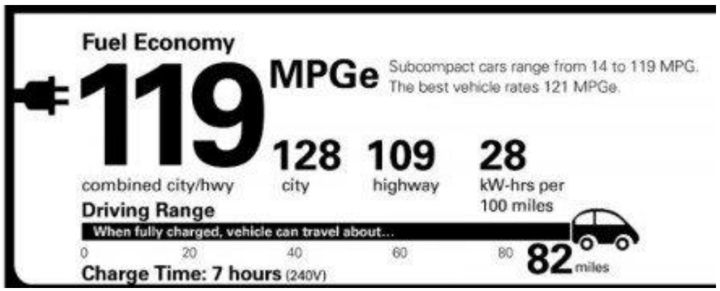


*National Research Council. *Cost, effectiveness, and deployment of fuel economy technologies for light-duty vehicles*. National Academies Press, 2015.

Efficiency analysis: Measurements

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





1) Fuel efficiency (HEV)

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

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

2) Energy efficiency (EV)

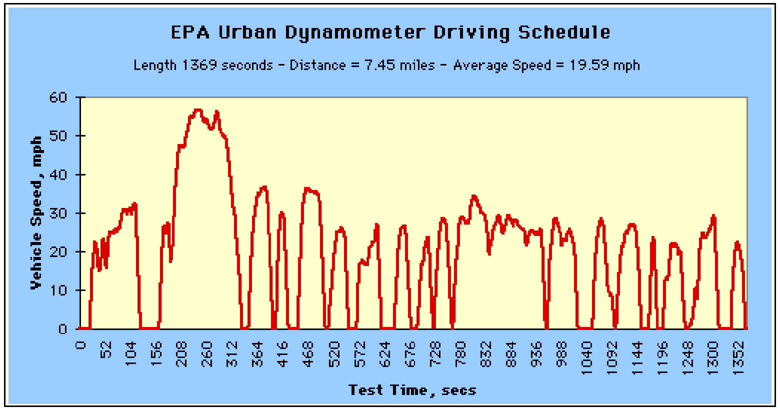
$$\text{km/kWh} = \frac{\text{Driving distance [km]}}{\text{Energy consumption [kWh]}}$$

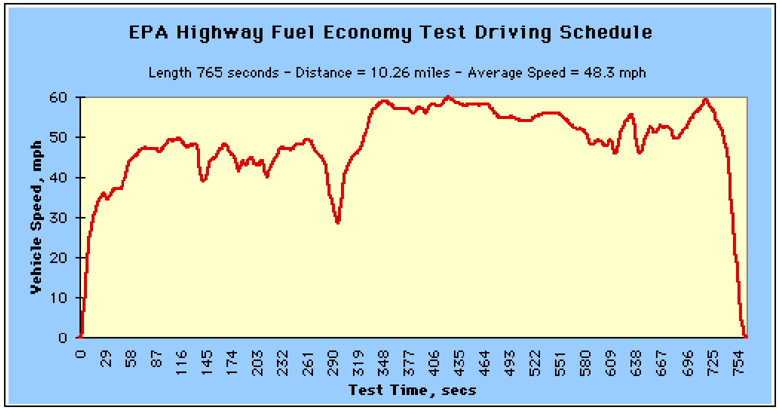
$$1\,\text{km/kWh} = \frac{\overset{\text{mile}}{\text{km}}}{1.609}\,\frac{33.705}{\underset{\text{eq. gallon}}{\text{kWh}}} = 20.95\,\text{MPGe}$$

Efficiency analysis: Driving cycles

- UDDS+HWFET(Korea, US), NEDC (Europe), WLTP

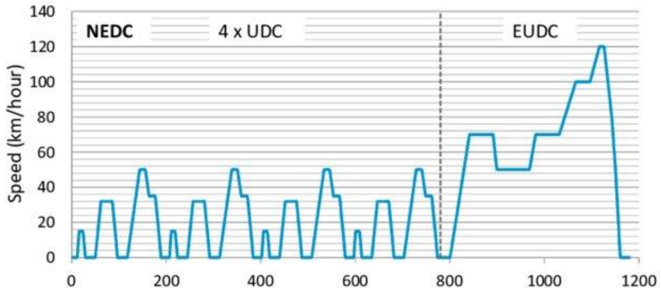
UDDS / HWFET

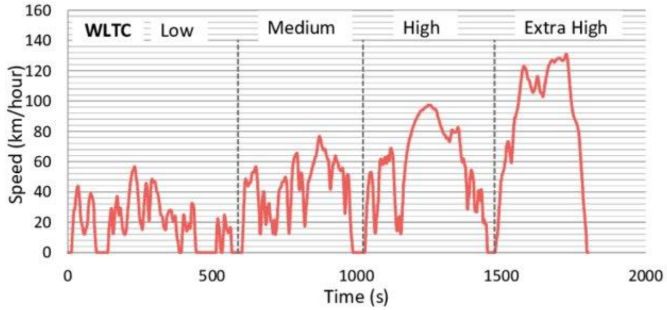




https://www.epa.gov/vehicle-and-fuel-emissions-testing/dynamometer-drive-schedules#Economic

NEDC / WLTP



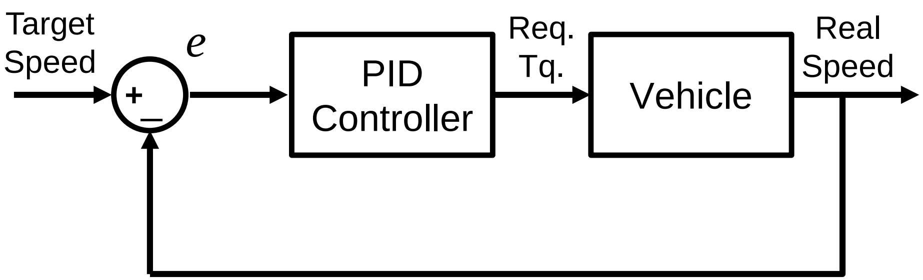


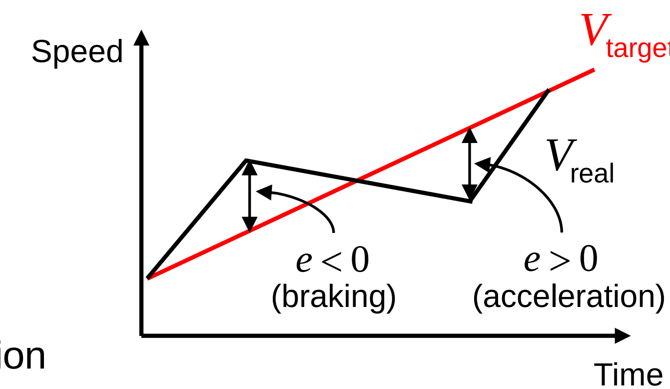
	NEDC	WLTC
Duration (s)	1180	1800
Total distance (km)	11.01	23.27
Average speed (km/h)	33.6	46.5
Maximum speed (km/h)	120	131.3
Stop duration (%)	23.73	13.00

Ref. : Georgios et al., The difference between reported and real-world CO_2 emissions: How much improvement can be expected by WLTP introduction? (2017)

Efficiency analysis: Speed control

- Concept for tracking vehicle speed of driving cycle





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

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

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

C_{brk} : Brake capacity [Nm]

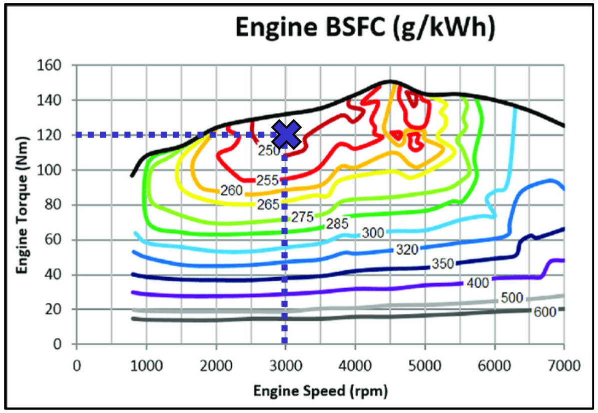
$T_{\max}$: Maximum torque of engine/motor [Nm]

Example

Target speed = 30 km/h, Real speed = 28 km/h
Proportional gain = 100
Request torque of driver?

Efficiency analysis: Engine

- Efficiency map
  - 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

$$\underbrace{\frac{250\,\mathrm{g}}{\mathrm{kWh}}}_{\text{BSFC}} \times \underbrace{\frac{120\times 3000}{1000}\frac{\pi}{30}}_{\text{Engine power [kW]}} \times \frac{1\,\mathrm{h}}{3600\,\mathrm{s}} \times \underbrace{\frac{1\,\mathrm{L}}{860\,\mathrm{g}}}_{\text{Fuel density}} = 0.003\ \mathrm{L/s}$$

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

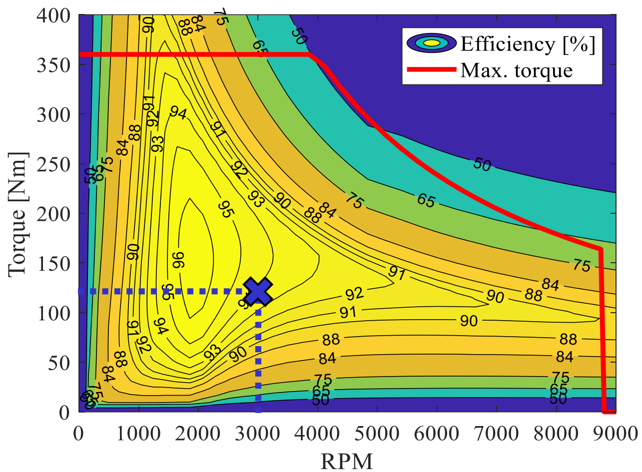
Driving distance: $\int_0^{5\ \mathrm{min}} V\ dt = \int_0^{5\ \mathrm{min}} \frac{\omega}{GR} R_{tire}\ dt = \left(\frac{3000}{4}\frac{\pi}{30}\times 0.3\right)\times 300\,\mathrm{s} = 7{,}068\,\mathrm{m}$

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

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

Efficiency analysis: Motor

- Efficiency map
  - Electric efficiency



Example

Motor: torque = 120 Nm, RPM = 3000
Battery: voltage = 350 V, capacity = 60 kWh
SOC consumption per second? (%/s)

Motor efficiency = 94%

$$\underbrace{120 \times 3000 \frac{\pi}{30}}_{\text{Motor power}} = \underbrace{0.94}_{\text{Eff.}} \times \underbrace{350}_{\text{Voltage}} \times I \qquad I = 114.59\,\mathrm{A}$$

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

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

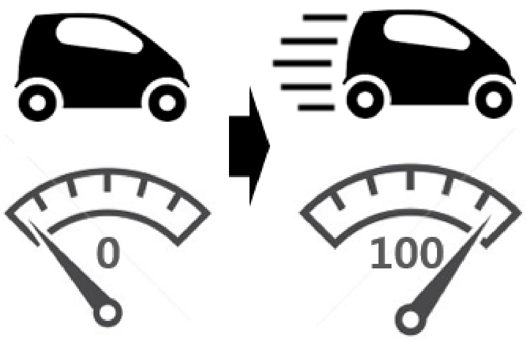
Energy consumption: $\Delta SOC = \int_0^{5\text{ min}} -0.019\ \%/\mathrm{s}\ dt = 300\ \mathrm{s} \times 0.019\,\%/\mathrm{s} = -5.7\ \%$

$$60\,\mathrm{kWh} \times 5.7\% = 3.42\,\mathrm{kWh}$$

Energy efficiency: $\dfrac{7.068\,\mathrm{km}}{3.42\,\mathrm{kWh}} = 2.07\ \mathrm{km/kWh}$

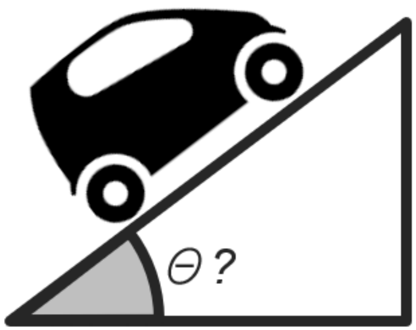
Performance analysis: Measurements

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



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

$$V = \text{maximum}$$



$$V > 0$$

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

Driving torque at wheel

Resistance torque at wheel

Performance analysis: Acceleration time

- Calculation

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

Parallel HEV

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

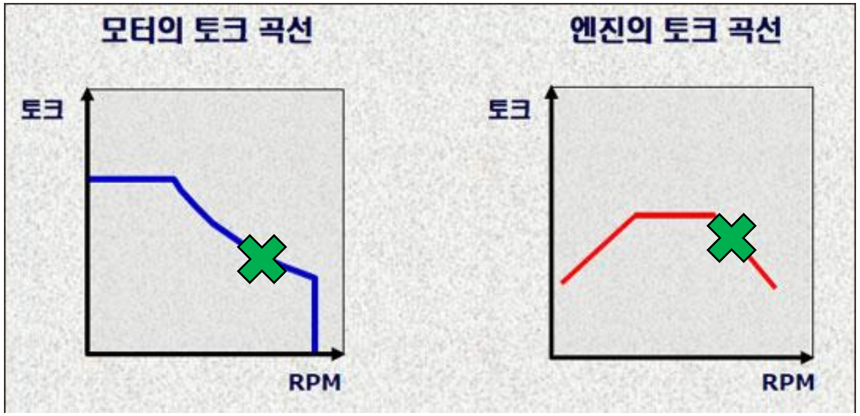
$$T_{drv} = (T_{eng}(t) + T_{mot}(t)) \times GR(t)$$

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: Maximum speed

- Calculation

Constant

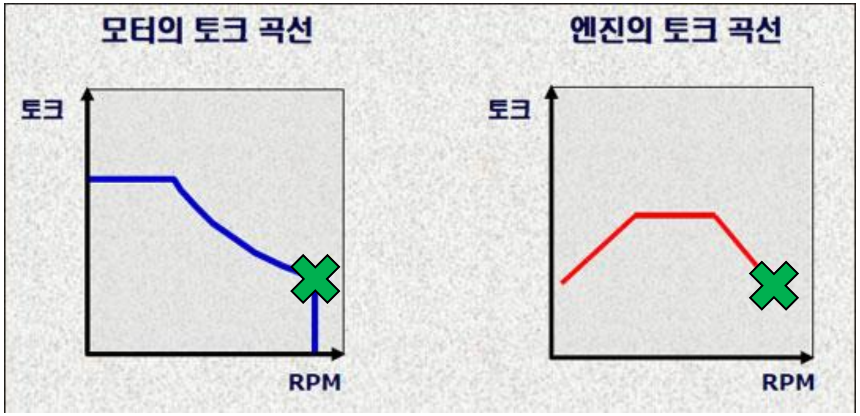
$$V_{\max} = \int \frac{(T_{drv} - T_{res})}{J_{eq}} dt \times R_{tire} = \frac{R_{tire}}{J_{eq}} (T_{drv}(V_{\max}) - T_{res}(V_{\max})) > 0$$

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

$$V_{\max} = \frac{\omega_{\max}}{GR_h} \times R_{tire}$$

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: Ascendable slope

- Calculation

Constant

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

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

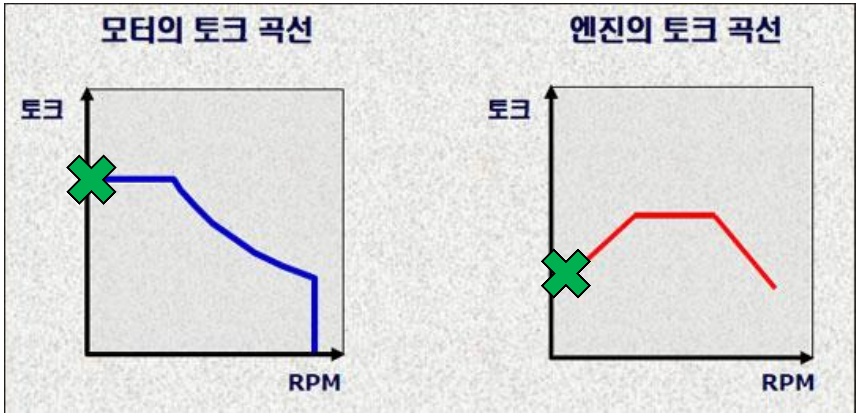
$$T_{drv}=(T_{eng}(0)+T_{mot}(0))\times GR_l$$

GR is maximum ratio at lowest speed (1st speed)

$$T_{res}=\left(\mu_r m_b g\cos\theta+m_b g\sin\theta\right)\times R_{tire}\approx m_b g\sin\theta\times R_{tire}$$

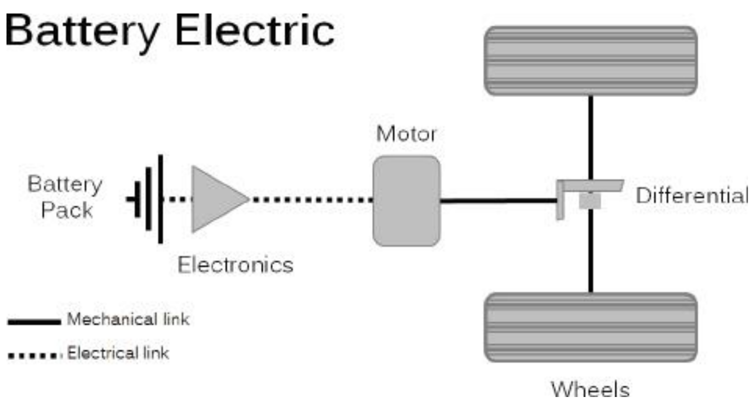
(if theta is large value)

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



Example (1)

- 2017 Chevrolet Bolt EV



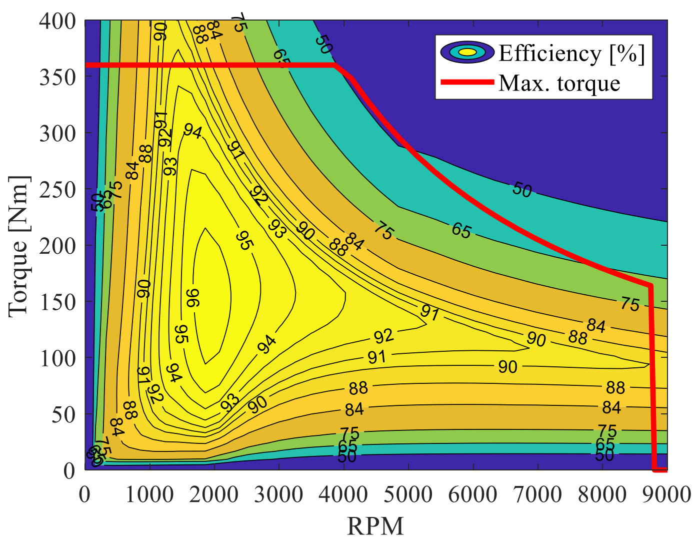


Table 2: Specification of reference vehicle.

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

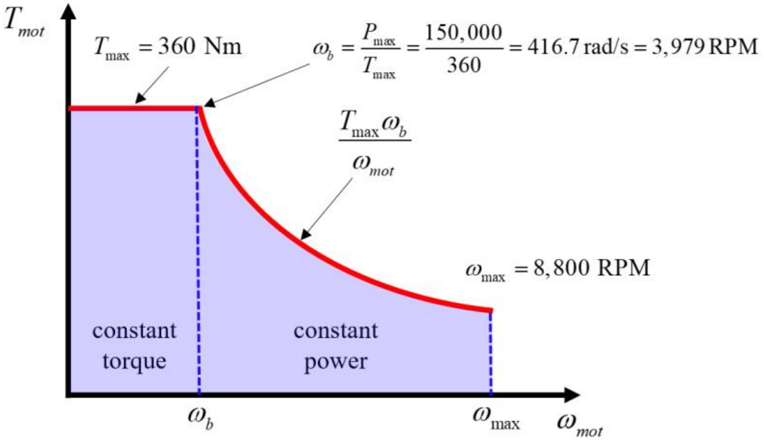
BASE BATTERY MEASUREMENTS

	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

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



- Maximum speed

$$V_{\max} = \frac{\omega_{\max}}{GR_h} \times R_{tire}$$

Tire 215/50 R17 ⟶ $R_{tire} = 215 \times \frac{50}{100} + \frac{17 \times 25.4}{2} = 323$ 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

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

$$\% \text{ slope} = \tan\theta = 56.6 \%$$