Vehicle Propulsion Systems
Lecture 12
Summary of the Course

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December 12, 2010

Vehicle Propulsion Systems

A diversity of powertrain configurations is appearing

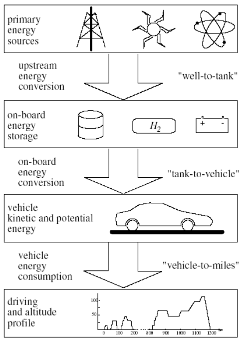
- Conventional Internal Combustion Engine (ICE) powertrain.
  Diesel, Gasoline, New concepts
- Hybrid powertrains – Parallel/Series/Complex configurations
- Fuel cell electric vehicles
- Electric vehicles

Course goal:

- Introduction to powertrain configuration and optimization problems
- Mathematical models and . . .
- . . . methods for
  - Analyzing powertrain performance
  - Optimizing the powertrain energy consumption

Outline

Energy System Overview



Primary sources

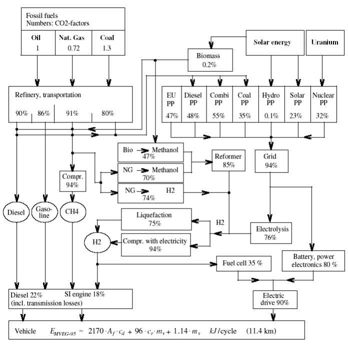
Different options for on-board energy storage

Powertrain energy conversion during driving

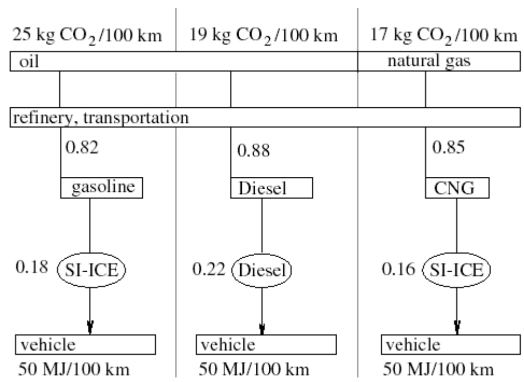
Cut at the wheel!

Driving mission has a minimum energy requirement.

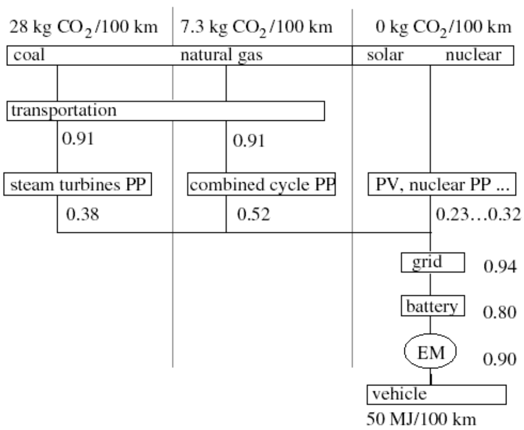
Example of Some Energy Paths



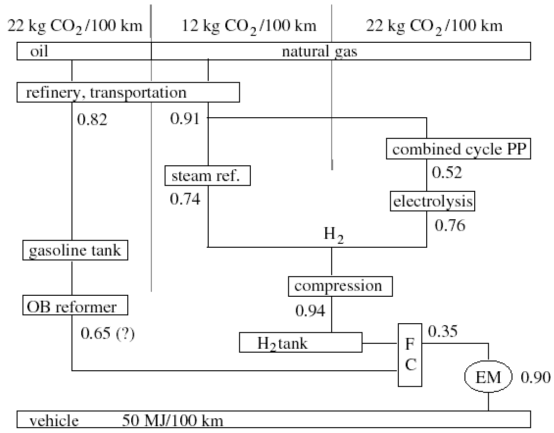
W2M – Conventional Powertrains



W2M – Electric Vehicle



W2M – Fuel Cell Electric Vehicle



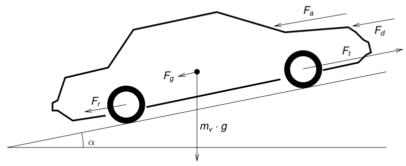
Outline

- Energy System for Vehicle Propulsion
- Energy Consumption of a Driving Mission
- Methods and tools
- IC Engine Models
- Gear-Box and Clutch Models
- Hybrid-Electric Vehicles
- Electric motors, Generators
- Batteries, Super Capacitors
- Optimal Control
- Short Term Storage
- Fuel Cells
- Reformers
- Case study 6: Fuel Optimal Trajectories of a Racing FCEV

The Vehicle Motion Equation

Newtons second law for a vehicle

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$



- F_t – tractive force
- F_a – aerodynamic drag force
- F_r – rolling resistance force
- F_g – gravitational force
- F_d – disturbance force

Vehicle Operating Modes

The Vehicle Motion Equation:

$$m_v \frac{d}{dt} v(t) = F_t(t) - (F_a(t) + F_r(t) + F_g(t) + F_d(t))$$

- $F_t > 0$ traction
- $F_t < 0$ braking
- $F_t = 0$ coasting

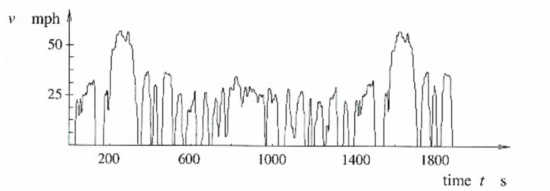
$$\frac{d}{dt} v(t) = -\frac{1}{2\, m_v} \rho_a A_f c_d v^2(t) - g\, c_r = \alpha^2 v^2(t) - \beta^2$$

Coasting solution for $v > 0$

$$v(t) = \frac{\beta}{\alpha} \tan\left(\arctan\left(\frac{\alpha}{\beta} v(0)\right) - \alpha \beta t\right)$$

Driving profiles

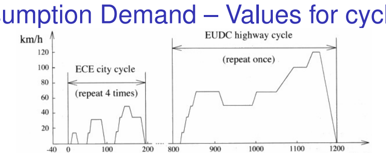
Velocity profile, American FTP-75 (1.5*FUDS).



Driving profiles in general

- First used for pollutant control now also for fuel cons.
- Important that all use the same cycle when comparing.
- Different cycles have different energy demands.

Fuel Consumption Demand – Values for cycles



Numerical values for MVEG-95, ECE, EUDC

$$\bar{F}_{trac,a} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i^3\, h = \{319, 82.9, 455\}$$

$$\bar{F}_{trac,r} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{v}_i\, h = \{.856, 0.81, 0.88\}$$

$$\bar{F}_{trac,m} = \frac{1}{x_{tot}} \sum_{i \in trac} \bar{a}_i\, \bar{v}_i\, h = \{0.101, 0.126, 0.086\}$$

$$\bar{E}_{\text{MVEG-95}} \approx A_f\, c_d\, 1.9 \cdot 10^4 + m_v\, c_r\, 8.4 \cdot 10^2 + m_v\, 10 \qquad kJ/100km$$

Tasks in Hand-in assignment

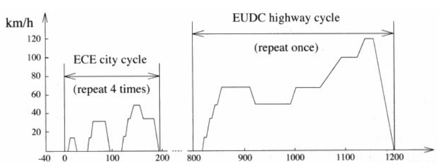
Approximate car data

$$\bar{E}_{\text{MVEG-95}} \approx A_f\, c_d\, 1.9 \cdot 10^4 + m_v\, c_r\, 8.4 \cdot 10^2 + m_v\, 10 \qquad kJ/100km$$

	SUV	full-size	compact	light-weight	PAC-Car II
$A_f \cdot c_d$	1.2 m^2	0.7 m^2	0.6 m^2	0.4 m^2	.25 · .07 m^2
c_r	0.017	0.017	0.017	0.017	0.0008
m_v	2000 kg	1500 kg	1000 kg	750 kg	39 kg
$\bar{P}_{\text{MVEG-95}}$	11.3 kW	7.1 kW	5.0 kW	3.2 kW	
$\bar{P}_{\max}$	155 kW	115 kW	77 kW	57 kW	

Average and maximum power requirement for the cycle.

Energy demand again – Recuperation



Recover the vehicle's kinetic energy during driving

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- Short Term Storage
- Fuel Cells
- Reformers
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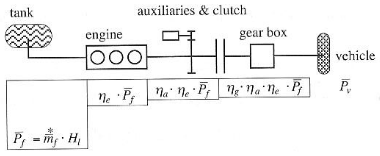
Methods and tools

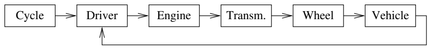
Average operating point method.



One task among in the Hand-in assignments.

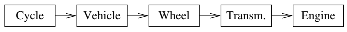
Two Approaches for Powertrain Simulation

- Dynamic simulation (forward simulation)



–“Normal” system modeling direction
–Requires driver model

- Quasistatic simulation (inverse simulation)



–”Reverse” system modeling direction
–Follows driving cycle exactly

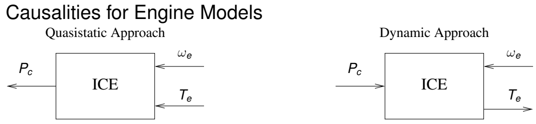
- Model causality

Outline

Causality and Basic Equations

High level modeling – Inputs and outputs

- Causalities for Engine Models



- Engine efficiency

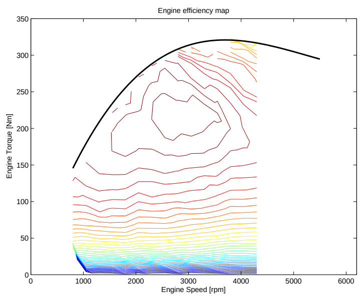
$$\eta_e = \frac{\omega_e \, T_e}{P_c}$$

- Enthalpy flow of fuel (Power $\dot{H}_{fuel} = P_c$)

$$P_c = \dot{m}_f \, q_{LHV}$$

Engine Efficiency Maps

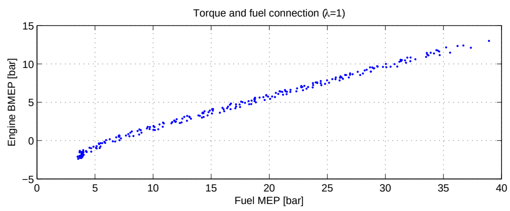
Measured engine efficiency map – Used very often



–What to do when map-data isn’t available?

Torque modeling through – Willans Line

- Measurement data: x: p_{mf} y: $p_{me} = BMEP$



- Linear (affine) relationship – Willans line

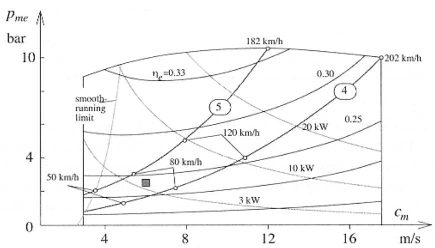
$$p_{me} = e(\omega_e) \cdot p_{mf} - p_{me,0}(\omega_e)$$

- Engine efficiency: $\eta_e = \frac{p_{me}}{p_{mf}}$

Outline

Selection of Gear Ratio

Gear ratio selection connected to the engine map.



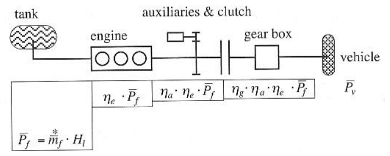
Additionally: Also geometric ratio between gears.
$\frac{i_{g,1}}{i_{g,2}} \approx \frac{i_{g,2}}{i_{g,3}} \approx \frac{i_{g,3}}{i_{g,4}} \approx \frac{i_{g,4}}{i_{g,5}}$

Selection of Gear Ratio

Optimizing gear ratio for a certain cycle.

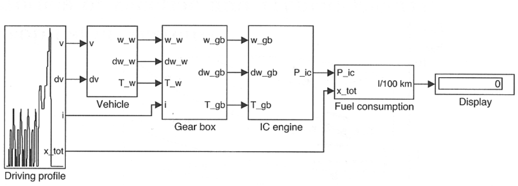
- Potential to save fuel.
- Case study 8.1 (we'll look at it later).

Average Operating Point Method



- Average operating point method
  –Good agreement for conventional powertrains.
- Hand-in assignment.

Quasistatic analysis – Layout



- More details and better agreement (depends on model quality)
  –Good agreement for general powertrains
- Hand-in assignment.

Outline

Definition

What characterizes a Hybrid-Electric Vehicle

- Energy carrier is a fossil-fuel.
- Presence of an electrochemical or electrostatic energy storage system.

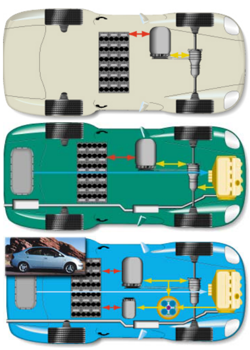
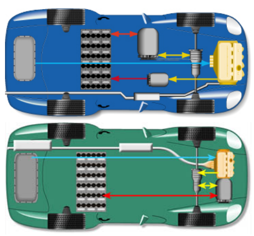
Potential for Energy Savings

Benefits of Hybrid-Electric Vehicles

- Downsize engine while maintaining maximum power requirement
- Recover energy during deceleration (recuperation)
- Optimize energy distribution between prime movers
- Eliminate idle fuel consumption by turning of the engine (stop-and-go)
- Eliminate the clutching losses by engaging the engine only when the speeds match

Possible improvements are counteracted by a 10-30% increase in weight.

Hybrid concepts

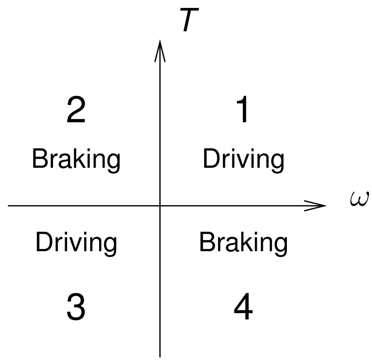
Electric Series
Parallel Parallel S/A
Combined

Degree of Hybridization

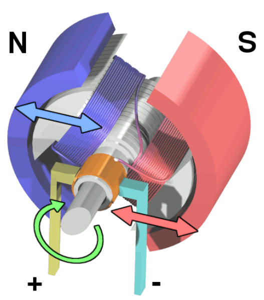
- Degree of hybridization
  –The ratio between electric motor power and engine power.
- Implemented hybrid concepts in cars
  Degree of hybridization varying between 15–55%
- True mild hybrid concepts
  Degree of hybridization varying 2–15%

Outline

The 4 Quadrants



Brushed DC-Machine



Wikipedia picture

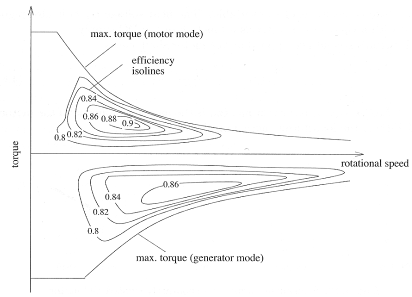
Brush-type DC motor:

- Rotor
- Stator
- Commutator
- Two subtypes:
  –Permanent magnet
  –Separately excited

Pros and cons

+ Simple to control
– Brushes require maintenance

Two Quadrant Maps for η_m



Mirroring efficiency is not always sufficient.

Outline

Batteries

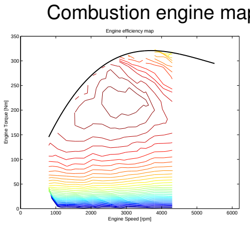
- Energy storage devices – Energy density important
- Performance – Power density important
- Durability

Battery type	Energy Wh/kg	Power W/kg	cycles
Lead-acid	40	180	600
Nickel-cadmium	50	120	1500
Nickel-metal hydride	70	200	1000
Lithium-ion	130	430	1200

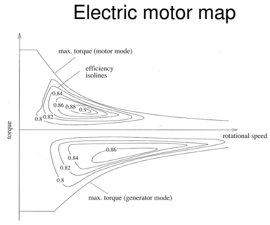
Component modeling

- Model energy (power) transfer and losses
- Using maps
- Using parameterized (scalable) models

Combustion engine map



Electric motor map



Outline

Optimal Control – Problem Motivation

Car with gas pedal $u(t)$ as control input:
How to drive from A to B on a given time with minimum fuel consumption?

- Infinite dimensional decision variable $u(t)$.
- Criterion function $\int_0^{t_f} \dot{m}_f(t)dt$
- Constraints:
  - Model of the car (the vehicle motion equation)

$$\begin{aligned} m_v \tfrac{d}{dt} v(t) &= F_t(v(t), u(t)) \quad -(F_a(v(t)) + F_r(v(t)) + F_g(x(t))) \\ \tfrac{d}{dt} x(t) &= v(t) \\ \dot{m}_f &= f(v(t), u(t)) \end{aligned}$$

  - Starting point $x(0) = A$
  - End point $x(t_f) = B$
  - Speed limits $v(t) \leq g(x(t)$
  - Limited control action $0 \leq u(t) \leq 1$
- In general difficult (impossible) problem to solve.

Dynamic Programming (DP) – Problem Formulation

- Find the optimal control sequence $\pi^0(x_0) = \{u_0, u_1, \ldots, u_{N-1}\}$ minimizing:

$$J(x_0) = g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, w_k)$$

- subject to:

$$\begin{aligned} x_{k+1} &= f_k(x_k, u_k, w_k) \\ x_0 &= x(t = 0) \\ x_k &\in X_k \\ u_k &\in U_k \end{aligned}$$

- Disturbance w_k
- Stochastic vs deterministic DP

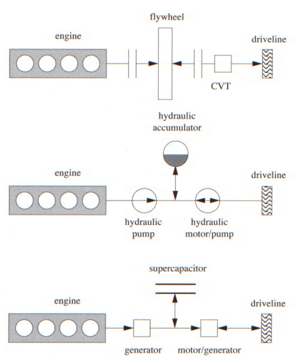
Calculation Example

- Problem 200s with discretization $\Delta t = 1$s.
- Control signal discretized with 10 points.
- Statespace discretized with 1000 points.
- One evaluation of the model takes 1μs
- Solution time:
  - Brute force:
    Evaluate all possible combinations of control sequences.
    Number of evaluations, 10^{200} gives $\approx 3 \cdot 10^{186}$ years.
  - Dynamic programming:
    Number of evaluations: $200 \cdot 10 \cdot 1000$ gives 2 s.

This example comes from ETH slides

Outline

Examples of Short Term Storage Systems



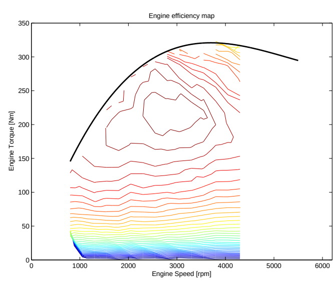
Short Term Storage – F1

FIA will allow the usage of 60 kW, KERS (Kinetic Energy Recovery System) in F1 in 2009.
Technologies:

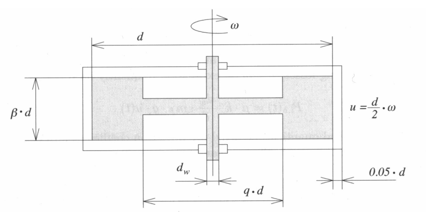
- Flywheel
- Super-Caps

Basic Principles for Hybrid Systems

- Kinetic energy recovery
- Use these points – Duty cycle.
  - Run engine (fuel converter) at its optimal point.
  - Shut-off the engine.



Flywheel accumulator



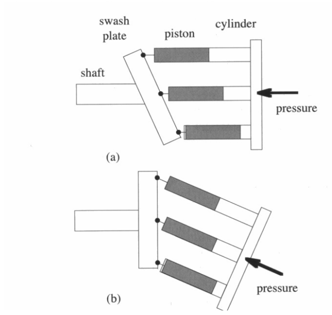
- Energy stored:

$$E_f = \frac{1}{2} \Theta_f \, \omega_f^2$$

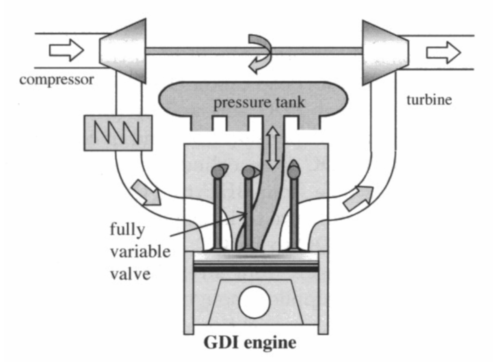
- Wheel inertia

$$\Theta_f = \rho \, b \int_{Area} r^2 \, 2 \, \pi \, r \, dr = \ldots = \frac{\pi}{2} \rho \frac{d^4}{16} (1 - q^4)$$

Hydraulic Pumps

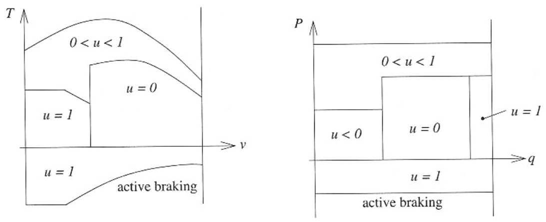


Pneumatic Hybrid Engine System



Heuristic Control Approaches

- Parallel hybrid vehicle (electric assist)



- Determine control output as function of some selected state variables:
  vehicle speed, engine speed, state of charge, power demand, motor speed, temperature, vehicle acceleration, torque demand

ECMS – Equivalent Consumption Minimization Strategy

- μ_0 depends on the (soft) constraint

$$\mu_0 = \frac{\partial}{q(t_f)}\phi(q(t_f)) = /\text{special case}/ = -w$$

- Different efficiencies

$$\mu_0 = \frac{\partial}{\partial q(t_f)}\phi(q(t_f)) = \begin{cases} -w_{dis}, & q(t_f) > q(0) \\ -w_{chg}, & q(t_f) > q(0) \end{cases}$$

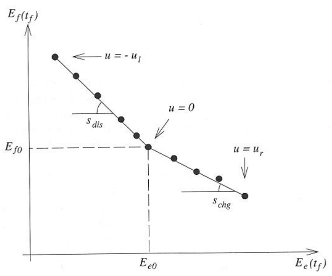
- Introduce equivalence factor (scaling) by studying battery and fuel power

$$s(t) = -\mu(t)\frac{H_{LHV}}{V_b\, Q_{max}}$$

ECMS – Equivalent Consumption Minimization Strategy

Determining Equivalence Factors II

- Collecting battery and fuel energy data from test runs with constant u gives a graph

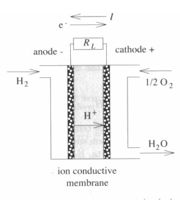


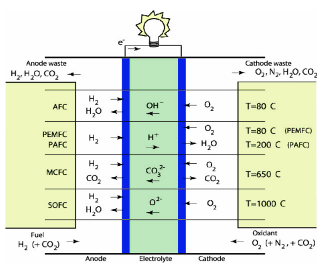
- Slopes determine s_{dis} and s_{chg}

Outline

Fuel Cell Basic Principles

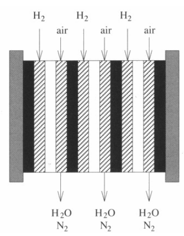
- Convert fuel directly to electrical energy
- Let an ion pass from an anode to a cathode
- Take out electrical work from the electrons

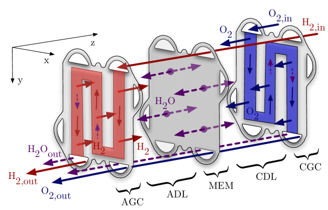




Fuel Cell Stack

- The voltage out from one cell is just below 1 V.
- Fuel cells are stacked.



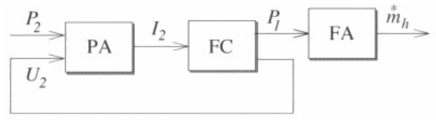


Hydrogen Fuel Storage

- Hydrogen storage is problematic - Challenging task.
- Some examples of different options.
  - High pressure bottles
  - Liquid phase – Cryogenic storage, -253°C.
  - Metal hydride
  - Sodium borohydride $NaBH_4$

Quasistatic Modeling of a Fuel Cell

- Causality diagram



- Power amplifier (Current controller)
- Fuel amplifier (Fuel controller)
- Standard modeling approach

Fuel Cell Thermodynamics

- Starting point reaction equation

$$H_2 + \frac{1}{2}\,O_2 \Rightarrow 2\,H_20$$

- Open system energy – Enthalpy H

$$H = U + pV$$

- Reversible energy – Gibbs free energy G

$$G = H + TS$$

- Open circuit cell voltages

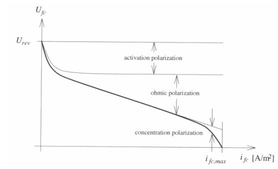
$$U_{rev} = -\frac{\Delta G}{n_e\,F}, \qquad U_{id} = -\frac{\Delta H}{n_e\,F}, \qquad U_{rev} = \eta_{id}\,U_{id}$$

  F – Faradays constant ($F = q\,N_0$)
- Under load

$$P_l = I_{fc}(t)\,(U_{id} - U_{fc}(t))$$

Fuel Cell Performance – Polarization curve

- Polarization curve of a fuel cell
  Relating current density $I_{fc}(t) = I_{fs}(t)/A_{fc}$, and cell voltage $U_{fc}(t)$



  Curve for one operating condition
- Fundamentally different compared to combustion engine/electrical motor
- Excellent part load behavior
  –When considering only the cell

Single Cell Modeling

- Fuel cell voltage

$$U_{fc}(t) =_{rev} - U_{act}(t) - U_{ohm} - U_{conc}$$

- Activation energy – Get the reactions going
  Semi-empirical Tafel equation

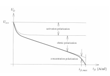
$$U_{act}(t) = c_0 + c_1 \ln(i_{fc}(t)), \text{ or } U_{act}(t) = \ldots$$

- Ohmic – Resistance to flow of ions in the cell

$$U_{ohm} = i_{fc}(t)\,\tilde{R}_{fc}$$

- Concentration, change in concentration of the reactants at the electrodes

$$U_{conc} = c_2 \cdot i_{fc}(t)^{c_3}, \text{ or } U_{conc} = \ldots$$



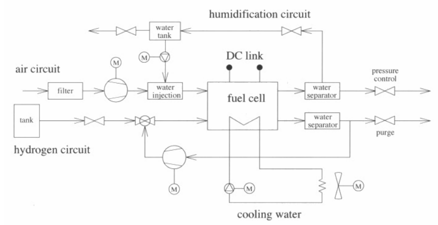
Fuel Cell System Modeling

- Describe all subsystems with models

$$P_2(t) = P_{st}(t) - P_{aux}(t)$$

$$P_{aux} = P_0 + P_{em}(t) + P_{ahp}(t) + p_{hp}(t) + P_{cl}(t) + p_{cf}(t)$$

  em–electric motor, ahp – humidifier pump, hp – hydrogen recirculation pump, cl – coolant pump, cf – cooling fan.



- Submodels for:
  Hydrogen circuit, air circuit, water circuit, and coolant circuit

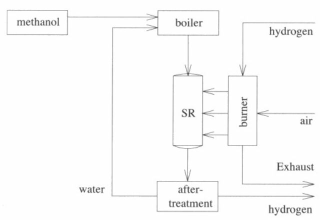
Outline

Energy System for Vehicle Propulsion
Energy Consumption of a Driving Mission
Methods and tools
IC Engine Models
Gear-Box and Clutch Models
Hybrid-Electric Vehicles
Electric motors, Generators
Batteries, Super Capacitors
Optimal Control
Short Term Storage
Fuel Cells
Reformers
Case study 6: Fuel Optimal Trajectories of a Racing FCEV

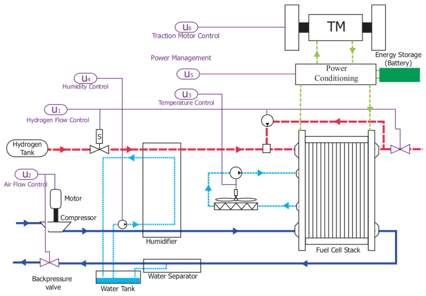
Reformers

- Fuel cells need hydrogen – Generate it on-board
  –Steam reforming of methanol.

$$2\,CH_3OH + O_2 \Rightarrow 2\,CO_2 + 4\,H_2$$



Fuel Cell Vehicles



Outline

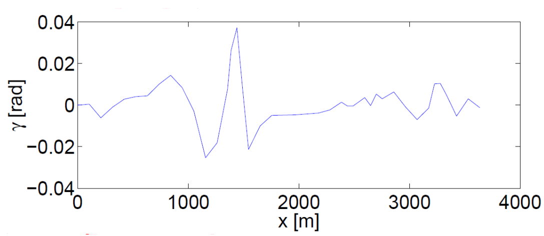
Problem Setup

- Run a fuel cell vehicle optimally on a racetrack

  - Start up lap
  - Repeated runs on the track
- Path to the solution
  - Measurements – Model
  - Simplified model
  - Optimal control solutions

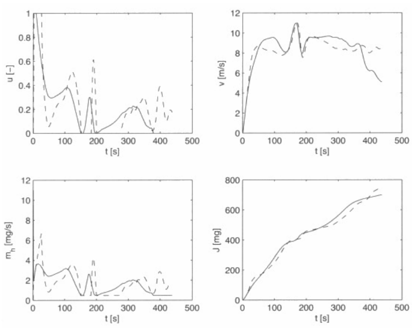
Problem Setup – Road Slope Given

Road slope $\gamma = \alpha(x)$



Fuel Optimal Trajectory – Start

Fuel optimal trajectory has 7% lower fuel consumption



Fuel Optimal Trajectory – Continuous Driving

Fuel optimal trajectory has 9% lower fuel consumption