MECA0527: SERIES HYBRID VEHICLES. DESIGN AND CONTROL

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References

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Outline

- Introduction
- Operation pattern
- Control strategies
- Sizing of major components
- Design examples

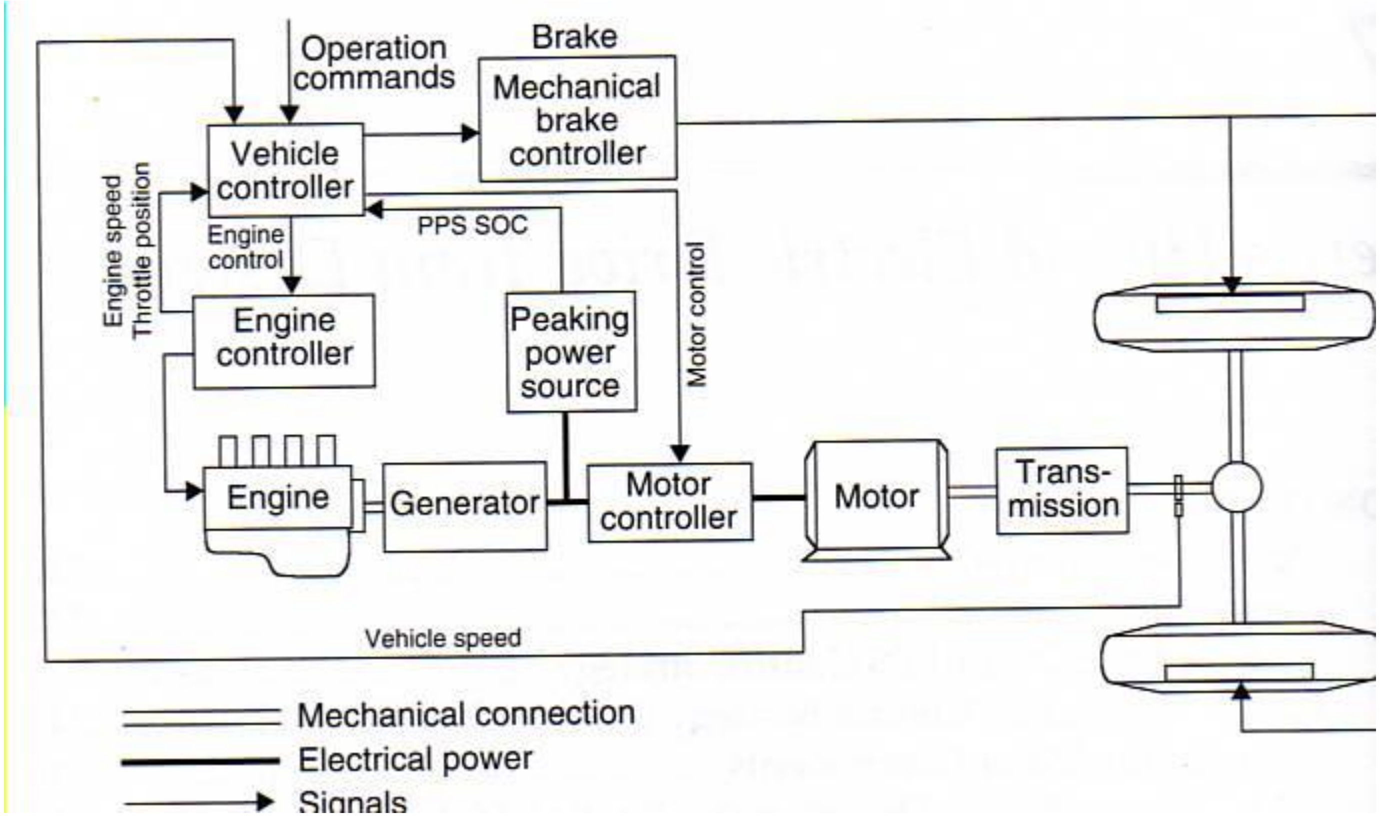
INTRODUCTION

Introduction

- Advantages of electric vehicles vs Internal Combustion Engines
  - Zero emission mode in city driving
  - Multiple sources of energy
  - Higher efficiency
- Disadvantages of present technologies
  - Limited drive range due to shortage of energy storage of in-board batteries
  - Limited payload and volume capacity due to heavy and bulky batteries
  - Longer battery charging time

- Initial objective of series hybrid vehicles: to extend the drive range by adding an engine / generator to charge the batteries on board

Introduction



Typical series hybrid electric drive train (Ehsani et al. 2005)

Introduction

- Series hybrid vehicles are propelled solely by their electric traction motor
- Traction motor is powered by
  - Battery pack
  - Engine / generator unit
- Engine / generator
  - Helps to power the traction motor when the power demand is large
  - Charges the batteries when the load power is small
- Motor controller
  - Control the traction motor to produce the power required by the vehicle motion

Introduction

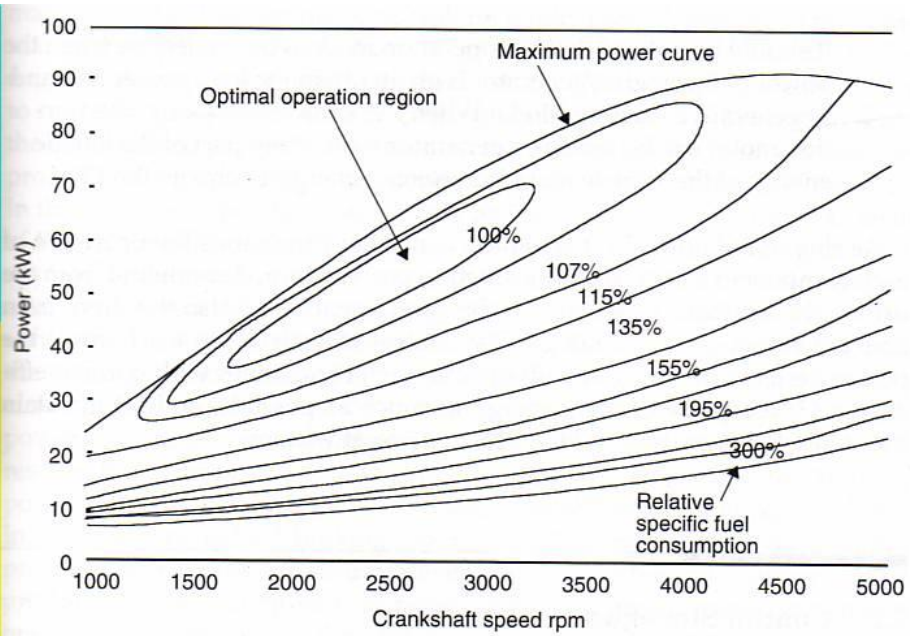
- Vehicle performance (acceleration, gradeability, max speed) is completely determined by the size and characteristics of traction e-motor
- Sizing of the e-motor and gears of transmission follows the same principles as pure electric vehicles
- Drive train control is different from pure electric vehicles because of the additional engine / generator
- Batteries
  - Act essentially as a peak power source (PPS)
  - Can be replaced in some cases by ultra capacitors of flywheels

Introduction

- Objective of this lesson:
  - Design of engine / generator system
  - Operation control and strategy
  - Battery (PPS) sizing

OPERATION PATTERNS

Operation patterns



- Engine is mechanically decoupled from driven wheels
  - Speed and torque of engine are independent from vehicle speed and torque traction demand
  - Can be controlled independently at any operating point on speed torque mapping
  - In particular control to operate at the optimal generation performance (minimum of fuel consumption and emissions)
  - Optimal regime is realizable but depends on operating modes and control strategies of drivetrain

Operation patterns

- Selection of several operating modes accordingly to driving conditions and the driver's command

1/ Hybrid traction mode

2/ Peak power source alone traction mode

3/ Engine / generator alone traction mode

4/ PPS charging from engine / generator

5/ Regenerative braking mode

Operation patterns

<u>1/ Hybrid traction mode</u>

- When a large of amount of power is demanded (e.g. acceleration pedal is deeply depressed)
- Both engine / generator and batteries have to supply the power to the electric motor drive
- Engine operates in its best operational region for efficiency and emissions
- PPS supplies the additional power to meet the demand

$$P_{\mathrm{demand}} = P_{\mathrm{e/g}} + P_{\mathrm{PPS}}$$

Operation patterns

2/ Peak power source alone traction mode

- Operating mode in which PPS alone supplies its power to the meet power demand

$$P_{\mathrm{demand}} = P_{\mathrm{PPS}}$$
$$P_{\mathrm{e/g}} = 0$$

3/ Engine / generator alone traction mode

- Engine / generator alone supplies power to meet the power demand

$$P_{\mathrm{demand}} = P_{\mathrm{e/g}}$$
$$P_{\mathrm{PPS}} = 0$$

Operation patterns

4/ PPS charging from engine / generator

- When energy of PPS is too low, PPS has to be charged using regenerative braking or by using the engine / generator
- Regenerative braking is generally too small or insufficient and the engine / generator power is split in two parts: car propulsion and charge of PPS

$$P_{\mathrm{demand}} = P_{\mathrm{e/g}} - P_{\mathrm{PPS}}$$

- This mode is only possible if

$$P_{\mathrm{e/g}} \geq P_{\mathrm{demand}}$$

Operation patterns

<u>5/ Regenerative braking mode</u>

- When vehicle is braking, the traction motor can be used as a generator, regenerative braking converts the kinetic energy into an energy charge of batteries

$$P_{\text{PPS}} = -P_{\text{Braking}}$$

Operation patterns

- Vehicle controller commands the operation of each component according to
  - The traction power and torque demand based on driver request
  - The feedback information from components and drivetrain
  - Preset control strategies

- Objectives of controller:
  1. Meet power demand from driver
  2. Operate components in their optimal efficiency
  3. Recapture the maximum braking energy
  4. Maintain the state of charge (SOC) of batteries in a preset window

CONTROL STRATEGIES

Control strategies

- Control rules are programmed in the hybrid management system (HMS) (vehicle controller) and commands the operation of each component
- Control rules make use of the driver's command and of the feedback information from the drivetrain and components status
- Control rules select the proper operation modes
- Actual performance (in terms of energy efficient use) of the drivetrain depends on controller quality and control strategy
- Two typical control strategies
  - Maximum state of charge of batteries
  - Engine on/off control strategies

Max state-of-charge strategy

Max state-of-charge control strategy

- Target of max state-of-charge control strategy

  ➔ Meet power demand given by driver

AND in the same time

  ➔ Maintain SOC of batteries at their highest possible level

- High SOC level guarantees the highest performance of the vehicle at any time

- Applications:
  - Vehicles whose performance relies heavily on Peak Power Source (frequent stop and go driving patterns)
  - Vehicles such as military or emergency vehicles for which carrying on the mission is of the highest importance

Max state-of-charge control strategy

- Point A: hybrid traction mode

$$P_{\text{traction}} > P_{\text{e/g}}$$

$$P_{\text{traction}} = P_{\text{e/g}} + P_{\text{PPS}}$$

- Point B:

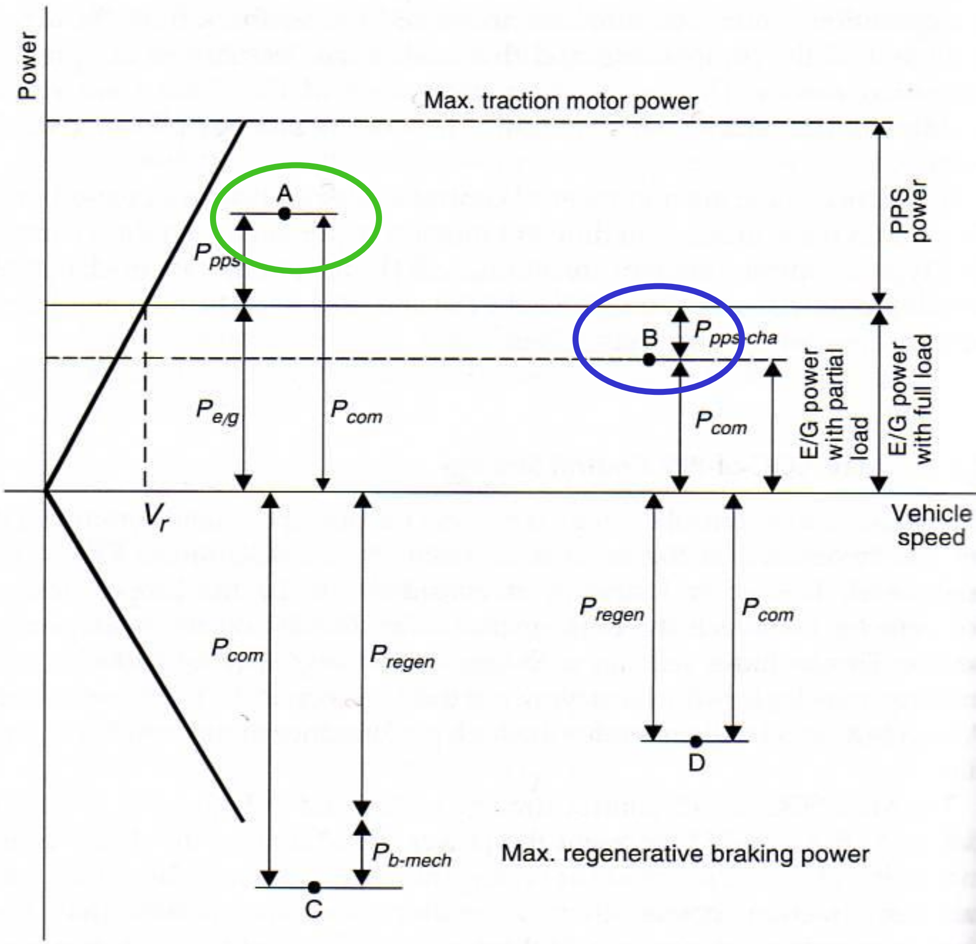
$$P_{\text{traction}} \leq P_{\text{e/g}}$$

- If $\text{SOC} < \text{SOC}_{max}$

$$P_{\text{traction}} = P_{\text{e/g}} - P_{\text{PPS}}$$

- If $\text{SOC} = \text{SOC}_{max}$

$$P_{\text{traction}} = P_{\text{e/g}}$$



(Ehsani et al. 2005)

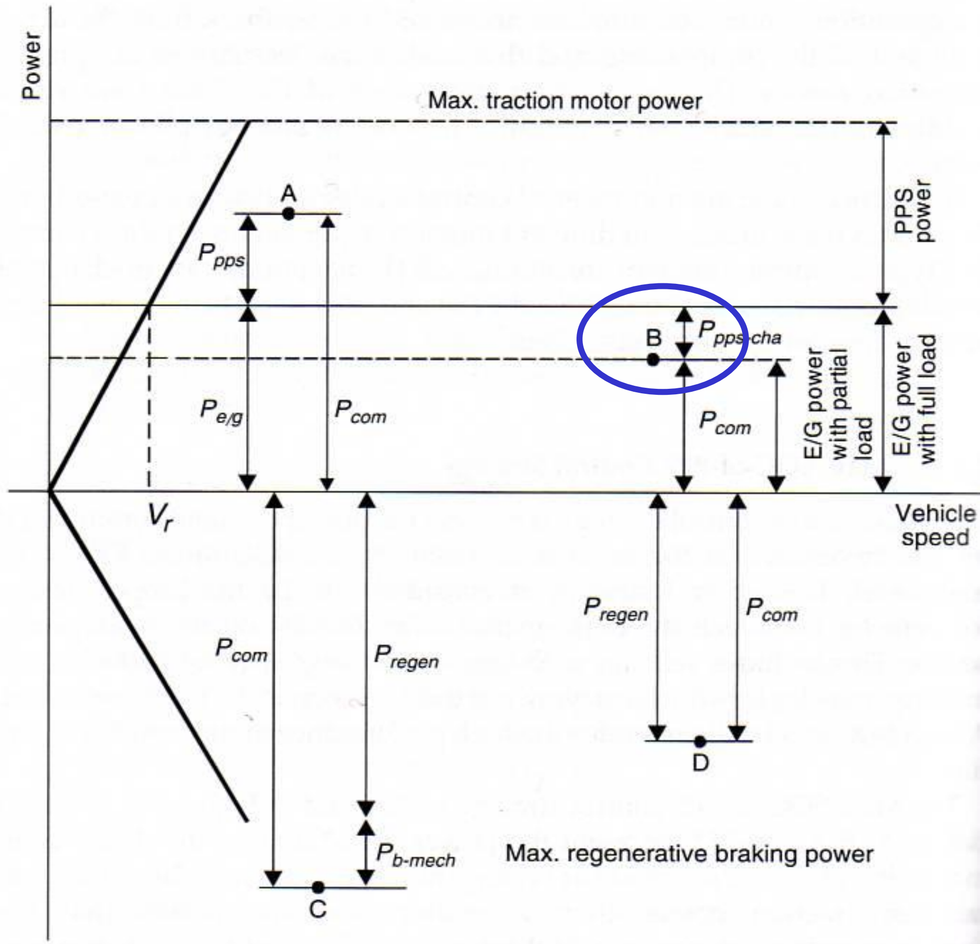
Max state-of-charge control strategy

- Point B: $P_{\text{traction}} \le P_{\text{e/g}}$
- If $\text{SOC} < \text{SOC}_{max}$
  PPS charging mode

$$P_{\text{traction}} = P_{\text{e/g}} - P_{\text{PPS}}$$

- If $\text{SOC} = \text{SOC}_{max}$
  engine/ generator alone traction mode

$$P_{\text{traction}} = P_{\text{e/g}}$$



(Ehsani et al. 2005)

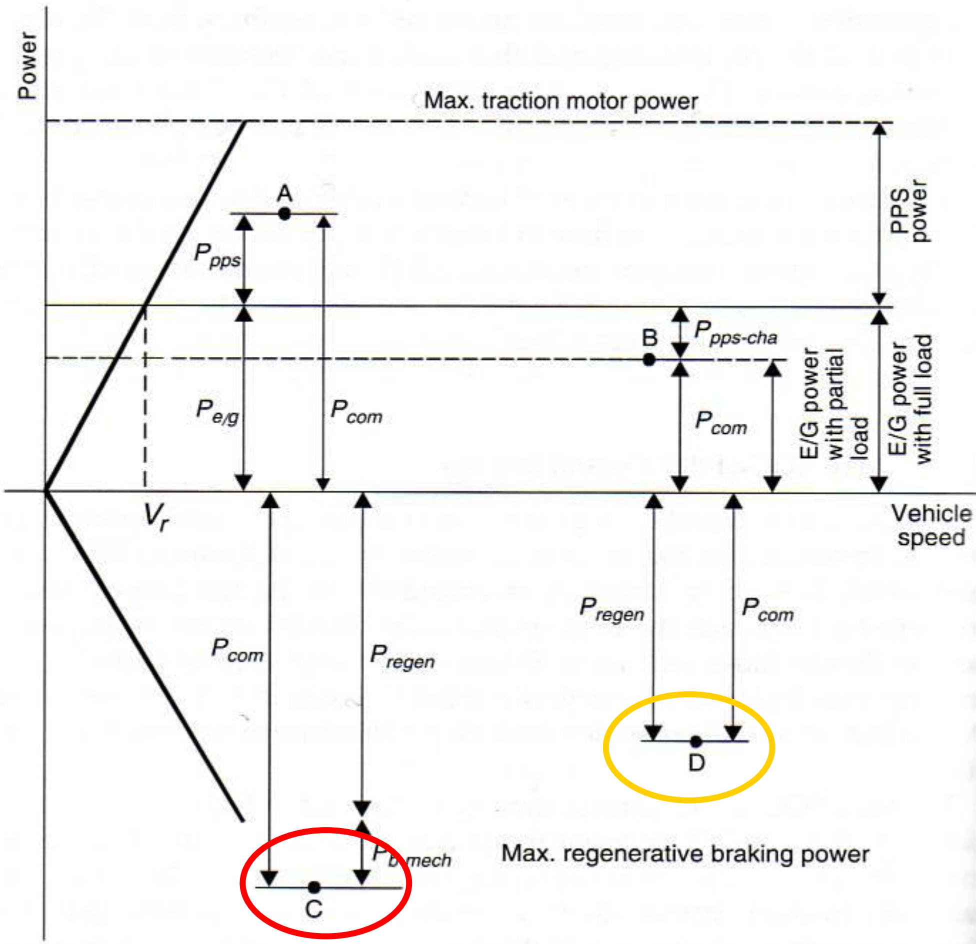
Max state-of-charge control strategy

- Point C: $P_{\text{braking}} > P_{\text{e/g}}$
  Hybrid braking mode

$$P_{\text{braking}} = P_{\text{e/g}} + P_{\text{brake}}$$

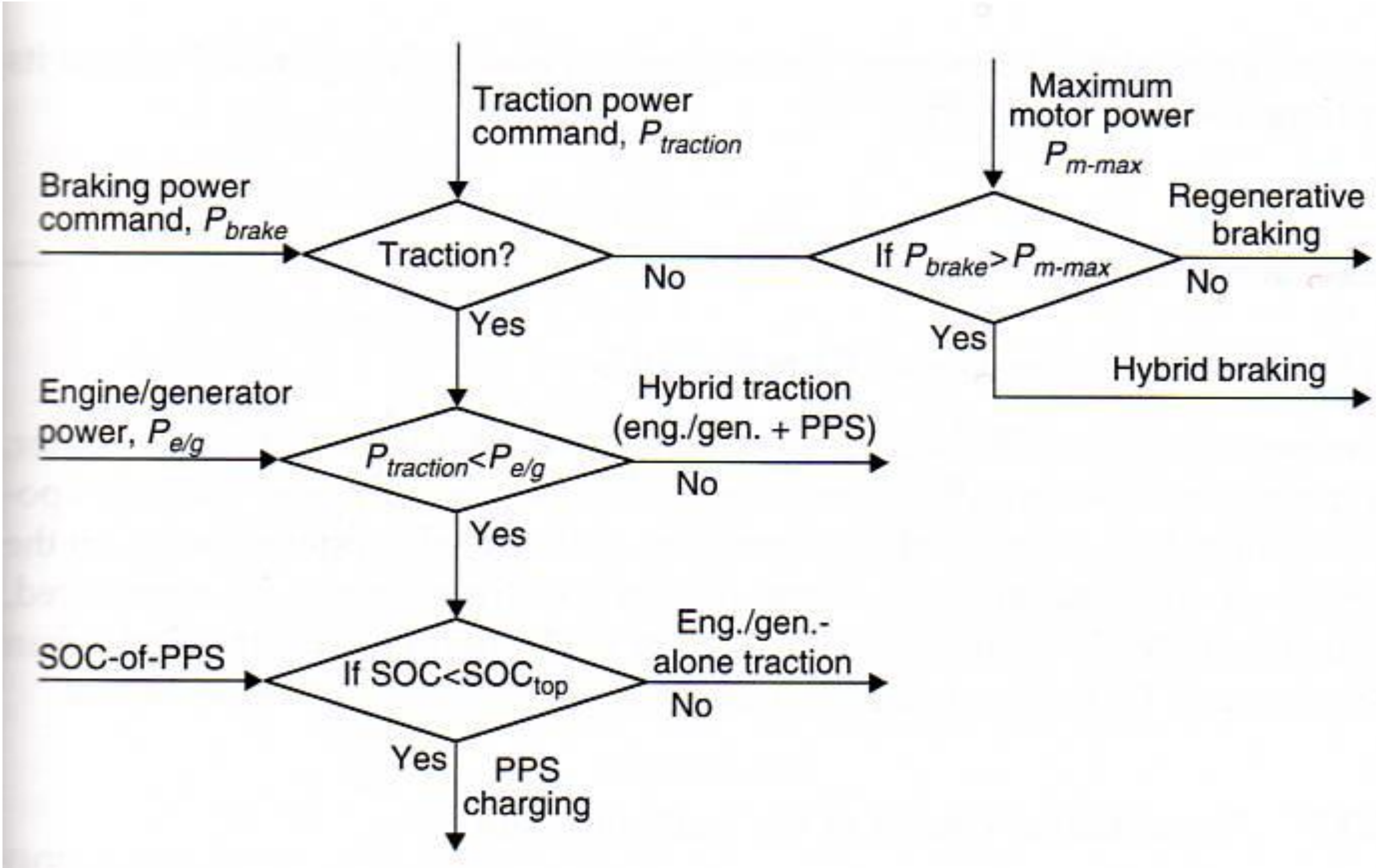
- Point D: $P_{\text{braking}} \leq P_{\text{e/g}}$
  Regenerative braking mode

$$P_{\text{braking}} = P_{\text{e/g}}$$



(Ehsani et al. 2005)

Max state-of-charge control strategy



Control flowchart of max SOC of batteries control strategy
(Ehsani et al. 2005)

On/off control strategy

On-off control strategy

- In some situations, such as long time driving with low / moderate load on highway and at constant speed, batteries can easily be charged at their max SOC level within a short time.
- Engine / generator should be forced to work at a power that is smaller than its optimum efficiency point
- Efficiency should be reduced
- In this case engine on-off (bang-bang controller) is more appropriate
- Operation is completely controlled by the SOC of the batteries or PPS
- Engine can be operated in its optimal efficiency map during ENGINE ON periods

On-off control strategy

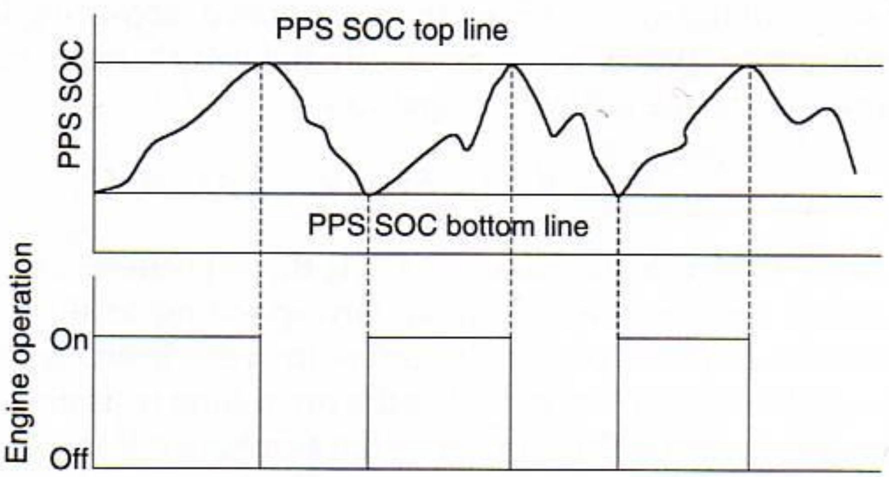


Illustration of thermostat control
(Ehsani et al. 2005)

- When SOC > preset top level:
  - Engine / generator is OFF
  - Vehicle propelled by batteries

$$P_{\text{traction}} = P_{\text{PPS}}$$

- When SOC < preset bottom level
  - Engine / generator is ON
  - Vehicle is propelled using engine/ generator

$$P_{\text{traction}} = P_{\text{e/g}} - P_{\text{PPS}}$$

SIZING OF MAJOR COMPONENTS

Sizing of major components

- Sizing of major components of series hybrid drive train
  - Traction motor
  - Engine / generator
  - Batteries or peak power sources

- Power rating of these components is the first important step of the system design

- Design constraints
  - Acceleration performance
  - Highway driving / urban driving
  - Energy balance in batteries

Power rating of traction motor

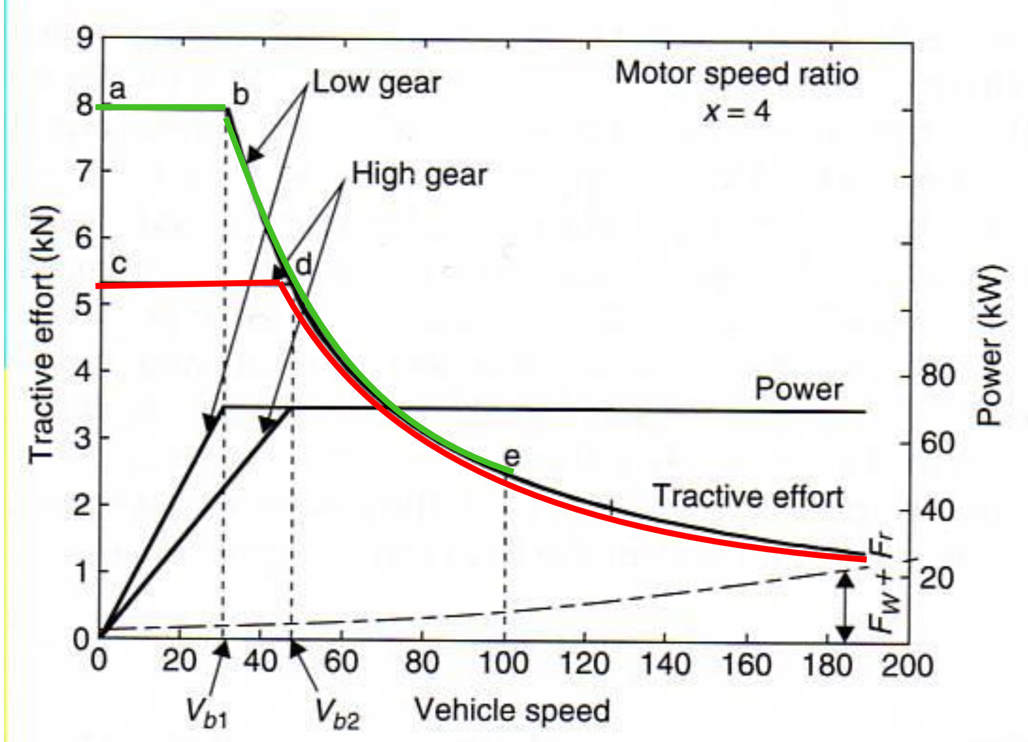
- Similar procedure to power rating of pure electric motor drive
- E-Motor characteristics and transmission are completely determined by vehicle acceleration performance requirement
- First iteration, acceleration performance (time to accelerate from 0 to V_f)

$$P_t = \frac{\gamma m}{2t_a}(V_f^2 + V_b^2) + \frac{2}{3}mgfV_f + \frac{1}{5}\rho S C_x V_f^3$$

  - m, mass of vehicle; γ correction factor for effective mass
  - t_a: time to accelerate
  - V_b base speed corresponding to switch from constant torque mode to constant power mode
- Exact performance evaluation requires a verification using a simulation code

Power rating of traction motor

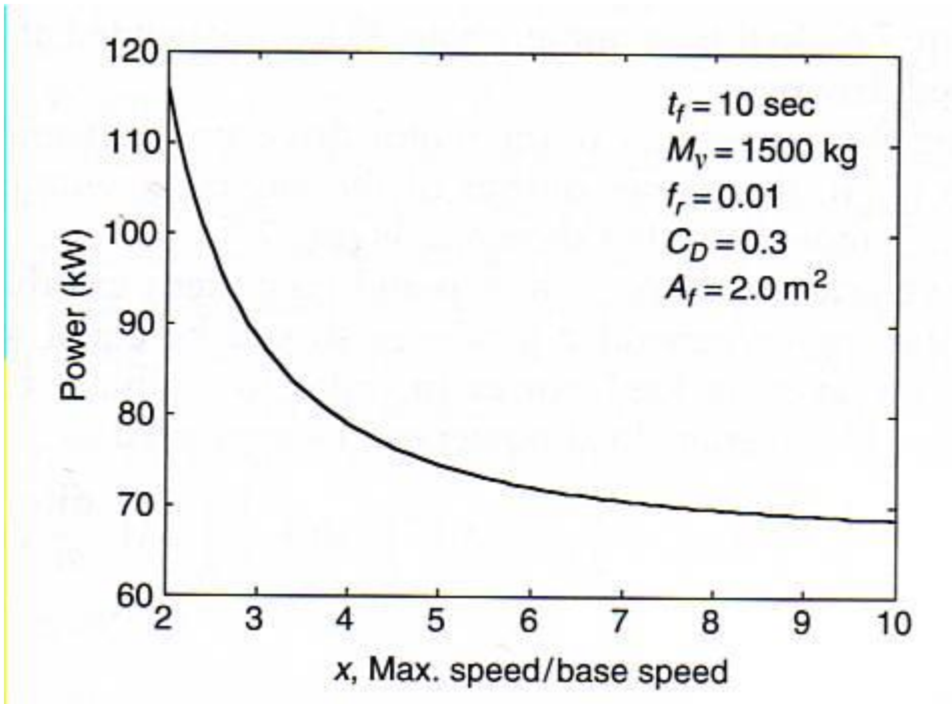
$$x = \frac{V_b}{V_{max}}$$



- Traction effort and traction power vs vehicle speed with a low and a high gear ratio
- Low gear ratio: a-b-d-e trace during acceleration
- High gear ratio: c-d-e-f trace

(Ehsani et al. 2005)

Power rating of traction motor



(Ehsani et al. 2005)

- Power rating versus base speed ratio

$$x = \frac{V_b}{V_{max}}$$

Power rating of engine / generator

- Engine / generator is used to supply steady state power in order to prevent the batteries from being discharged completely

- Design of engine / generator considers two driving situations
  - Driving for a long time with constant speed (highway driving, intercity driving)
  - Driving with frequent start and stops (city driving)

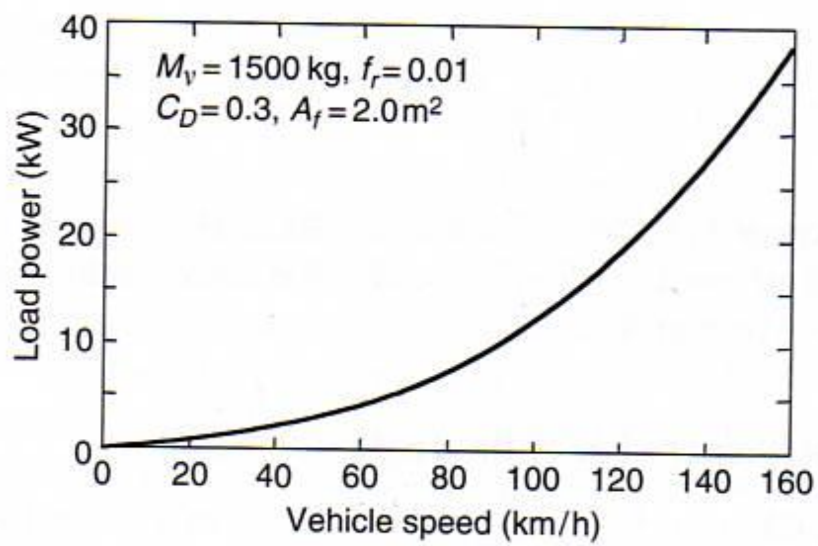
- The selection of the engine / generator system should be such that the power capability is greater than both the maximum power for constant speed driving scenarios (highway driving) and the average power requested when driving in urban areas (evaluated using typical standard drive cycles).

Power rating of engine / generator

- Driving for a long time with constant speed
  - Engine / generator and drivetrain do not rely on batteries to support operation at 130 km/h for instance
  - Engine / generator should be able to produce sufficient power to support this speed

- Driving in frequent stop and go
  - Engine / generator produces sufficient power to maintain energy storage at a certain level while enough power can be delivered to support vehicle acceleration
  - Energy consumption is closely related to control strategy

Power rating of engine / generator



(Ehsani et al. 2005)

- Estimation of power output needed to cruise at constant speed on a flat road

$$P_{\mathrm{e/g}} = \frac{V}{\eta_t \, \eta_m} \left(mgf \, + \, \frac{1}{2} \rho S C_x V^2 \right)$$

- Power is much less than for acceleration
  - Ex. Passenger car (1500 kg) at 130 km/h: P ~ 35 kW

- Effect of transmission efficiency and motor efficiency is to increase the power sizing by 20 to 25%

Power rating of engine / generator

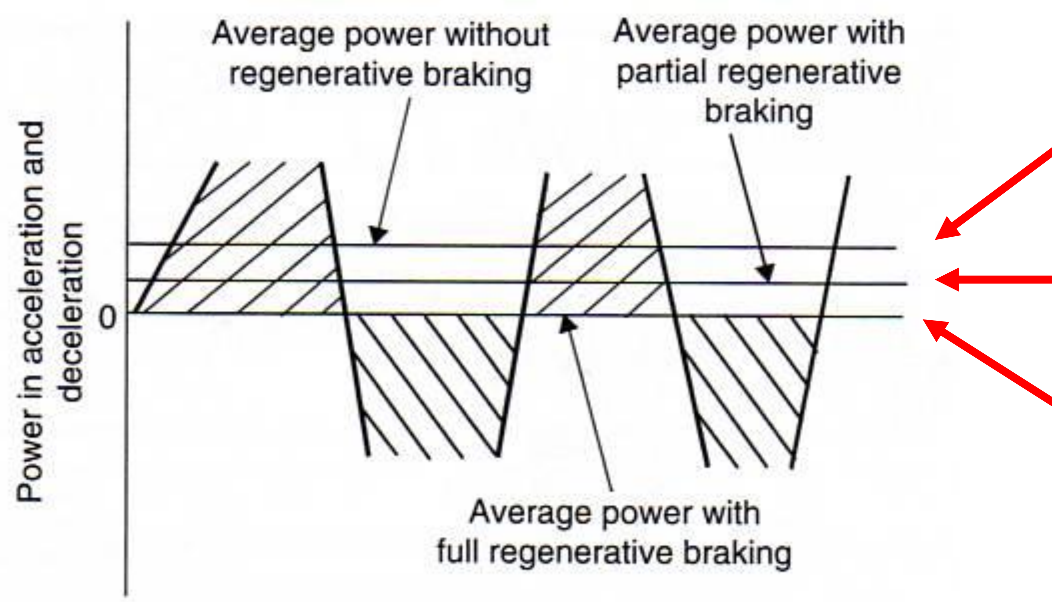
- During stop and go patterns in urban areas, power generation by engine / generator must be equal or slightly greater than average power load to maintain the balance of PPS energy storage
- Average load power:

$$P_t^{\text{ave}} = \frac{1}{T}\int_0^T \left(mgf + \frac{1}{2}\rho S C_x V^2 \right) V\, dt + \frac{1}{T}\int_0^T \gamma\, m \frac{dV}{dt} V\, dt$$

- When vehicle is able to recover fully kinetic energy, the average power consumed in acceleration / deceleration (second term) is zero otherwise it is greater than zero

$$P_{\text{e/g}} \geq \frac{1}{\eta_t \eta_m} P_t^{\text{ave}}$$

Power rating of engine / generator



$\alpha = 0.00$

$0 < \alpha < 1$

$\alpha = 1.00$

$$\frac{1}{T}\int_0^T \gamma\, m \left[\frac{dV}{dt}\right]_+ V\,dt - \frac{\alpha}{T}\int_0^T \gamma\, m \left[\frac{dV}{dt}\right]_- V\,dt$$

Design of batteries and PPS

DESIGN CRITERIA

1. Batteries must be capable of delivering sufficient power to the traction motor at any time
2. Batteries store sufficient energy to avoid failure of power delivery during too-deep discharging

POWER CAPACITY

- To fully use electric motor power, the power capacity of the energy source and of the engine / generator must be greater than the max rated power of the electric motor

$$P_{\mathrm{PPS}} + P_{\mathrm{e/g}} \geq \frac{P_{mot}^{max}}{\eta_m} \quad \Leftrightarrow \quad P_{\mathrm{PPS}} \geq \frac{P_{mot}^{max}}{\eta_m} - P_{\mathrm{e/g}}$$

Design of batteries and PPS

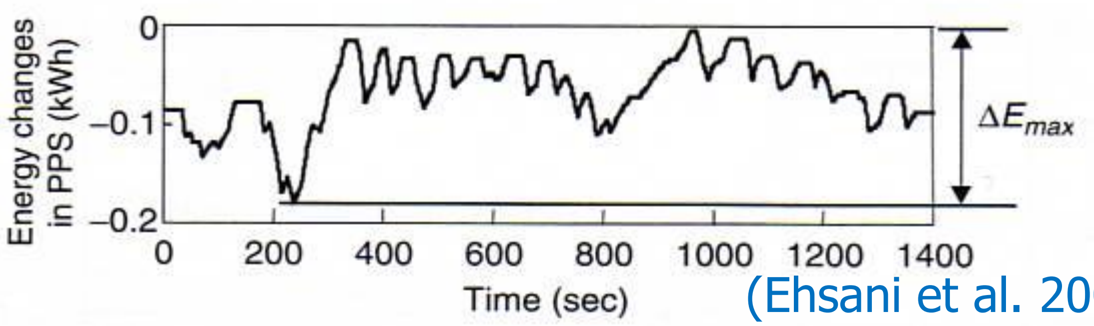
ENERGY CAPACITY

- In some driving conditions, frequent acceleration / deceleration driving patterns can result in low SOC
- Determine the energy changes in PPS during typical driving cycles to size the energy capacity of the peak power sources

$$\Delta E = \int_0^T P_{\mathrm{PPS}}\, dt$$

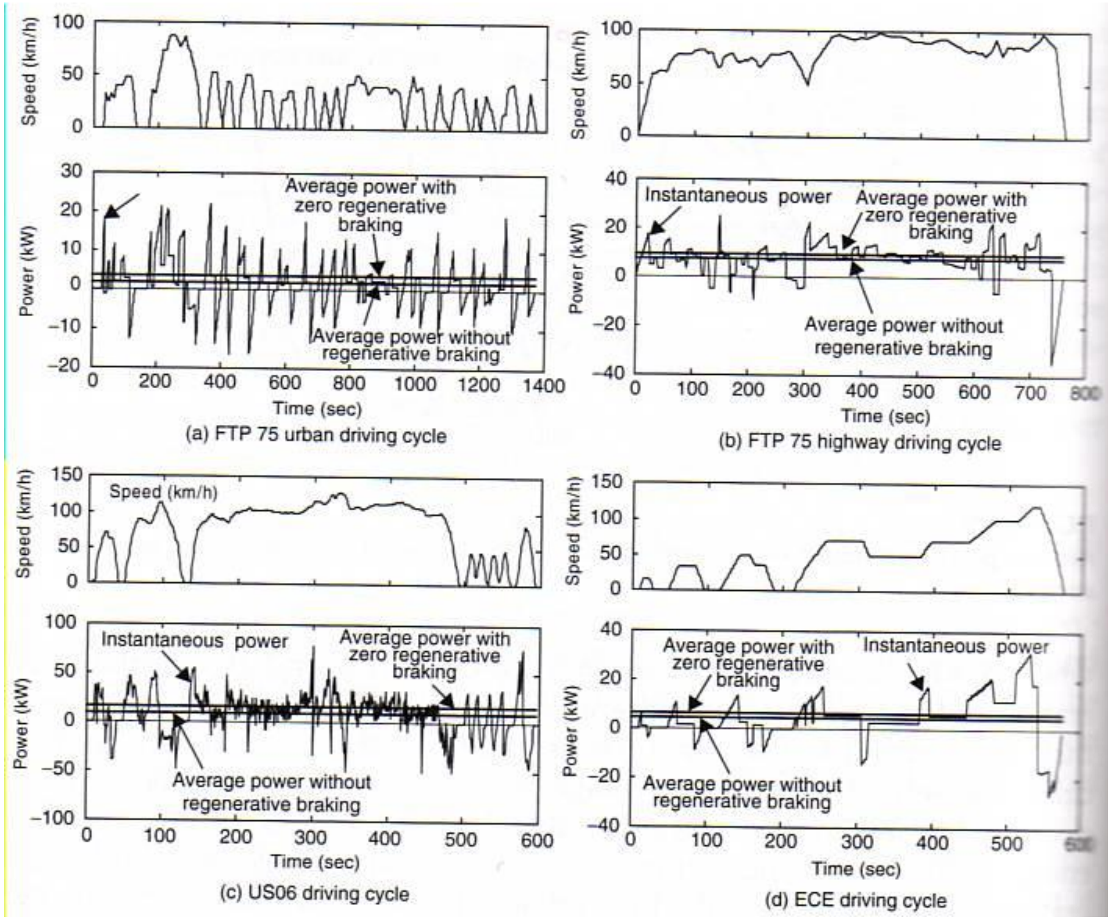
- Check if

$$\Delta E \in [\mathrm{SOC}_{min}, \mathrm{SOC}_{max}]$$



(Ehsani et al. 2005)

Design of batteries and PPS



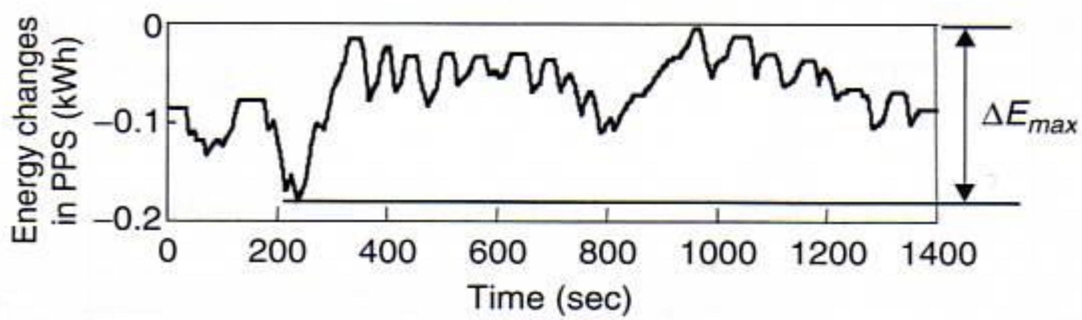
(Ehsani et al. 2005)

Instantaneous power and average power with full and zero regenerative braking in typical drive cycles

Design of batteries and PPS

- Range of SOC depends on the operating characteristics of PPS.
  - Max efficiency of batteries in range [0.4 , 0.7]
  - Ultra capacitors have a limited range rate [0.8 , 1.0]

$$E_{PPS} = \frac{\Delta E_{max}}{\mathrm{SOC}_{max} - \mathrm{SOC}_{min}}$$



(Ehsani et al. 2005)

Design example

- Design specification
  - M=1500 kg
  - f = 0,01 Cx= 0,3 S=2 m²
  - Transmission ratio efficiency η_t=0,9

- Performance specifications
  - Acceleration time (0 to 100 km/h): 10 ± 1 s
  - Maximum gradeability: 30% @ low speed and 5% @ 100 km/h
  - Maximum speed 160 km/h

Design of traction motor size

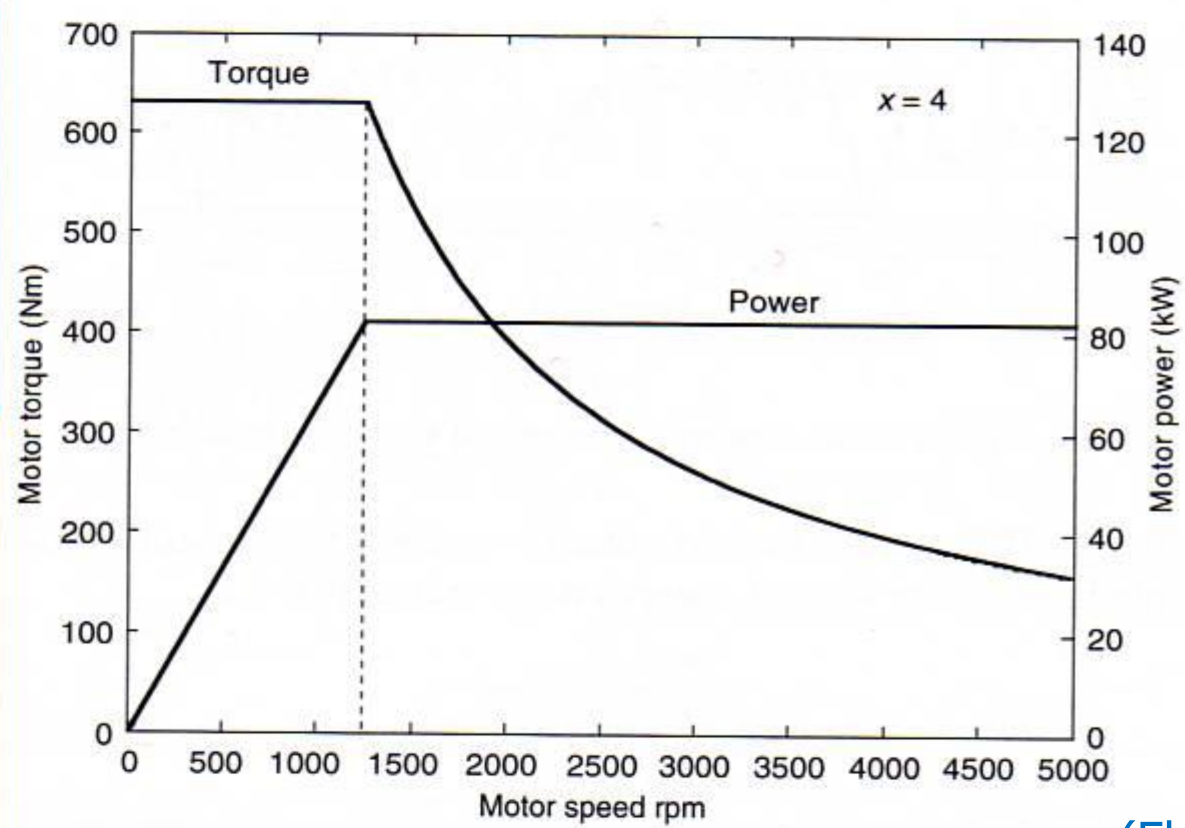
- Equation for motor power rating

$$P_t = \frac{\gamma\, m}{2\, t_a}(V_f^2 + V_b^2) \;+\; \frac{2}{3} m\, g\, f\, V_f \;+\; \frac{1}{5}\rho S C_x V_f^3$$

- Acceleration time (0 to 100 km/h): 10 ± 1 s
- Assume x=4 (induction motor), it comes

$$P_{e-mot}^{max} \;\geq\; 82.5\,\mathrm{kW}$$

Design of traction motor size



(Ehsani et al. 2005)

Characteristics of traction motor vs motor rpm and vehicle speed

Design of gear ratio

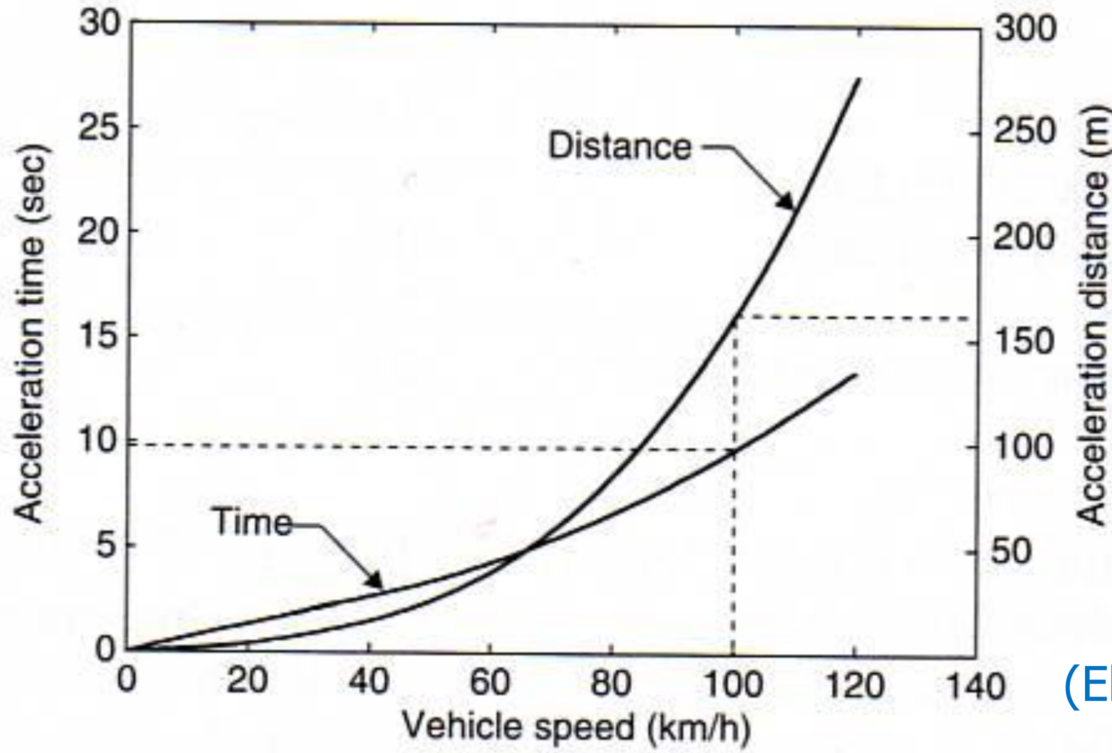
- Gear ratio is designed such that the vehicle reaches its maximum speed at the motor maximum rotation speed
- Use

$$i = \frac{\pi \, N_{max} \, R_e}{30 \, V_{max}}$$

- Data
  - N_{nom}=5000 rpm, v_{max} = 44,4 m/s (160 km/h) and R_e=0,2794 m

- It comes $i = 3.29$

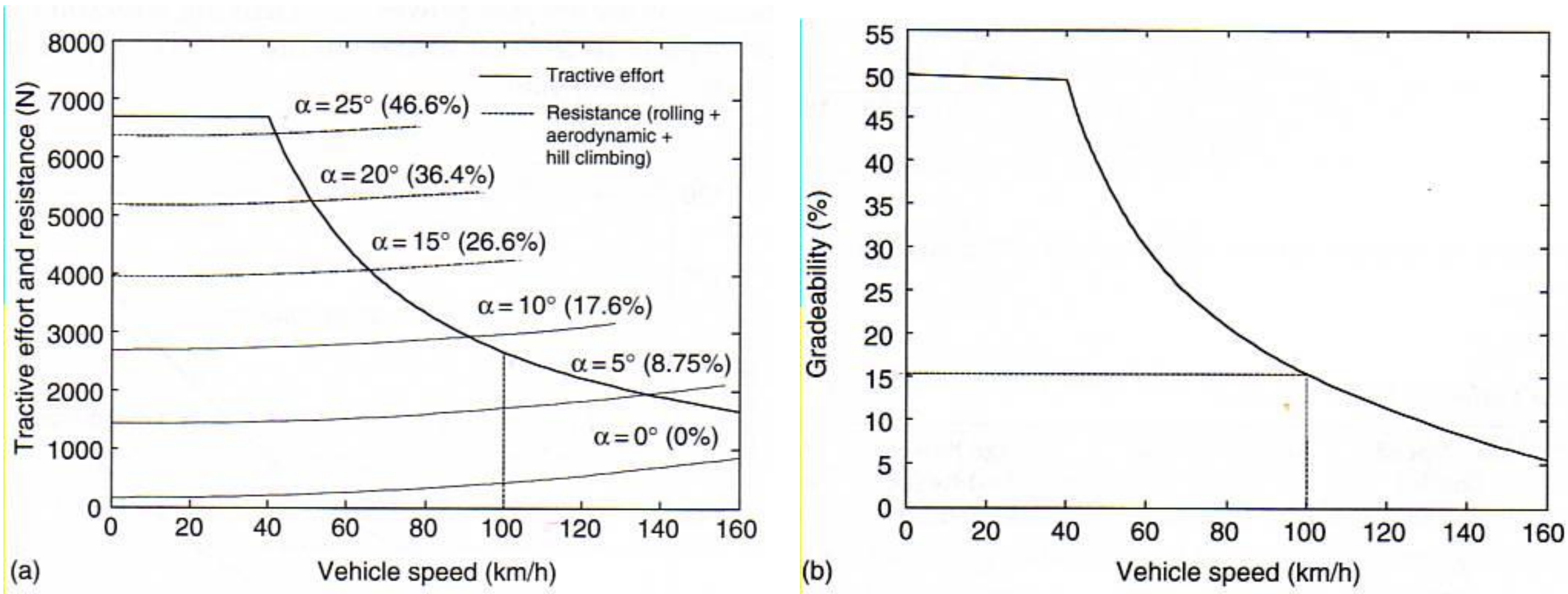
Verification of acceleration time



(Ehsani et al. 2005)

Simulated acceleration time and distance vs speed

Verification of gradeability



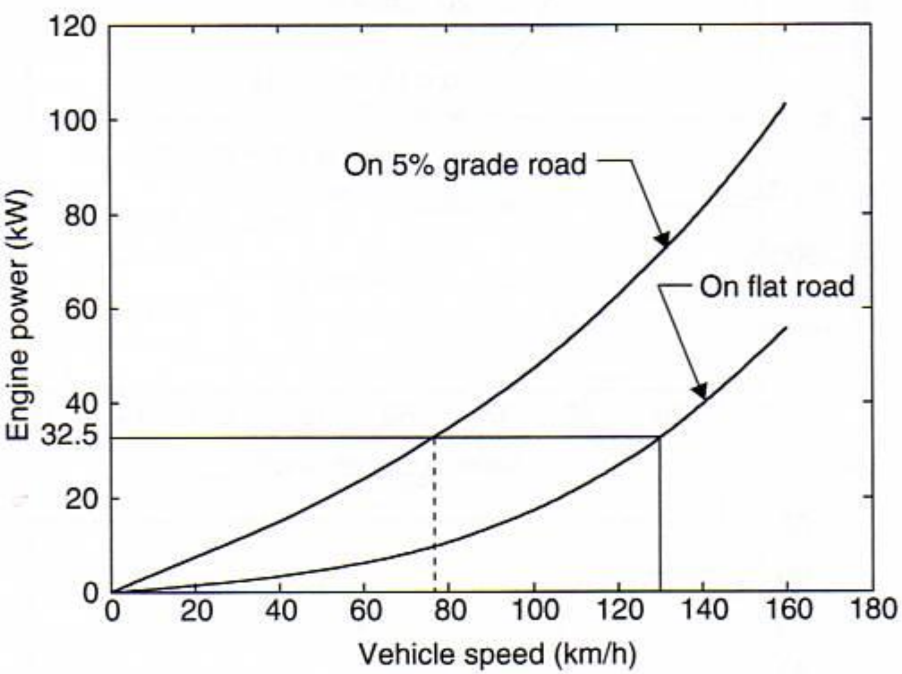
(Ehsani et al. 2005)

Traction effort and resistance of the vehicle vs speed

Verification of gradeability

- Gradeability is calculated using tractive effort and resistance
- From the plots of resistance force vs speed, it can be checked that the gradeability is satisfied
- It implies that for a passenger car, the power needed for acceleration is usually larger than the one needed for gradeability specifications
- Acceleration specification generally determines the motor power rating

Design of engine / generator



(Ehsani et al. 2005)

- Power rating of engine / generator is designed to be able to support the vehicle motion during a highway drive (130 km/h) on level road
- Numerical example
  - Data: efficiency of transmission: 90%, motor: 85%, generator: 90%

$$P_{\mathrm{e/g}} = \frac{V}{\eta_t\,\eta_m}\left(mgf + \frac{1}{2}\rho S C_x V^2\right)$$

  - Power of 32,5 kw is sufficient
  - It can maintain a speed of 78 km/h with a 5% road

Design of engine / generator

- Second consideration in power rating of engine / generator: average power when driving with typical stop and go driving cycles

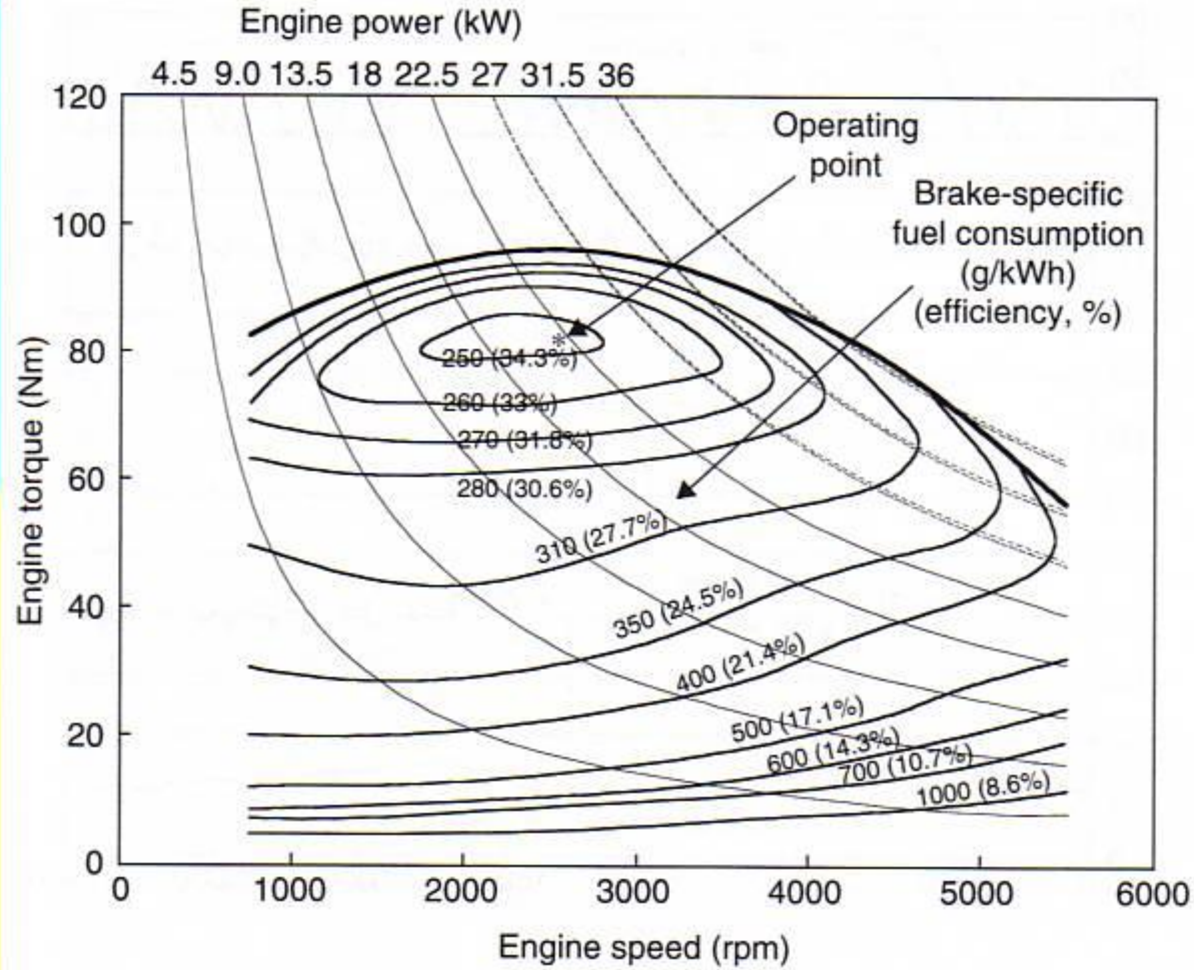
	Max speed (km/h)	Average speed (km/h)	Average power with full regen. Braking (kW)	Average power with no regen. Braking (kW)
FTP 75 urban	86,4	27,9	3,76	4,97
FTP 75 highway	97,7	79,6	12,60	14,10
US06	128	77,4	18,30	23,00
ECE-1	120	49,8	7,89	9,32

Design of engine / generator

- Compared to power needed for gradeability and acceleration, average power of city driving is smaller
- P=32,5 kW is sufficient

$$P_{\mathrm{e/g}} \geq 32,5\,\mathrm{kW}$$

Design of engine / generator



(Ehsani et al. 2005)

Design of Power Capacity of PPS

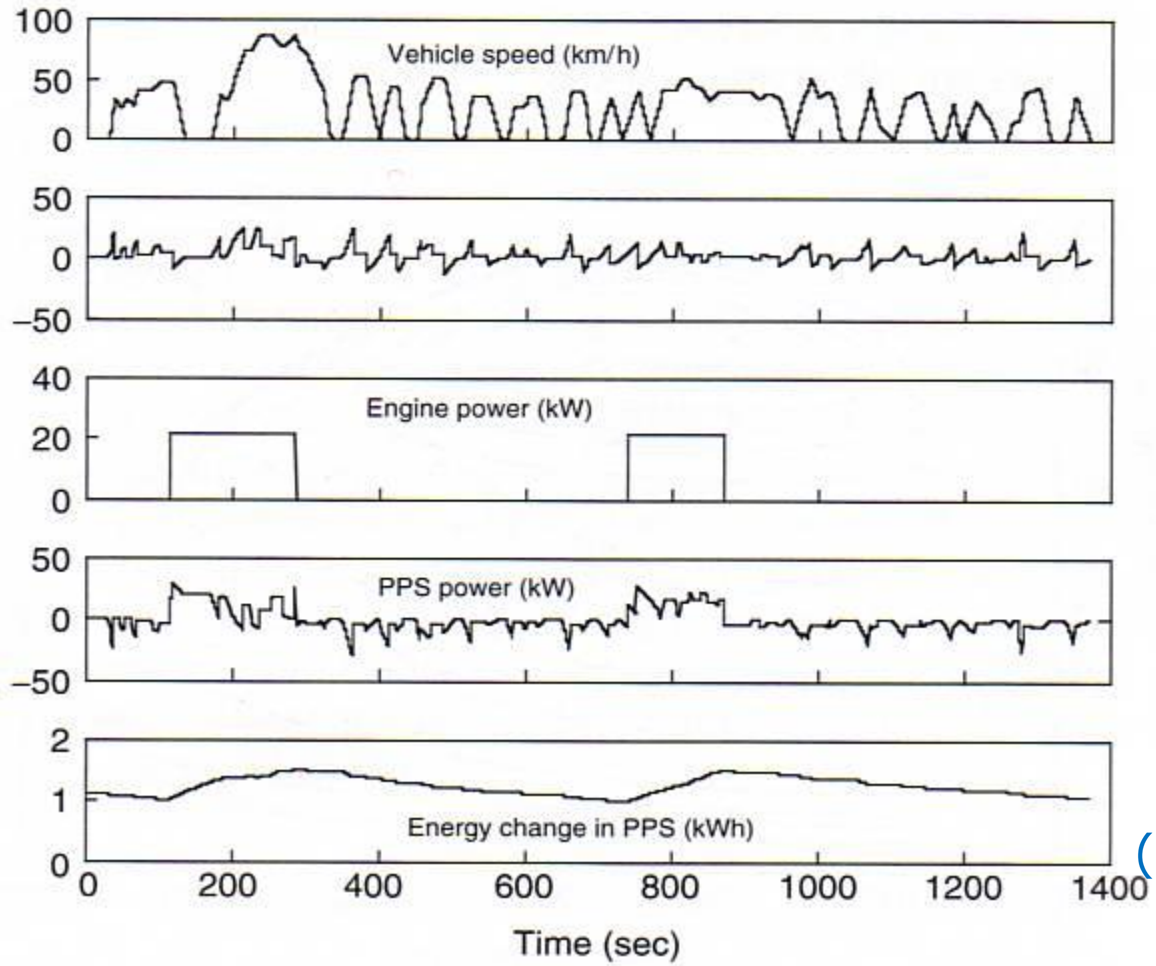
- Sum of the output power of engine/ generator and of the PPS should be greater than the input power of traction motor

$$P_{\mathrm{PPS}} \geq \frac{P_{e-mot}^{max}}{\eta_m} - P_{\mathrm{e/g}} = \frac{82.5}{0.85} - 32.5 \times 0.9 = 67.8\,\mathrm{kW}$$

Design of energy capacity of PPS

- Energy capacity heavily depends on the driving cycles and control strategy
- Here since the power capacity of the engine / generator is much greater than the average power, the bang-bang controller is chosen
- Simulation results for FTP 75 urban driving cycle using regenerative braking

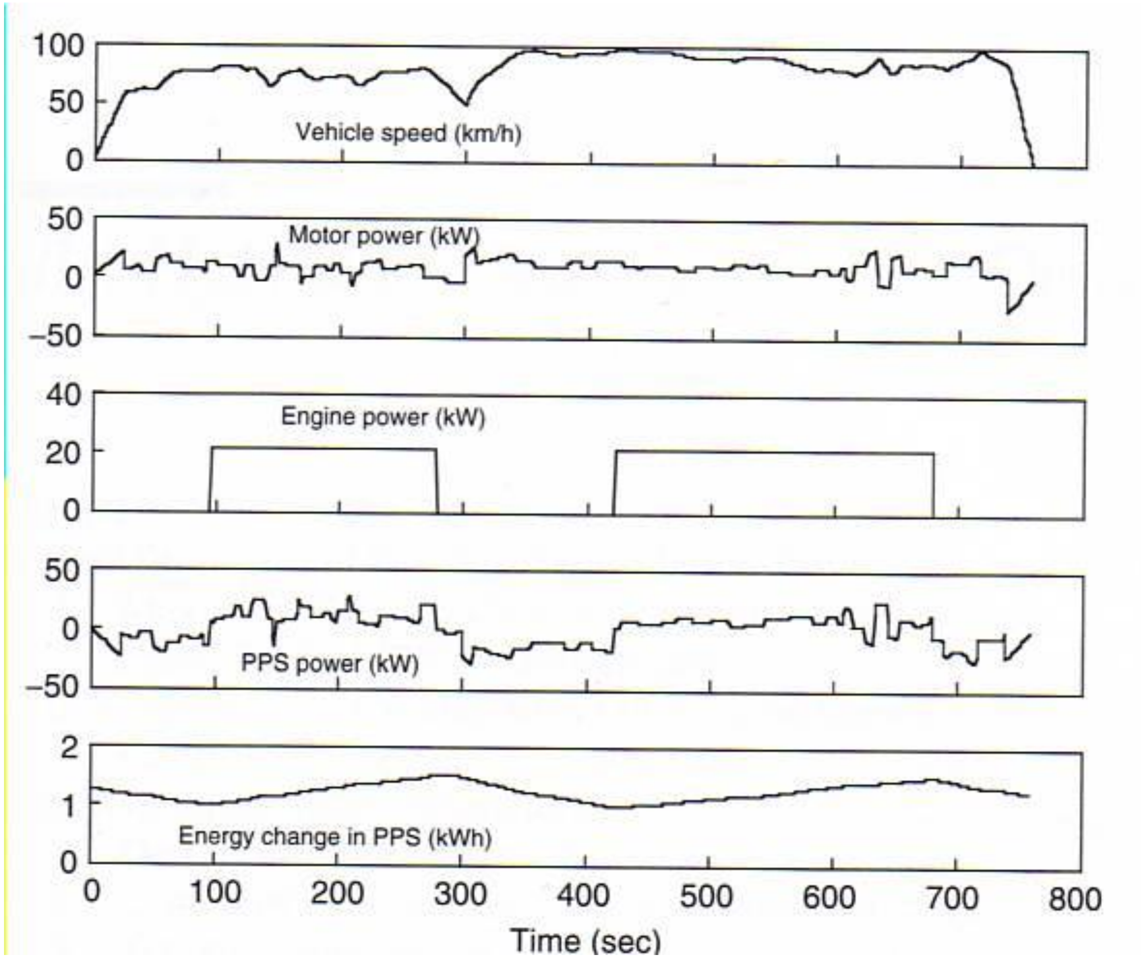
Design of energy capacity of PPS



(Ehsani et al. 2005)

Simulation results for FTP75 urban drive cycle

Design of energy capacity of PPS



(Ehsani et al. 2005)

Simulation results for FTP75 <u>highway drive cycle</u>

Design of energy capacity of PPS

- Result of the control strategy for the battery sizing:
  - Maximum energy variation:

$$\Delta E_{max} = 0.5\,\mathrm{kWh}$$

  - Operation in the SOC range of 0,2, that is in [0.4 , 0.6] for optimal efficiency

- Control strategy for supercaps
  - Operation in the SOC range of 0.2 will limit terminal voltage variation to 10%
  - Total energy in supercapacitors

$$E_{\mathrm{PPS}} = \frac{\Delta E_{max}}{\Delta \mathrm{SOC}} = \frac{0.5}{0.2} = 2.5\,\mathrm{kWh}$$

Fuel consumption

- Fuel consumption is evaluated using a simulation on two FTP75 driving cycles.
  - For FTP75 urban driving, one estimates the fuel consumption to 17,9 km/l or 5,59 l/100 km
  - For FTP75 highway drive cycles, one has a fuel consumption of 18,4 km/l or 5,44 l/100 km
- Fuel consumption is lower than with an ICE because of the high operating efficiency of the engine and the significant energy recovery exploiting regenerative braking