MECA0527: PLUG-IN HYBRID ELECTRIC VEHICLES. DESIGN AND CONTROL

Pierre Duysinx

Research Center in Sustainable Automotive Technologies of University of Liege

Academic Year 2021-2022

References

- C.C. Chan and K.T. Chau. « Modern Electric Vehicle Technology » Oxford Science Technology. 2001.
- C.M. Jefferson & R.H. Barnard. Hybrid Vehicle Propulsion. WIT Press, 2002.
- J. Miller. Propulsion Systems for Hybrid Vehicles. IEE Power & Energy series. IEE 2004.
- M. Ehsani, Y. Gao, S. Gay & A. Emadi. Modern Electric, Hybrid Electric, and Fuel Cell Vehicles. Fundamentals, Theory, and Design. CRC Press, 2005.

Outline

- Introduction

- Control strategies
  - Maximum state-of-charge of peak power source strategy
  - Engine on-off strategy

- Sizing of major components

Introduction

- In charge sustaining HEV, the net energy consumption of energy storage is zero around a complete driving cycle
- All propulsion energy comes from the fuel (gasoline, diesel, CNG… in ICE or hydrogen in FC vehicles)
- The charge of the PPS fluctuates in a narrow window.
- The PPS sizing is governed by power rating rather than the energy storage capacity.
- PPS acts rather like an energy buffer so as the name Peak Power Storage (PPS).
- The function can be realized either by batteries or supercapacitors of fly wheels, or even better an optimized combination of these ones.

Introduction

- With the development of advanced battery technologies, the energy storage capacity of batteries has significantly improved.
- Using high energy batteries as peak power sources is a waste.

- Plug-in hybrid electric drivetrains are designed to fully or partially use the storage capacity of modern batteries.
- Energy storages are used to displace part of the primary chemical energy source (gasoline, diesel, CNG…) by electrical consumption from the electrical network.

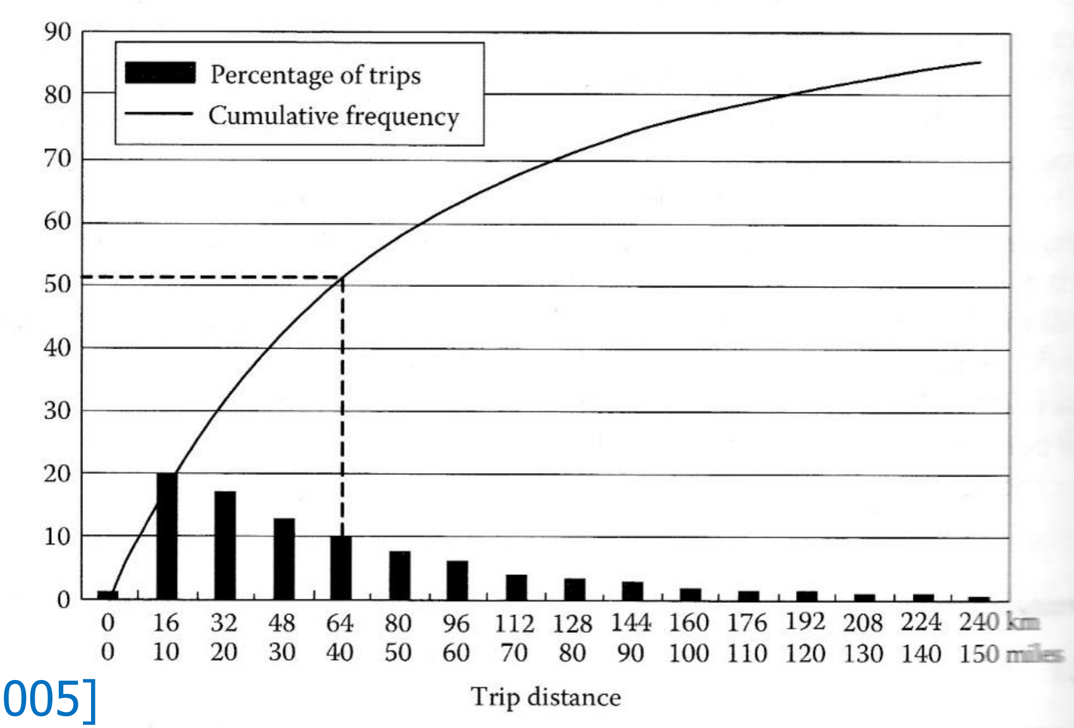
- Most of differences between energy storage of plug-in hybrid drivetrain wrt charge sustaining HEV are in the drivetrain control strategy.

Statistics of Daily Driving Distance

- The amount of petrol fuel displaced to utility electricity network stems mainly from the amount of electrical energy that be stored by recharge and so it depends on:
  - The battery / energy storage capacity;
  - The total distance between two recharges;
  - The daily driving distance;
  - The electrical power usage profiles;
  - The driving cycle profiles;
  - The control strategy.

Statistics of Daily Driving Distance

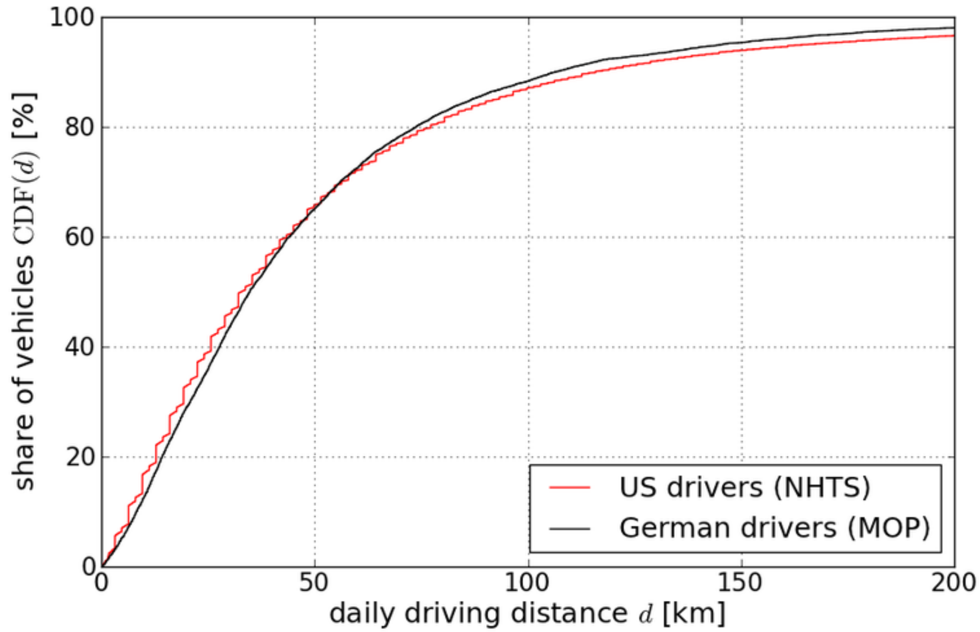
- Daily driving distance distribution and cumulative factor (from Eshani et al., 2010) derived from 1995 US National Personal Transport Survey data.



[Ehsani et al. 2005]

Statistics of Daily Driving Distance

- Daily driving distance distribution and cumulative factor: comparison of US and Germany



Ref: Vehicle charging infrastructure demand for the introduction of plug-in electric vehicles in Germany and the US Conference Paper. May 2012. Electric Vehicle Symposium (EVS) 26

Statistics of Daily Driving Distance

- The daily driving distance distribution and cumulative factor reveals that about half of the driving distances are less than 64 km per day.
- Designing a vehicle for an electric range of 64 km will have half of its driving distance in pure EV and so will lead to the same amount of oil displacement.
- Even with 32 km of electrical range, there is still a huge amount of oil that can be saved and substituted by electricity taken from the grid.

ENERGY MANAGEMENT STRATEGY

- Charge depleting mode (CD): an operation mode in which the SOC of the energy storage may fluctuate, but on the average decreases while driving.
- Charge sustaining mode (CS): An operation mode in which the SOC of the energy storage may fluctuate but on average is maintained a certain level while driving.
- All Electric Range (AER): After a full recharge, the total distance (km) driven electrically (engine off) before the engine turns on for the first time.
- Electric Vehicle Kilometers (EVKM): After a full recharge, the cumulative kilometers driven electrically (engine off) before the vehicle reaches the charge sustaining mode (CS).

ENERGY MANAGEMENT STRATEGY

- Charge depleting range (CDR): after a full recharge, the total number of kilometers driven before the vehicles reaches charge sustaining mode (CS).
  - The EVKM dictates pure electric driving. However, CDR may include engine propulsion but, on the average, the SOC of the energy storage decreases till the sustaining level.

- PHEVxy: A PHEV with a useable energy storage equivalent to xy km of driving energy on a reference driving cycle.
  - For instance, PHEV20 can replace 20 miles/km <u>equivalent</u> of driving using oil by the same distance using electrical energy from the grid.
  - PHEV20 for instance does not imply that the vehicle will achieve 20 km in AER, EVKM or CDR on the reference driving cycle.

All Electric Range focused Control strategy

- The idea behind the AER control strategy is to use the energy of the battery storage intensively.

- One possibility ➔ to allow the driver to manually select between CS mode and full EV operating mode.
- Flexibility for the driver to determine where and when to use the pure EV mode.

- Useful for vehicles operating in regions where combustion engine is restricted e.g. low emission zone.
  - Select pure EV mode just before entering low emission zones
  - In other places, pure EV mode can be selected depending on the energy status of the battery storage and the power demand.

All Electric Range focused Control strategy

- In <u>other driving conditions</u>, one can select the pure EV mode or the Charge Sustaining mode.
  - Pure EV mode may be selected in the start of the trip to use fully the electric energy.

- AER control strategy divides the whole trip in two modes: pure EV and Charge Sustaining (CS).
- ➔ Possibility to reuse other design and control strategies developed for HEV and EV .

All Electric Range focused Control strategy

- For series hybrids, the power rating of the e-motor, the engine/ generator, the energy storage are almost the same as for CS hybrid.
- The e-motor power ensures the acceleration performance, the grade-ability and the top speed performance.
- The engine / generator power supports the vehicle driving at constant speed on flat and mild roads.
- The energy storage power should be larger than the power minus the engine/generator power.

$$\boxed{P_{Bat} \geq P_{e-mo} - P_{E-G}}$$

All Electric Range focused Control strategy

- For parallel or series/parallel hybrids, the e-motor power should meet the peaking power demand of the reference driving cycles unless the vehicle will be somewhat sluggish compared to the driver's expectations.

All Electric Range focused Control strategy

- Calculation of component power requirement:
  - Traction power needed at the wheels

$$P_t\,[kW] = \frac{V}{1000}\left(m\,g\,f_{RR} + \frac{1}{2}\rho_a\,C_D\,S\,V^2 + m\,\gamma\,\frac{dV}{dt} + m\,g\,\sin\theta\right)$$

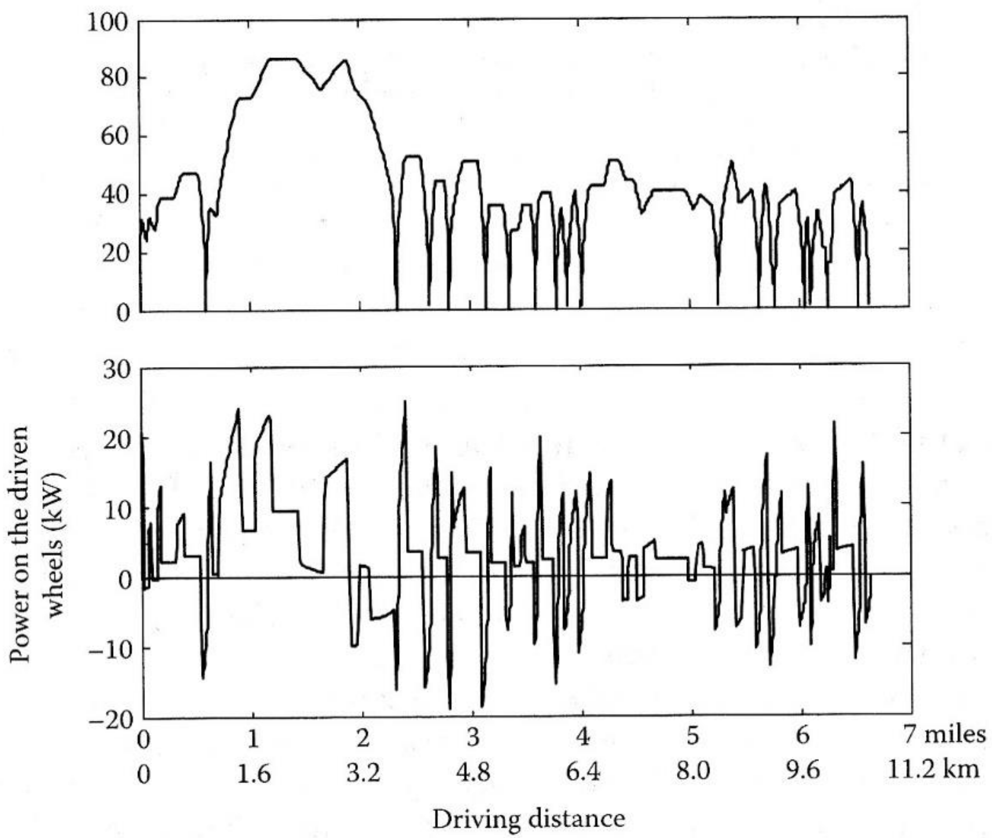
  - Account for the drivetrain efficiency to size the output power of the e-motor

$$P_{e-m} = \frac{P_t}{\eta_t}$$

  - The peaking power of the energy storage has also to consider the efficiency of the e-motor efficiency, of the power electronics, and the transmission.

$$P_{bat} = \frac{P_{e-m}}{\eta_{e-m}\eta_{Ctrl}} = \frac{P_t}{\eta_t\eta_{e-m}\eta_{Ctrl}}$$

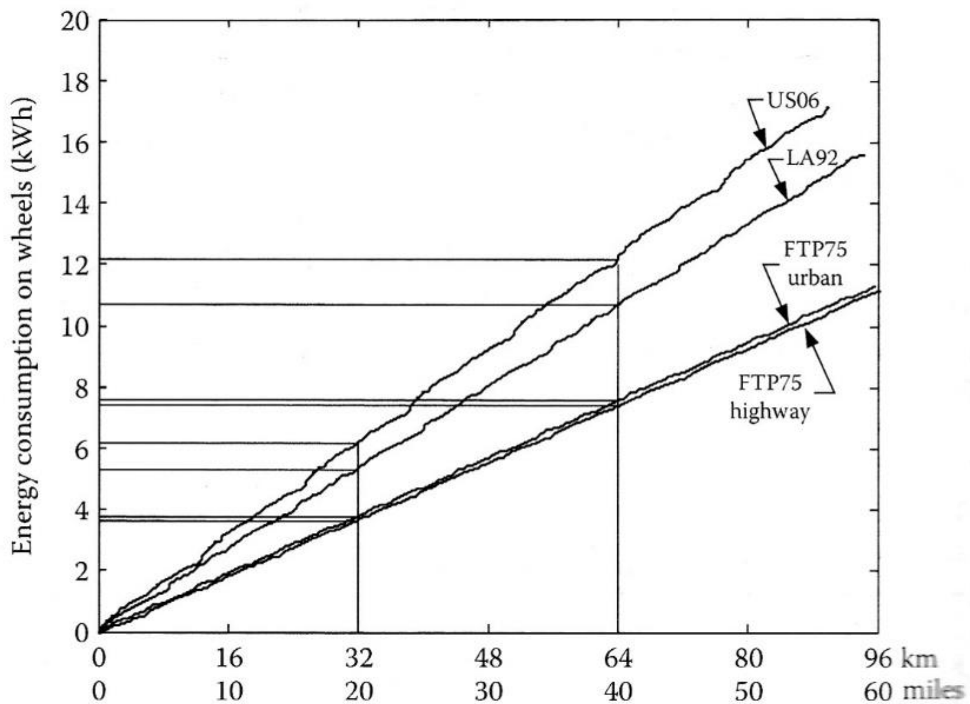
All Electric Range focused Control strategy



[Ehsani et al. 2005]

All Electric Range focused Control strategy

- Integrating the electrical power consumption over the time will provide the energy consumption by the propulsion



[Ehsani et al. 2005]

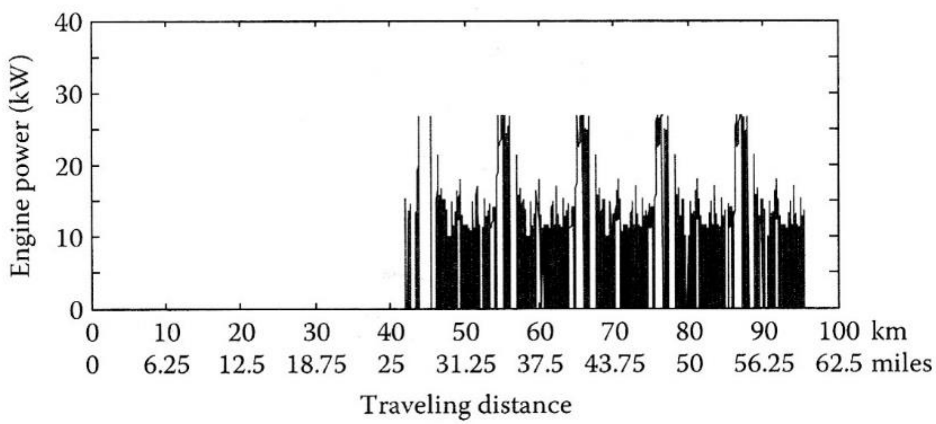
All Electric Range focused Control strategy

- Appropriate driving cycles should be considered for the design.
  - Aggressive driving cycles with large accelerations will need large motor drive and energy storages and will give rise to good vehicle acceleration and drive-ability performance
  - Mild driving cycles will yield small motor power rating and energy storage but also the feeling to a have a sluggish vehicle performance.

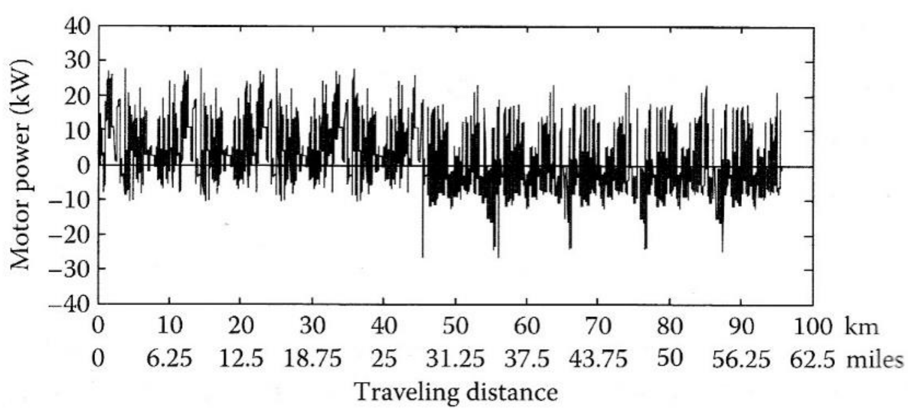
All Electric Range focused Control strategy

- Simulation of typical passenger car on FTP75 driving cycle
  - Masse m = 1700 kg
  - Rolling resistance f_{RR}= 0.01
  - Drag coefficient C_D: 0.3
  - Frontal area S: 2.2
  - Rotational inertia factor: γ=1.05

All Electric Range focused Control strategy



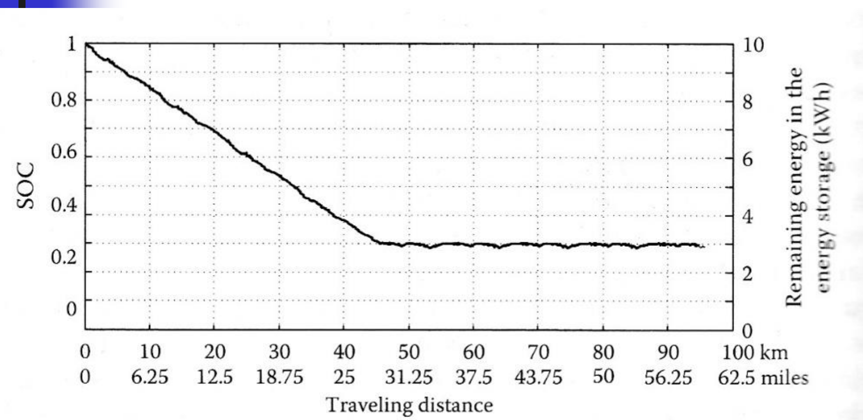
- Engine power vs travel distance in charge depleting mode against FTP75 driving cycle.

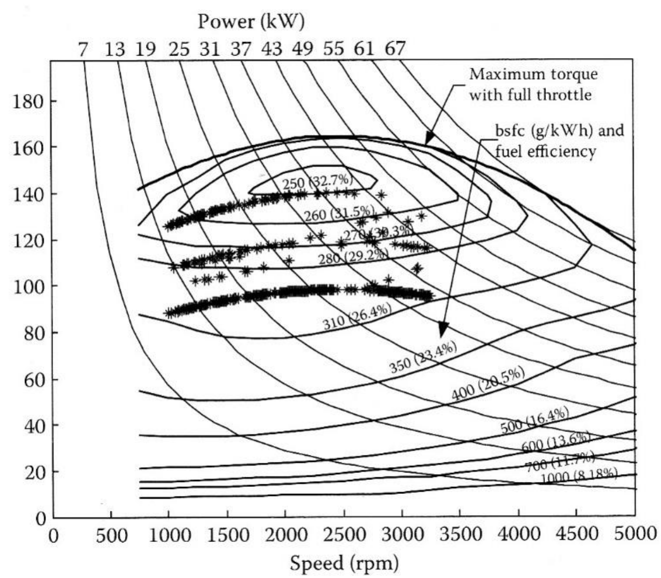


- Motor power vs travel distance in charge depleting mode.

[Ehsani et al. 2005]

All Electric Range focused Control strategy

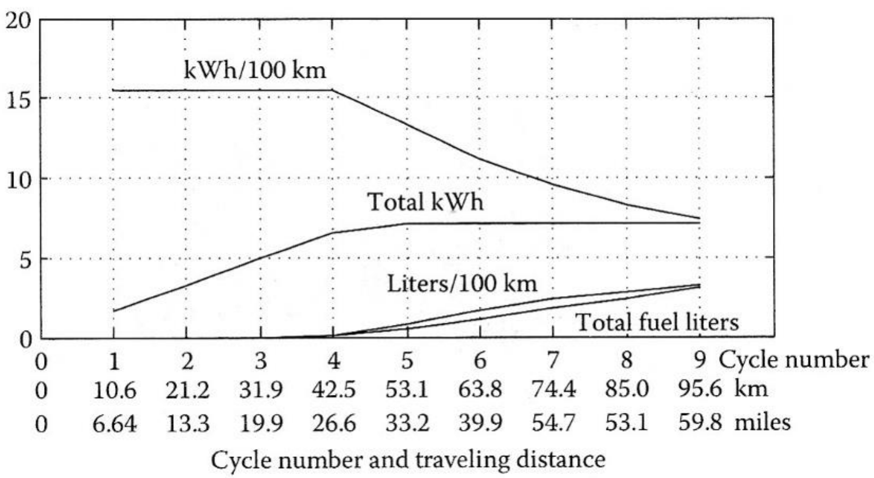


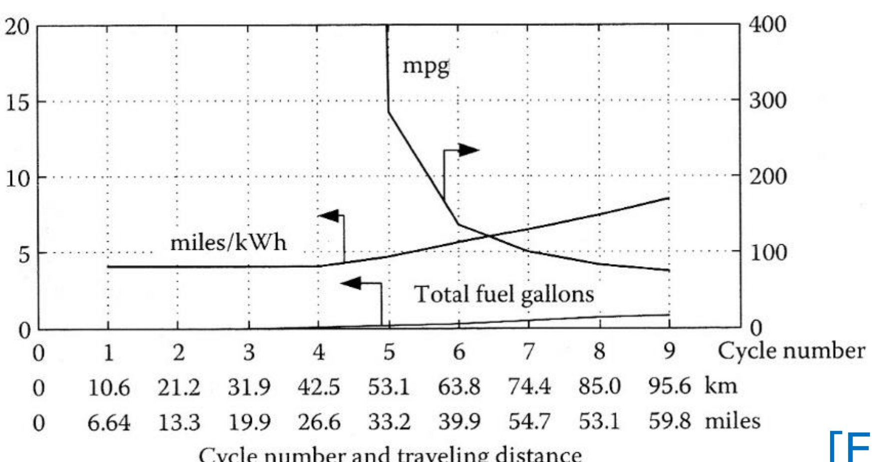


- SOC of the energy storage and the remaining energy in the battery against the driving distance.
- Pure EV range is about 32 km
- Engine operation points on the engine map showing the specific fuel consumption at each time.

[Ehsani et al. 2005]

All Electric Range focused Control strategy





- Fuel and electric energy consumption.
- When the traveling distance is less than 4 driving cycles (42.5 km) the vehicle fuel consumption is completely substituted by electrical energy from the grid.
- With an increasing reference travelling distance the average oil substitution is reduced.
- For 9 driving cycles (96 km), the fuel consumption is about 3.2 l/100km and 7.42 kWh/100km

[Ehsani et al. 2005]

Blended control strategy

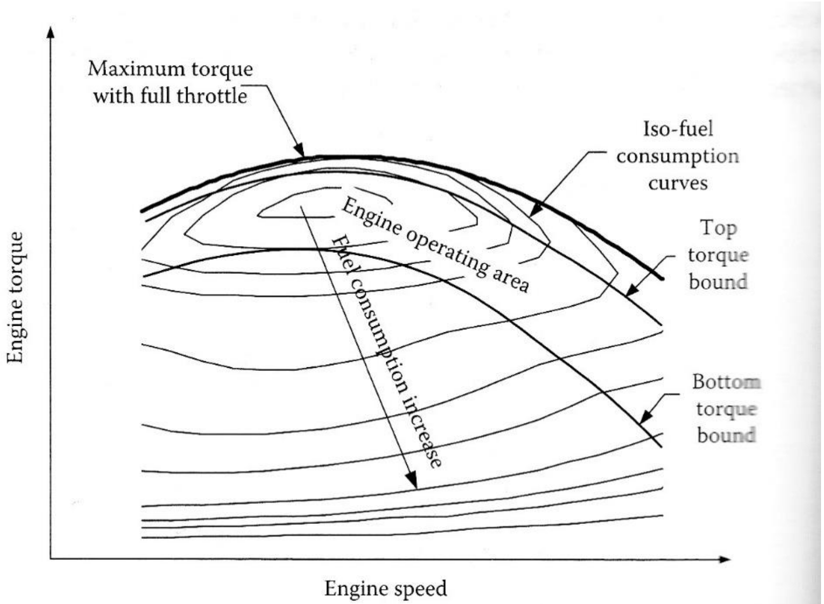
- The blended control strategy uses both the engine and the e-motor for traction with a Charge Depleting (CD) mode until the SOC of the battery reaches its specified low threshold. Beyond this point the vehicle will operate only in Charge Sustaining (CS) mode.

- In the charge depleting mode (CD), both engine and e-motor may operate at the time.
- The range before entering charge sustaining mode is longer that in pure EV mode.
- Control strategies are needed to control the engine and the e-motor and meet the power demand of the driver.
- There are many control strategies which are possible.

Blended control strategy

- Example of possible strategy to conduct the charge depleting mode. The engine and the motor alternatively propel the car with no battery charging from the engine.

- An engine operating area is defined.



[Ehsani et al. 2005]

Blended control strategy

- When the requested engine torque is larger than the upper torque boundary, the engine is controlled to operate on this boundary and the remaining torque is supplied by the electric motor

$$\text{if } P_t > P_{ICE}^{Up} \text{ then } P_{ICE} = P_{ICE}^{Up}$$
$$P_{e-m} = P_t - P_{ICE}^{Up}$$

- When the requested engine torque is between the upper and lower boundaries, the engine alone propels the car

$$\text{if } P_{ICE}^{Low} < P_t < P_{ICE}^{Up} \text{ then } P_{ICE} = P_t$$
$$P_{e-m} = 0$$

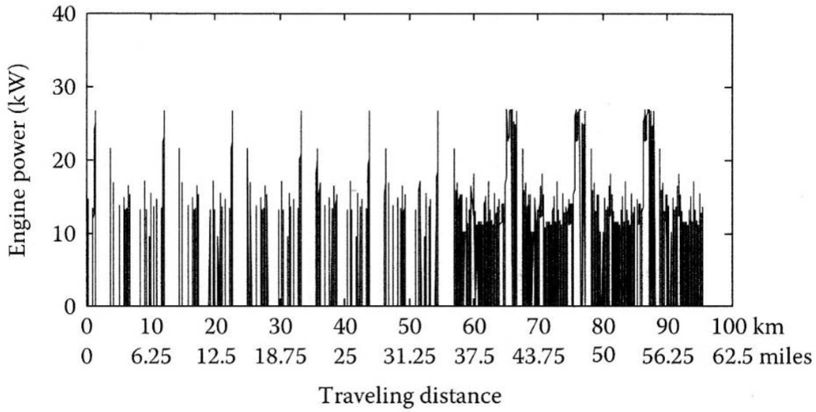
Blended control strategy

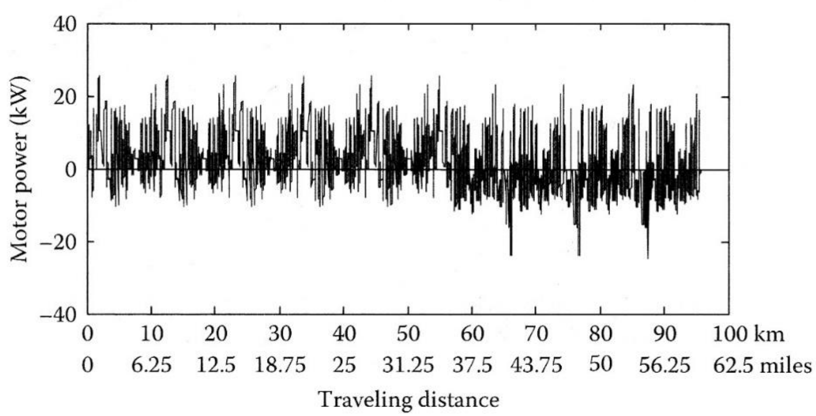
- When the requested engine torque is below the lower torque boundary, the engine is stopped, and the tractive torque is supplied by the electric motor alone:

$$\text{if } P_{ICE}^{Low} > P_t \text{ then } P_{ICE} = 0$$
$$P_{e-m} = P_t$$

- In this way the engine operation is constrained within its optimal efficiency layer.
- Due to the absence of battery charging mode from the engine, the battery energy level will continuously fall down to its lower level.

Blended control strategy



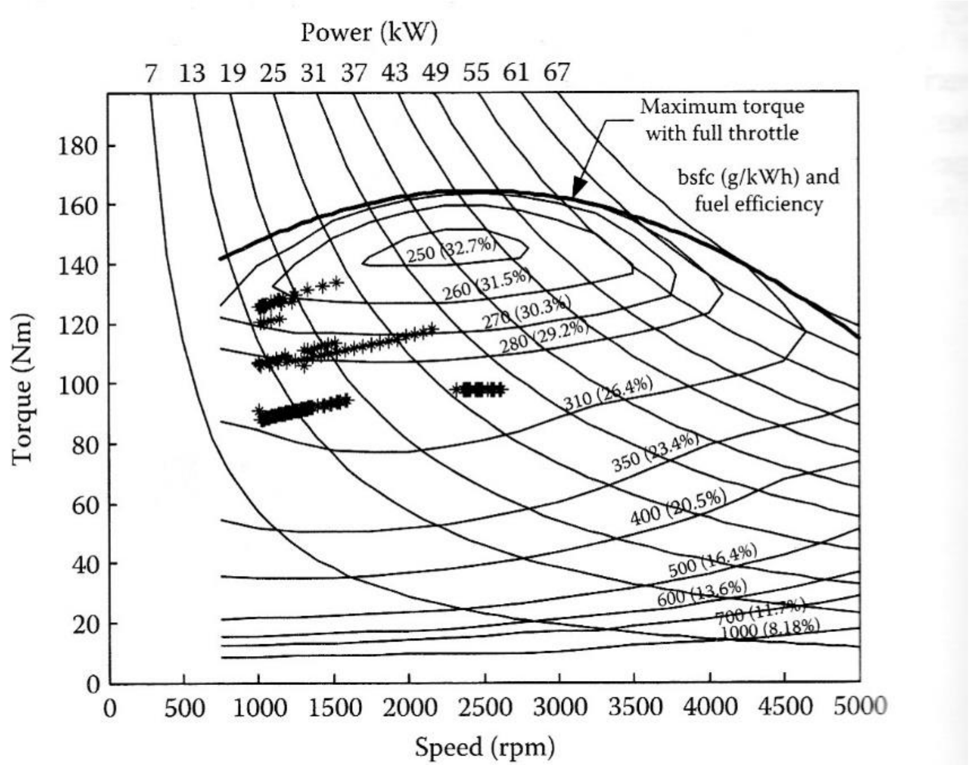


- Engine power vs travel distance in charge depleting mode against FTP75 driving cycle.
- Motor power vs travel distance in charge depleting mode

[Ehsani et al. 2005]

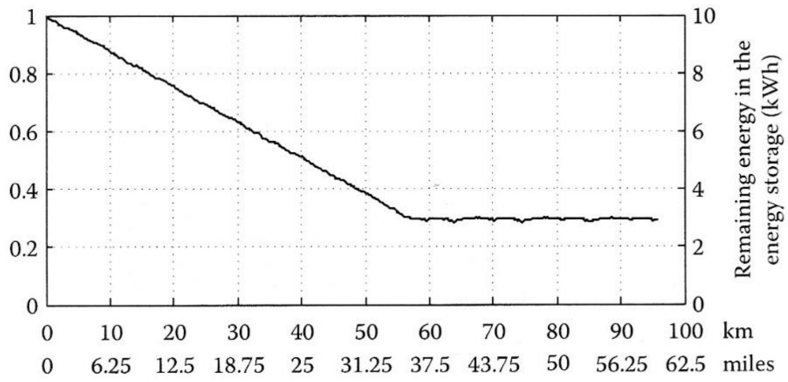
Blended control strategy

- Engine operation points overlapping its fuel consumption map in the FTP75 driving cycle with charge depleting mode



[Ehsani et al. 2005]

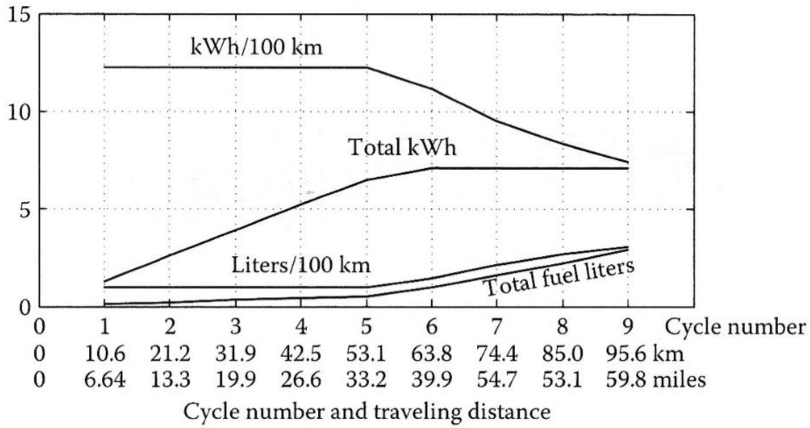
Blended control strategy

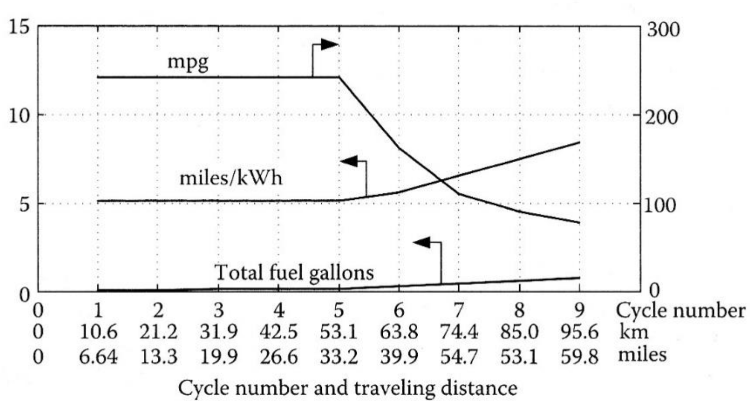


[Ehsani et al. 2005]

- SOC of charge and the remaining energy in the battery vs travel distance in FTP75 driving cycles.
- In the following simulation, the useable energy is about 7 kWh.

Blended control strategy





- Fuel and electric energy consumption vs the number of FTP75 driving cycles and the travelling distance using charge depleting mode.
- Fuel and electric energy consumption vs number of FTP75 driving cycles and the traveling distance in CD mode.

[Ehsani et al. 2005]

Energy storage design

- Energy storage is one of the most important components in the plug-in hybrid vehicles.
- It is closely related to the vehicle performance, fuel consumption, fuel displacement, initial cost and operation cost.

- The most important parameters in the energy storage design are the storage energy and its power capacities.

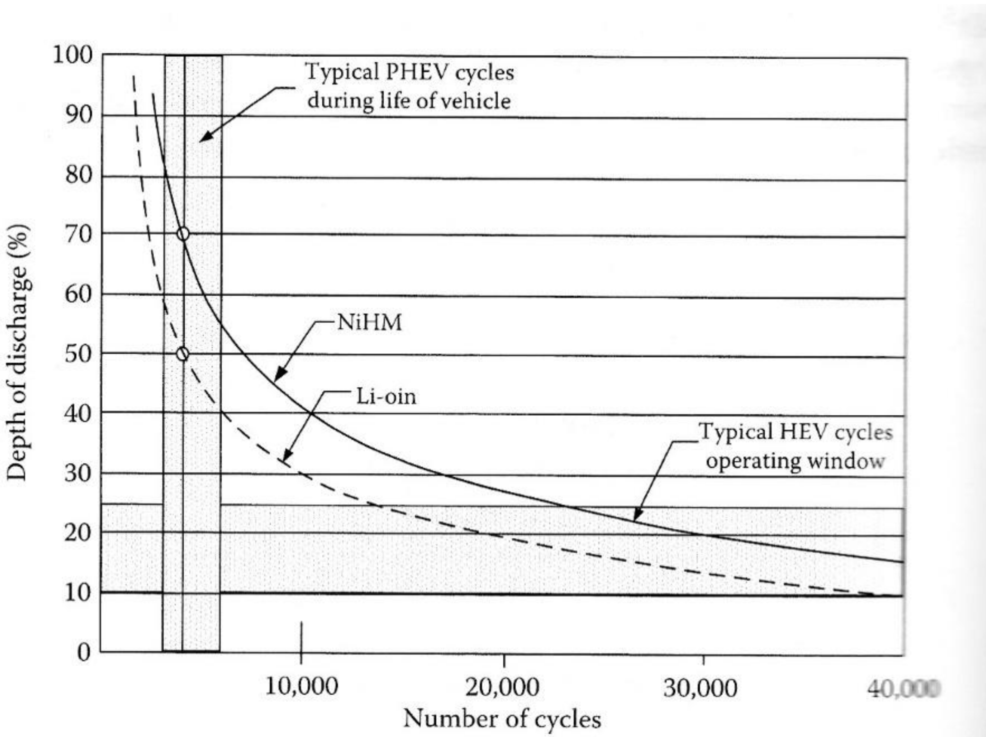
Energy storage design

- The total energy capacity is given by

$$E_c = \frac{E_{\mathrm{Usable}}}{\mathrm{SOC}_{\mathrm{Top}} - \mathrm{SOC}_{\mathrm{Bottom}}}$$

- E_{usable}: is the usable energy in the storage system consumed during the pure EV and the charge depleting mode (CD)
- SOC_{Top}: the upper level of the SOC with fully charged energy storage (usually 1)
- SOC_{Bottom}: the lower level of the SOC at which the operation mode is switched from pure EV or charge depleting (CD) mode to charge sustaining mode (CS)

Energy storage design



[Ehsani et al. 2005]

- The Depth of Discharge (DOD) of the batteries is closely related to their life.
- For one deep charge per day, a total of 4000+ deep charges would be required for a 10-15-year lifetime.
- With the characteristics of the given NiMH batteries 70% DOD for NiMH and 50% DOD for Li ions batteries would given the proper designs.

Energy storage design

- Finally, the power requirement of the battery is completely determined by the electric motor power rating

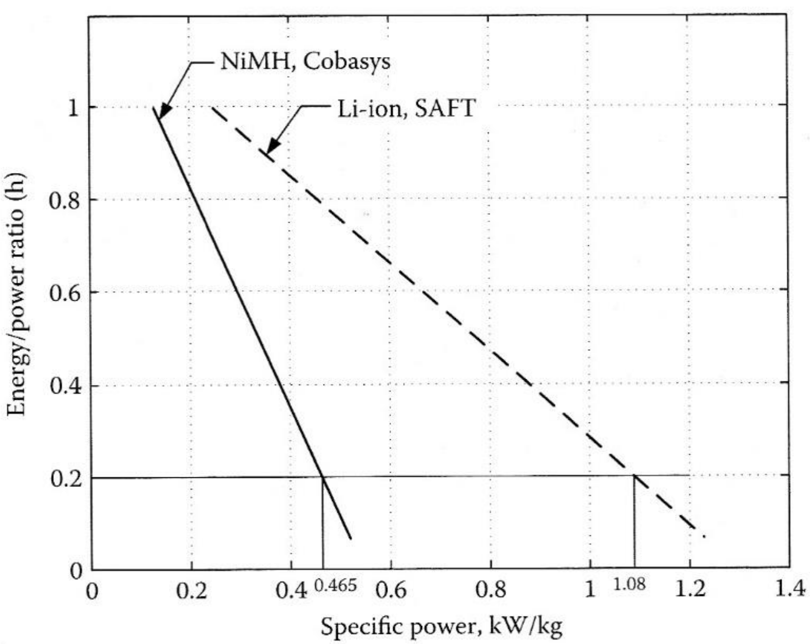
$$P_{Bat} \geq \frac{P_{e-m}}{\eta_{e-m}\eta_{Pe-}}$$

- This power level should be designed to work at low SOC such as 30% since the energy storage always works at this low SOC level in the charge sustaining mode.

Energy storage design

- The energy/power ratio of an energy storage is a good measure of suitability. The size of the energy storage will be minimized when its energy /power ratio equals the required one

$$R_{E/P} = \frac{\text{Energy}}{\text{Power at operating SOC}}$$



[Ehsani et al. 2005]