MECA0527: PARALLEL HYBRID ELECTRIC VEHICLES. DESIGN AND CONTROL

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References

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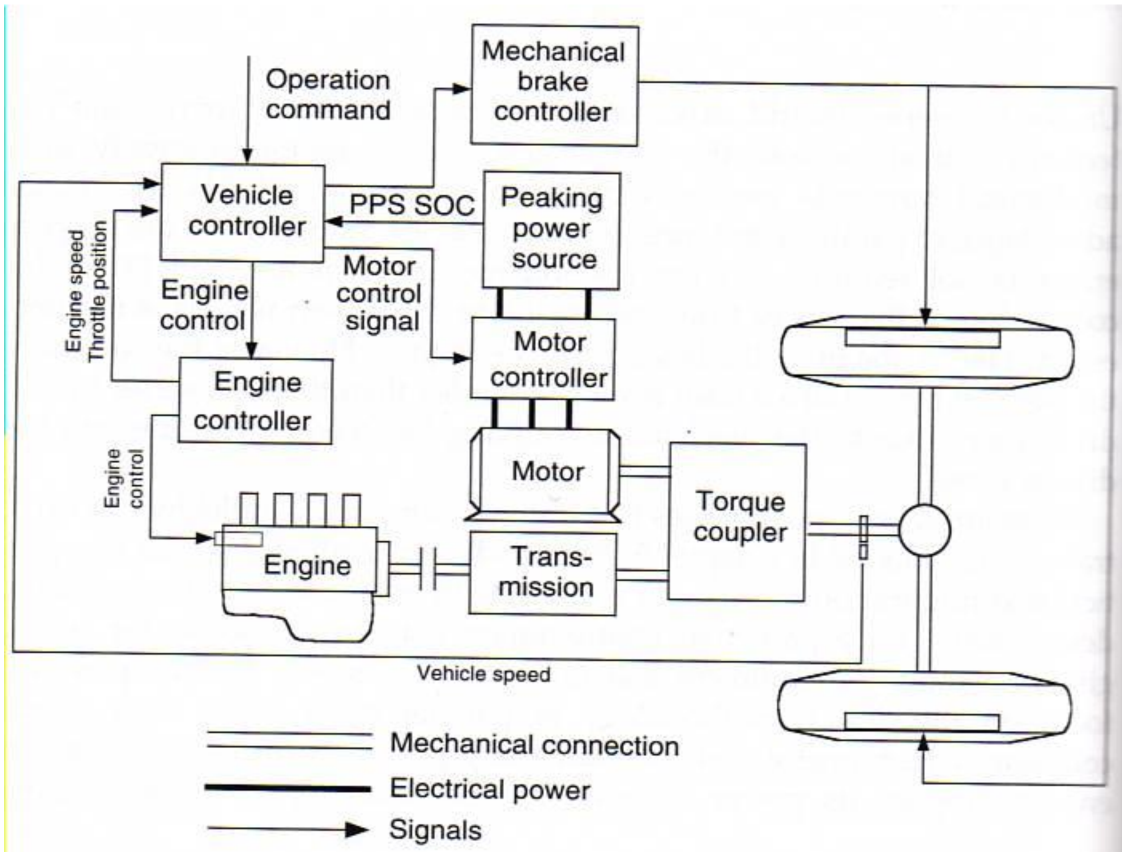
Outline

- Introduction
- Control strategies
  - Maximum state-of-charge of peak power source strategy
  - Engine on-off strategy
- Sizing of the major components

Introduction

- Parallel hybrid drivetrains allow both engine and electric traction motor to supply their power to the driven wheels
- <u>Advantages</u> of parallel hybrid electric vehicles vs series hybrid
  - Generator is not necessary (save one component)
  - Electric traction motor is smaller
  - Reduce the multiple energy conversions from the engine to the driven wheels ➔ Higher overall efficiency
- <u>Counterparts</u>
  - Control of parallel hybrids is more complex because of the mechanical coupling between the ICE engine and the driven wheels
  - No general design methodology: a design approach may be valid for only one particular configuration.
  - Design results for one configuration may be applicable for only a particular given environment and mission requirements.

Introduction

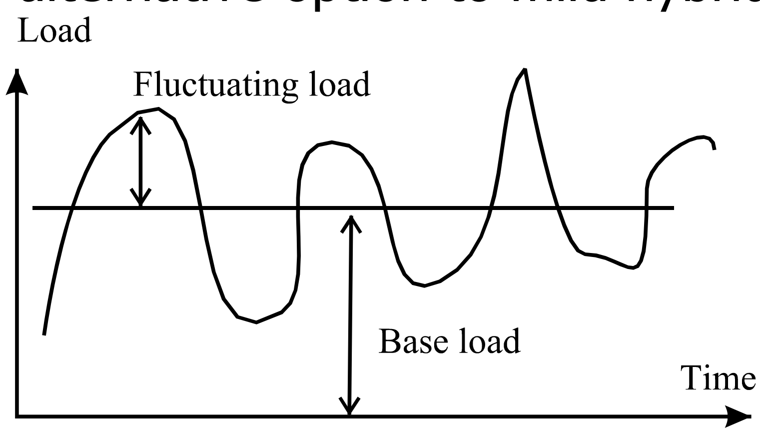


Configuration parallel torque coupling hybrid electric drive train

[Ehsani et al. 2005]

Introduction

- Here: focus on the design methodology of parallel hybrid drivetrains with torque coupling which operate on the electrically peaking principle
  - Engine supplies its power to meet the base load operating at a given constant speed on flat and mild grade roads or working at an average load in case of a stop-and-go drive pattern.
  - Electrical traction supplies the power to meet the peaking fluctuating part of the load.
- This is an alternative option to mild hybrids



Introduction

- In normal urban and highway driving, the base load is much lower than the peaking load
- Engine power rating is thus lower than electrical power rating ➔ downsizing
- Because of the better torque / speed characteristics of electric traction motors (compared to the engine) a transmission with a single ratio is often sufficient for the electric drivetrain.

Introduction

- Objective of this lesson:
  - Design of parallel hybrid electric drivetrains with torque coupling

- Design specifications:
  1. Satisfy the performance requirements (gradeability, acceleration, max cruising speed, etc.)
  2. Achieve high overall efficiency
  3. Maintain the battery state-of-charge (SOC) at a reasonable level during operation without charging from outside the vehicle
  4. Recover a maximum of braking energy

Control strategies of parallel hybrid drive trains

- Available <u>operation modes</u> in parallel hybrid drive train;
  - Engine alone traction
  - Electric alone traction
  - Hybrid traction (engine + electric motor)
  - Regenerative braking
  - Peak power source (batteries) charging mode

- During operation, the proper operation mode should be used to:
  - Meet the traction torque requirements
  - Achieve high level of efficiency
  - Maintain a reasonable level of SOC of PPS
  - Recover as much as possible braking energy

CONTROL STRATEGIES

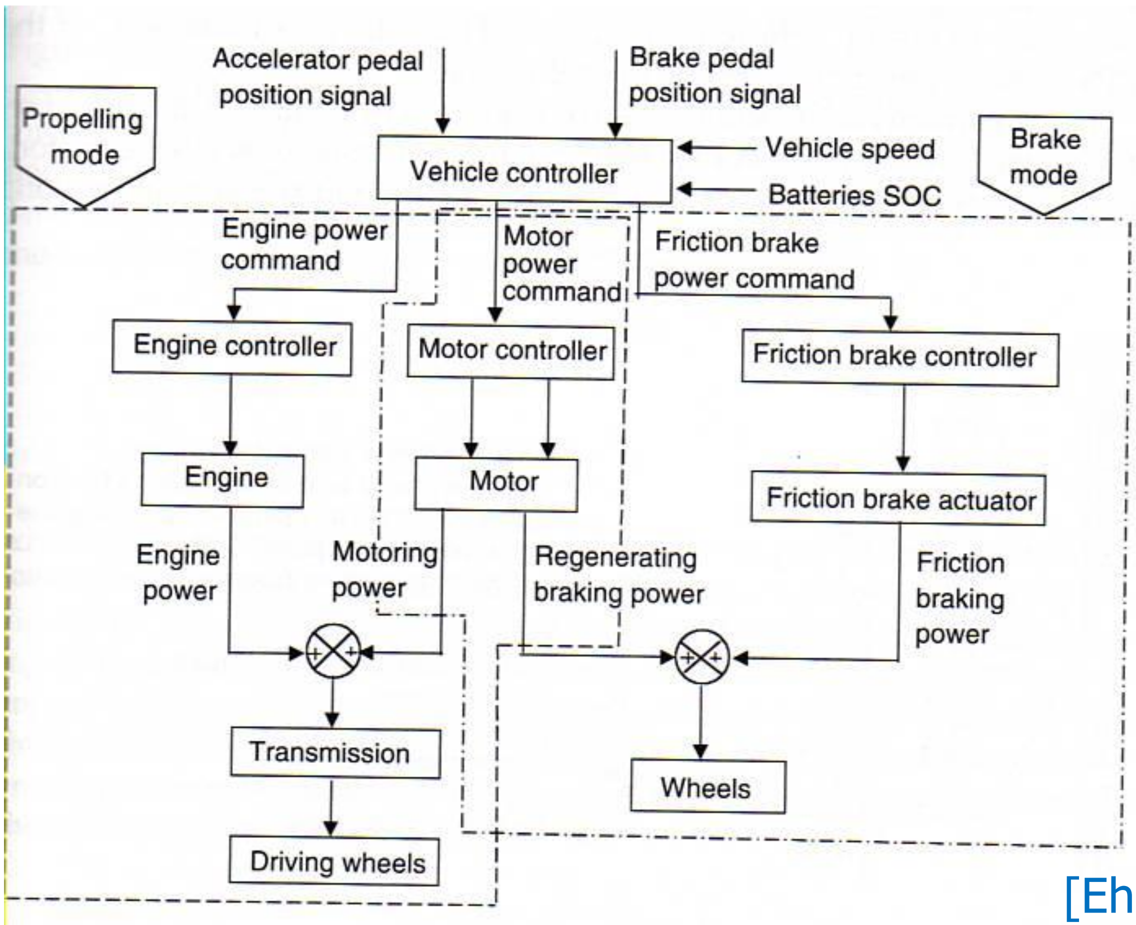
Control strategies of parallel hybrid drive trains

Vehicle controller

Engine controller | Motor controller | Battery controller | Brake controller

- Control level based on a two-level control scheme
  - Level 2: vehicle level = high level controller
  - Level 1: low level controller = subordinate controllers
    - Engine, motor, brake, battery, etc.

Control strategies of parallel hybrid drive trains



[Ehsani et al. 2005]

Overall control scheme of the parallel hybrid drive train

Control strategies of parallel hybrid drive trains

- Vehicle system level controller
  - Control commander
  - Assign torque commands to lower-level controllers (local or component controllers)
  - Command based on
    - Driver demand
    - Component characteristics and feed back information from components (torque, speed)
    - Preset control strategies

- Vehicle system controller has a central role in the operation of drive train
  - Fulfill various operation modes with correct control commands to each components
  - Achieve an overall high efficiency

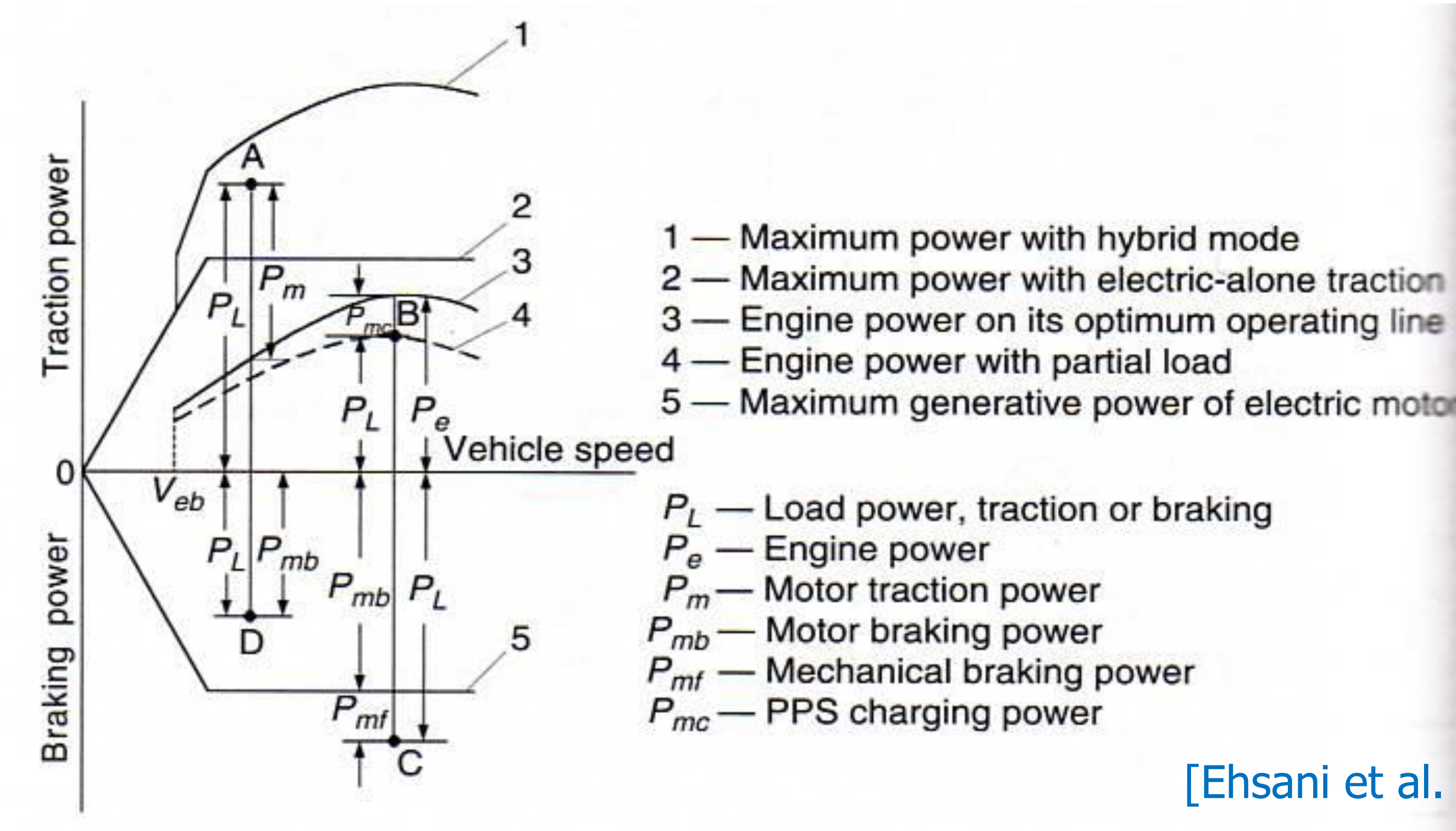
Control strategies of parallel hybrid drive trains

- Component controllers
  - Engine, motor, batteries, brakes, torque coupler, gear box, clutches, etc.
  - Control the components to make them work properly
  - Control operations of corresponding components to meet the requirements from the drivetrain and to reach prescribed values assigned by system controller

Maximum PPS state-of-charge strategy

- When vehicle is operating in a stop-and-go driving pattern, batteries must deliver their power to the drivetrain frequently. PPS tends to be discharged quickly.
- So, maintaining a high SOC is necessary to ensure vehicle performance
- Max state-of-charge is an adequate option.

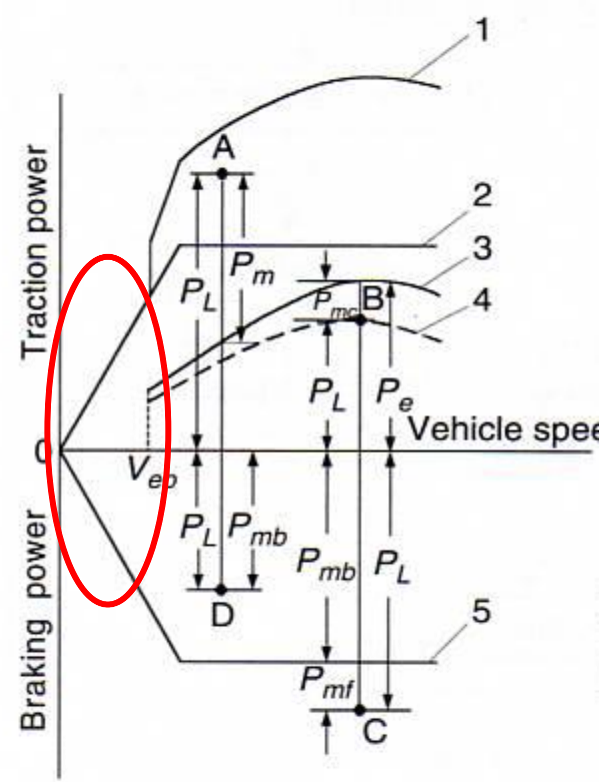
Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

Various operation modes based on power demand

Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

Electric Motor alone propelling mode:

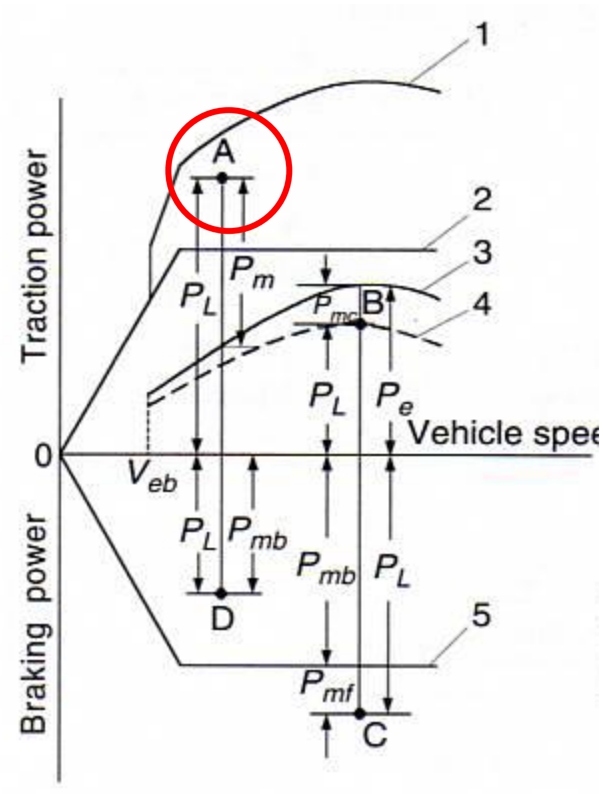
- If the vehicle speed is below a preset value V_{eb}, a vehicle speed below which the engine cannot operate properly in steady state
- Electric motor alone supplies the whole power to the driven wheels
- Engine is shut down or idling

$$P_e = P_{\mathrm{ICE}} = 0$$

$$P_{e-m} = \frac{P_L}{\eta_{t,e-m}} > 0$$

$$P_{\mathrm{PPS}-d} = \frac{P_{e-m}}{\eta_{e-m}} < 0$$

Maximum PPS state-of-charge strategy

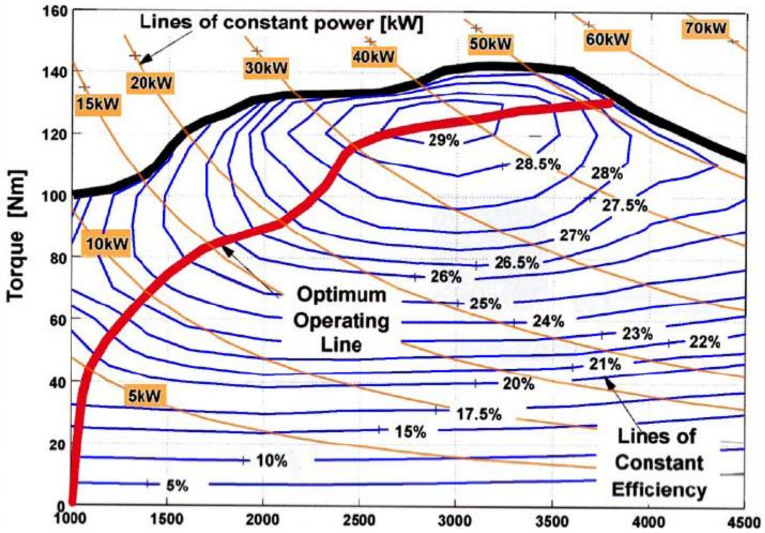


Ehsani et al. 2005

Hybrid propelling mode:

- Example: case A
- Load demand is greater than the engine power
- Both engine and e-motor have to deliver their power to the wheels simultaneously
- <u>Engine operates at its max efficiency line</u> by controlling the throttle to produce P_e
- Remaining power is supplied by the electric motor $P_{e\text{-}m}$

Maximum PPS state-of-charge strategy



Hybrid propelling mode:

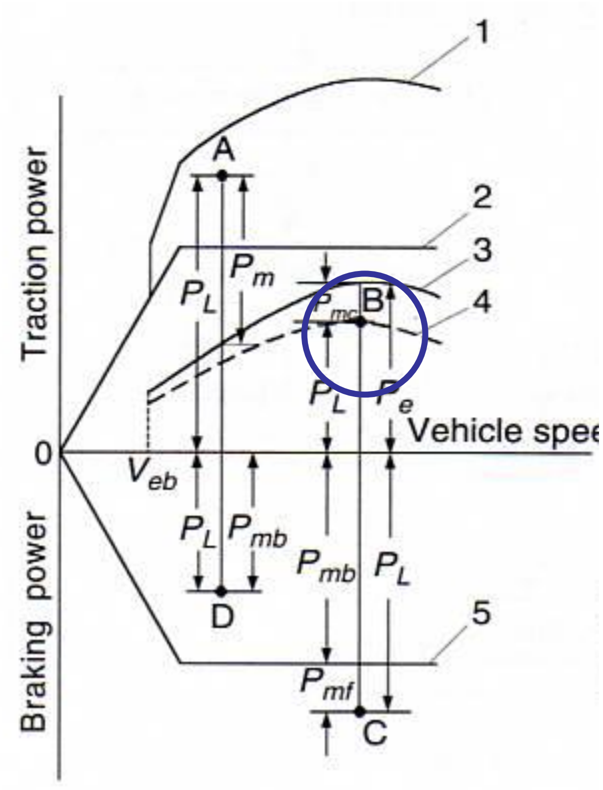
- Engine operates at its max efficiency line by controlling the throttle to produce P_e
- Remaining power is supplied by the electric motor

$$P_e = P_{ICE}^{opt}(V = \omega R_e) > 0$$

$$P_{e-m} = \frac{P_L - \eta_{t,e} P_{ICE}}{\eta_{t,e-m}} > 0$$

$$P_{\mathrm{PPS}-d} = \frac{P_{e-m}}{\eta_{e-m}} < 0$$

Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

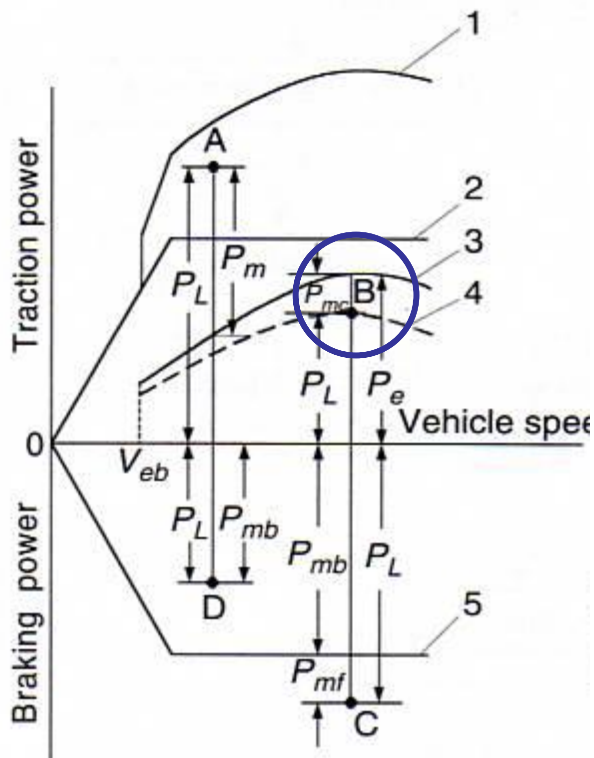
Batteries / PPS charging mode:

- Situation of for instance point B
- When the power demand is less than the power produced by engine in its optimum operation line

When batteries are below their max SOC

- Engine is operated in its optimum line
- E-motor works as a generator and converts the extra power of the engine into electro power stored in batteries

Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

Batteries / PPS charging mode:

$$P_e = P_{\text{ICE}}^{opt}(V = \omega R_e) > 0$$

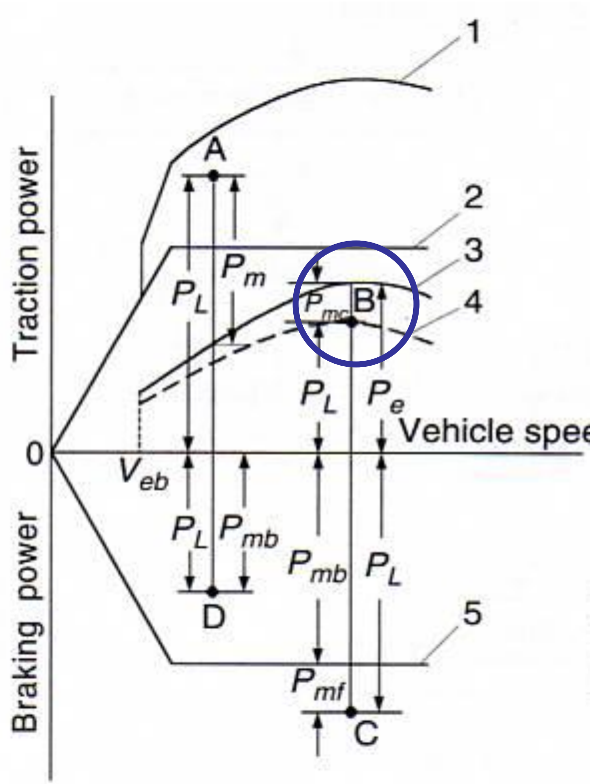
$$P_{e-m} = \left(P_{\text{ICE}} - \frac{P_L}{\eta_{t,e}} \right) \eta_{t,e,m}\, \eta_{e-m} < 0$$

$$P_{\text{PPS}-c} = P_{e-m} > 0$$

with

$$\eta_{t,e,m} = \eta_{t,e}\, \eta_{t,e-m}$$

Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

Engine alone propelling mode:

- When load power demand (point B) is less than power engine can produce while operating on its optimum efficiency line

When PPS has reached its maximum SOC

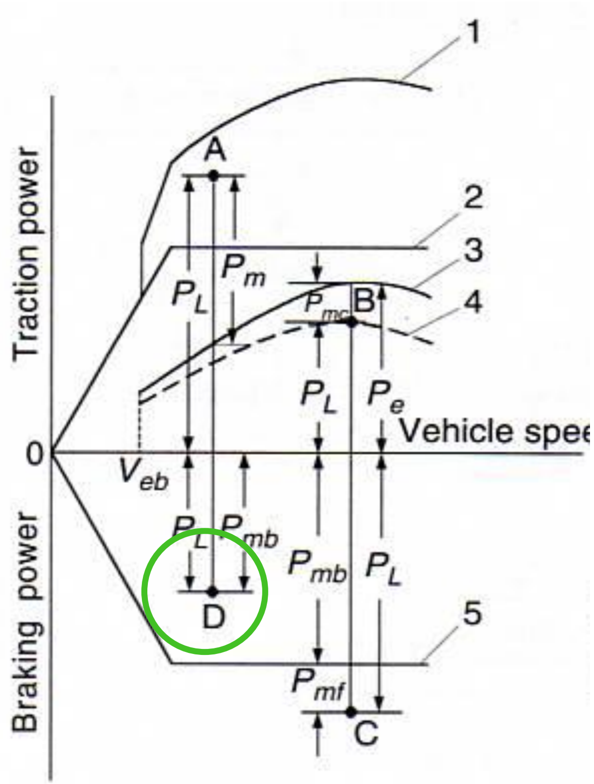
- Engine alone supplies the power operating at part load
- Electric motor is off

$$P_e = \frac{P_L}{\eta_{t,e}} > 0$$

$$P_{e-m} = 0$$

$$P_{\text{PPS}-c} = 0$$

Maximum PPS state-of-charge strategy



Regenerative alone braking mode:

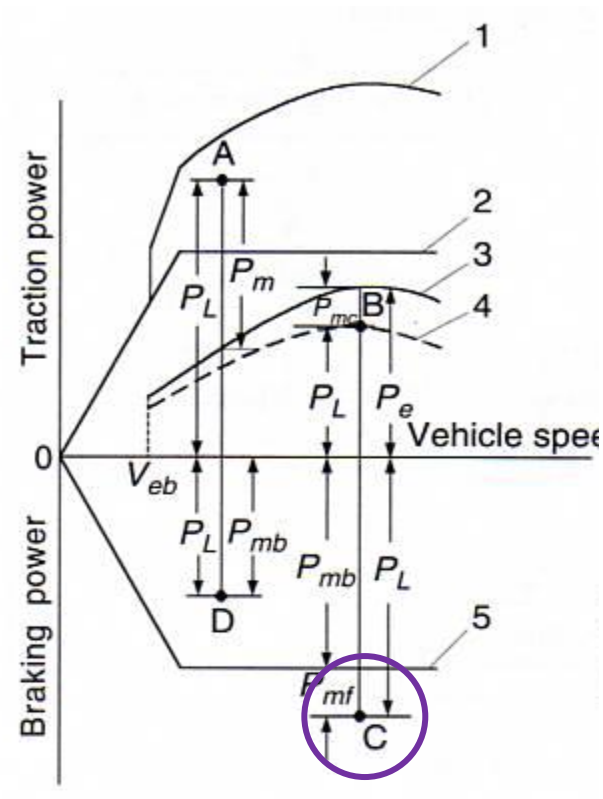
- When braking demand power is less than the maximum regeneration capability of electric motor (point D)
- Electric motor is controlled to work as a generator to absorb the demand power

$$P_{\text{e-m-braking}} = P_L \, \eta_{t,e-m} \, \eta_{e-m} < 0$$

$$P_{\text{PPS}-c} = P_{\text{e-m-braking}}$$

[Ehsani et al. 2005]

Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

Hybrid braking mode:

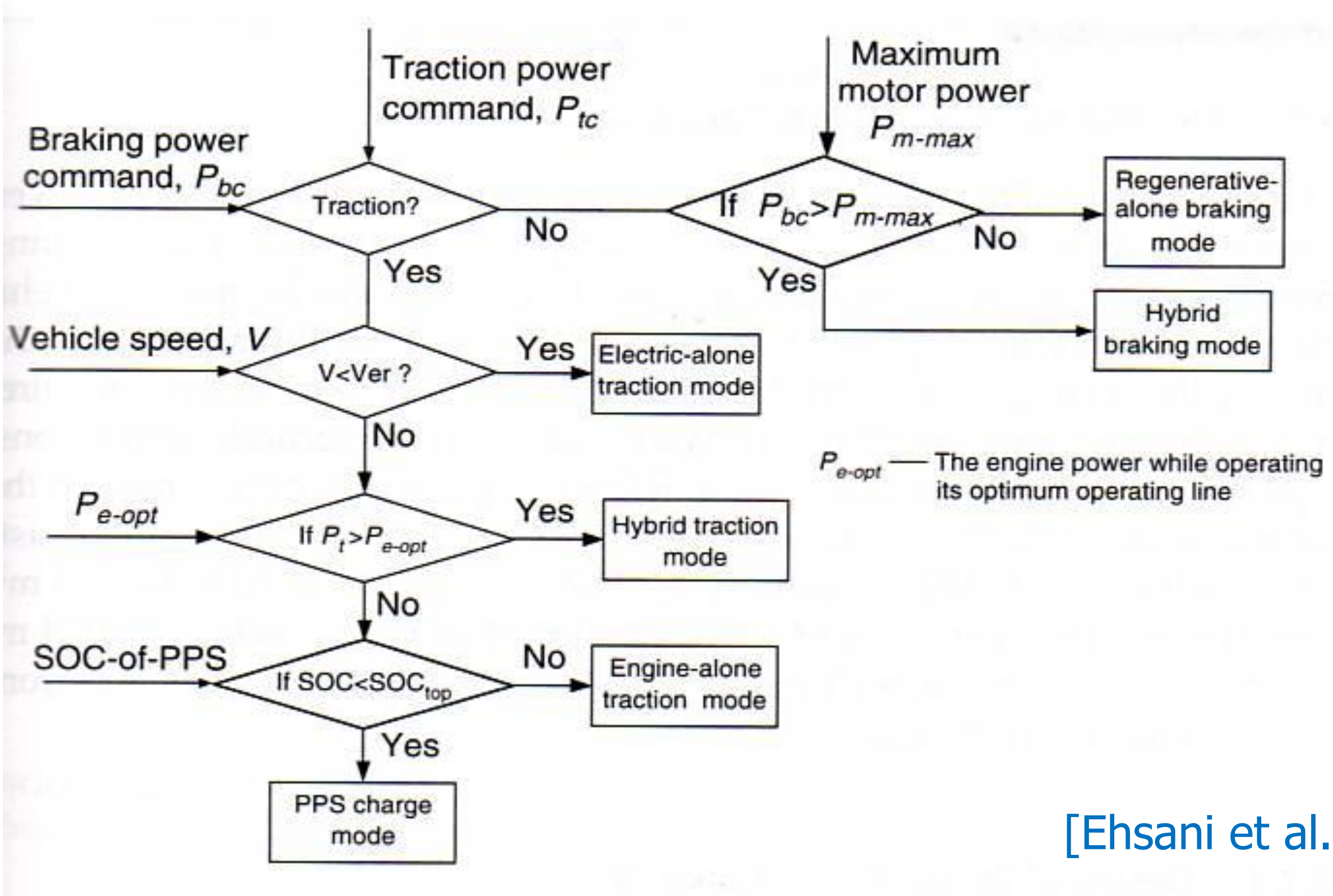
- When braking demand power is greater than maximum regeneration capability of electric motor (point C)
- Electric motor is controlled to deliver its maximum braking regenerative power
- Mechanical brakes provide the remaining part

$$P_{\text{e-m-braking}} = P^{max}_{\text{e-m-braking}}\,\eta_{e-m} < 0$$

$$P_{\text{PPS}-c} = P_{\text{e-m-braking}}$$

$$P_{\text{M-Brakes}} = P_{\text{Brake}} - P_{\text{e-m-braking}}$$

Maximum PPS state-of-charge strategy



[Ehsani et al. 2005]

Flowchart of max SOC of PPS strategy

On-off control strategy

- Similar strategy to the one used in series hybrid drive train
- Engine on-off strategy may be used in some operation conditions, typically:
  - With low speed and moderate accelerations
  - When engine can produce easily enough extra power to recharge quickly the batteries
- Engine on-off is controlled by the SOC of the PPS or batteries
- When SOC reaches its max level, engine is turned off and vehicle is propelled in electric mode only
- When SOC reaches again its low level, engine is turned on and propelled by the engine in PPS charging mode until max SOC is reached

On-off control strategy

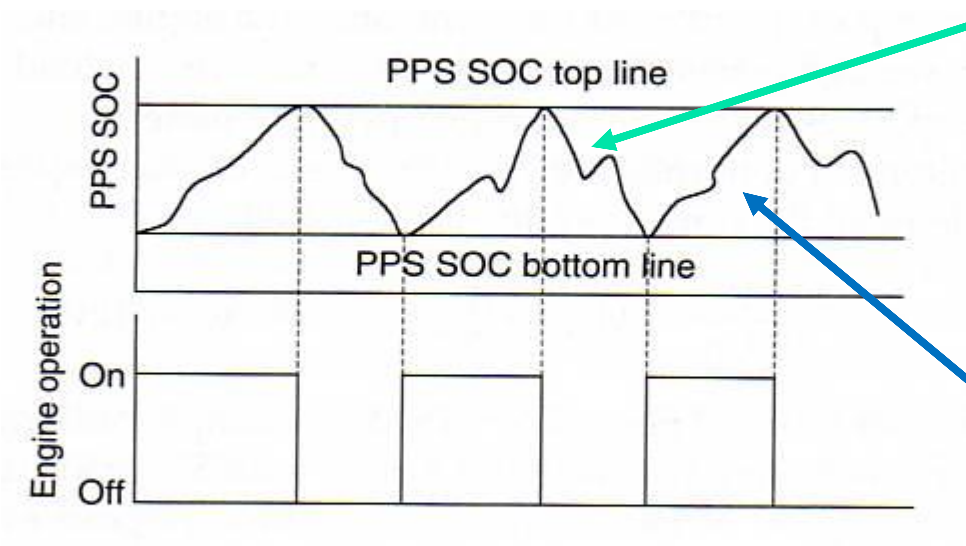


Illustration of thermostat control

[Ehsani et al. 2005]

- When SOC reaches its max level, engine is turned off and vehicle is propelled in electric motor only mode
- When SOC reaches again its low level, engine is turned on and propelled by the engine in PPS charging mode until max SOC is reached

DESIGN OF A PARALLEL HYBRID VEHICLE

Design of parallel hybrid components

- Key parameters
  - Engine power
  - Electric motor power
  - Gear ratio of transmissions
  - Batteries or peak power sources

- Great influence on the overall vehicle performance and operation efficiency

- Design methodology
  - 1/ Preliminary choice based on performance requirements
  - 2/ Accurate selection with detailed simulations

Illustrative design example

- Design specification
  - M=1500 kg
  - f = 0,01 Re=0,279 m Cx= 0,3 S=2 m²
  - Transmission ratio efficiency: $\eta_{t,e}$=0,9 $\eta_{t,em}$=0,95

- 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

Power rating of engine

- Engine should supply sufficient power to support the vehicle operation at normal constant speed on both flat or mild grade road without the help of PPS

- Engine should be able to produce an average power that is larger than the load power requested when operating in a stop-and-go pattern

Power rating of engine

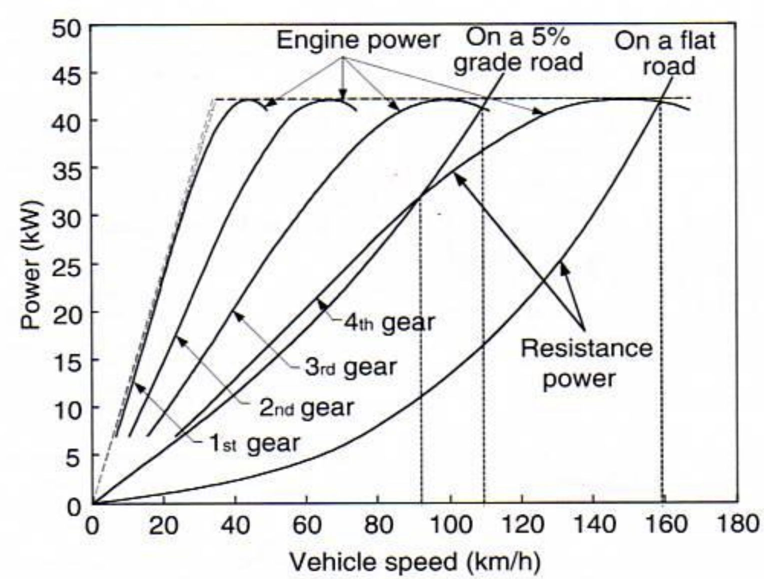
- Operating on highway at constant speed on flat road or mild grade road

$$P_{\text{ICE}} = \frac{P_{\text{RES}}}{\eta_{t,e}} = \frac{V}{\eta_{t,e}} \left(mgf\cos\theta + \frac{1}{2}\rho S C_x V^2 + mg\sin\theta \right)$$

- Illustrative example
  - V=160 km/h requires 42 kW
  - With a gear box with 4 ratios
  - Engine allows driving

    road at 5 % at 92 km/h in gear 4

    road at 5 % at 110 km/h in gear 3



[Ehsani et al. 2005]

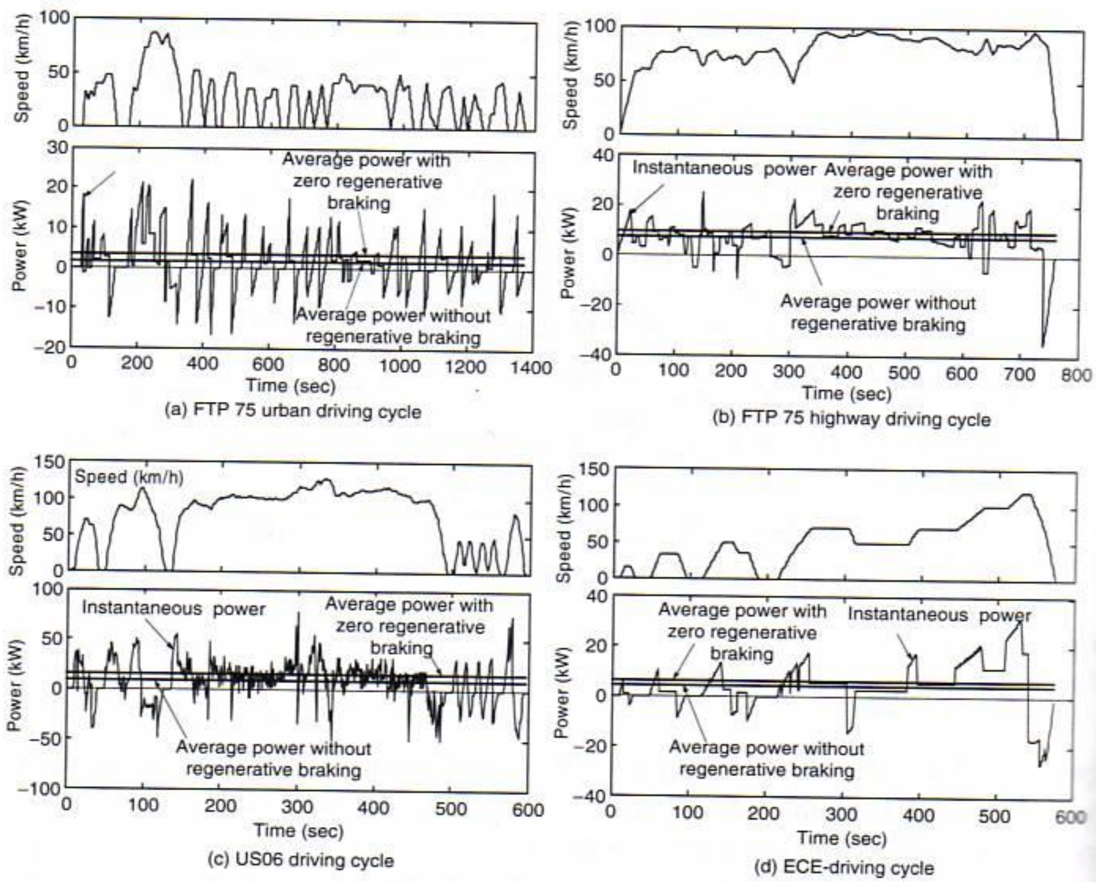
Power rating of engine

- Engine is able to supply the average power requirement in stop-and-go driving cycles

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

- The average power depends on the degree of regeneration braking (α coefficient).
- Two extreme cases: full and zero regenerative braking:
  - Full regenerative braking (α=1.0) recovers all the energy dissipated in braking and can be calculated as above
  - No regenerative braking (α=0.0) , average power is larger so that when power is negative, third term is set to zero.

Power rating of engine



[Ehsani et al. 2005]

Instantaneous and average power with full and regenerative braking in typical driving cycles

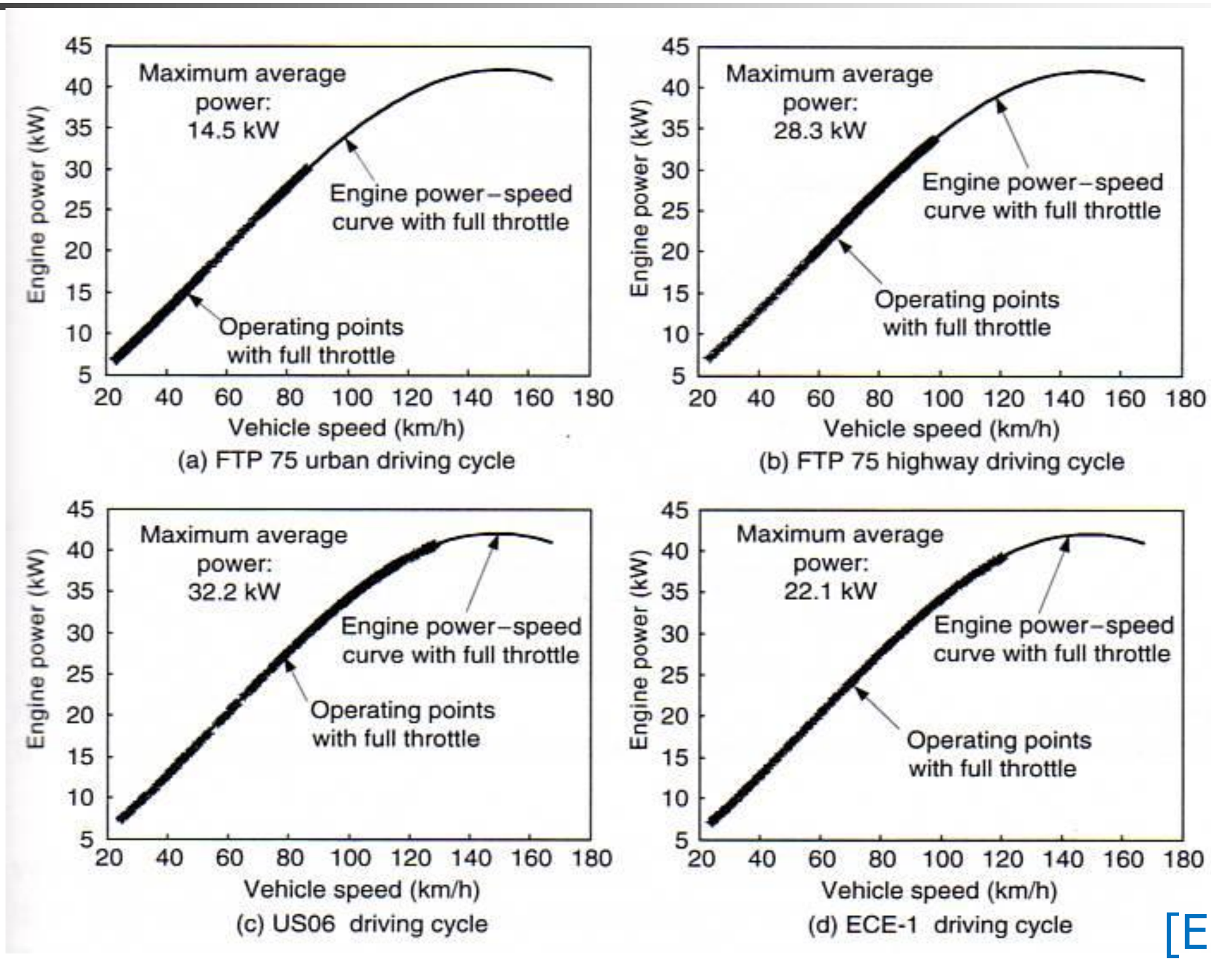
Power rating of engine

- Average power of the engine must be greater than the average power load.
- Problem is more difficult than in series hybrid because the engine is coupled to the driven wheels
  - Engine rotation speed varies with vehicle speed
  - Engine power varies with rotation speed and vehicle speed
- Estimation of the average power delivered by the engine in variable conditions: ➔ Calculate the average power that the engine can produce <u>with full open throttle</u> during a given driving cycle

$$P_{\mathrm{ICE}}^{ave} = \frac{1}{T} \int_0^T P_{\mathrm{ICE}}(\omega_e = i\,\frac{V}{R_e})\,dt$$

Power rating of engine

42 kW Engine is OK



[Ehsani et al. 2005]

Average power of a 42 kW engine

Design of electric motor power capacity

- Electric motor function is to supply the peak power to the drivetrain
- Design criteria: provide acceleration performance and peak power demand in typical driving cycles
- Difficult to directly design the e-motor power for a prescribed acceleration performance
- Methodology
  - Provide good estimates first in a preliminary approach
  - Final design with detailed simulations
- Assumption to calculate some initial estimates
  - Steady state road loads (rolling resistance, aero drag) are handled by engine while dynamic load (acceleration) is handled by electric motor

Design of electric motor power capacity

- Acceleration related to the torque output of the electric motor working alone

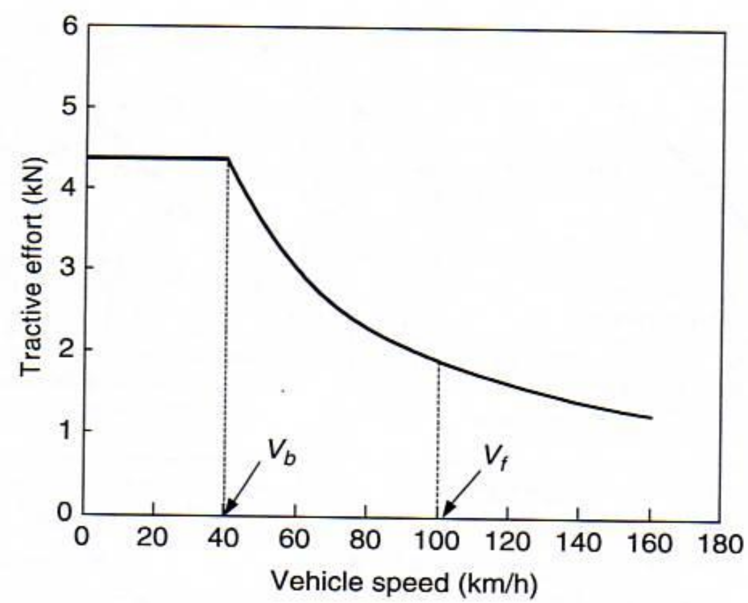
$$\eta_{t,e-m} \frac{C_{e-m} i_{t,e-m}}{R_e} = \gamma m \frac{dV}{dt}$$

- Power rating

$$P_{e-m} = \frac{\gamma\, m}{2\, \eta_{t,e-m}\, t_a} (V_f^2 + V_B^2)$$

- Illustrative example
  - Passenger car V_{max}=160 km/h, V_b=40 km/h (x=4), V_f=100 km/h
  - t_a (0 – 100km/h)=10 s, γ=1,04

Design of electric motor power capacity

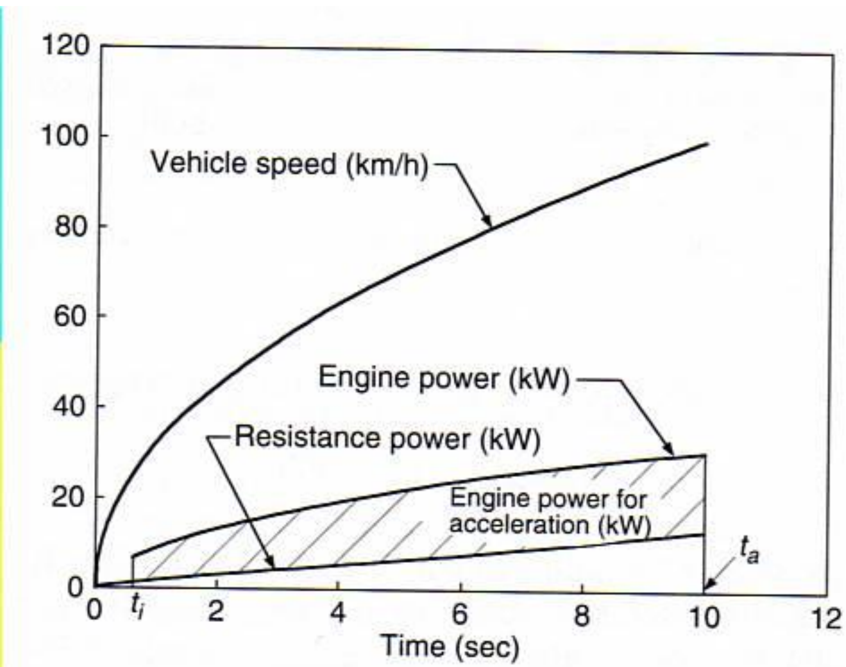


[Ehsani et al. 2005]

- Illustrative example
  - Passenger car V_{max}=160 km/h, V_b=40 km/h, V_f=100 km/h
  - t_a (0 – 100km/h)=10 s, γ=1,04

$$P_{e-m} = 74\,\mathrm{kW}$$

Design of electric motor power capacity



[Ehsani et al. 2005]

Engine remaining power: 17 kW

$$P_{e-m} = 74 - 17 = 57\,\mathrm{kW}$$

- The approach overestimates the e-motor power, because the engine has some remaining power to accelerate the vehicle also
- Average remaining power of the engine used to accelerate the vehicle

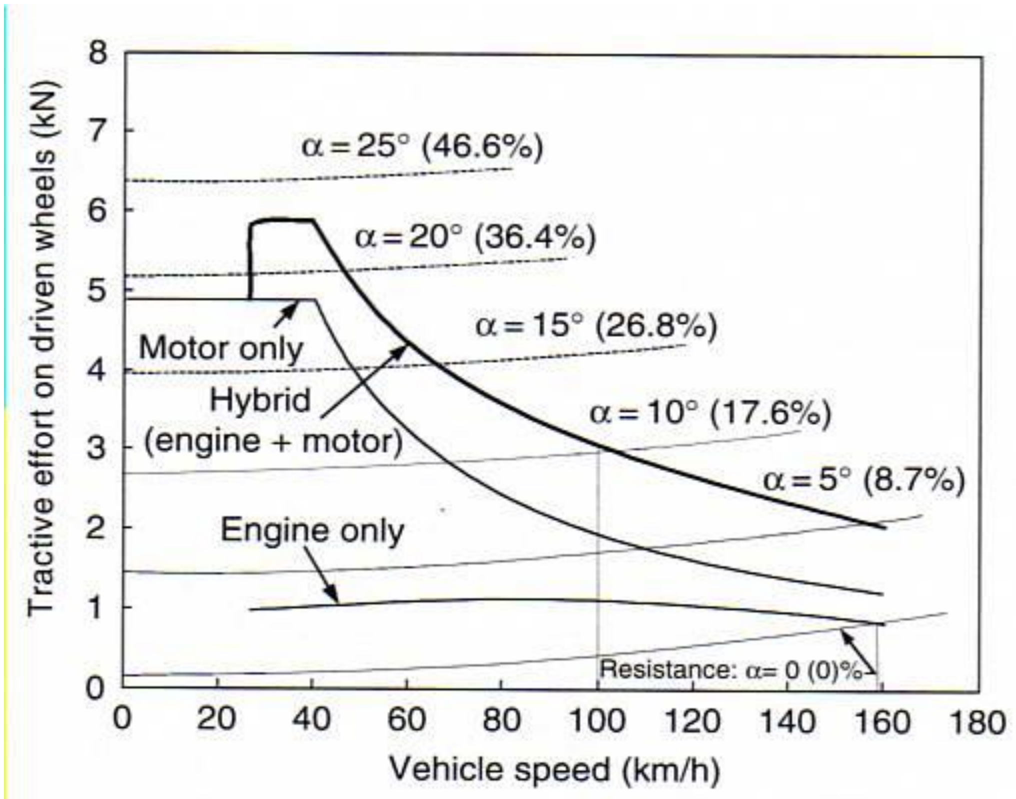
$$P_{\mathrm{ICE},accel} = \frac{1}{t_a - t_i}\int_{t_i}^{t_a} \left(P_{\mathrm{ICE}} - P_{\mathrm{RES}}\right) dt$$

- This value depends on gear ratio, so that it varies with the engaged gear ratio and it increases with the gear ratio.

Design of electric motor power capacity

- When the power ratings of engine and electric motor are initially designed, more accurate calculations must be carried out to assess the precise vehicle performance:
  - Max speed
  - Gradeability
  - Acceleration
- Gradeability and max speed can be obtained from the diagram of tractive effort and resistance forces vs speed

Design of electric motor power capacity

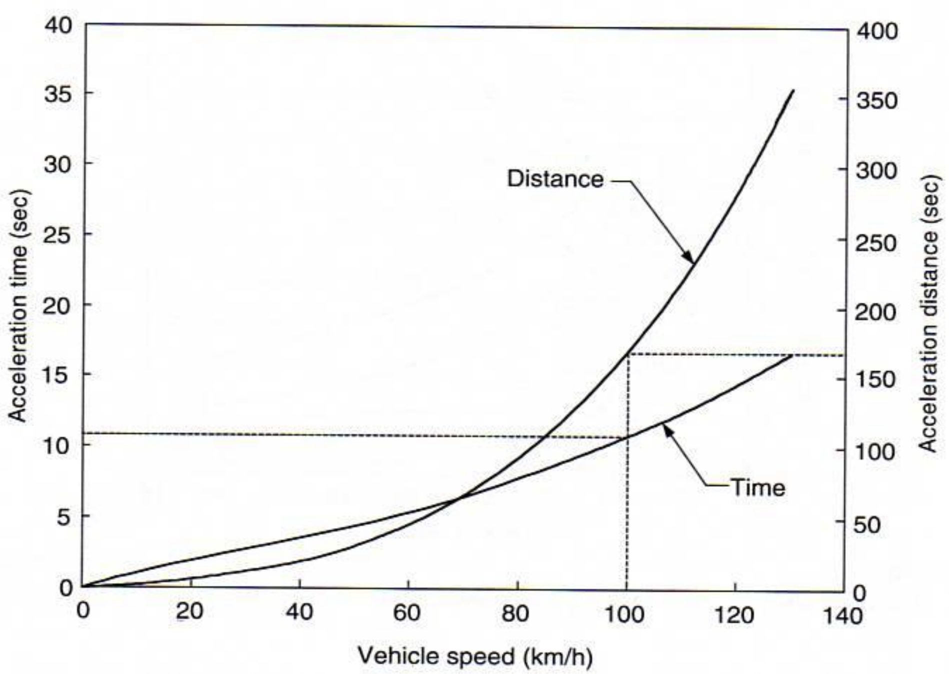


[Ehsani et al. 2005]

Illustrative example

- At 100 km/h, gradeabiltiy of 4,6% for engine alone and 18,14% for hybrid mode

Design of electric motor power capacity



[Ehsani et al. 2005]

Illustrative example

- Acceleration performance for 0-100 km/h:
  - t_a=10,7 s
  - d=167 m

Transmission design

Transmission ratio for electric motor

- Because the electric motor supplies the peak power and because it has a high torque at low speed, <u>a single ratio transmission between motor and the driven wheels</u> is generally sufficient to produce high torque for hill climbing and acceleration

Transmission ratio for engine

- Multi gear transmission between engine and wheels can enhance the vehicle performance

Transmission design

Multi gear transmission ratio between engine and wheels

- (+) Increase the remaining power of the engine and so the vehicle performance (acceleration and gradeability)
- (+) Energy storage can be charged with the large engine power
- (+) Improve the vehicle fuel economy because the engine can operate closer to its optimal speed

- (-) More complex system
- (-) Heavier and larger
- (-) Complicated automatic gear shifting control

Design of batteries and PPS

- Batteries and PPS are sized according to the power and to the energy capacity criteria

POWER CAPACITY

- Battery power must be greater than the input electric power of the electric motor

$$P_{\mathrm{PPS}} \geq \frac{P_{e-m}^{max}}{\eta_{e-m}}$$

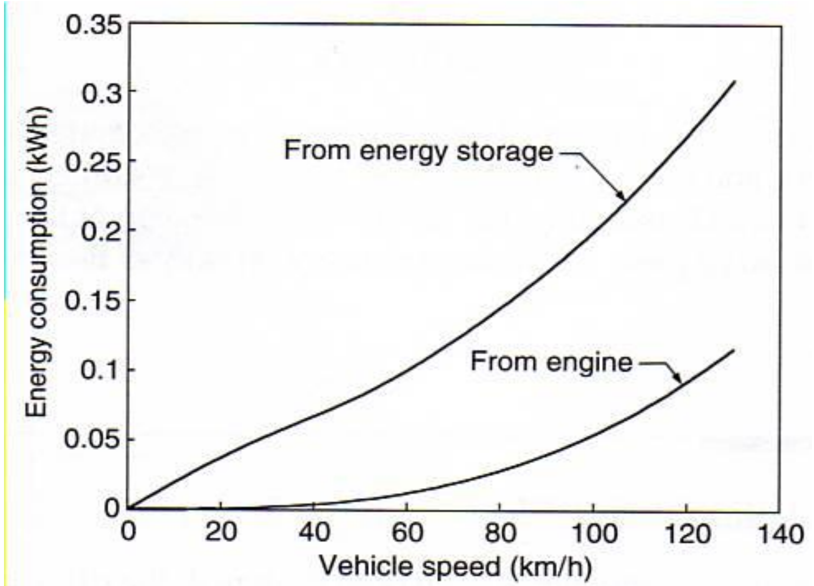
Design of batteries and PPS

ENERGY CAPACITY

- Related to the energy consumption in various driving patterns (mainly full load acceleration and typical driving cycles)
- Evaluate the energy required from the PPS and from the engine during acceleration period

$$E_{\mathrm{PPS}} = \int_0^{t_a} \frac{P_{e-m}}{\eta_{e-m}}\, dt$$

$$E_{\mathrm{ICE}} = \int_0^{t_a} P_{ICE}\, dt$$



[Ehsani et al. 2005]

- Illustrative example:
  - Energy from batteries 0,3 kWh

Design of batteries and PPS

ENERGY CAPACITY

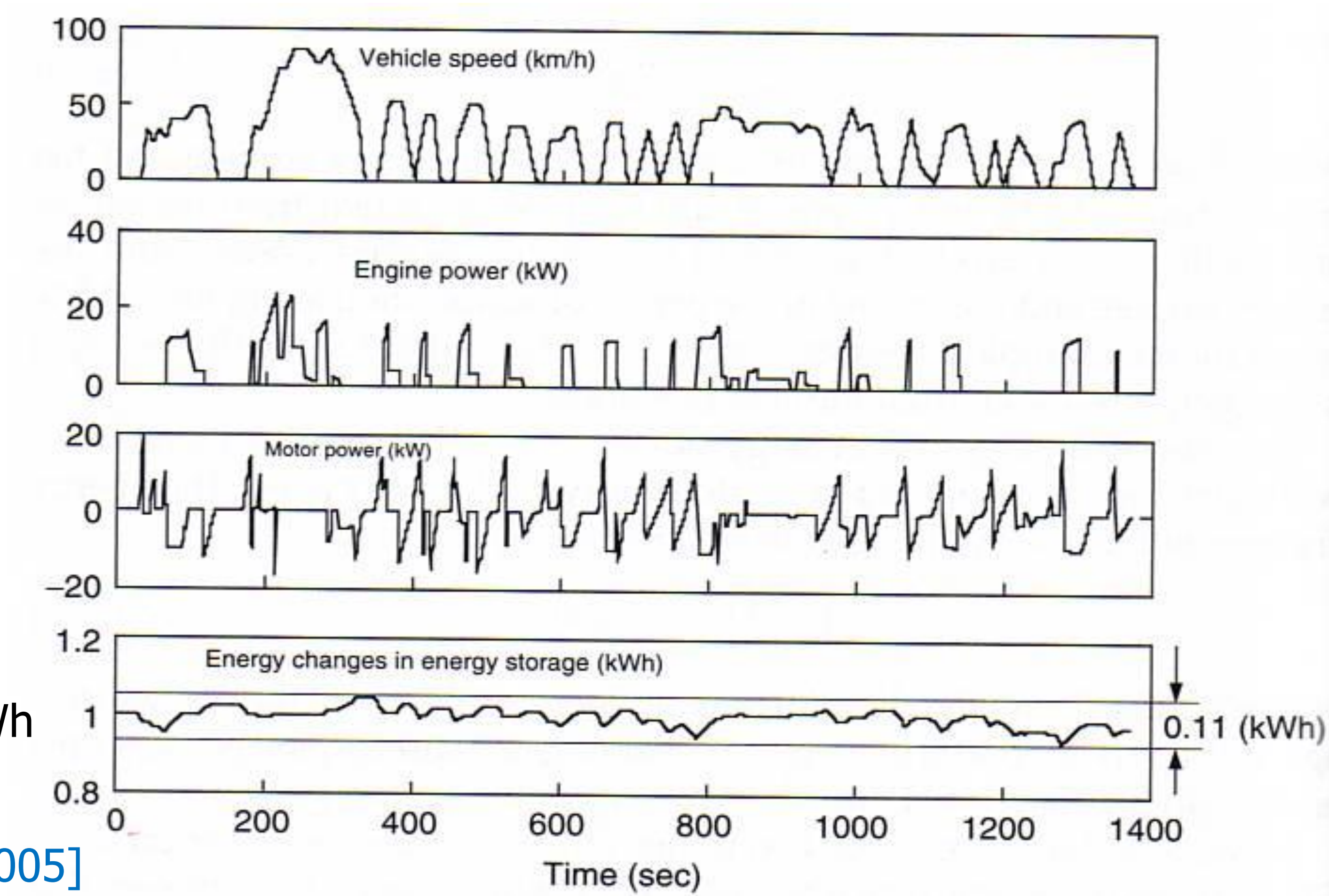
- Energy capacity must meet the energy requirements during driving pattern in drive cycles

$$\Delta E = \int_0^T \left(P_{\text{PPS-d}<0} - P_{\text{PPS-c}>0}\right)\, dt$$

- For a given control energy strategy charging and discharging power of energy storage can be obtained from simulation

- Generally, the energy consumption (and capacity sizing) is dominated by full load acceleration

Design of batteries and PPS



Max energy change: 0,11 kWh

[Ehsani et al. 2005]

Simulation results for FTP75 urban driving cycle

Design of batteries and PPS

- Not all energy stored can be used to deliver power to the drive train
  - Batteries: low SOC will limit power output and reduce the efficiency because of the increasing internal resistance
  - Ultracapacitors: low SOC results in low voltage and affects the performances
  - Flywheels: low SOC is low flywheel velocity and low voltage at electric machine to exchange port
- Only part of the stored energy can be available for use
- Part available is given by a certain percentage of its SOC

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

Design of batteries and PPS

- Energy capacity of the energy storage

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

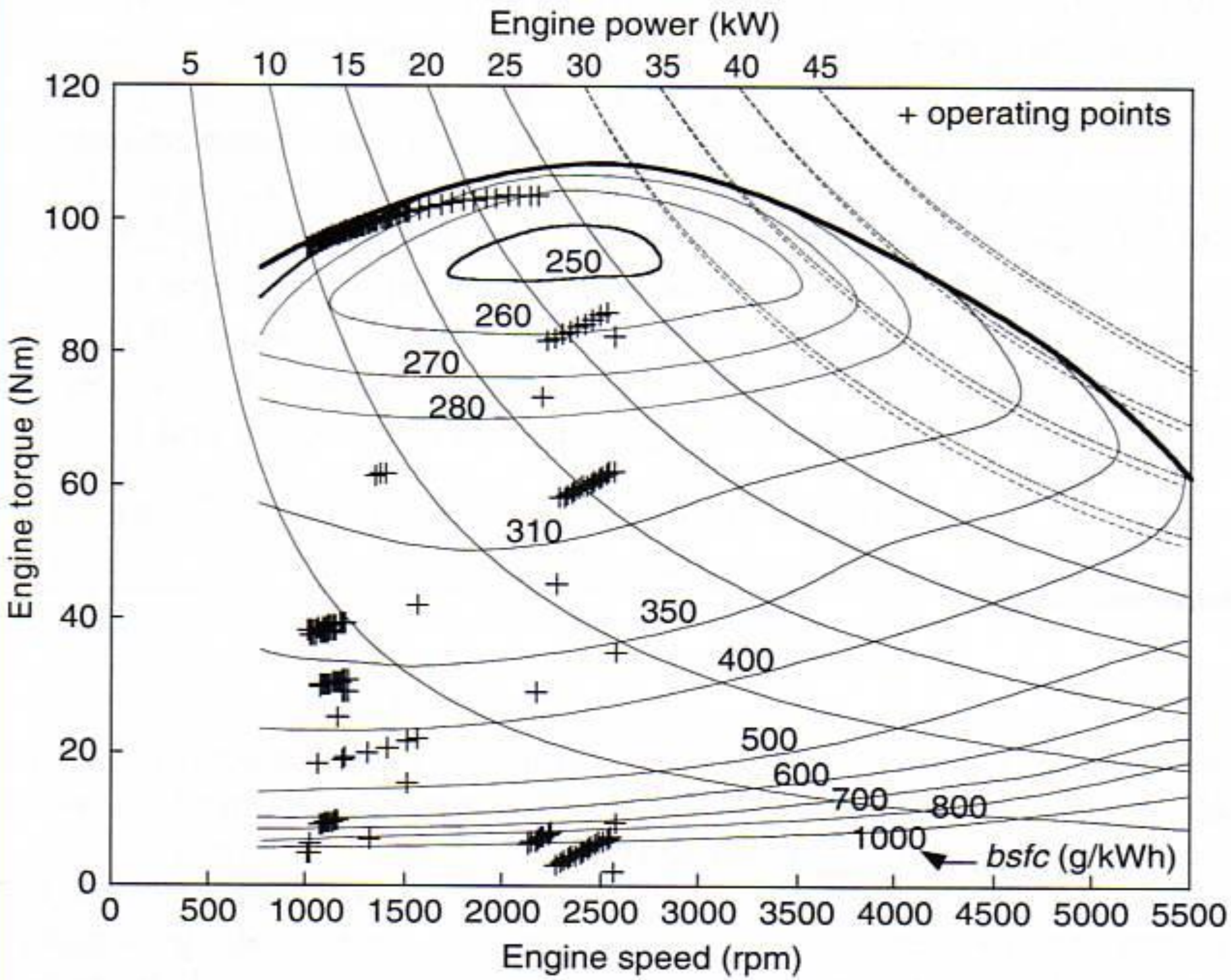
- Illustrative example
  - $\Delta E = 0{,}3$ kWh
  - $SOC_{max} - SOC_{min} = 0{,}3$
  - Ecap= 1 kWh

$$\Delta E_{\mathrm{SCap}} = \frac{0.3}{0.3} = 1\,\mathrm{kW}$$

Accurate simulation

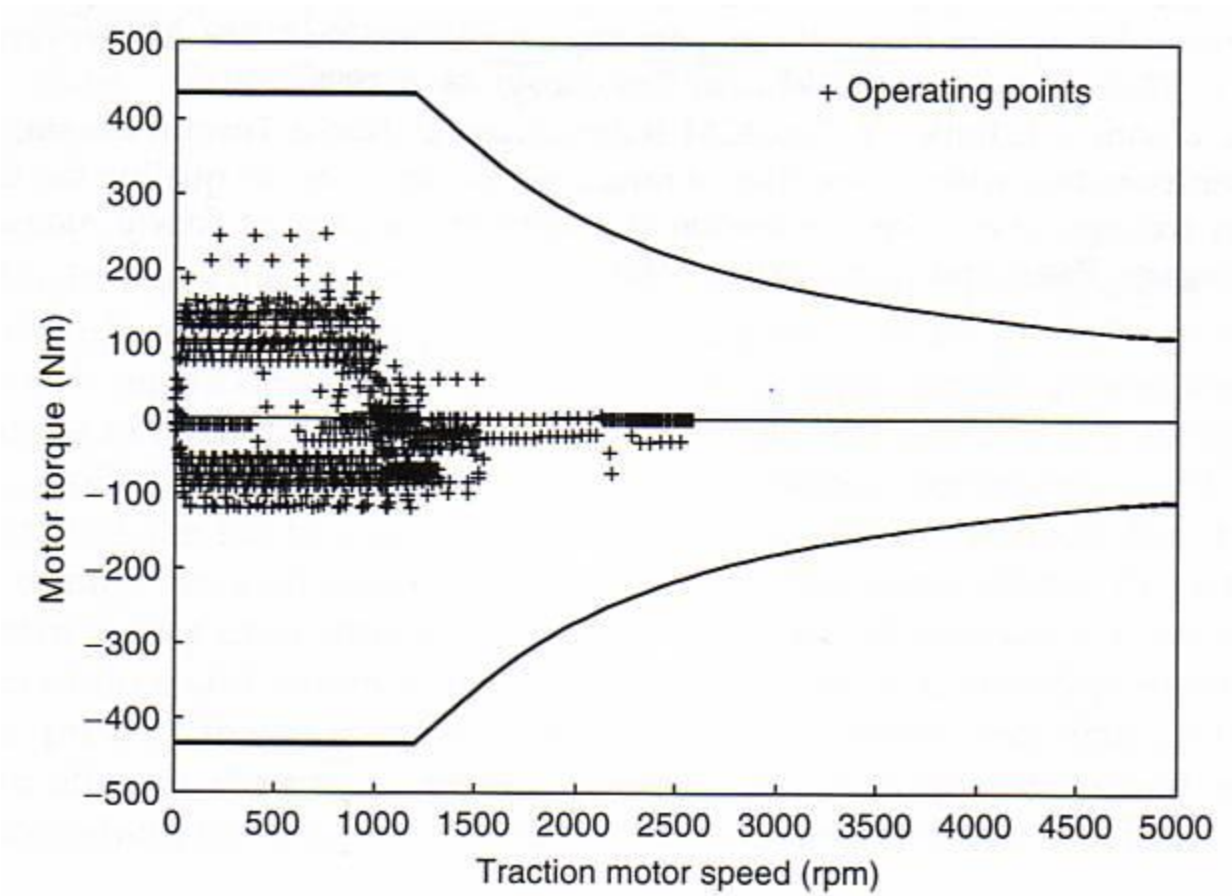
- Once the major components have been designed, the drive train has to be simulated to obtain a detailed assessment of the vehicle
- Simulation on typical drivetrain brings useful information:
  - Engine power
  - Electric motor power
  - Energy changes in energy storage
  - Engine operating points
  - Motor operating points
  - Fuel consumption

Accurate simulation



[Ehsani et al. 2005]

Accurate simulation



[Ehsani et al. 2005]

SIZING OF PARALLEL HYBRID VEHICLES USING SIMULATION AND NUMERICAL OPTIMIZATION

Application: bus optimization

- Modelling & Simulation: ADVISOR
- VanHool A300 Bus
  - Typical 12 meters bus used by public operators in Belgium
- Reference propulsion system
  - ICE Man diesel engine 205 kW (here Detroit Diesel engine from ADVISOR)
  - Number of passengers: 33-110 ➔ here 66 passengers
- Driving Cycles
  - SORT 2 Bus Drive Cycle by IUTP
  - Commercial speed: 17 kph (urban driving situation)

TABLE I
TABLE 1: VANHOOL A300 CHARACTERISTICS

Engine	Power	205 kW
	Max Efficiency	44 %
Aerodynamics	Wet surface	7.24 m^2
	Cx	0.79
Tires	Rolling resistance	0.00938
	Rolling Radius	0.5 m

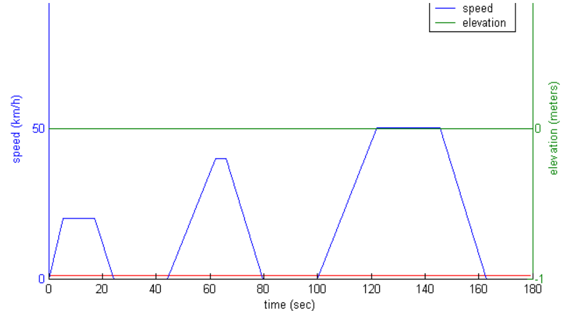


Figure 5: SORT 2 drive cycle, for easy urban cycle

Hybrid Electric Vehicles

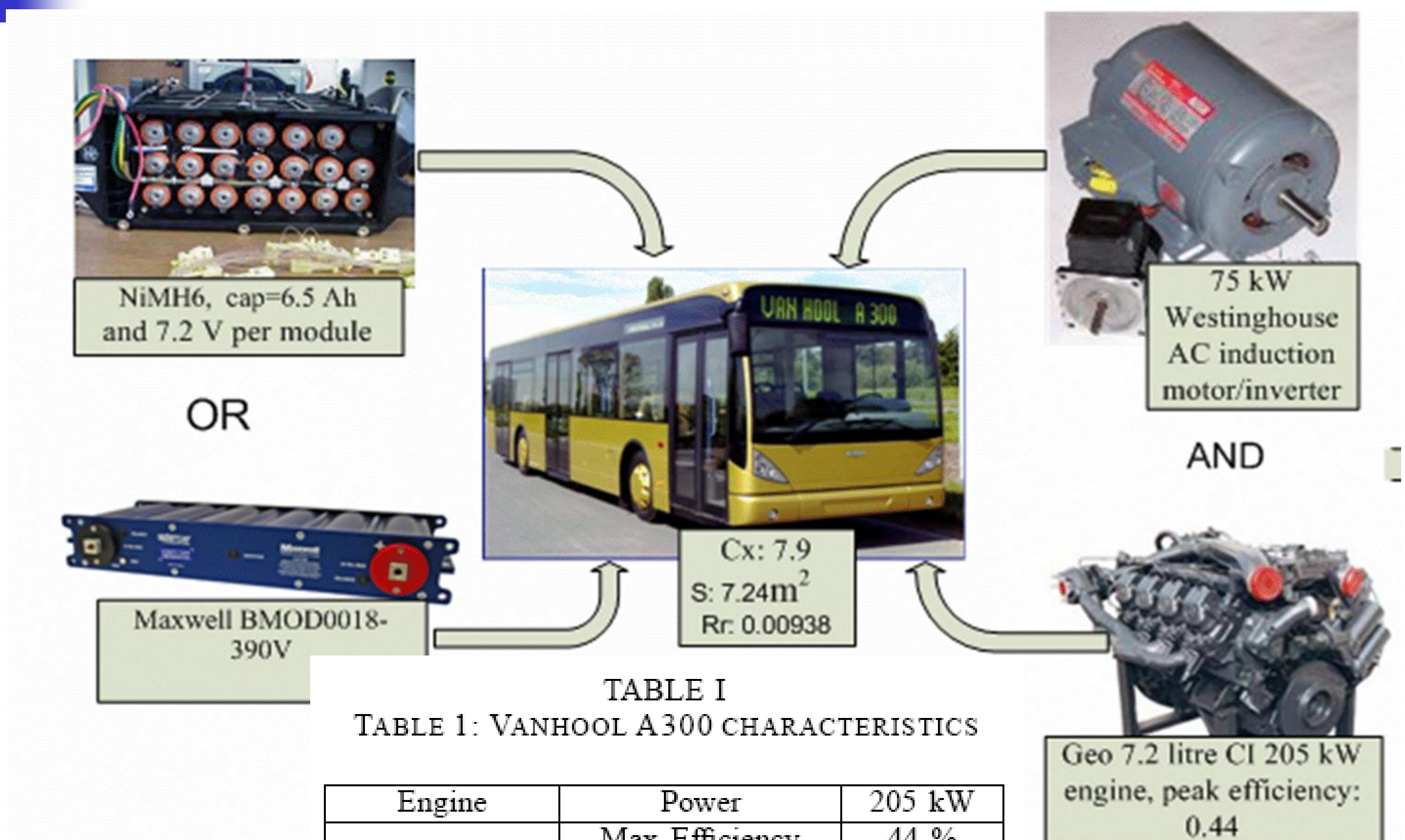
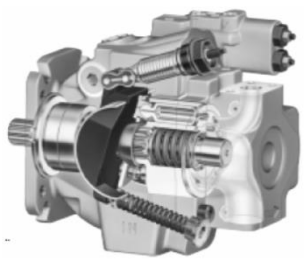
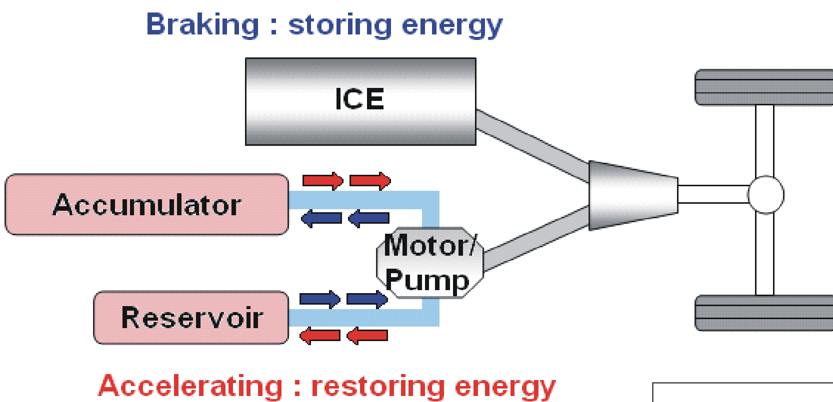


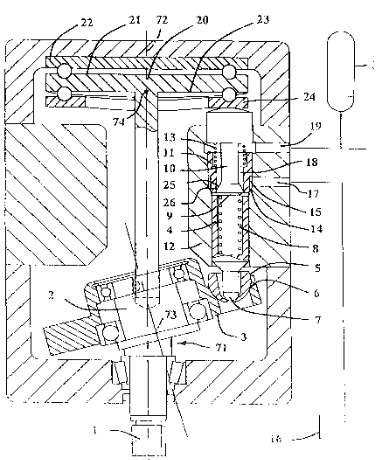
TABLE I
TABLE 1: VANHOOL A300 CHARACTERISTICS

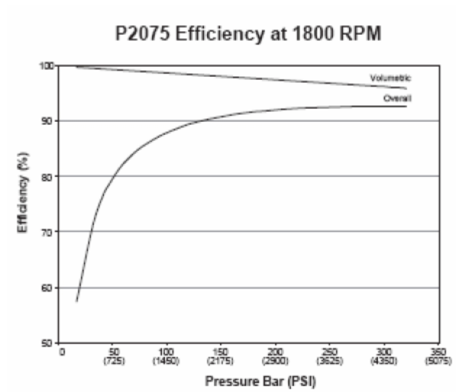
Engine	Power	205 kW
	Max Efficiency	44 %
Aerodynamics	Wet surface	7.24 m^2
	Cx	0.79
Tires	Rolling resistance	0.00938
	Rolling Radius	0.5 m

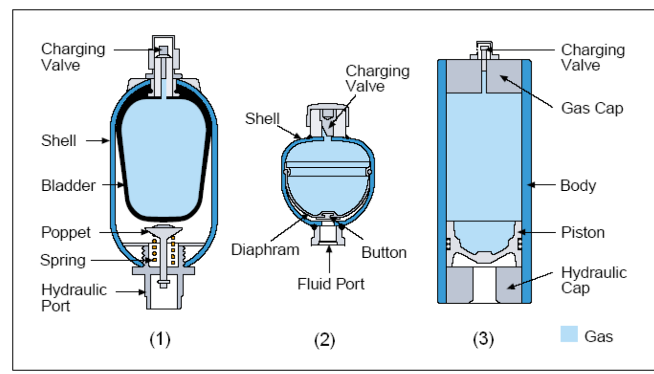
Hybrid Hydraulic Vehicle









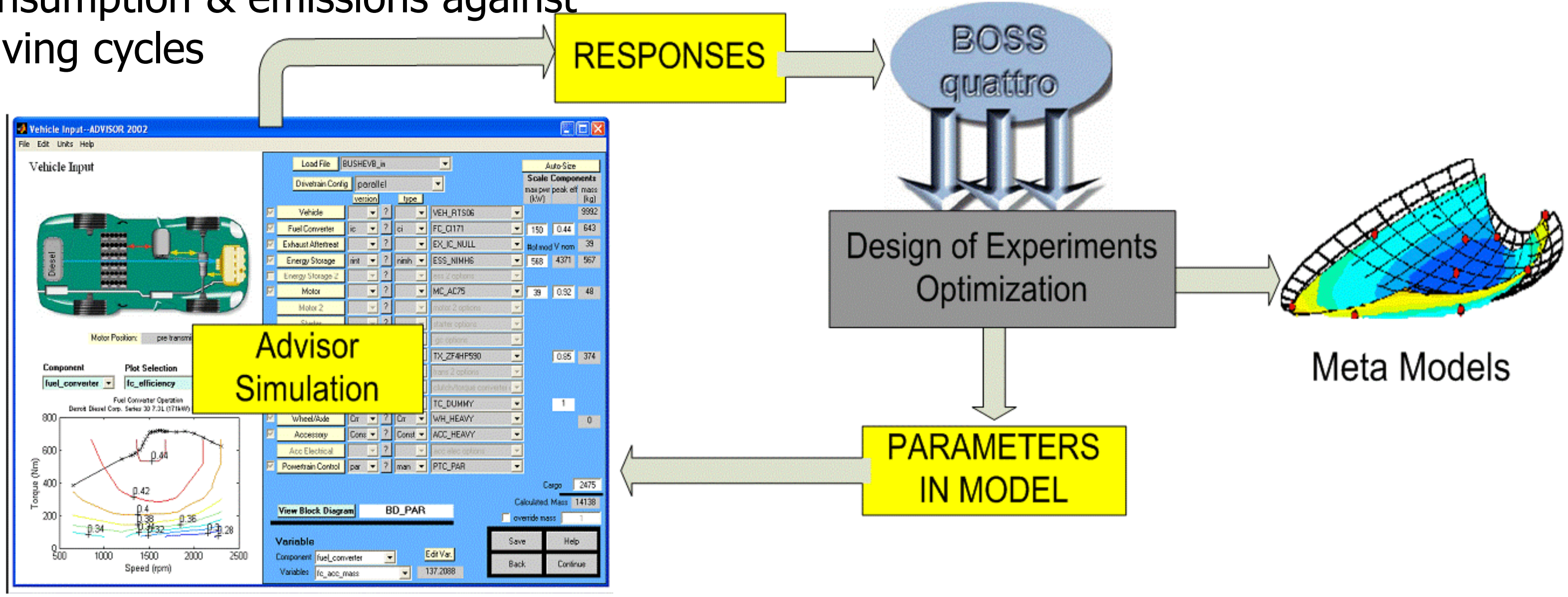


New reversible hydraulic motor /pump: Low drag, high efficiency, fluid=water
➔ Parker P2 or P3 series

Hydraulic accumulators (HP) / Reservoir (LP): high efficiency (95%)
En.: 0,63 Wh/kg Power ~ 90 kW/kg
➔ Hydac

ECOEFFICIENCY: AN OPTIMIZATION APPROACH

- Parametric models (scaling factors) in ADVISOR
- Simulation of performances and fuel consumption & emissions against driving cycles
- A parametric study is made in BOSS QUATTRO to construct some response surface approximations of US and Ecoscore



- The ecoefficiency design optimization problem is solved using a multi objective genetic algorithm (MOGA) available in BOSS-QUATTRO based on response surface method

Optimization: Problem Statement

- Mathematical multi objective design problem statement:

Minimize: $F(X) = \{f_1(X) = \tilde{E}_{\text{Ecoscore}}, f_2(X) = 1/\tilde{\text{US}}\}$

With respect to $X = (P_{\text{ICE}}, P_{\text{e-motor}}, N_{\text{Bat/SCap}})$

Subject to:

$$t_{acc:0-60km/h} \leq 20 \text{ s}$$
$$V_{max} \geq 100 \text{ km/h}$$
$$\theta_{max} \geq 5\ \%$$
$$m \leq 20000 \text{ kg}$$
$$\text{Cost} \leq 500.000 \text{ euro}$$
$$150 \leq P_{\text{ICE}} \leq 200$$
$$50 \leq P_{\text{e-motor}} \leq 100$$
$$400 \leq N_{\text{Bat}} \leq 800$$

Numerical Application

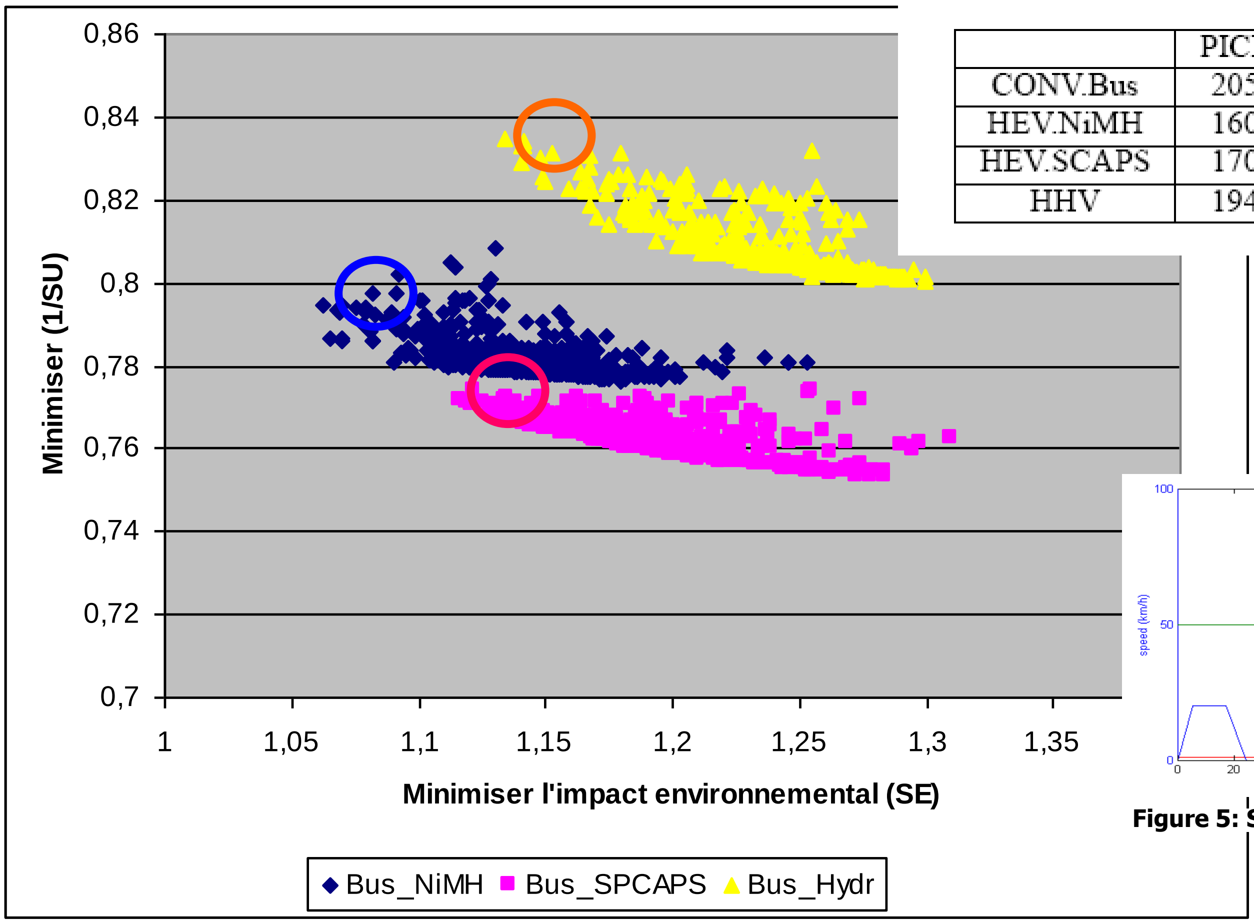


TABLE II
OPTIMIZED COMPONENTS SIZES COMPARISON COMPONENTS

	PICE	Pmotor	NBat,UCP,HACC
CONV.Bus	205		
HEV.NiMH	160	100	666
HEV.SCAPS	170	86	578
HHV	194	88	633

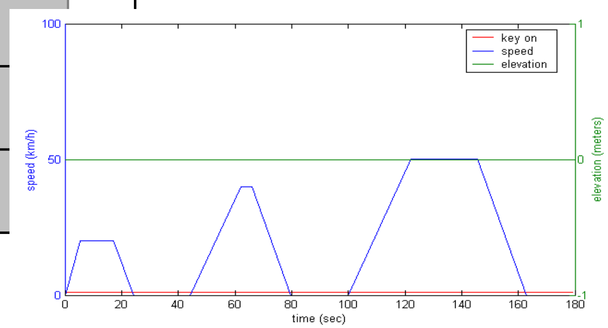


Figure 5: SORT 2 drive cycle, for easy urban cycle

Numerical Application

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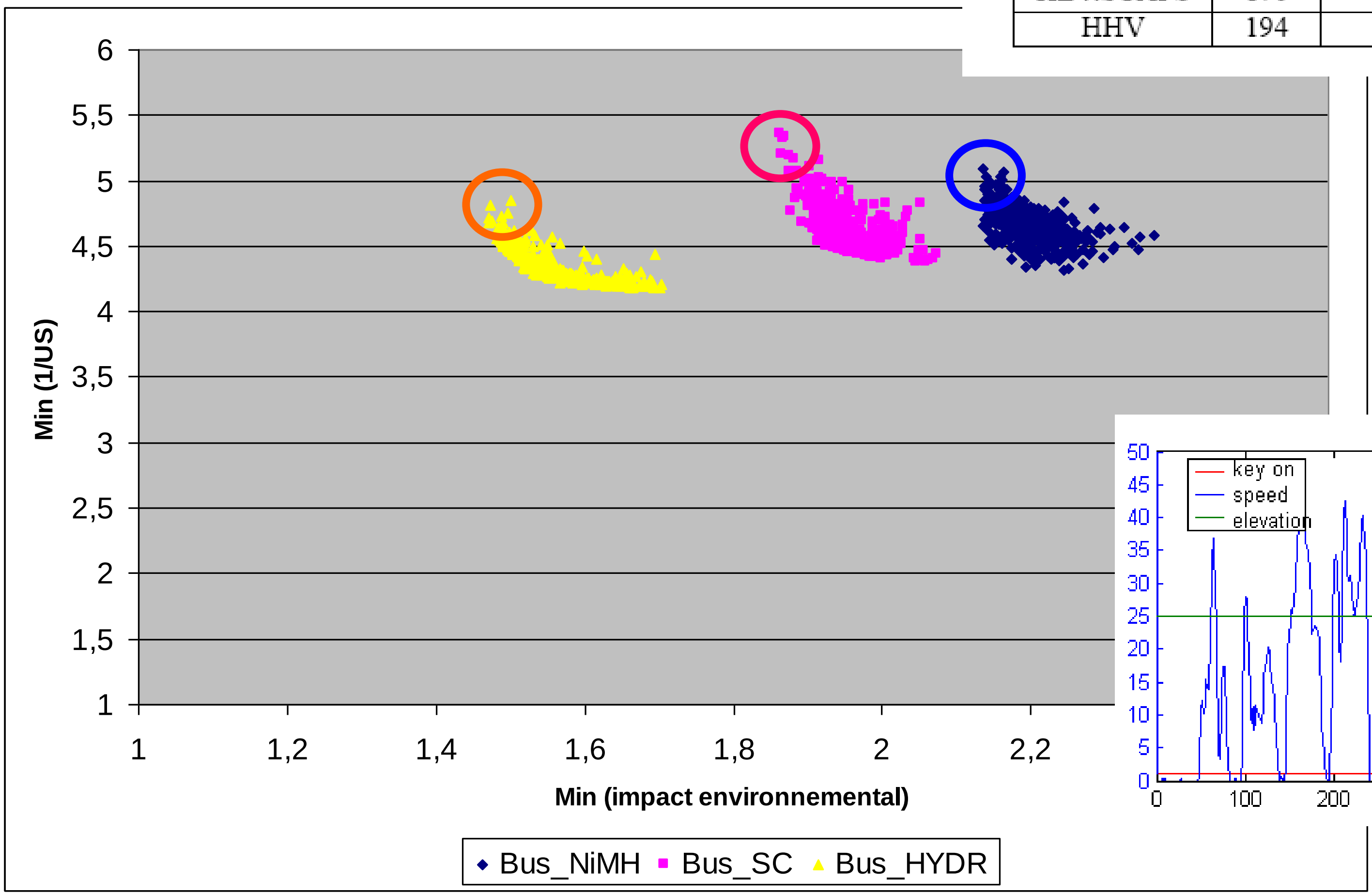

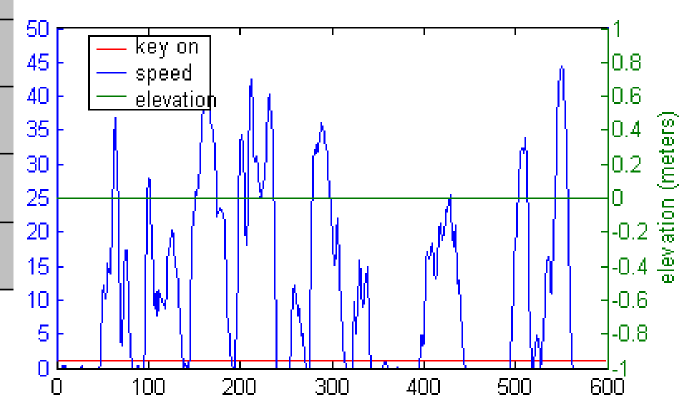

Many thanks for your kind attention

All the best in your future professional life