METU EE7566
Electric Drives in Electric and Hybrid Electric Vehicles

Emine Bostancı

Office: C-107

Content

Regenerative braking

Overview - components in passenger cars

Overview - power conversion devices

Hybrid Functions Overview

Start-Stop system automatically shuts down and restarts the internal combustion engine to reduce the amount of time the engine spends idling in order to reducing fuel consumption and emissions.

Regenerative braking is the energy recovery mechanism that is applied to convert the kinetic energy into a form that can be stored or used for another purpose.

Propulsion assist means that electric motor assists internal combustion engine when extra power is required.

In **pure electric drive**, electric motor propels the vehicle, which is applied at low speeds due to low efficiency of internal combustion engine.

	Start-stop	Regenerative braking	Propulsion assist	Pure electric drive
Micro	✓	✓		
Mild	✓	✓	✓	
Full	✓	✓	✓	✓

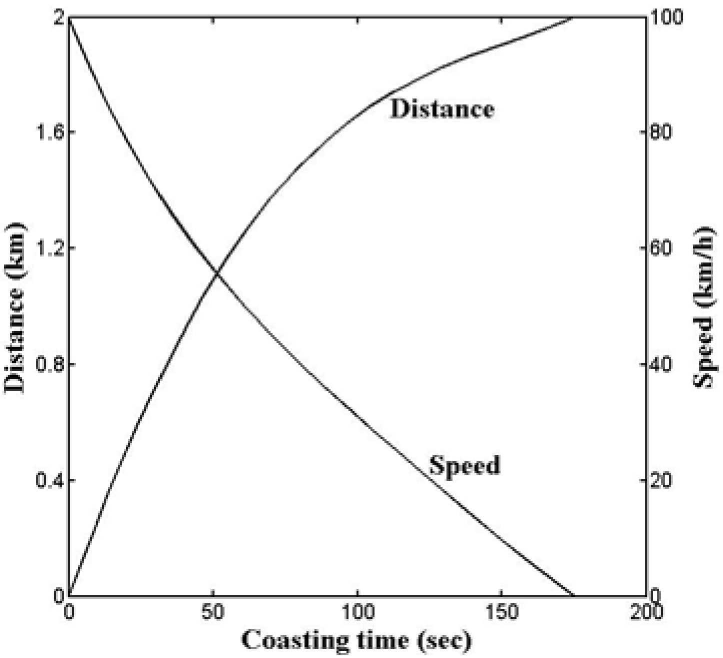
Hybrid Functions - Regenerative Braking

Requirements on brake system:

- Emergency braking: bring the vehicle in rest in the shortest possible distance
- Vehicle's direction must be controllable, steerable

Regenerative braking is limited by the followings:

- Braking power (force) on driven wheels
- Maximum power of the electric machine at low speeds
- Maximum charging power of the battery
- State of charge (SOC) of the battery

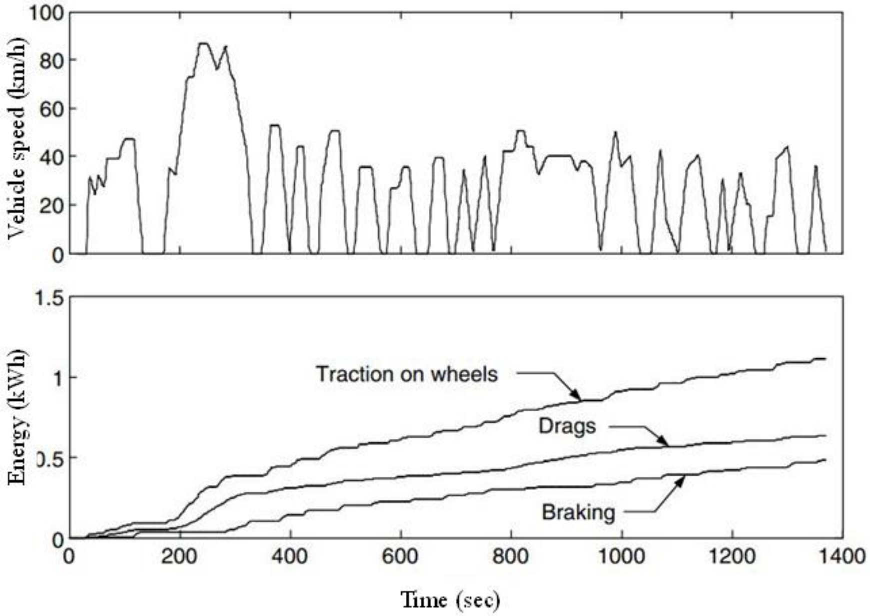


Equivalent cruising distance of a 1500 kg vehicle at 100 km/h with no breaking (0.16 kWh)

➢ **In electrified vehicles both of electrical and mechanical braking are implemented.**

Hybrid Functions - Regenerative Braking

Total traction energy and energies consumed by drags and braking in an FTP 75 urban drive cycle



Example:
1500 kg vehicle
FTP 75 urban drive cycle
$L = 2.7$ m, $L_a = 0.4$ L, $L_b = 0.6$ L, $h_g = 0.55$ m

	FTP 75 Urban	FTP 75 Highway	New York City
Maximum speed (km/h)	86.4	97.7	44.6
Average speed (km/h)	27.9	79.3	12.2
Total traction energy[a] (kWh)	10.47	10.45	15.51
Total energy consumed by drags[a] (kWh)	5.95	9.47	4.69
Total energy consumed by braking[a] (kWh)	4.52	0.98	10.82
Percentage of braking energy to total traction energy (%)	43.17	9.38	69.76

Maximum Speed, Average Speed, Total Traction Energy, and Energies Consumed by Drags and Braking per 100 km Traveling Distance in Different Drive Cycles measured on Driven Wheels for a 1500 kg vehicle

- **There is high potential for energy recovery especially in city driving.**

Hybrid Functions - Regenerative Braking

Load Transfer during Braking

$$W_f = \frac{\mathbf{1}}{\boldsymbol{L}}\left\{L_b M_v g cos(\alpha) - \boldsymbol{h_g}\left(F_g + \boldsymbol{M_v}\frac{\boldsymbol{dv}}{\boldsymbol{dt}}\right) - h_w F_w\right\}$$

$$W_r = \frac{\mathbf{1}}{\boldsymbol{L}}\left\{L_a M_v g cos(\alpha) + \boldsymbol{h_g}\left(F_g + \boldsymbol{M_v}\frac{\boldsymbol{dv}}{\boldsymbol{dt}}\right) + h_w F_w\right\}$$

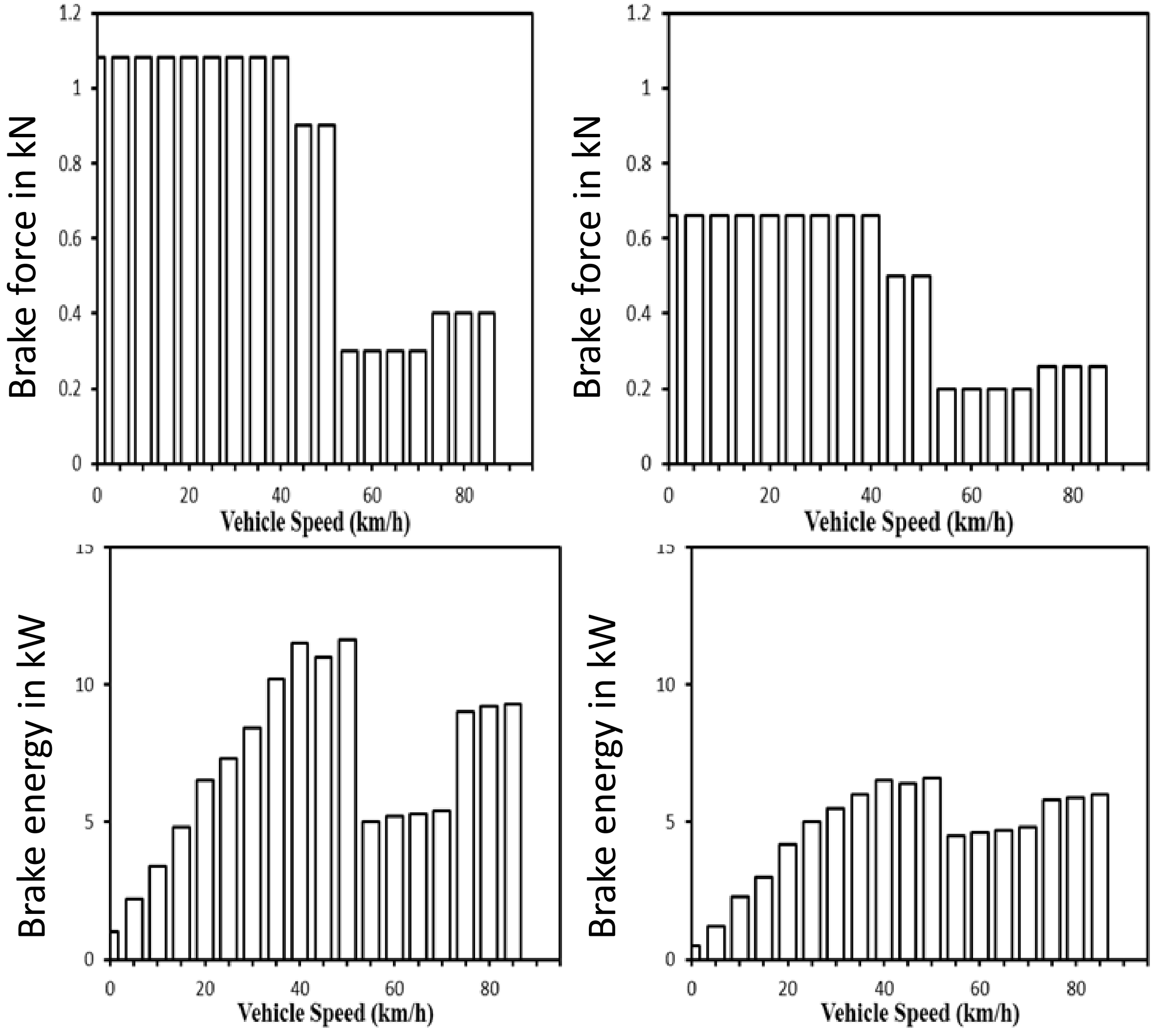
Braking forces on front and rear tires during deceleration j>0 (without vehicle drags):

$$F_{bf} = \frac{M_v g}{L} h_g \left\{\frac{j}{g}\right\} \qquad F_{br} = \frac{M_v g}{L} h_g \left\{-\frac{j}{g}\right\}$$

Deceleration in m/s²

- The front wheels consume about 65% of the total braking power and energy.
- Regenerative braking on front wheels, if available only on one axle, is more effective than on rear wheels.
- Most braking energy is consumed in the speed range of 10 to 50 km/h.

Hybrid Functions - Regenerative Braking



Front wheels

Rear wheels

Example: 1500 kg vehicle
FTP 75 urban drive cycle
$L = 2.7$ m, $L_a = 0.4$ L
$L_b = 0.6$ L, $h_g = 0.55$ m

Hybrid Functions - Regenerative Braking

Regenerative Braking in EVs and HEVs

Design questions:

- Distribution of the total braking forces required between the regenerative brake and the mechanical friction brake
- Distribution of the total braking forces on the front and rear axles so as to achieve a steady-state braking

Brake System of EVs and HEVs:

- Series Brake — Optimal Feel
- Series Brake — Optimal Energy Recovery
- Parallel Brake

Braking torque

$$F_b = \frac{T_b}{r_d}$$

Braking force

Adhesive coef. of tire-ground contact

$$F_{bmax} = \mu W$$

Max. braking force

Vehicle road speed km/h	Tire condition	Dry road	Wet road (depth of water 0.2 mm)	Heavy rain (depth of water 1 mm)	Puddles (depth of water 2 mm)	Icy (black ice)
50	new	0.85	0.65	0.55	0.5	0.1 and below
	worn out	1	0.5	0.4	0.25	
90	new	0.8	0.6	0.3	0.05	
	worn out	0.95	0.2	0.1	0.0	
130	new	0.75	0.55	0.2	0	
	worn out	0.9	0.2	0.1	0	

Anti-lock Brake System ABS video:
https://www.youtube.com/watch?v=hwwXukJaTlM

Hybrid Functions - Regenerative Braking

Series Brake — Optimal Feel

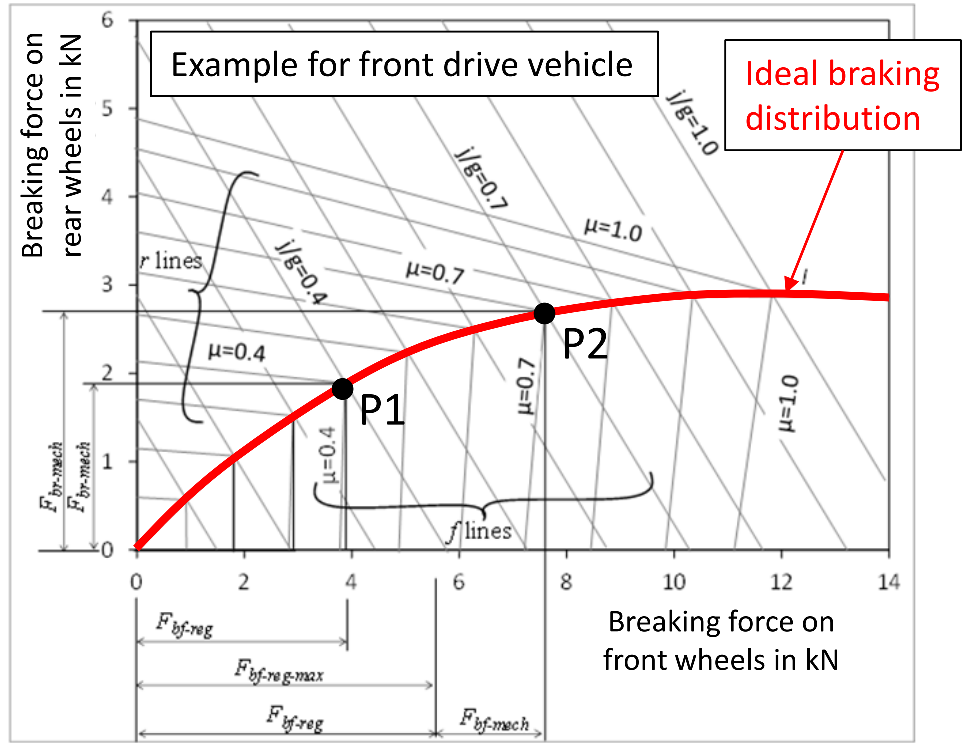
<u>Objectives:</u>

- Minimize stopping distance
- Optimize driver’s brake feeling – optimum distribution of the braking forces among front and rear wheels

<u>Application:</u>

- Only regenerative braking up to decelerations of 0.2g on driven wheels (same as engine slow down when gas pedal is not used)
- During higher decelerations, braking forces on the front and rear wheels follow the ideal F_b distribution and braking force on the driven wheels is divided into:
  - Regenerative braking force, $F_{bf\text{-}reg}$ (applied first)
  - Mechanical braking force, $F_{bf\text{-}mech}$

Front wheels



P1 → j/g=0.4

P2 → j/g=0.7

Hybrid Functions - Regenerative Braking

Series Brake — Optimal Energy Recovery

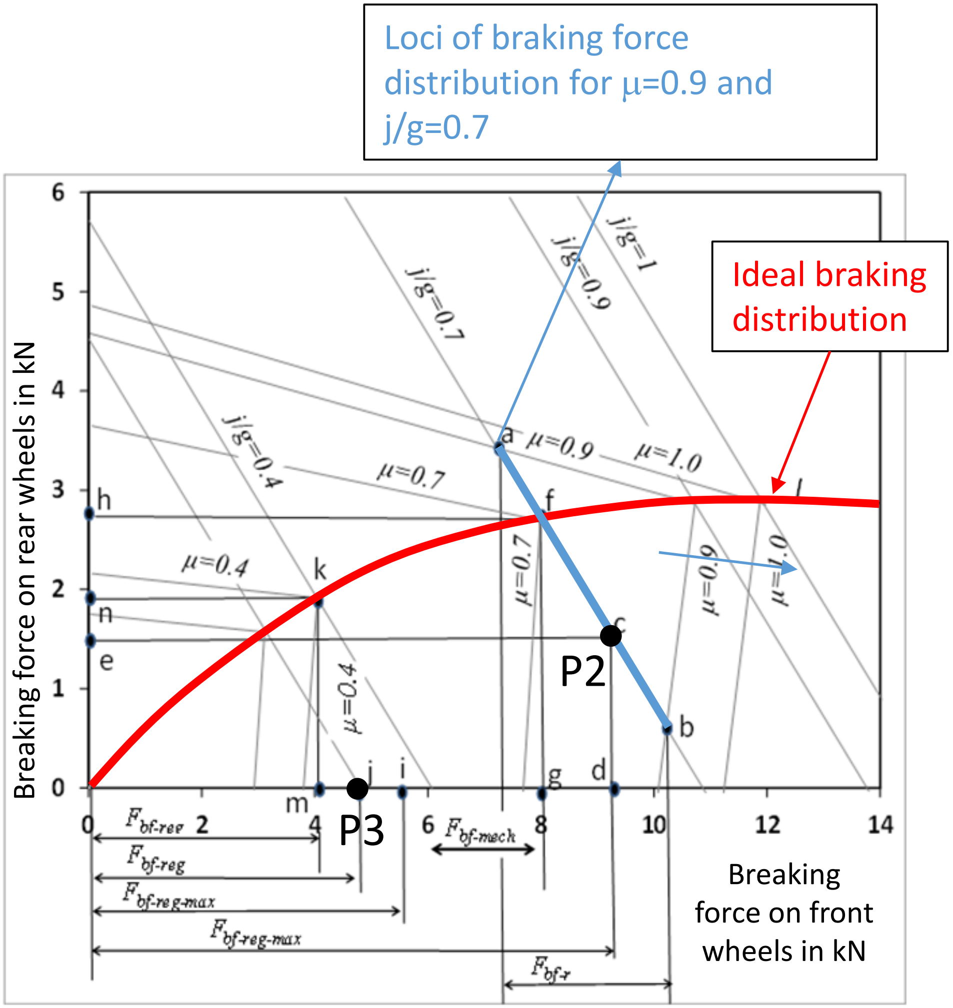
Objectives:

- Minimize stopping distance
- Recover braking energy as much as possible

Application:

Keep F_{bf}+F_{br}=F_b and maximize the share of regenerative on driven wheels.

- If j/g > μ line, this rate can not be reached, maximum forces are on the ideal curve.
- If j/g = μ line, the distribution must be on the ideal curve.
- If j/g <μ line, we can vary the distribution on front and rear wheels.
  Example for μ=0.9 and j/g=0.7 (P2):
  Total braking force: F_b= g + h (optimum point is f)
  We are free to chose a distribution corresponding to a-f-c-b line
  If $F_{bf\text{-}reg\text{-}max}$ = d, we need to chose operate at point c, F_b= d + e
- If j/g <<μ, we can only use only regenerative braking on driven wheels.
  Example for μ=0.9 and j/g=0.3 (P3):
  If $F_{bf\text{-}reg\text{-}max}$ = d, we chose to operate at point j, F_b= j



Hybrid Functions - Regenerative Braking

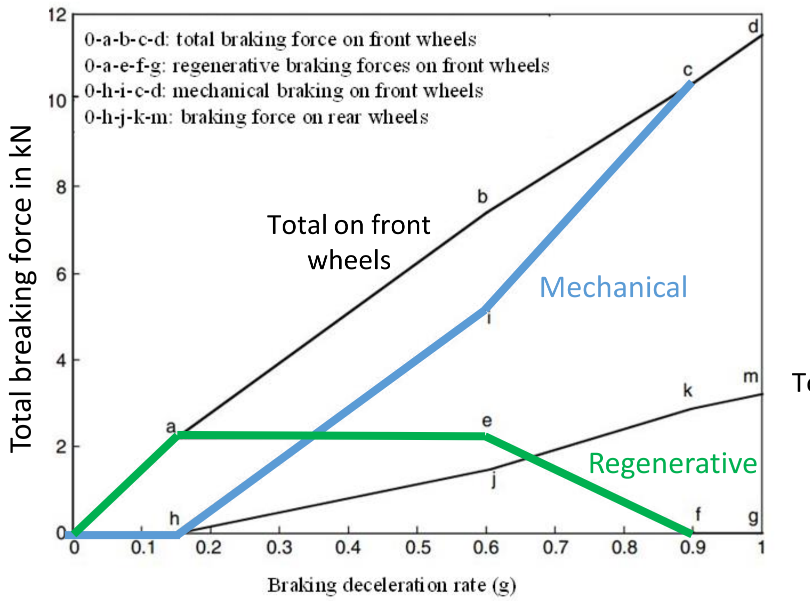
Parallel Brake

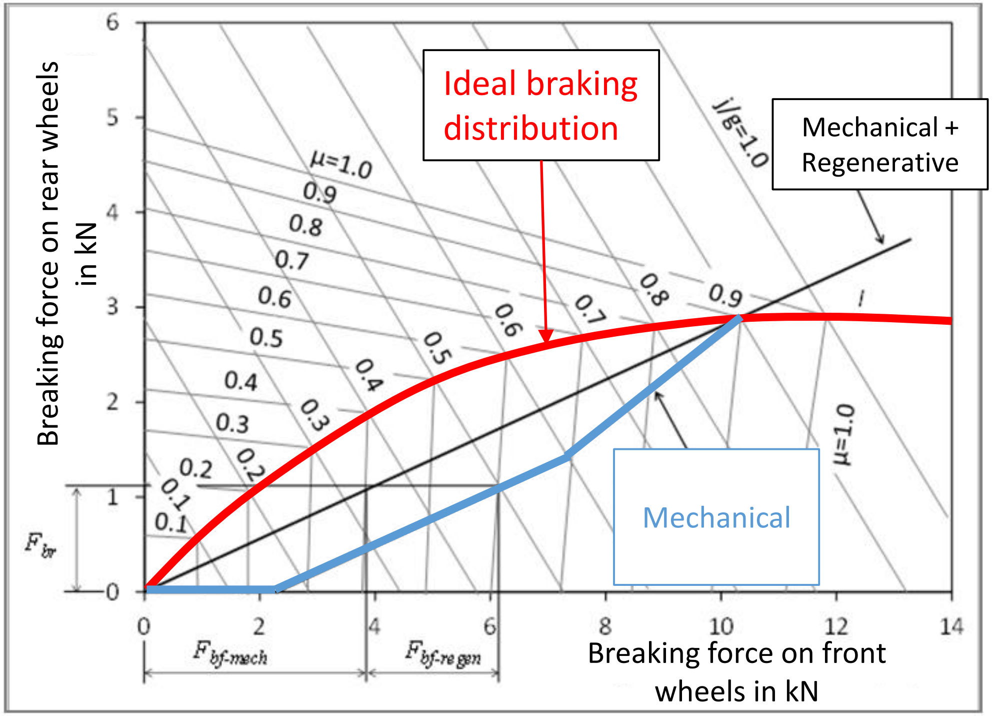
Objectives:

- Determine the regenerative and mechanical braking forces as a function of deceleration rate j/g
- No need for an electrical control

Application:

Keep F_{bf} and F_{br} as a function of j/g





Overview - Components in Passenger Cars

Drivetrain Components:

Energy storage

- Physical (container: tank)
- Mechanical
- Chemical
- Electrical

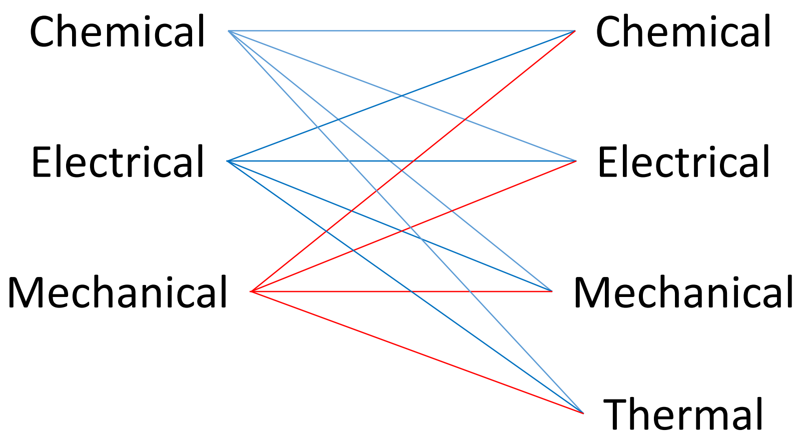
Power conversion

- Chemical to chemical
- Chemical to mechanical
- Chemical to electrical
- Mechanical to chemical
- Mechanical to mechanical
- Mechanical to electrical
- Electrical to chemical
- Electrical to electrical
- Electrical to mechanical

Intermediate and byproducts:
Thermal power
Electromagnetic power

- Accessories

Overview - Power Conversion Devices



Driver

Electric generator

Fuel cell

Internal combustion engine

Transmission (gear box)

Inverter

Electrolyzer

Rectifier

Wheels

Hydro motors

Differential

Electric motor

Solar Photovoltaics

Converter

Hydrogen reformers

Supercapacitor

Piezoelectric

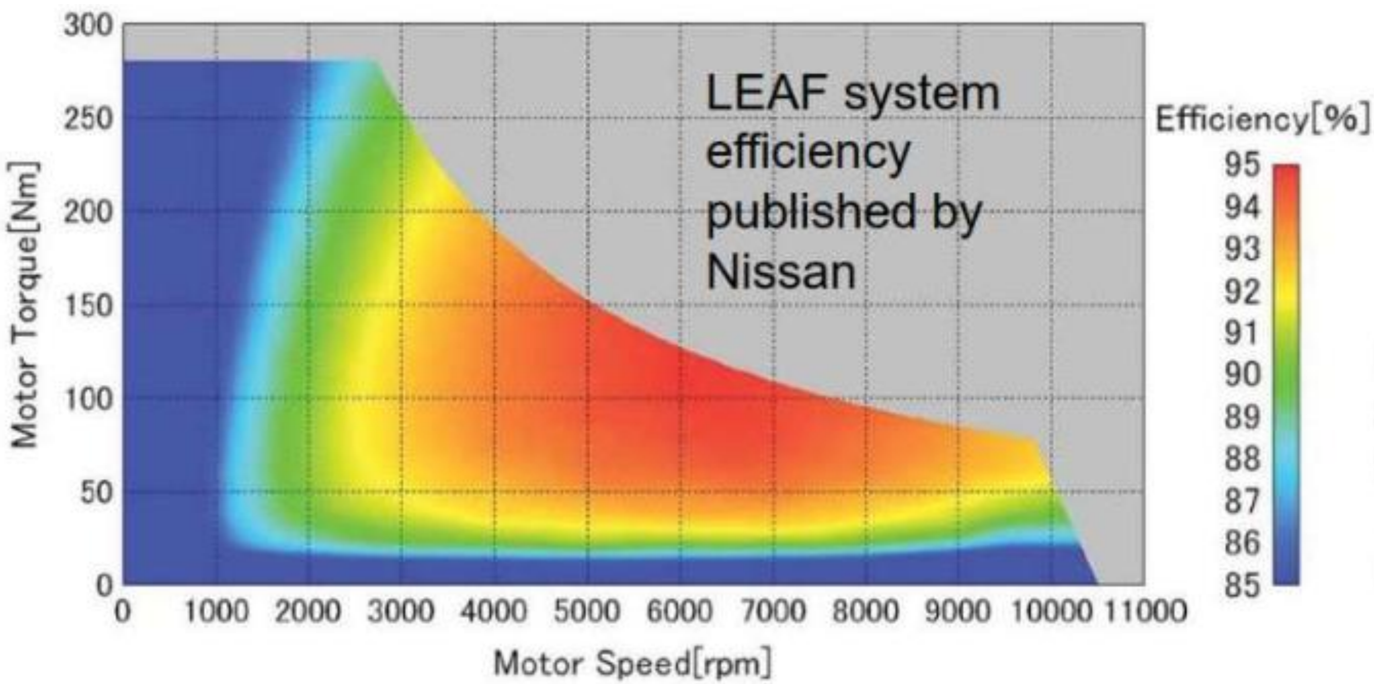
Power unit of battery

Power unit of flywheel

Acceleration Time Calculation

Limitations to be considered:

- Maximum torque that can be delivered by electric machine
- Maximum force that can be applied to the tire-ground surface



Videos

ABS, EBD, BA (Automatic Braking System, Electronic Brake Distribution, Brake Assist)

Why Brake-By-Wire Is Coming To Your Car

Formula 1'i tanıyalım: Frenler

Advertisement of the week:

BMW M5 - Motor Sport 5 Series

Textbooks:

Ehsani, M. and Gao, Y. and Emadi, A., “Modern Electric, Hybrid Electric, and Fuel Cell Vehicles: Fundamentals, Theory, and Design”, 2nd Edition, CRC Press LLC, 2009.

Chau, K. T., “Electric Vehicle Machines and Drives: Design, Analysis and Application” Wiley-IEEE Press, August 2015.