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Sustainable and Clean
Energy Research Group

TOR VERGATA
UNIVERSITÀ DEGLI STUDI DI ROMA

Development of Platform for Fuel Cell Hybrid Electric Vehicle Design and Control Strategies Testing

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Introduction

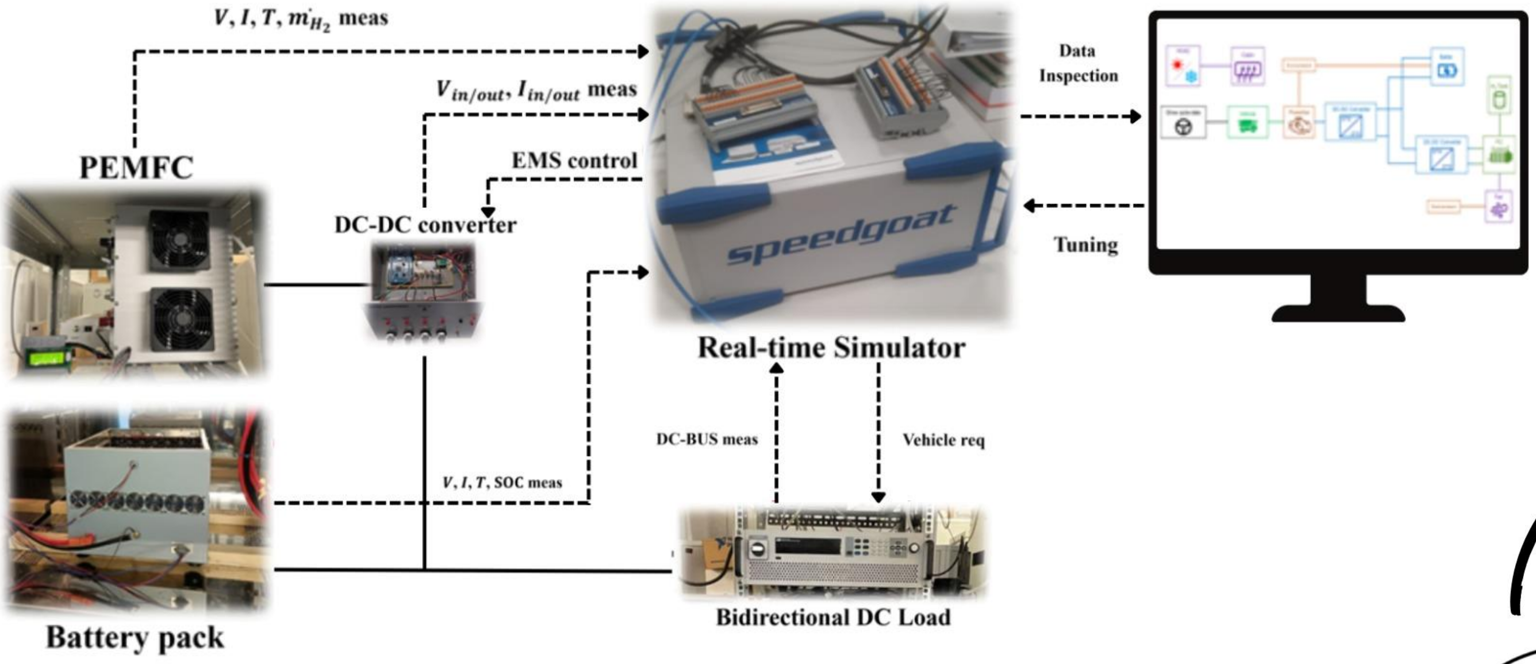
Fuel cell vehicles couple the benefits of hydrogen and battery powered technologies such as Long driving ranges, Low noise, Quick dynamic response, Short refueling times, High efficiency

The use of **light personal vehicle (LPV)** has been demonstrated as an innovative urban transport solution to move towards a sustainable mobility sector in urban area the, providing flexible, sustainable, and cost-effective alternative to traditional private vehicles especially in a shared framework.

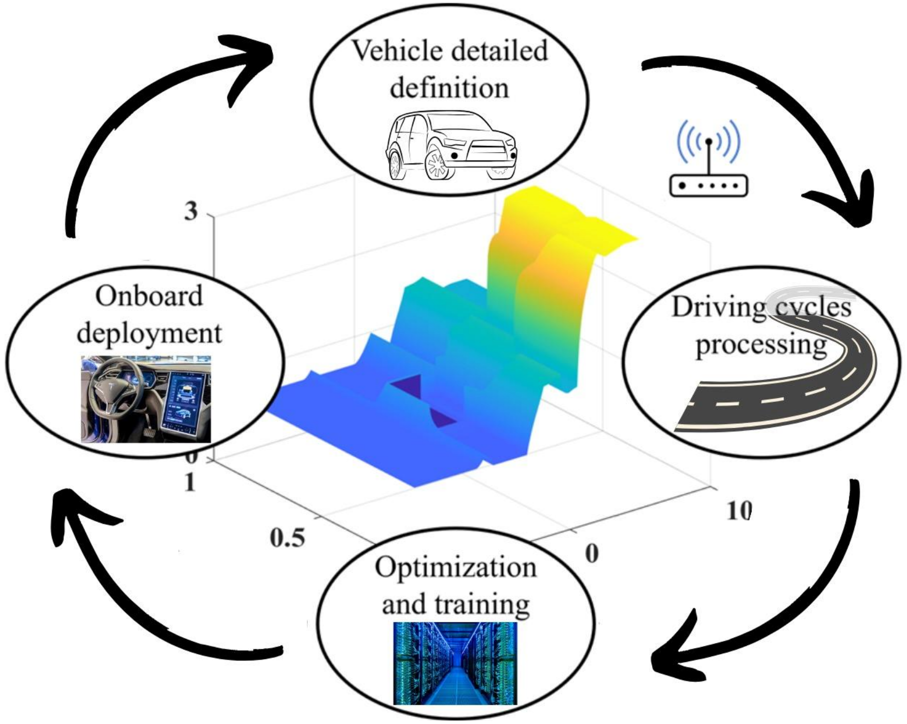
Proper design and effective power splitting strategies are crucial to maximize the benefits from such technologies.

In this perspective, **Simulation platforms**, **Digital Twins (DTs)** and **Hardware-in-the-Loop (HIL) test benches** are gaining importance for their time-and-cost saving characteristics with respect to prototype manufacturing.

- ❑ Vehicle Powertrain Design
- ❑ Control Strategy Development and Testing

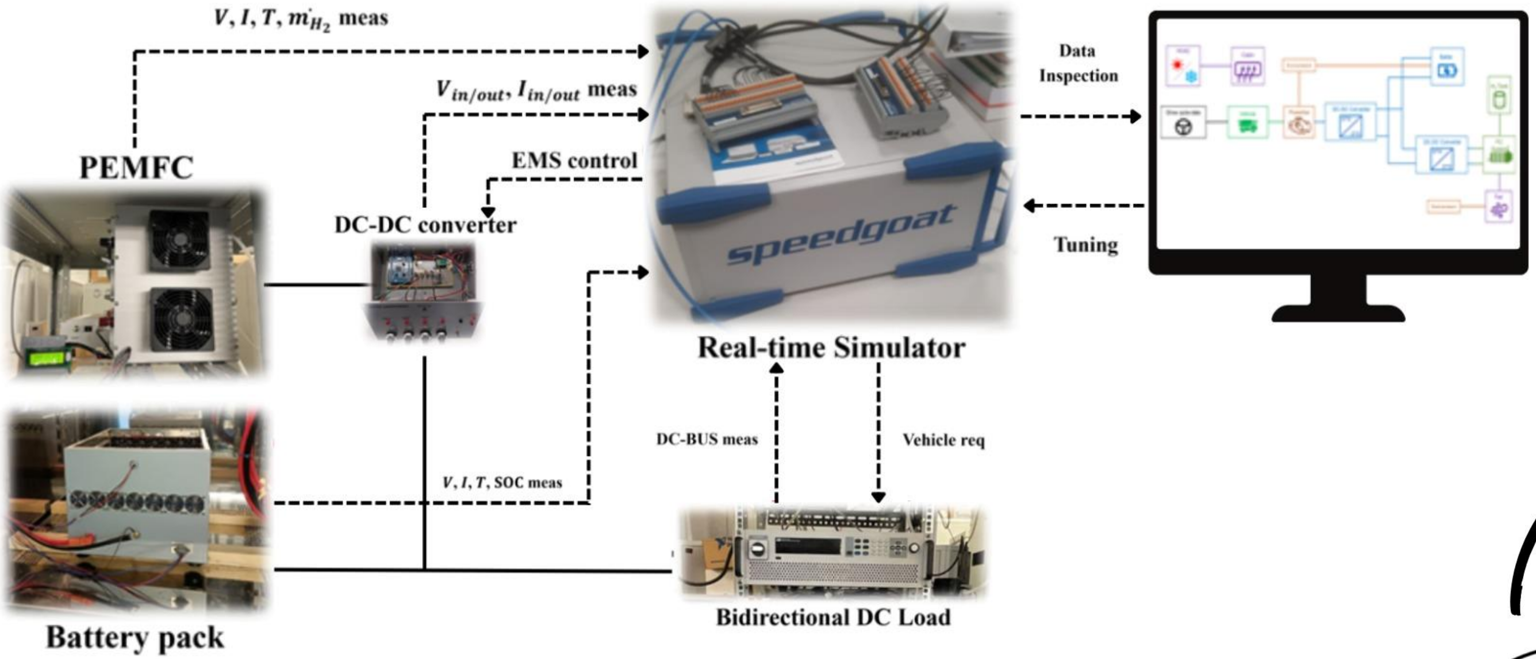


Hardware in the Loop approach
- to test the physical components under real-like operating conditions
- to verify the feasibility of the proposed control strategy and its effects on components performance



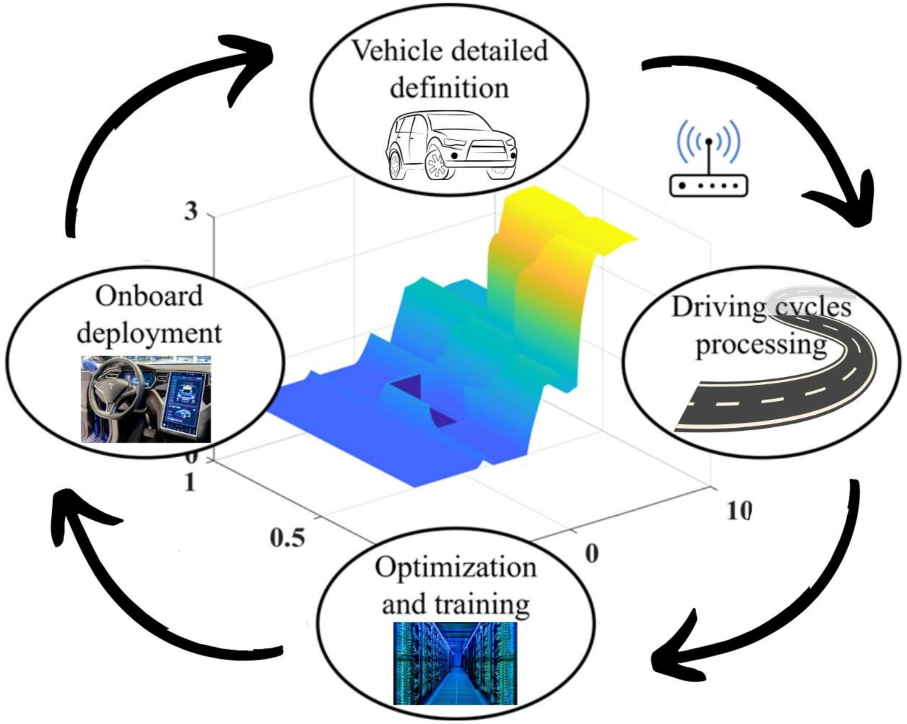
High Performance Computing use
- to analyze the performance of the vehicle under a wide range of operating conditions and generate control maps trained using optimal solutions for specific reference conditions

Methodology



Hardware in the Loop approach

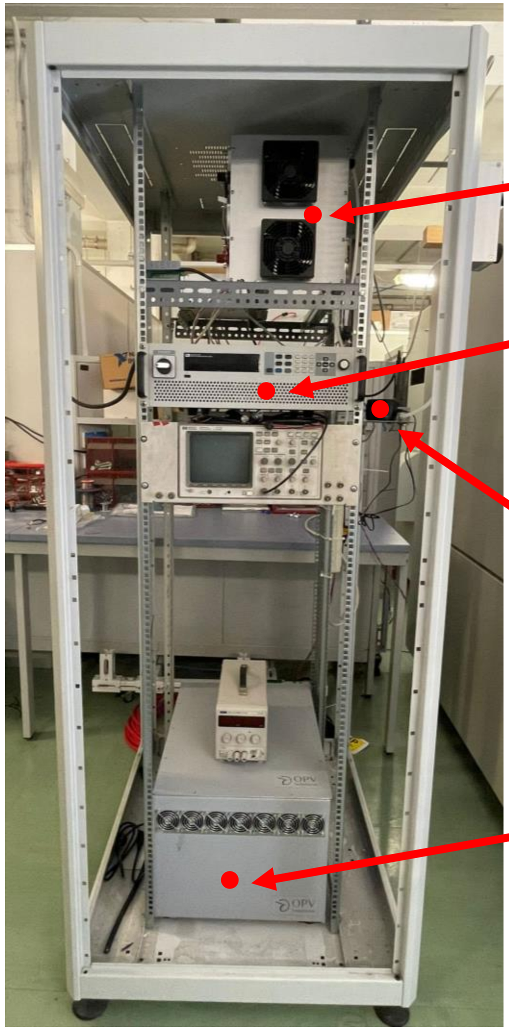
High Performance Computing use



The resulting integrated approach is **scalable** and can be easily generalized to other class of vehicles – currently part of our collaboration with **IVECO Group** for the application to <u>light commercial vehicles.</u>

IVECO • GROUP

Methodology – Experimental Setup



❑ **Fuel Cell stack**

❑ **Bidirectional power supply:**
ITECH IT6010C-80-300

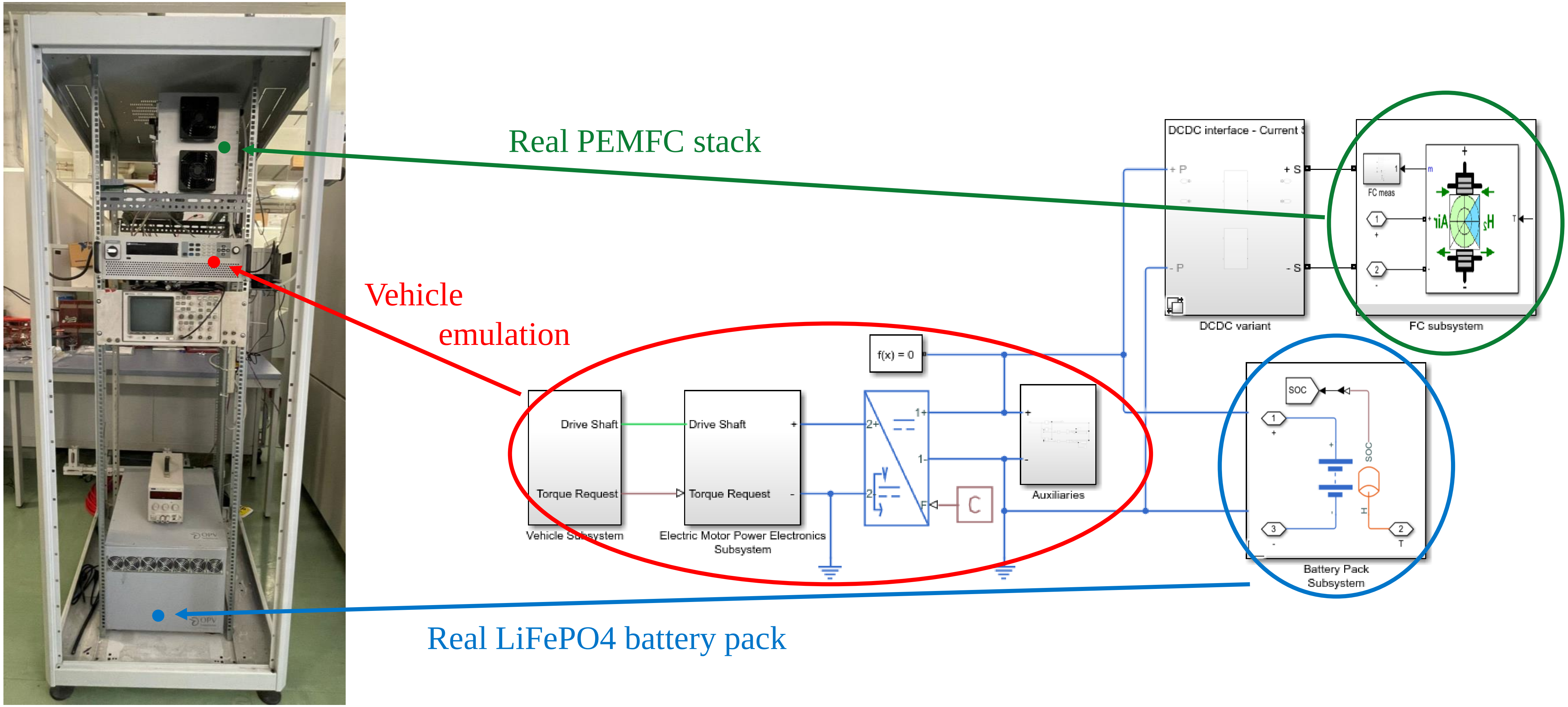
- Max Current: 300 A
- Max Voltage: 80 V
- Max Power: 10 kW

❑ **Hydrogen flow rate sensor:**
Aalborg DPM37

❑ **Battery Pack**

- Technology: LiFePO4
- Nominal Voltage: 51,2 V
- Nominal Capacity: 100 Ah

Slide Validazione e Modello



Data analisys for selecting the most representative driving patterns

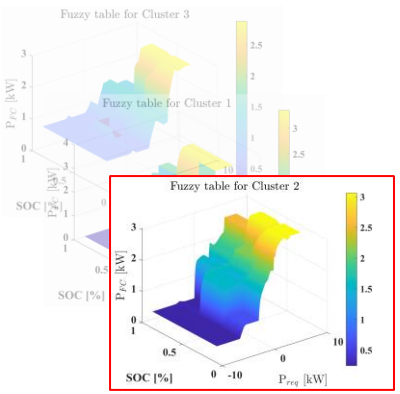
Recognition of the actual driving pattern and EMS definition

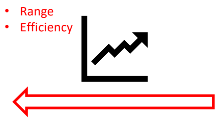
On board application

Driving Cycles' dataset generation → Clustering phase →

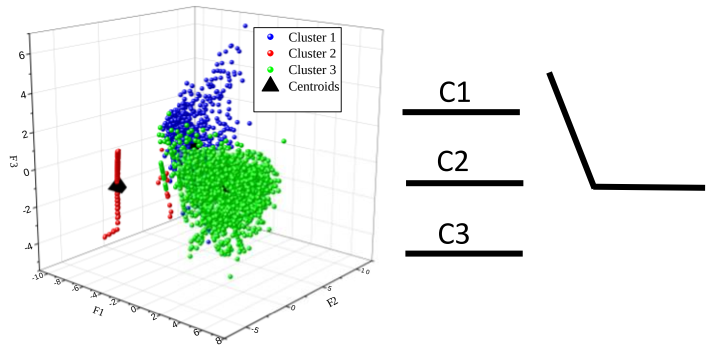
- **Driving Pattern recognition technique** based on data clustering results
- **Dynamic Programming** on the most representative driving patterns → **Fuzzy training** on the DP results and **Tables generation** to implement Fuzzy strategy on the model

→ **Integrated Real Time EMS**

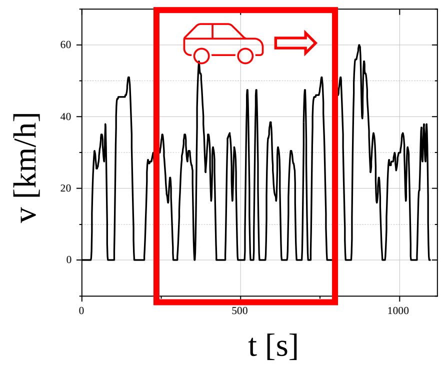




Strategy decision maker



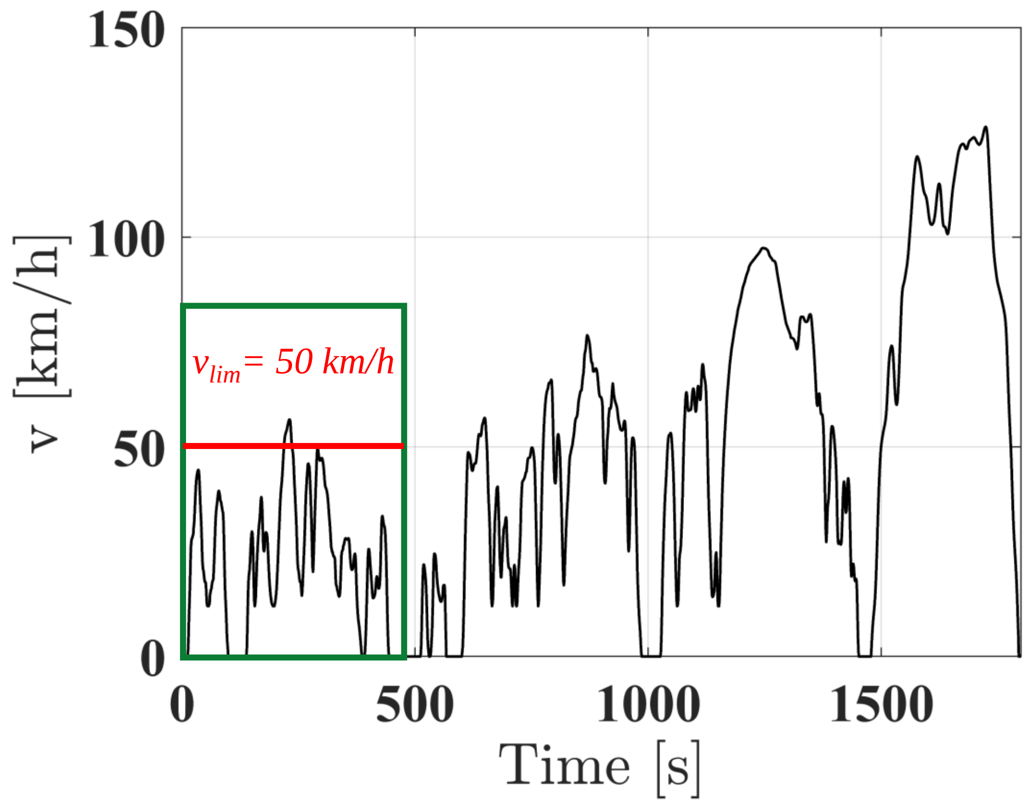
Window sampling
actual driving segment



Results – Vehicle performance

The fist stretch of the Worldwide harmonized Light vehicles Test Procedure (**WLTP**) has been used for the platform test, corresponding to the **microcar application** (urban and sub-urban driving conditions).

The simulations have been carried out to **full hydrogen pressurized tank discharge** (0,3 kg) and to **zero net battery energy** ($SOC_{in} = SOC_{end}$).

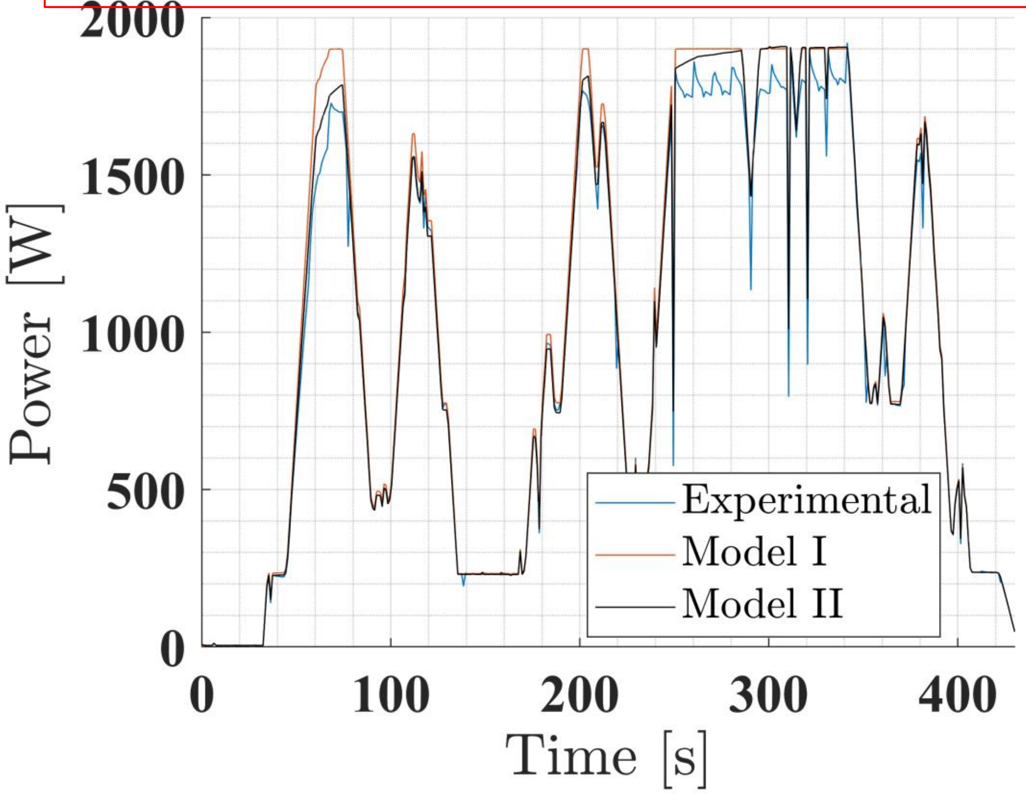


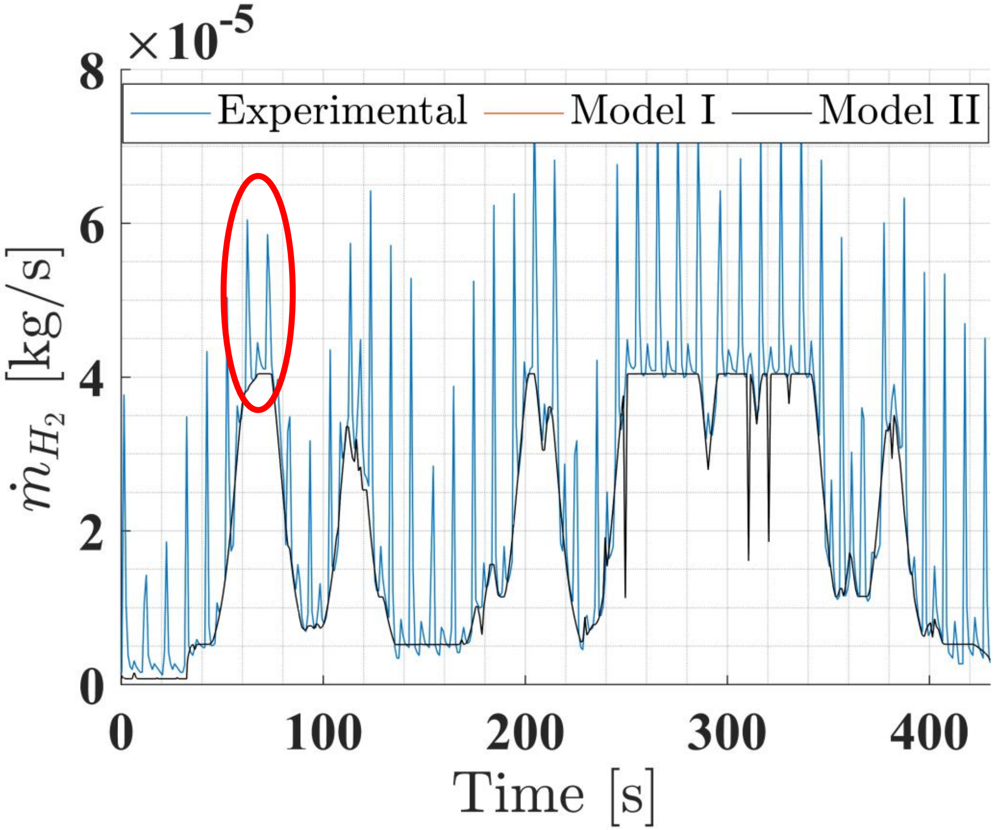
Results – Dynamic test

A **real-application test** has been experimentally carried out by taking the **simulated FC stack current** in the same stretch of the WLTP driving cycle and **dynamically controlling the bidirectional power supply**.

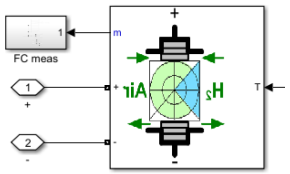
- **High-intensity peaks** are due to **purge phase**, a data-driven model is currently under development in order to account also that amount of gas consumption into the overall BoP.

- The models **accurately** estimate the **hydrogen consumption profile**

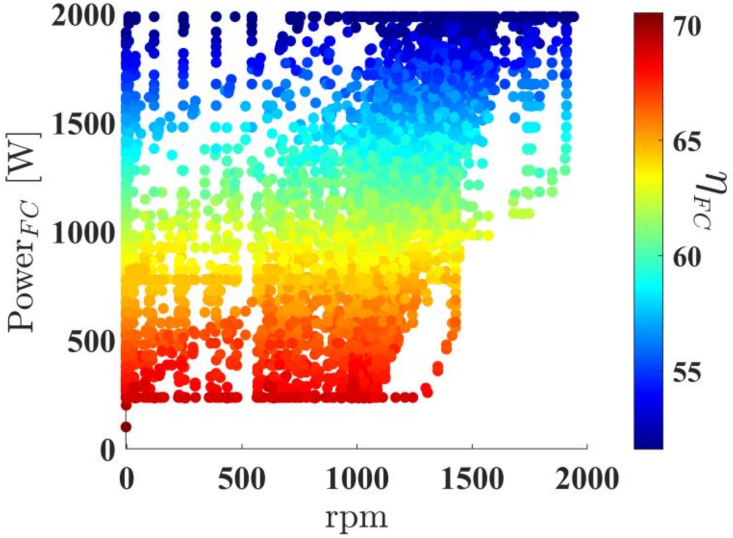


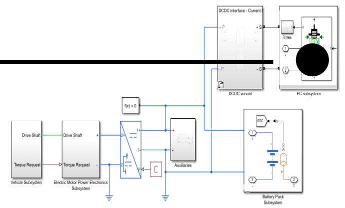


Results – Single vs Double FC stacks

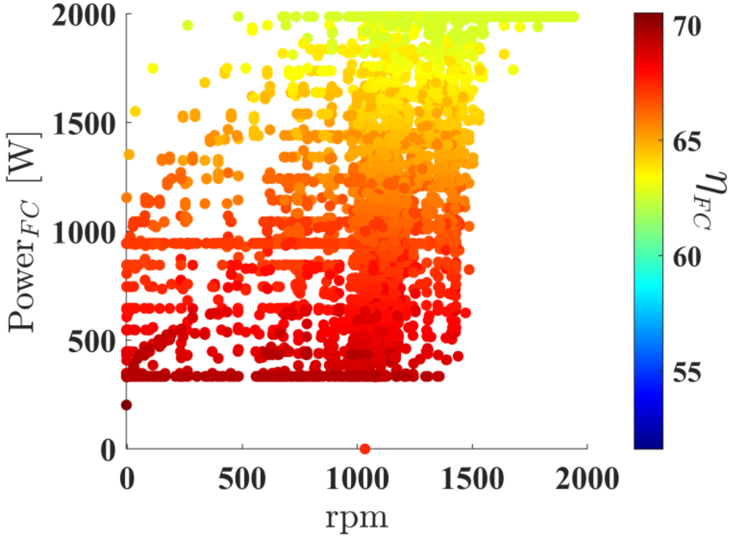


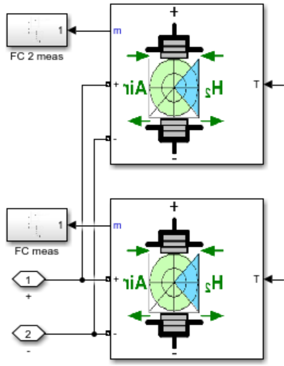
- **Baseline layout**:
  2kW FC system





- **Improved layout**:
  4kW FC system

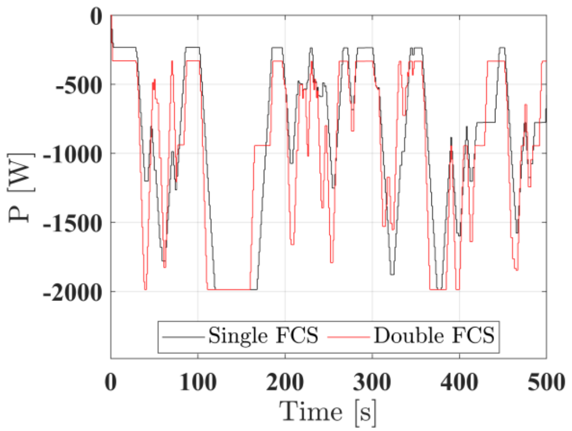




The density of **efficiency points** has been shifted over the **higher region**

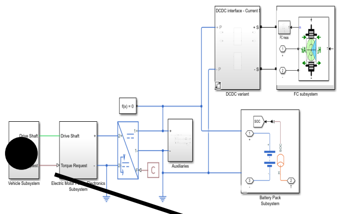
A comparison between two different powertrain layouts has been carried out for **improving the vehicle performance**.
The same fuzzy controller and constraints (charge sustaining working mode) has been tested for a robust and reliable comparison.

EMS control

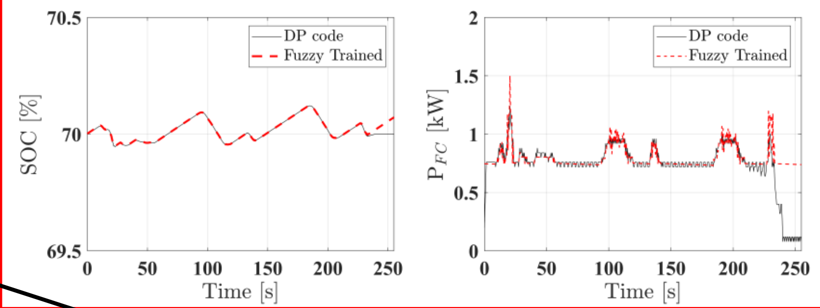


	Baseline Layout	Improved Layout
	Estimated range	
Fuzzy control	87.1 km	92.6 km
Gain	-	**6.3%**
	FCS efficiency	
Fuzzy control	61.65%	**66.36%**
	Powertrain efficiency [%]	
Fuzzy control	57.90%	62.20%

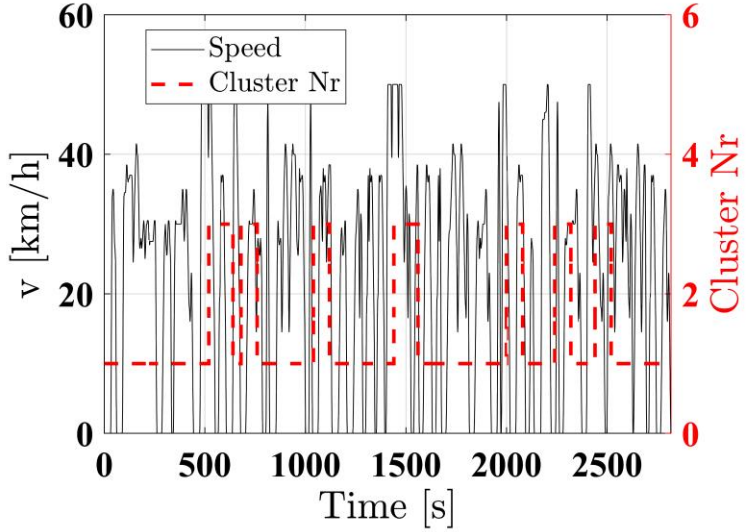
The EMS has been tested on a random driving cycle for **underling the potential with respect to the optimal trajectories** given by the DP technique. Moreover, a critical driving cycle has been built for testing the **robustness** of the applied approach **under severe operating conditions**.



Fuzzy training



- **Random driving cycle**

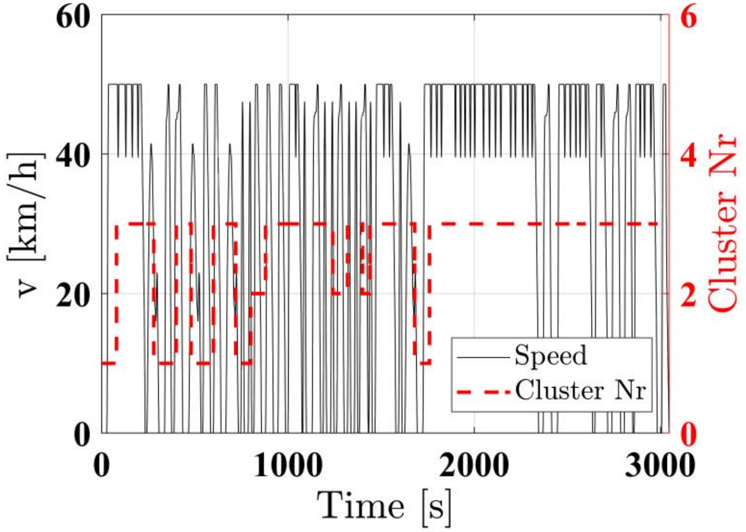


	Random driving cycle	
	DP code	**Proposed EMS**
m_{H_2} **[g]**	50.4	51.9
Loss [%]	-	**3.0**

	Critical driving cycle	
	DP code	**Proposed EMS**
m_{H_2} **[g]**	100.7	104.4
Loss [%]	-	**3.7**

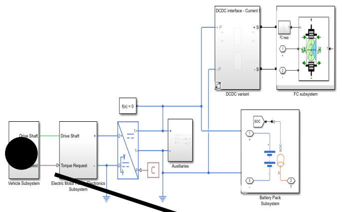
The **accuracy of the DPR** in recognizing the driving cluster has led to a proper **management of the charge sustaining mode** along both the entire missions.
The sub-optimality of the controllers achieved a **very small deviation from the optimal DP control (3%)**.

- **Critical driving cycle**

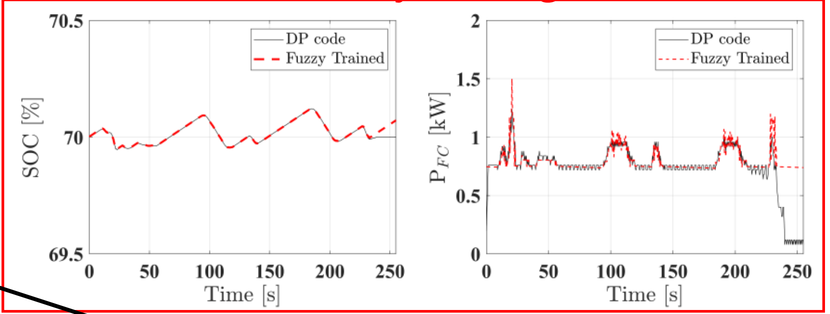


Results – DPR vs DP control logics

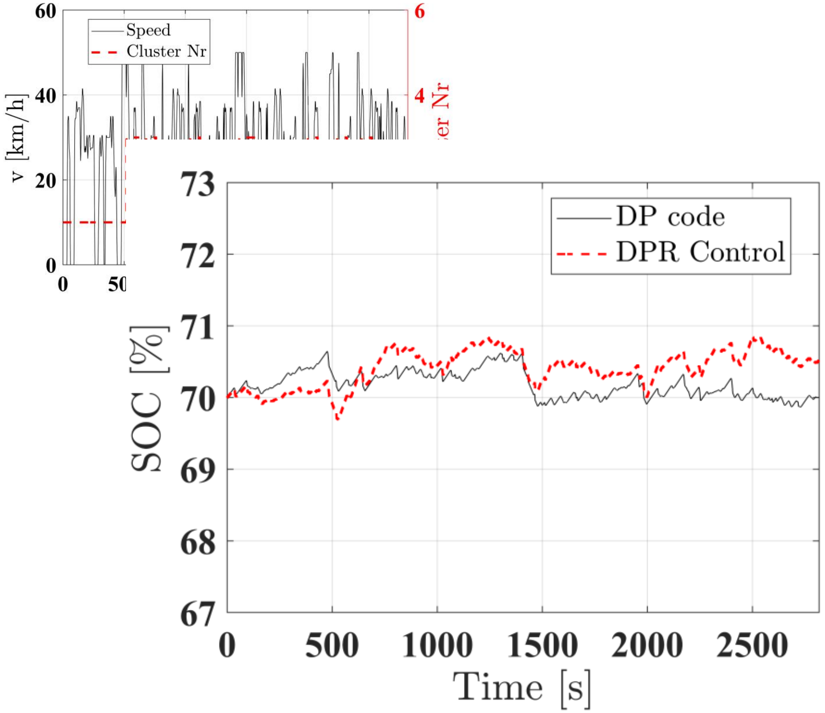
The EMS has been tested on a random driving cycle for **underling the potential with respect to the optimal trajectories** given by the DP technique. Moreover, a critical driving cycle has been built for testing the **robustness** of the applied approach **under severe operating conditions**.



Fuzzy training



- **Random driving cycle**



Random driving cycle		
	DP code	**Proposed EMS**
m_{H_2} **[g]**	50.4	51.9
Loss [%]	-	**3.0**
Critical driving cycle		
	DP code	**Proposed EMS**
m_{H_2} **[g]**	100.7	104.4
Loss [%]	-	**3.7**

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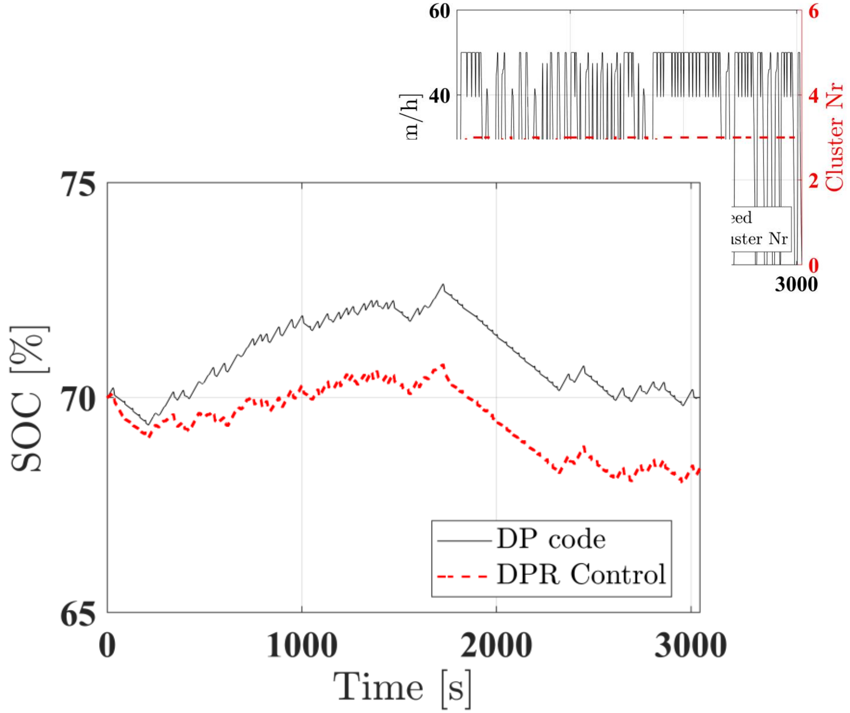
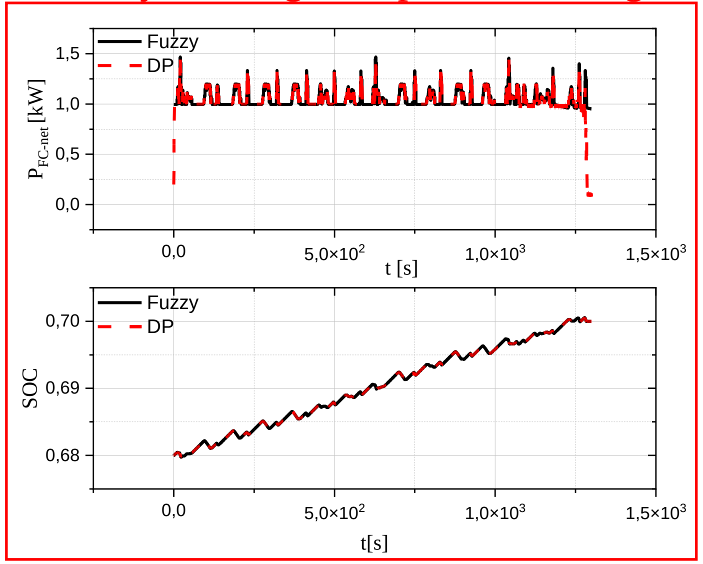
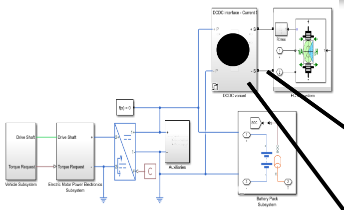
- **Critical driving cycle**

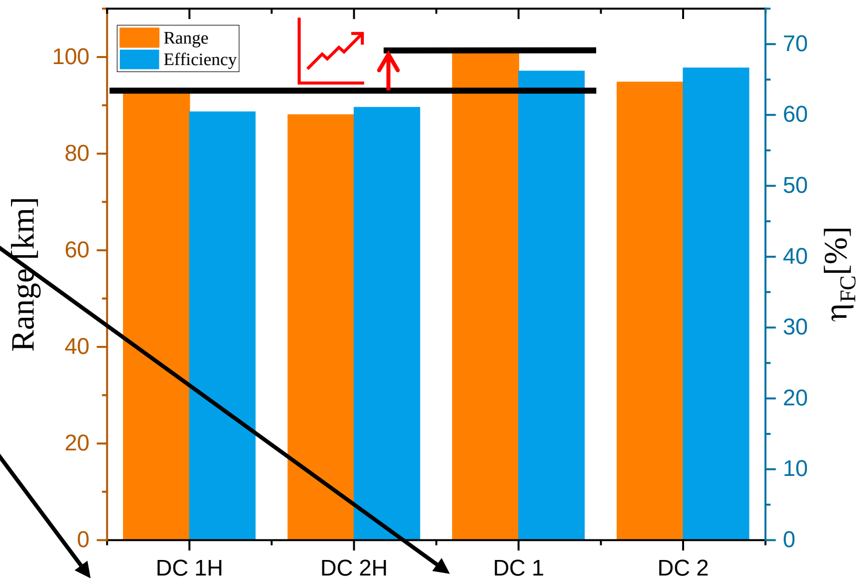


Results – DPR vs RE control logics

Fuzzy training for optimal recharge

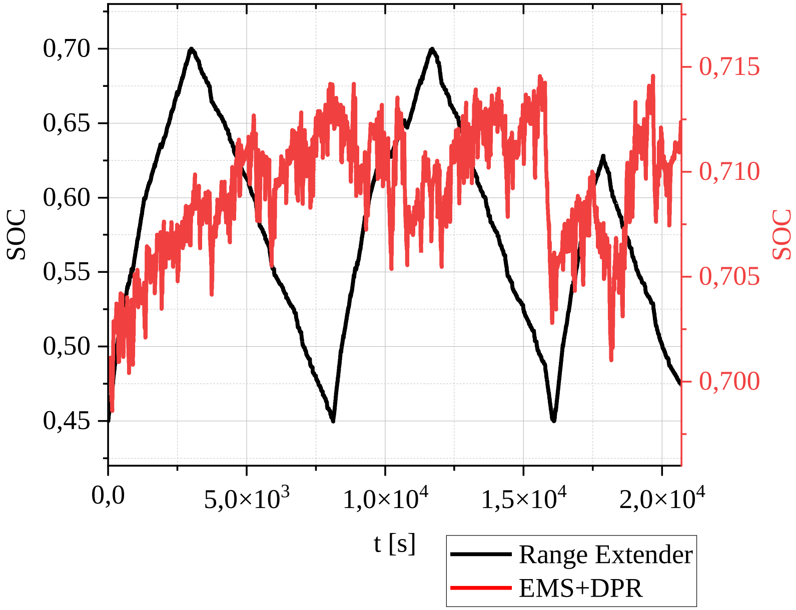




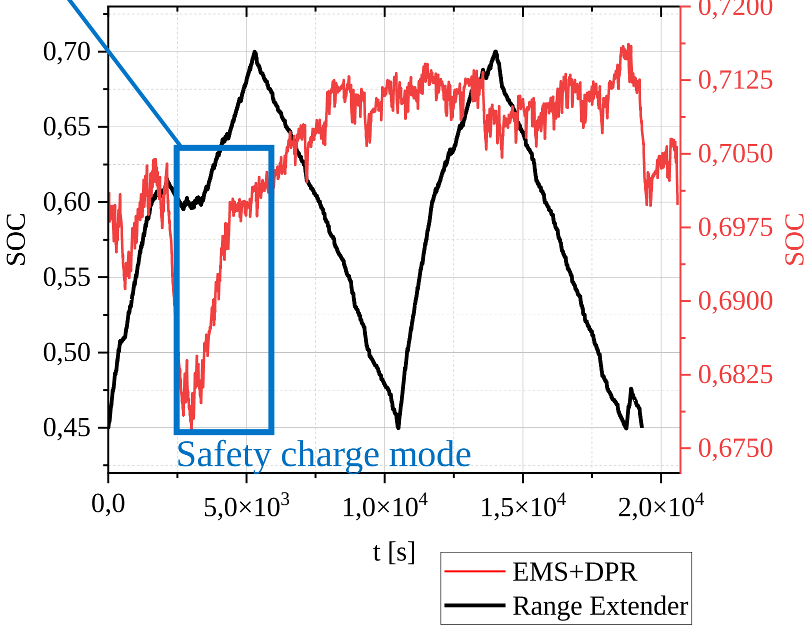


- **Range Extender**
- **Proposed EMS**

- **Random driving cycle**



- **High power driving cycle**



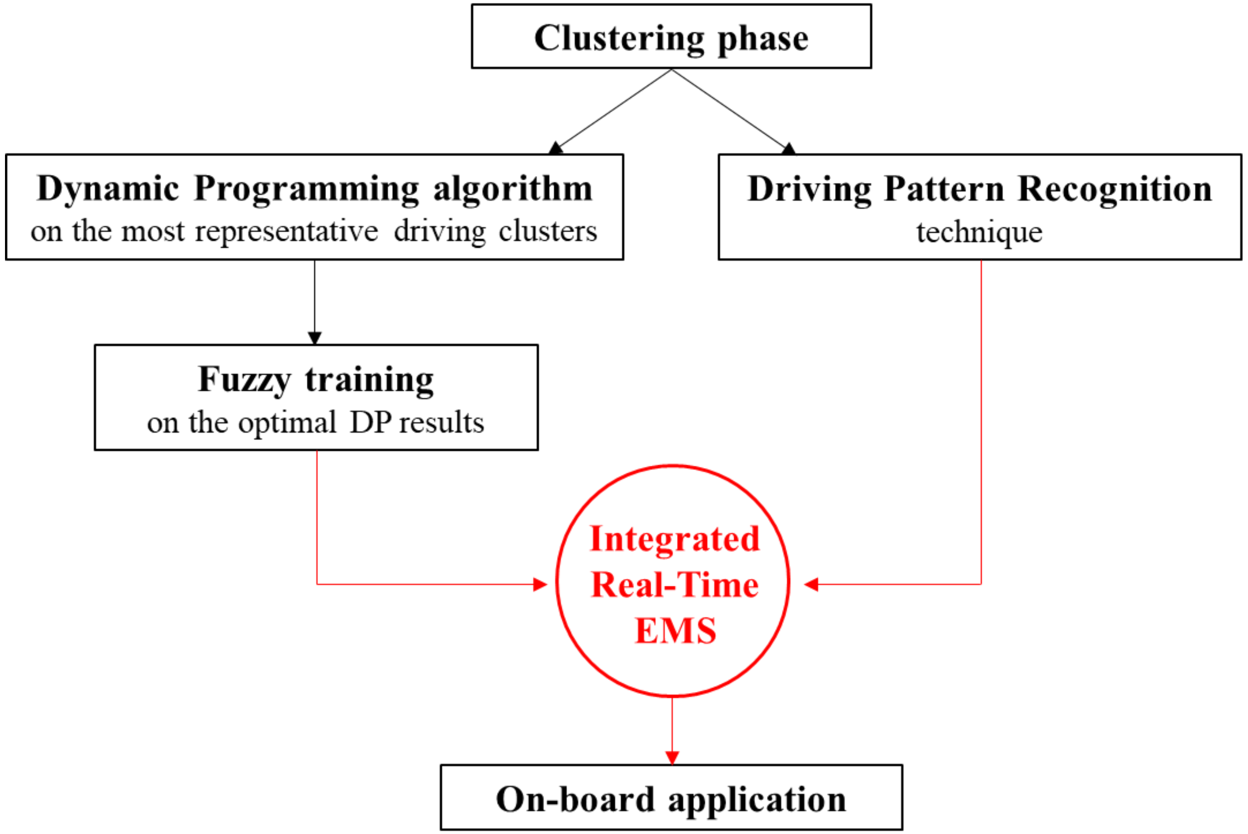
A comparison between a simple Range Extender strategy with three priori defined power levels and the proposed EMS has been carried out for a full hydrogen tank discharge (0,3 kg).

Strong improvements have been achieved in vehicle **estimated range** on both the missions (**9% and 7,6%**) by adopting the novel EMS, as well as the average fuel cell **stack efficiency** (**10% and 8,3%**).

Conclusions

The proposed platform has been confirmed as a valuable tool for both **powertrain design** and **control logic development** and test.

- **Experimental data** gathered under **real-like** operating conditions has been to validate an accurate **digital-twin** of the vehicle and powertrain components to be used in the **HiL** setup to emulate the vehicle request e to control the components performance under different operating conditions.
- The implemented **Real-Time EMS** that integrate a fuzzy trained through a DP algorithm for relevant driving cycles with a Driving Pattern Recognition technique has been tested highlighting **significant savings** compared to baseline control and demonstrating to perform **close to the optimal** target set by DP.
- Currently the **DC/DC component** to integrate FC and batteries over the same bus is under test and the **training procedure** (after a full automation of the process) is being extended to a wider dataset of urban driving cycle using massive parallel simulations on **HPC**.



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