EMR'23, Lille (France)

# EMR-based Energy management to optimize regenerative braking in a dual-mode locomotive

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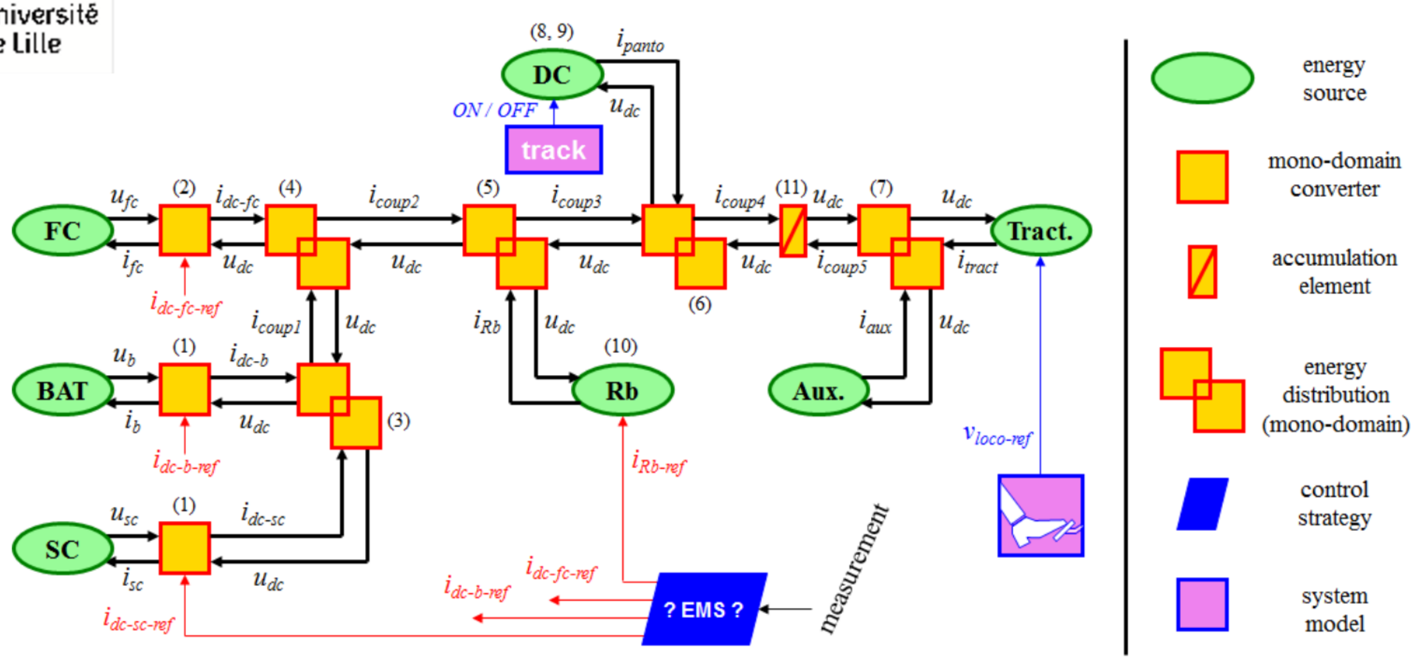
# Final EMR user experience

**IEEE VTS Motor Vehicles Challenge 2019 - Energy Management of a dual-mode locomotive**

**Simulation program done by Dr. Walter LHOMME**
**University of Lille, MEGEVH, France**
**Last Update: 17th of July 2018**



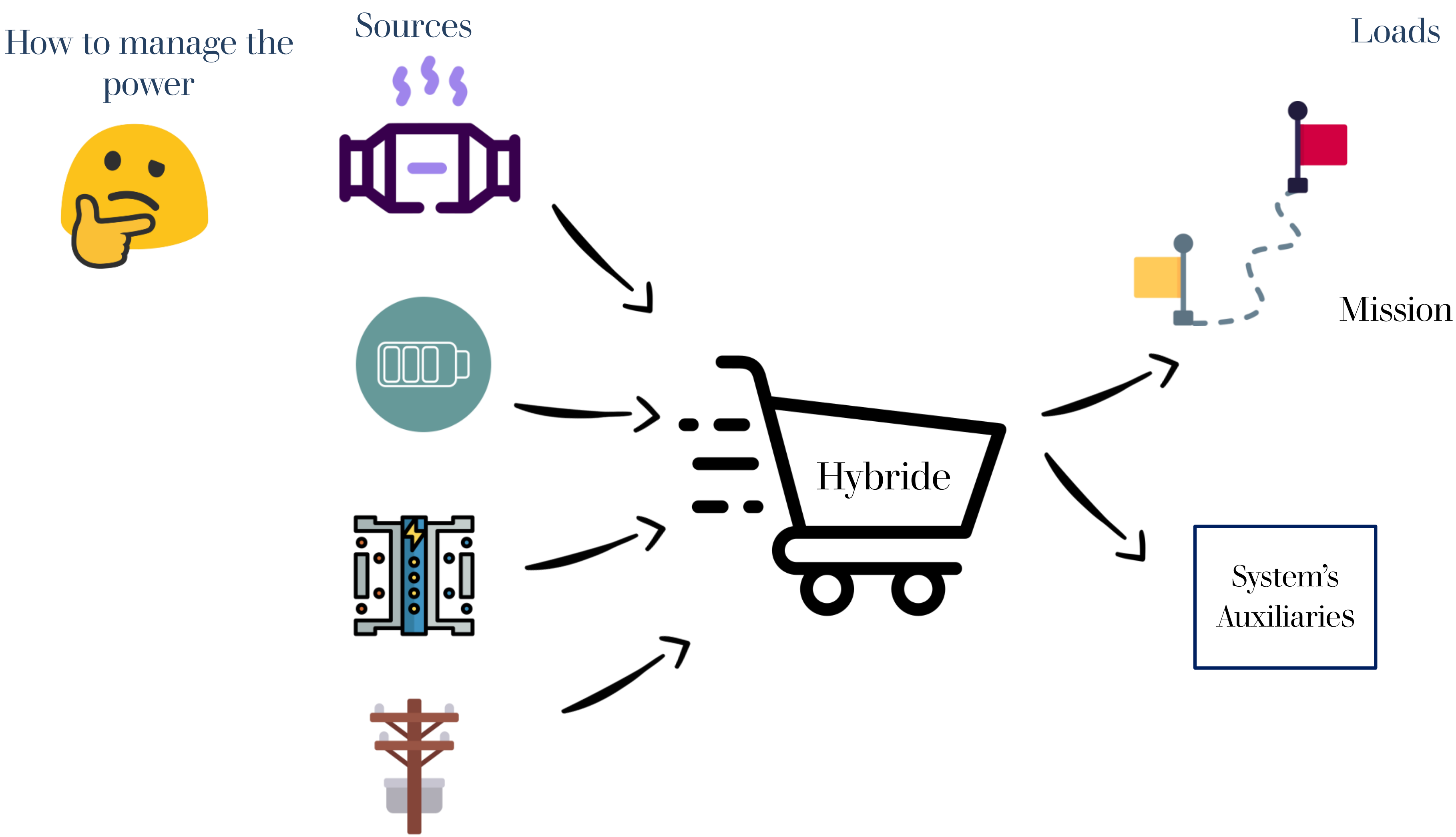

W. Lhomme *et al.*, "IEEE VTS Motor Vehicles Challenge 2019 - Energy Management of a Dual-Mode Locomotive," *2018 IEEE Vehicle Power and Propulsion Conference (VPP*.

# - Outline -

1. **Problem statement EMS**
2. **Model of a dual mode locomotive**
3. **EMS of a dual locomotive**
4. **Results**

# «Problem statement EMS»

# About Energy Management



## Current/power balance

$$\sum_{i=1}^{m} i_{s_i} = \sum_{k=1}^{n} i_{L_k}$$

## Constraints of the sources

$$V_{\mathrm{kmin}} < v_{\mathrm{k}}(t) < V_{\mathrm{kmax}}$$

$$SOC_{\mathrm{kmin}} < SOC_{\mathrm{k}}(t) < SOC_{\mathrm{kmax}}$$

$$I_{\mathrm{kmin}} < i_{\mathrm{k}}(t) < I_{\mathrm{kmax}}$$

$$\frac{dI_{\mathrm{k}}}{dt}_{min} < \frac{di_{\mathrm{k}}}{dt}(t) < \frac{di_{\mathrm{k}}}{dt}_{max}$$

$$P_{\mathrm{ksmin}} < p_{\mathrm{ks}}(t) < P_{\mathrm{ksmax}}$$

## Objective function to minimize

$$\mathrm{J} = \underbrace{\int_{t_o}^{t_f} f_1(P_s(t), I_s(t), V_s(t), SoC_s(t))dt}_{\text{Energy consumption and Degradation}} + \underbrace{f_2(SoC_s(t_f))}_{\text{Final state ESS}}$$

# «Model of a dual mode locomotive»

# Model of a dual mode locomotive

## IEEE VTS Motor Vehicles Challenge 2019 – Energy Management of a dual-mode locomotive

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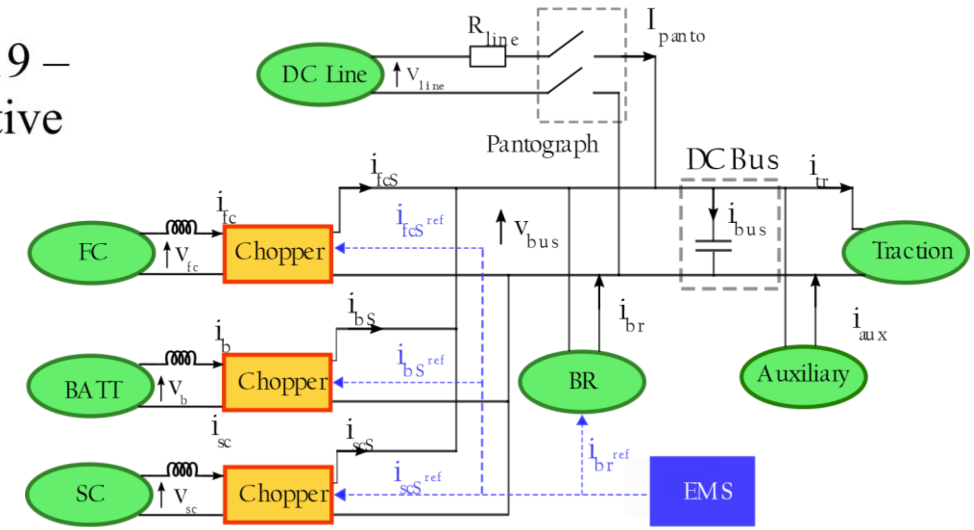
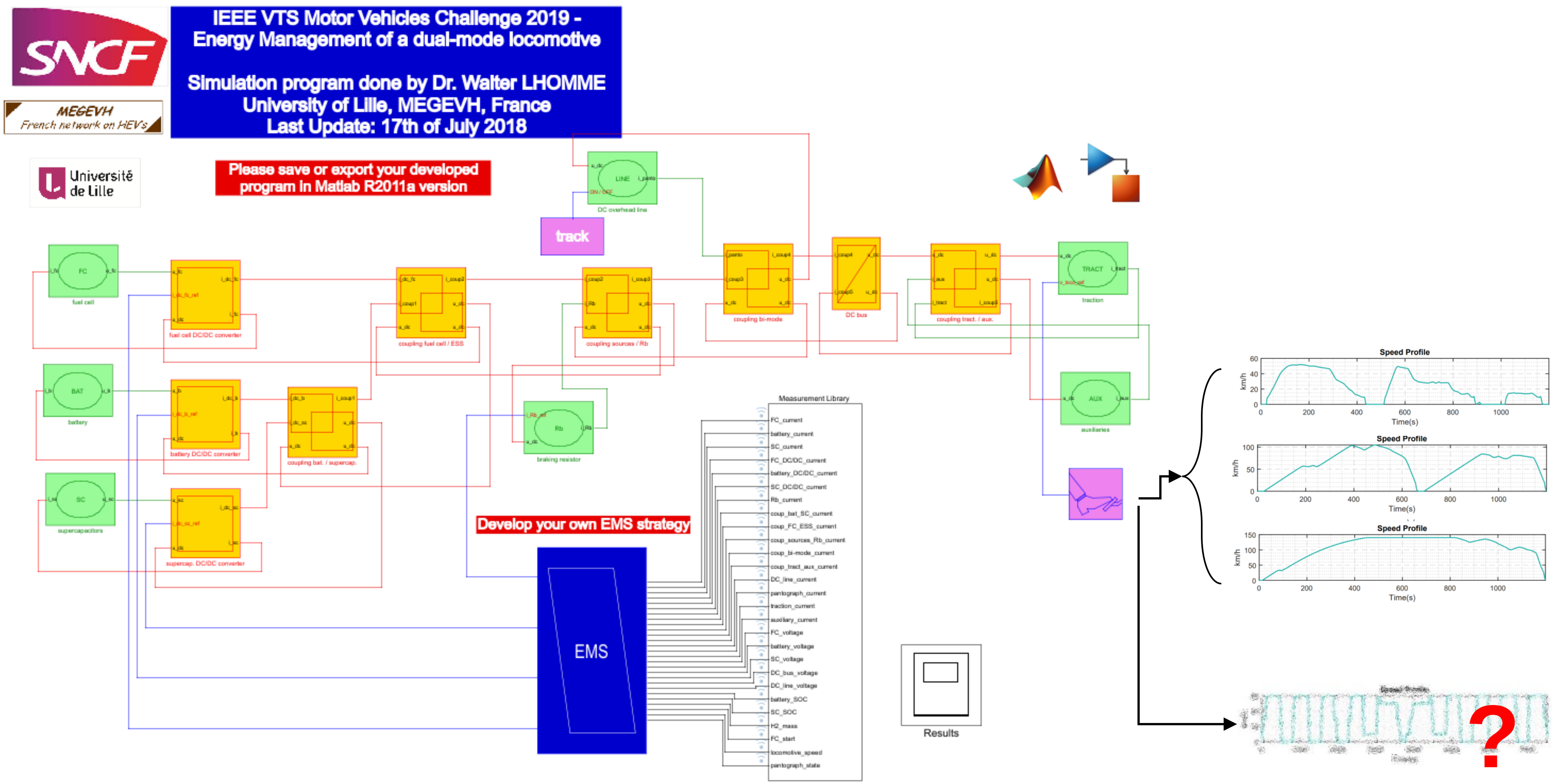



W. Lhomme *et al.*, "IEEE VTS Motor Vehicles Challenge 2019 - Energy Management of a Dual-Mode Locomotive," *2018 IEEE Vehicle Power and Propulsion Conference (VPP*.

# Model of a dual mode locomotive






W. Lhomme *et al.*, "IEEE VTS Motor Vehicles Challenge 2019 - Energy Management of a Dual-Mode Locomotive," *2018 IEEE Vehicle Power and Propulsion Conference (VPPC)*.

## Model of a dual mode locomotive



### 1. the hydrogen consumption H2 cost

$$€_{H_2}(t) = \frac{H_{2-cost}}{1.10^3} \int_0^t m\dot{}_{H2}(t)d\,t$$

### 2. Fuel cell degradation cost

$$€_{fc}(t) = \frac{P_{fc-rat}}{1.10^3} FC_{cost} \Delta_{fc}(t)$$

$$\Delta_{fc}(t) = N_{start} \Delta_{start}(t) + \int_0^t \delta(t)d\,t$$

$$\delta(t) = \frac{\delta_0}{3600} \left(1 + \frac{\alpha}{P_{fc-rat}^2} \left(p_{fc}(t) - P_{fc-rat}\right)^2\right)$$

### 3. Supercapacitor's degradation cost

$$€_{sc}(t) = E_{sc-rat} SC_{cost} \Delta_{sc}(t)$$

$$\Delta_{sc}(t) = \frac{t_{use}}{30.10^3}$$

W. Lhomme *et al.*, "IEEE VTS Motor Vehicles Challenge 2019 - Energy Management of a Dual-Mode Locomotive," *2018 IEEE Vehicle Power and Propulsion Conference (VPP*.

## Model of a dual mode locomotive



### 4. Batteries degradation cost

$$€_b(t) = E_{b-rat} B_{cost} \Delta_b(t)$$

$$\Delta_b(t) = \frac{1}{3600.15 \cdot 10^3 \cdot Q_{b-rat}} \int_0^t |f(SoC_b) \cdot g(i_b) \cdot i_b(t)| d\,t$$

### 6. the battery and SC charge sustaining cost after the cycle

$$€_{sust}(t) = \frac{N\,cost}{1.10^3} \left( \eta_{dc\_b\_avg} \cdot E_{b\_end} + \eta_{dc\_sc\_avg} \cdot E_{sc\_\mathrm{end}} \right)$$

### 5. Energy consumed from the network cost

$$€_{net}(t) = \frac{N_{cost}}{3600.1 \cdot 10^6} \int_0^t p_{line}(t) d\,t$$

### Total Cost Function

$$€_{tot} = €_{net} + €_{H_2} + €_{fc} + €_{sc} + €_b + €_{sust}$$

W. Lhomme *et al.*, "IEEE VTS Motor Vehicles Challenge 2019 - Energy Management of a Dual-Mode Locomotive," *2018 IEEE Vehicle Power and Propulsion Conference (VPP*.

# «EMS of a dual locomotive»

# Global EMS of a Dual-Mode Locomotive



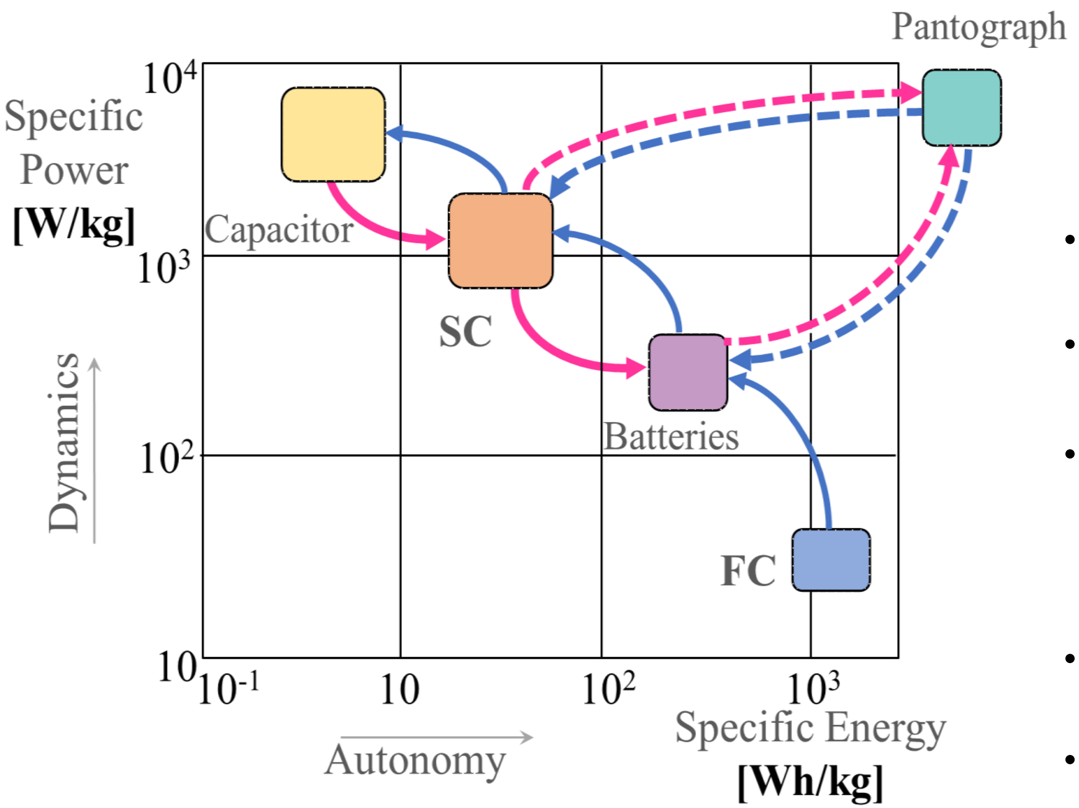



Figure 2. Ragone – Plot of the dual mode locomotive

## General Rules

- The FC will delivery the average energy.
- Batteries and <u>SC</u> will assume the transient energy.
- SC must have and adequate SOC to recover energy in the braking and supply energy in the acceleration
- Batteries perform SC SOC regulation
- FC performs batteries' SOC regulation

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## Algorithms Organization



**Algorithm 1:** FC local EMS

Output ← **Result:** Define $i_{fcS_{ref}}$

Source's parameters and constrains ← read FC parameters: $I_{fc_{max}}, dI_{fc_{max}}$

EMS parameters to optimize ← read FC EMS parameters: $K_{fc}$, $SoC_{b_{ref}}, I_{fc_{low}}, a_{min}$

inputs ← read measures: $SOC_b$, $i_{fc}$, $a_{loco}$

**if** $a_{loco} \leq a_{min}$ **then**

$\quad i_{fc_{ref}} * = I_{fc_{low}}$

**else**

$\quad i_{fc_{ref}} ** = K_{fc}(SOC_{b_{ref}} - SOC_b)$

$\quad i_{fc_{ref}} * = max(I_{fc_{low}}, min(I_{fc_{max}}, i_{fc_{ref}} **))$

**end**

# Fuel Cell Local EMS



**Algorithm 1:** FC local EMS

**Result:** Define $i_{fcS_{ref}}$

read FC parameters: $I_{fc_{max}}$, $dI_{fc_{max}}$

read FC EMS parameters: $K_{fc}$, $SoC_{b_{ref}}$, $I_{fc_{low}}$, $a_{min}$

read measures: $SOC_b$, $i_{fc}$, $a_{loco}$

**if** $a_{loco} \leq a_{min}$ **then**

$i_{fc_{ref}}* = I_{fc_{low}}$

**else**

$i_{fc_{ref}} ** = K_{fc}(SOC_{b_{ref}} - SOC_b)$

$i_{fc_{ref}}* = max(I_{fc_{low}}, min(I_{fc_{max}}, i_{fc_{ref}} **))$

**end**

Second Operation mode

Strong braking is detected

First Operation mode

## Fuel Cell Local EMS





**Algorithm 2:** Batteries Local EMS

**Result:** Define $i_{bS_{ref}}$

read batteries parameters: $I_{batt_{max}}, I_{batt_{min}}$

read EMS parameters: $SOC_{sc_{Vel0}}, SoC_{sc_{Vel_{max}}}, Vel_{max}$

read measures: $SOC_{sc}, Vel_{loco}$

$$SoC_{sc_{ref}} = SOC_{sc_{Vel0}} - \frac{Vel_{loco}}{Vel_{max}}(SOC_{sc_{Vel0}} - SOC_{sc_{Vel_{max}}})$$

$$i_{bS_{ref}}* = K_b(SOC_{sc_{ref}} - SOC_{sc})$$

$$i_{bS_{ref}} = max(I_{batt_{min}}, min(I_{batt_{max}}, i_{bS_{ref}}*))$$

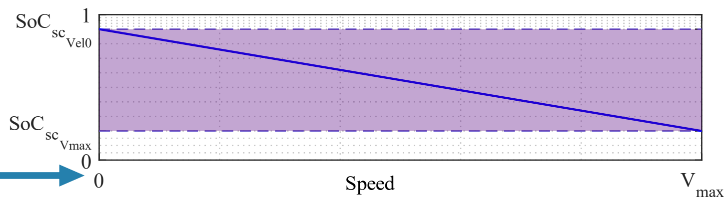



Figure 6. Reference for $SOC_{scS\_ref}$

## Supercapacitors and Braking Resistor Local EMS





The SC system balances the currents

**Algorithm 3:** Supercapacitors Local EMS

**Result:** Define $i_{sc_{ref}}$

read SC parameters: $I_{scs_{max}}, I_{scs_{min}}$

read control references: $I_{bus_{ref}}$

read measures: $i_{tr}, i_{aux}, i_{fcS}, i_{bS}$

$i^*_{scS_{ref}} = i_{bus_{ref}} + i_{tr} + i_{aux} - i_{fcS} - i_{bS}$

$i_{scS_{ref}} = max(I_{scs_{min}}, min(I_{scs_{max}}, i^*_{scS_{ref}}))$

The braking resistor use must be avoided

**Algorithm 4:** Braking resistor Local EMS

**Result:** Define $i_{br_{ref}}$

read measures: $i_{tr}, i_{aux}, i_{fcS}, i_{bS}, i_{scS}$

$i^*_{br_{ref}} = i_{tr} + i_{aux} - i_{fcS} - i_{bS} - i_{scS}$

$i_{br_{ref}} = max(0, i^*_{br_{ref}}))$

# Supercapacitors and Braking Resistor Local EMS

**Algorithm 1:** FC local EMS

**Result:** Define $i_{fcS_{ref}}$

read FC parameters: $I_{fc_{max}}, dI_{fc_{max}}$

read FC EMS parameters: $K_{fc}, SoC_{b_{ref}}, I_{fc_{low}}, a_{min}$

read measures: $SOC_b, i_{fc}, a_{loco}$

**if** $a_{loco} \le a_{min}$ **then**

  $i_{fc_{ref}}* = I_{fc_{low}}$

**else**

  $i_{fc_{ref}}** = K_{fc}(SOC_{b_{ref}} - SOC_b)$

  $i_{fc_{ref}}* = max(I_{fc_{low}}, min(I_{fc_{max}}, i_{fc_{ref}}**))$

**end**

**Algorithm 2:** Batteries Local EMS

**Result:** Define $i_{bS_{ref}}$

read batteries parameters: $I_{batt_{max}}, I_{batt_{min}}$

read EMS parameters: $SOC_{sc_{Vel0}}, SoC_{sc_{Vel_{max}}}, Vel_{max}$

read measures: $SOC_{sc}, Vel_{loco}$

$SoC_{sc_{ref}} = SOC_{sc_{Vel0}} - \frac{Vel_{loco}}{Vel_{max}}(SOC_{sc_{Vel0}} - SOC_{sc_{Vel_{max}}})$

$i_{bS_{ref}}* = K_b(SOC_{sc_{ref}} - SOC_{sc})$

$i_{bS_{ref}} = max(I_{batt_{min}}, min(I_{batt_{max}}, i_{bS_{ref}}*))$

**Algorithm 3:** Supercapacitors Local EMS

**Result:** Define $i_{sc_{ref}}$

read SC parameters: $I_{scs_{max}}, I_{scs_{min}}$

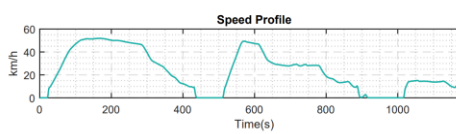
read control references: $I_{bus_{ref}}$

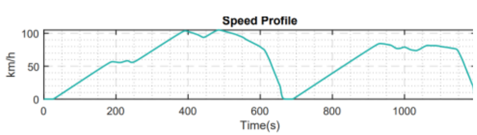
read measures: $i_{tr}, i_{aux}, i_{fcS}, i_{bS}$

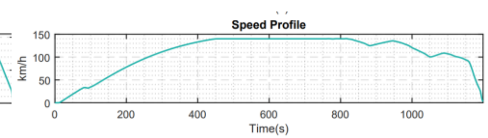
$i^*_{scS_{ref}} = i_{bus_{ref}} + i_{tr} + i_{aux} - i_{fcS} - i_{bS}$

$i_{scS_{ref}} = max(I_{scs_{min}}, min(I_{scs_{max}}, i^*_{scS_{ref}}))$

Heuristic approach
'home-made'

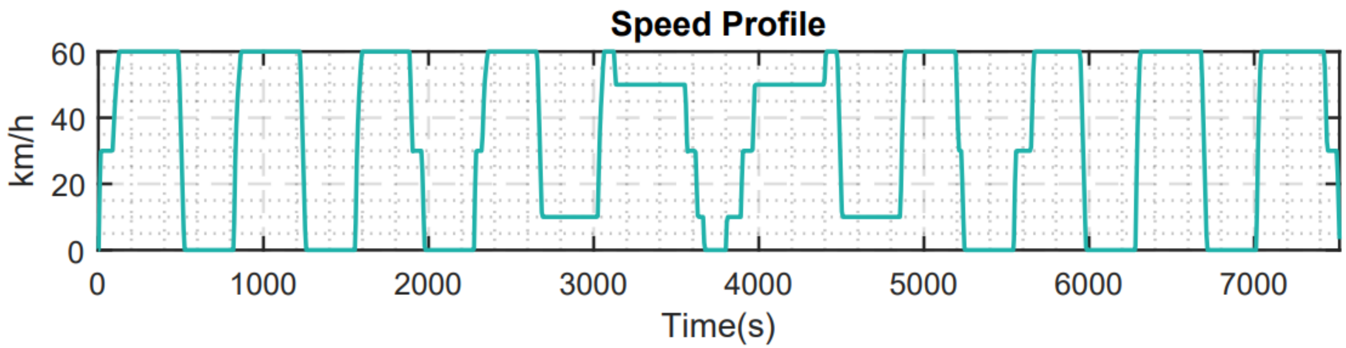


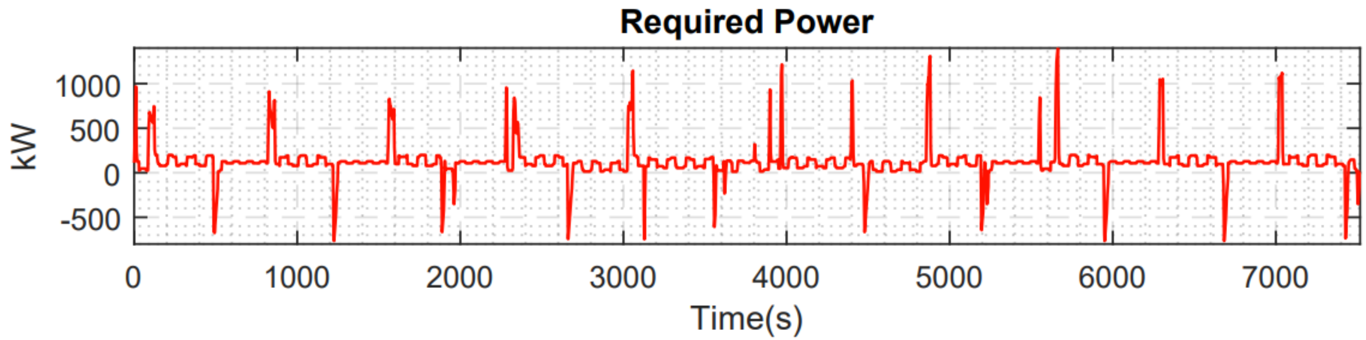



# «EMS results»

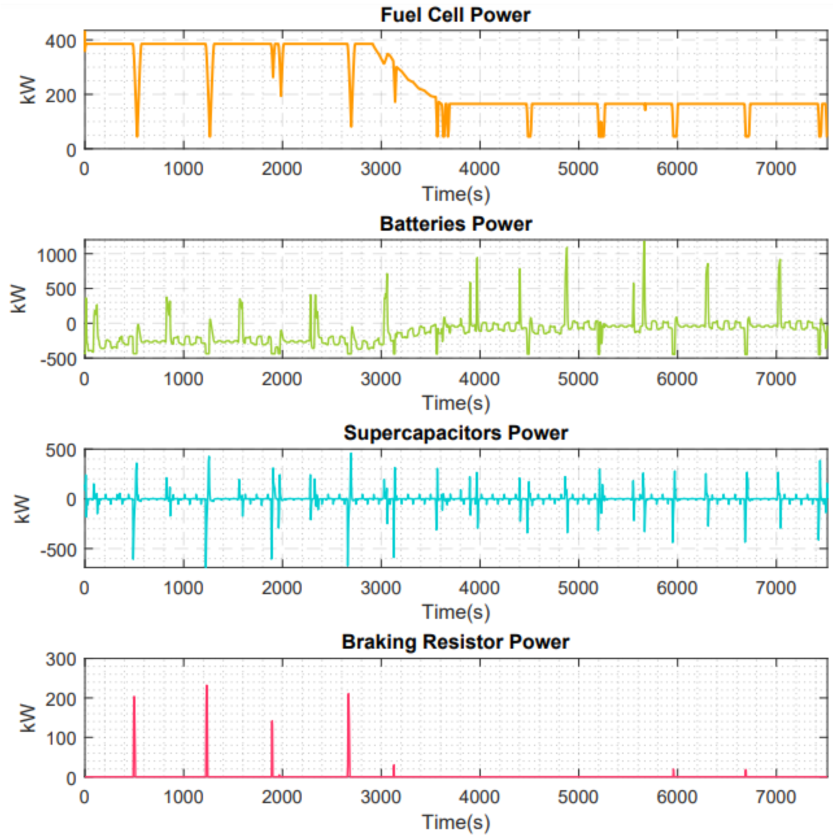
# Study case

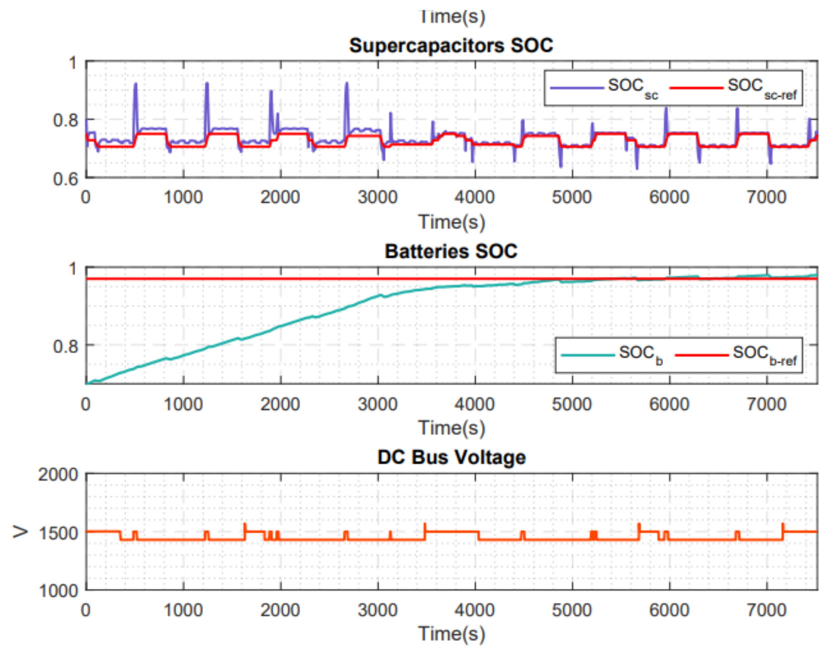



Performing evaluation profile
IEEE VTS Motor vehicles challenge 2019

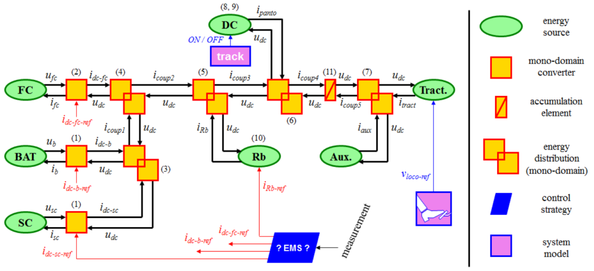
# Sources results



# Conclusion

- The EMR allows to focus on final user objectives and not in the complexity of the model.

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