Electro-Chemical Commercial Vehicle – ECCV
IFAC World Congress 2023 – Competition
The Benchmark Problem: Model and Control Goals

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Outline

1. Introduction to the Benchmark Problem
    - Control for sustainable transport
2. Fuel Cell Electric Commercial Vehicles and Driving Missions – Complexity of the Problem
3. Vehicle Model and Scenario Details
    - Overview
    - Vehicle and Transmission
    - Powertrain
        - Electric Motor
    - Battery
    - Fuel Cell
    - Cooling System
4. Control Challenges
    - Hard Constraints
    - Performance – Soft Constraints
5. Conclusion

Control is a key technology for sustanability

- Modern Society Relies on Transportation of People and Goods
  - We need it in the society and need to make it sustainable
- Electromobility can be a key solution for sustainability
  - Battery Electric Vehicles on Renewable Electricity
  - Fuel Cell Hybrid Electric Vehicles on Green Hydrogen
- Control Plays a Key Role in Accomplishing a Sustainable Transport Solution
  - Electric Motor Control; Drive and Regenerative Braking
  - Vehicle Speed Control – Planning
  - Energy management; Kinetic, Potential, Battery and Fuel Cell.
  - Battery control and monitoring
  - Fuel cell control and monitoring
  - Cooling system management and control

Designed a Complete Fuel Cell Powered Commercial Vehicle Model and Specified a Control Benchmark Problem

Modelbased Product Development

General Issues in Industrial Resarch and Development

- We're searching the details of how the best system will look.
- It is not operational so there is no system data.
- The performance will depend on how the system is controlled.
- The system is very complex to handle and control.

Approach

- Use component-based modeling, Lego.
- Engage a big group of experts, researchers.
- Provide a reward, joint Journal paper.
- Gamification.

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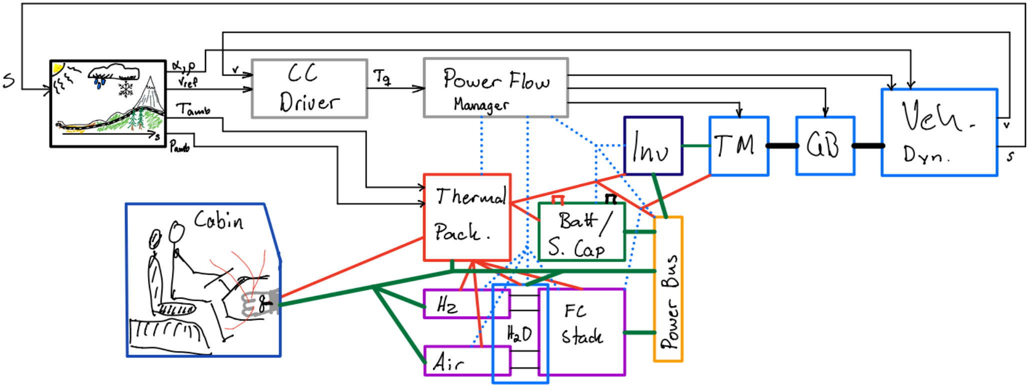
Fuel Cell Electric Vehicles and Commerical Vehicle Driving Missions



- Drive from A to B
- Altitude profile is key
- Planning kinetic and potential energy
- Need to deliver in time
- Overspeeding ⚠
- Monitor limits $I_b(t)$, $T_{fc}(t)$, $SOC(t)$
- Driving slower reduces fuel
- Battery $SOC(t_f) > 40\%$
- Protect Components

Benchmark Signals

13 Control signals

Control	Sensor
Torque Request	Motor Current
Gear number	Velocity
Brake	*Road Slope*
Burn-off resistor	Bus Voltage
Battery Current	Battery Voltage
Fuel Cell Current	Fuel cell Voltage
Compressor speed	Cathode Flow
Fuel Cell Throttle	Cathode Pressure
Relative Hymidity	Cathode Humidity
Hydrogen Massflow	Anode Pressure
Coolant Flow	Fuel Cell Temperature
Coolant valve	Coolant Return Temperature
Coolant fan	*Ambient Temperature*

From driving mission: Position, Speed limit, Road Slope, Altitude, Ambient Pressure and Temperature (NASA Atmospheric Model).

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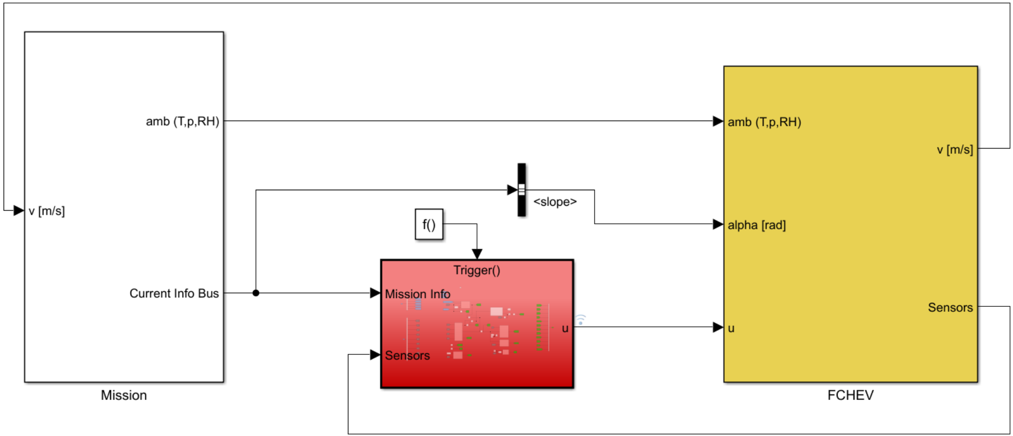
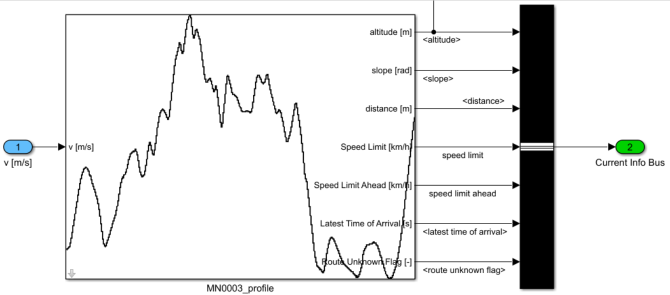
Overview

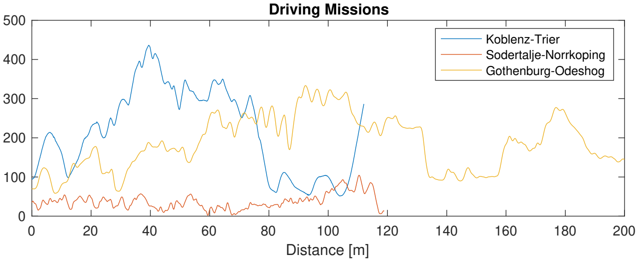


- Mission – Testing relevant transportation scenarios
- FCHEV – Vehicle, Model Developed by University and Approved by Industry
- Controller – Developed by benchmark participants, sampled system

Mission specification

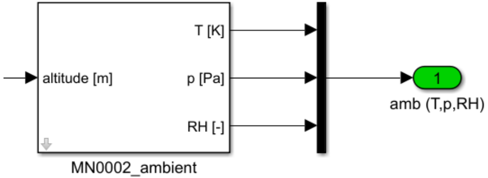
Altitude Profiles - 2(3) to select from





Mission specification

Ambient - To evaluate critical missions in other environments



NASA Trophosphere Model[1]

$$T = T_0 - 0.00649h \tag{1}$$

$$p = p_0 \left(\frac{T}{288.078} \right)^{5.256} \tag{2}$$

- h: Altitude
- T_0: Temperature at sea-level
- p_0: Pressure at sea-level

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[1] (*Earth Atmosphere Model - Metric Units*. URL: https://www.grc.nasa.gov/www/k-12/airplane/atmosmet.html [visited on 12/15/2022])

Vehicle

Vehicle - Newton's Second Law

$$F = Tq_w r_w - F_g(\alpha) - F_r(\alpha, v) - F_a(v) - F_b(u_{brake})$$

- F_g - Gravitational Force
- F_r - Rolling Resistance
- F_a - Air Drag Resistance
- F_b - Brake Force

Gearbox

$$Tq_w = Tq_{em} i_{fd} i_g \eta_{gb}^{\mathrm{sign}(Tq_{in})}$$
$$\omega_{em} = \omega_w i_{fd} i_g$$

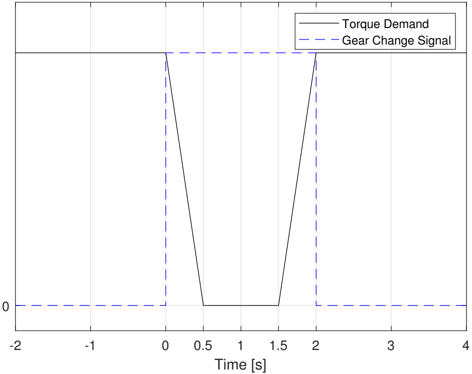
Four gears to select from

TCU - Transmission Control Unit

Same implementation as Truck Benchmark AAC 2016[2].

Gear Change Stages

- 0 – 0.5 s ramp down torque to 0 Nm.
- 0.5 – 1.5 s 0 Nm torque while changing gear.
- 1.5 – 2 s ramp up torque again.
- Total Cost: 2 seconds and a loss in torque.



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[2] Lars Eriksson, Anders Larsson, and Andreas Thomasson. "The AAC2016 Benchmark - Look-Ahead Control of Heavy Duty Trucks on Open Roads". en. In: *IFAC-PapersOnLine*. 8th IFAC Symposium on Advances in Automotive Control AAC 2016 49.11 (Jan. 2016), pp. 121–127. ISSN: 2405-8963. DOI: 10.1016/j.ifacol.2016.08.019. URL: https://www.sciencedirect.com/science/article/pii/S2405896316313404 (visited on 12/19/2022).

Electric Motor

- Acting as a motor or generator.
- Bus voltage dependency

Motor Power

$$\begin{aligned} P_{m,em} &= Tq_{em}\omega_{em} \\ P_{m,el} &= eP_{m,em} + P_0\left(\omega_e\right) \\ I_m &= \frac{P_{m,el}}{U_{bus}} \\ Q_m &= P_{m,el} - P_{m,em} \end{aligned}$$

Generator Power

$$\begin{aligned} P_{g,em} &= |Tq_{em}|\omega_{em} \\ P_{g,el} &= \frac{P_{g,em} - P_0\left(\omega_e\right)}{e} \\ I_g &= \frac{P_{g,el}}{U_{bus}} \\ Q_g &= P_{g,em} - P_{g,el} \end{aligned}$$

Electric Motor

Characteristics[3]

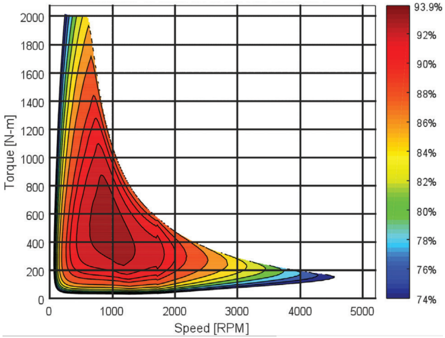

Figure: Efficiency Map

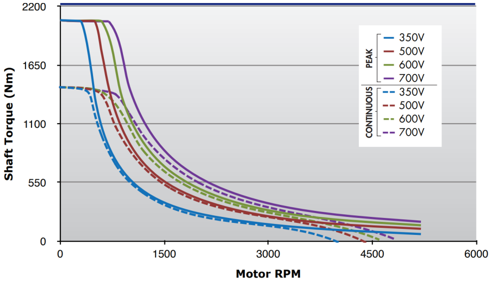

Figure: Torque curves for different voltages.

- Engine speed dependency of max torque is scaled with $\frac{U_{bus}}{U_{nominal}}$, up to $U_{nominal}$ (700 V).

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[5] (*BorgWarner HVH410-150 Electric Motor*. URL: https://cdn.borgwarner.com/docs/default-source/default-document-library/remy-pds---hvh410-

Power Sizing

Basic sizing has been provided by industry:
Generic vehicle with approximately the right performance for these types of missions.

Battery

- 200 kWh
- 350 Ah (200 kWh @ 571 V)
- Max. Charge/Discharge: 1 C
- SOC 20 % - 90 %

- DC-Bus Voltage: 700 V
- 3 pcs 150 kW motors in parallel
- **Fuel Cell Stack**
  - 750 cells
  - 420 cm^2
  - 250 kW (750 A, 4 bar Cathode Pressure)

Due to limited available measurements, parametrization of the models are mainly from other works and inputs from industry partners.

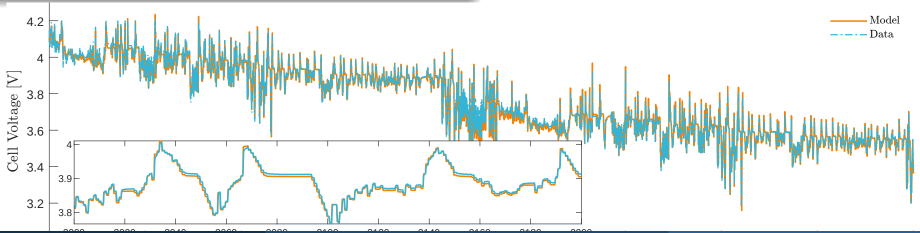
Battery

Equations

$$U_{battery} = U_{OCV} - U_{dyn}(I, T)$$
$$Q_{battery} = (U_{OCV} - U_{battery})\,|I| = U_{dyn}(I, T)|I|$$

Battery model is developed from an extensive dataset of a Panasonic cell and includes a dynamic model with internal resistance and two RC elements.

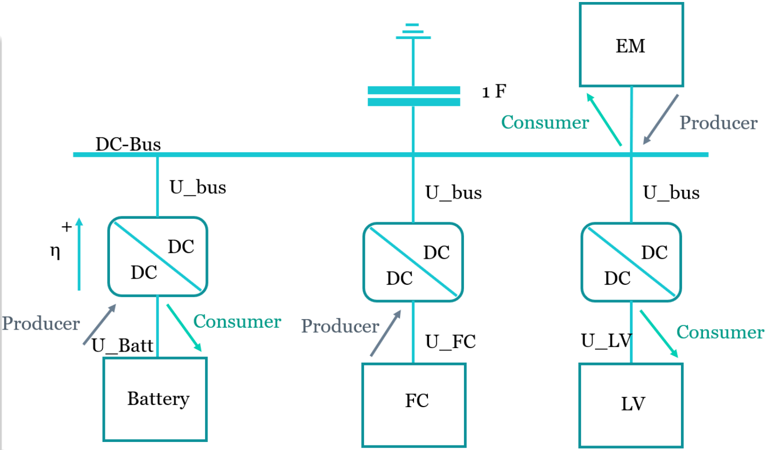
- 200 kWh
- 350 Ah (200 kWh @ 571 V)
- Max. Charge/Discharge: 1 C
- 21 600 pcs Panasonic NCR18650PF
  - 120 in parallel
  - 180 in series
- SOC 20 % - 90 %
- Validation on a complete BEV truck



Power Management

Properties

- $U_{bus} = 700\,V$ (Target)
- DC-DC Efficiency, η (98 %)
- Producers
- Consumers
- Super Capacitor
- Electric Machine connected to DC-Bus
- Low Voltage, 24 V
  - Cooling Fan
  - Coolant Pump
  - Compressor
  - Battery H.P



Cathode

Gas Exchange

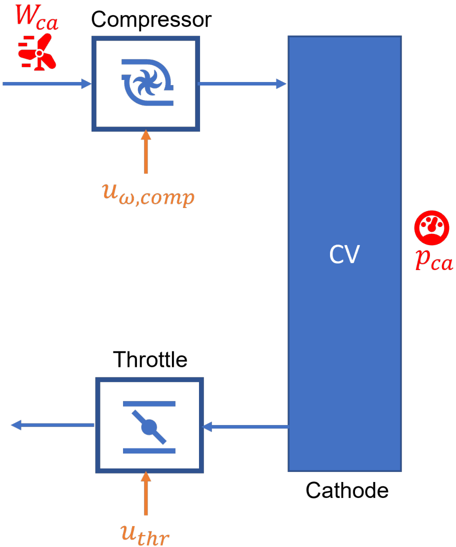
Models

- No control of humidifier, controlled to 80 % RH at cathode.
- Ellipse Compressor Model[4]

$$W_{ca} = f(\Pi, \omega_{comp}, T_{amb})$$
$$P_{comp} = W_{ca} c_p \Delta T$$

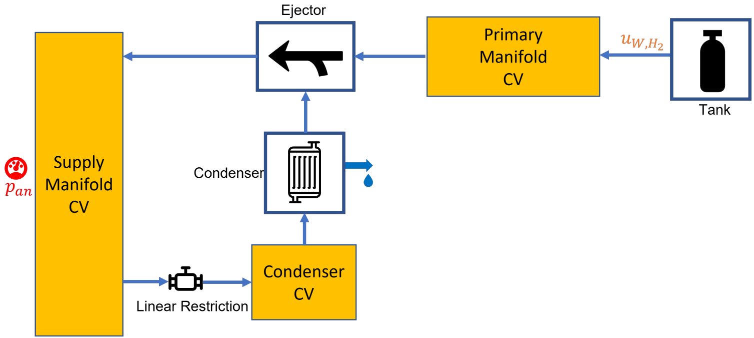
- Throttle, Compressible Flow Model[5]

$$W_{thr} = \frac{p_{ca}}{\sqrt{RT_{ca}}} A_{eff}(u_{thr}) \Psi(\Pi)$$



Anode

Gas Exchange



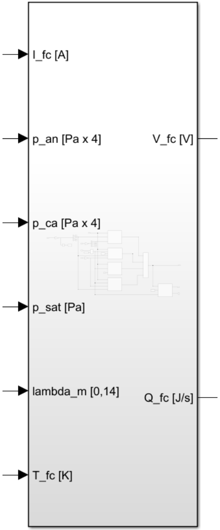
Notes

- Perfect Condenser, 100 % RH.
- Flow from condenser if Primary to Supply flow is choked.
- Controls mass flow of hydrogen from tank.

Fuel Cell Voltage

Definitions

- V_{fc} - Fuel Cell Voltage
- Q_{fc} - Generated Heat
- I_{fc} - Fuel Cell Current
- T_{fc} - Fuel Cell Temperature
- λ_m - Membrane Water Content $[0, 14]$
- p_{ca} - Cathode Partial Pressures
- p_{an} - Anode Partial Pressures
- p_{sat} - Water Saturation Pressure



Cell Voltage

Fuel Cell Voltage[6]

Definitions

- V_{fc} - Fuel Cell Voltage
- Q_{fc} - Generated Heat
- E - Reversible Voltage
- V_{act} - Activation Overvoltage
- V_{ohm} - Ohmic Overvoltage
- V_{conc} - Concentration Overvoltage
- j_{fc} - Current Density $\left(\frac{I_{fc}}{A_{fc}}\right)$

Equations

$$
\begin{aligned}
V_{fc} &= E - V_{act} - V_{ohm} - V_{conc} \\
E &= f_1(T_{fc}, p_{ca}, p_{an}) \\
V_{act} &= f_2(T_{fc}, j_{fc}, p_{ca}, p_{sat}) \\
V_{ohm} &= f_3(T_{fc}, j_{fc}, \lambda_m) \\
V_{conc} &= f_4(T_{fc}, j_{fc}, p_{ca}, p_{sat}) \\
Q_{fc} &= P_{tot} - P_{elec}
\end{aligned}
$$

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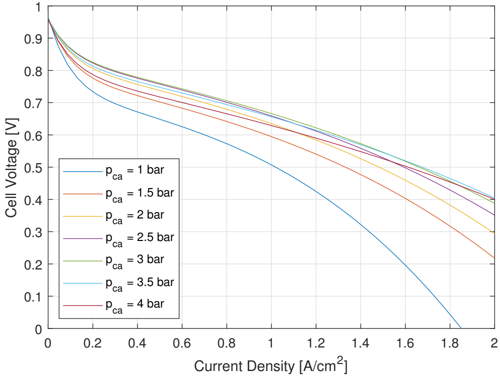
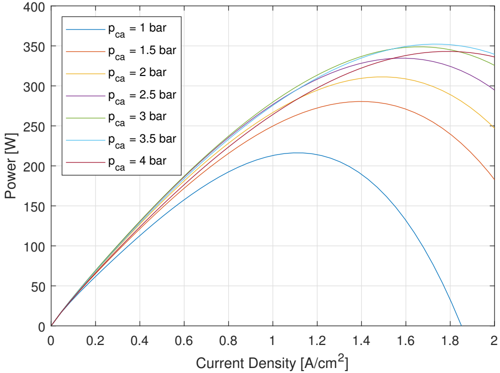
[4] (Jay T. Pukrushpan, Huei Peng, and Anna G. Stefanopoulou. “Control-Oriented Modeling and Analysis for Automotive Fuel Cell Systems”. In: *Journal of Dynamic Systems, Measurement, and Control* 126.1 [Apr. 2004], pp. 14–25. ISSN: 0022-0434. DOI: 10.1115/1.1648308. URL: `https://doi.org/10.1115/1.1648308` [visited on 12/14/2022])

Fuel Cell Voltage

Cathode Pressure Dependency

- 80 °C
- Δp : 0 Pa
- 80 % RH
- 100 % Membrane Humidity (λ_m)

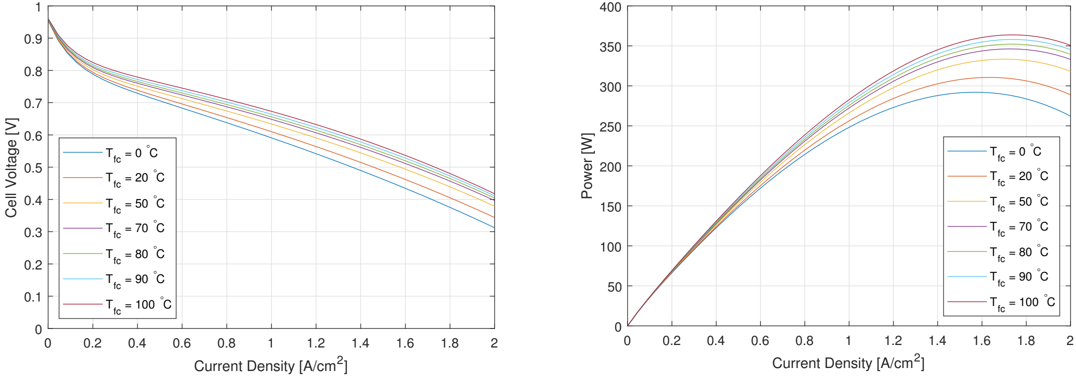




Fuel Cell Voltage

Fuel Cell Temperature Dependency

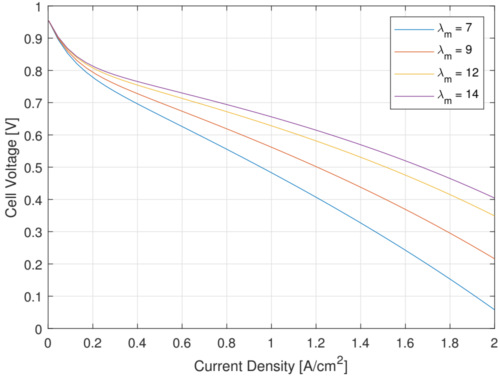
- p_{ca} : 3.5 bar
- Δp : 0 Pa
- 80 % RH
- 100 % Membrane Humidity (λ_m)

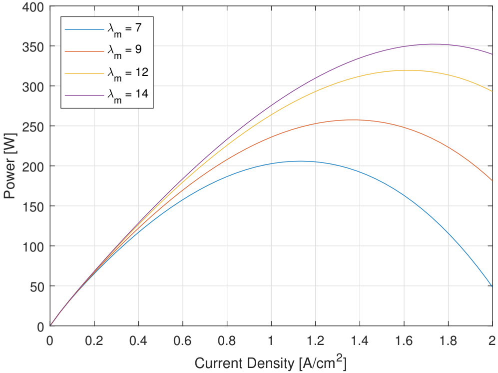


Fuel Cell Voltage

Membrane Humidity Dependency

- p_{ca} : 3.5 bar
- Δp : 0 Pa
- 80 % RH
- 80 °C





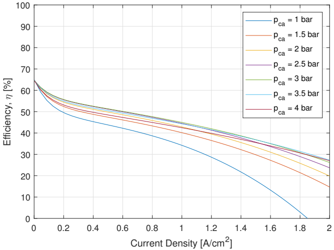
Fuel Cell Voltage

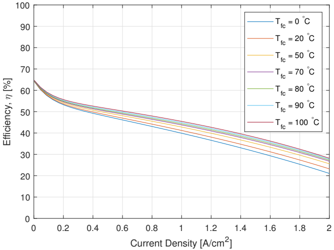
Heat Generation

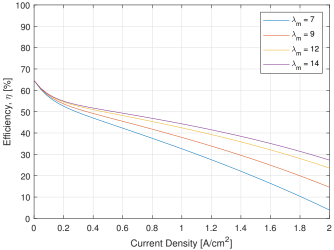
Efficiency, η

$$\eta = \frac{P_{elec}}{P_{tot}}$$

$$Q_{fc} = (1 - \eta)P_{tot}$$



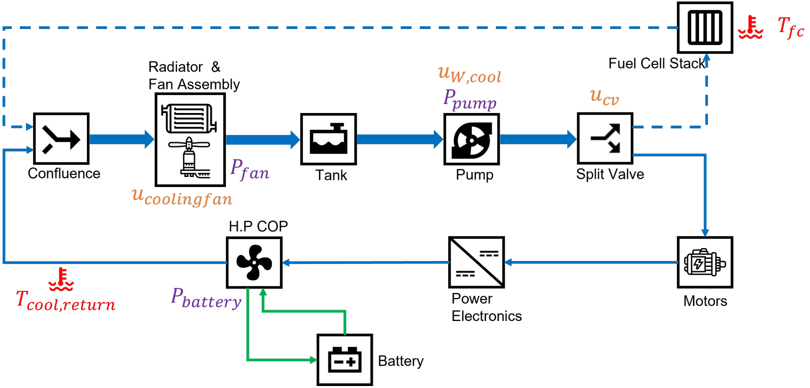




Cooling System

Cooling System

- Two different main flows
- Low temp cooling circuit for battery
- 3 Control Signals
- 3 Low Voltage Consumers
- 2 Temperature measurements
- Condenser in front of radiator



Cooling System

Definitions

Equations

- Coolant Pump (2 atm after pump)

$$P_{pump} = \frac{1}{\eta_{em}} \frac{\Delta p}{\rho_{cool} \eta_{pump}} \dot{m}_{cool}, \qquad \dot{m}_{cool} = u_{W,cool}$$

- Battery Cooling Circuit

$$P_{battery} = \frac{1}{\mathrm{COP}} Q_{battery}, \qquad \mathrm{COP} = 4$$

- Fan Power

$$P_{fan} = f(u_{coolingfan})$$

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Evaluation criteria

Hard constraints

- Vehicle speed – The vehicle is not allowed to over-speed, this could happen in steep downhills. $v_{max} = 90$ km/h must never be passed. Overspeeding is a failure.
- Average speed/trip time – The vehicle must arrive in time (or before) at the destination to deliver the goods according to schedule. A missed delivery is a failure.
- Battery SOC limits – The SOC must be maintained in the window 20-80 %. Going outside this window is a failure.
- Battery SOC at the end of a mission has to be at least 40 %.
- Battery current limits – The limits on the current is ± 1 C.
- Fuel Cell temperature is not allowed to go above 100 °C.
- Coolant return flow temperature is not allowed to go above 90 °C.
- Cathode Relative Humidity is not allowed to go above 100 %

Evaluation criteria

- The main goal is low hydrogen consumption

$$\int \dot{m}_{H_2}(t)dt$$

- High fuel cell voltage and high temperature stresses the fuel cell

$$\int (\max \left[U_{fc}(t) - 718.5 + 5.85 \cdot (T_{fc}(t) - 303), 0\right.$$

- Large pressure difference over the fuel cell membrane causes mechanical stress on the Membrane Electrode Assembly (MEA)

$$\int (p_{an}(t) - p_{cat}(t) - 2 \text{ kPa})^2 dt$$

- Time to simulate the mission, including the

Notation

- m_{H_2} – Hydrogen Mass [kg]
- U_{fc} – Fuel Cell Stack Voltage [V]
- T_{fc} – Fuel Cell Stack Temperature[K
- p_{an} – Anode pressure [Pa]
- p_{ca} – Cathode pressure [Pa]

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The Teams and Their Solution Focus

Team Origin	Speed Planning	Energy Management	Fuel Cell Opt	FC MEA	FC Thermal	Vehicle Thermal	Total FC
Kuyngpook National University, KR		✓			✓	✓	
TU Eindhoven, NL	✓	✓					✓
TU Wien, AT	✓	✓		✓			✓
University of Salerno, IT			✓	✓		✓	✓
University of Alabama, US	✓	✓					
Ohio State University, US		✓		✓	✓	✓	

Conclusion

- Very Challenging Problem
- Impressed by the teams efforts and results
- No Silver bullet among the teams
- Learned something from all teams
- Rewarding on all fronts
  - Industry satisfied
  - We as developers
  - Competing teams

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Max Johansson, + engineers at Scania CV, TitanX, and Volvo Trucks

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