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Integrated Energy and Thermal Management Analysis of a Hyundai Tucson Hybrid Electric Vehicle using Predictive Control Strategies

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Agenda

1. Introduction
2. Hyundai Tucson Digital Twin Model
3. Energy Management Optimization Techniques
4. Conclusions

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1. **Introduction**
2. Hyundai Tucson Digital Twin Model
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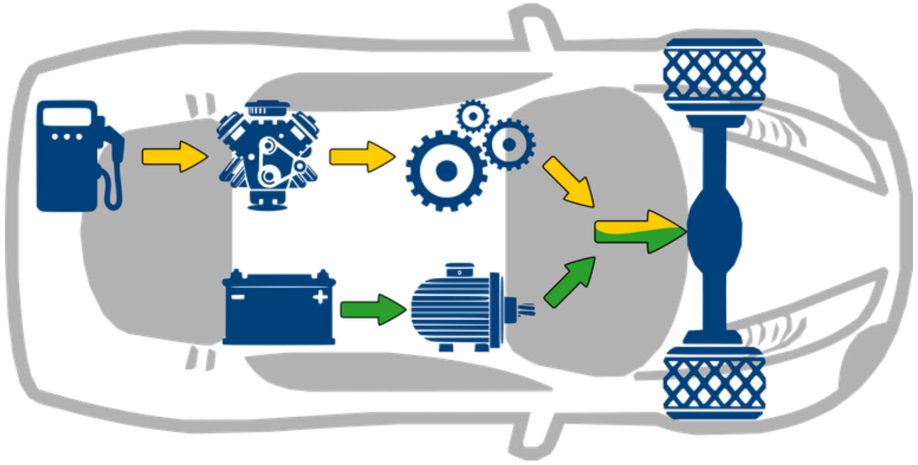
1. Introduction

- Global trend: Reducing **CO_2 emissions** and **pollutant emissions in urban areas** especially
- Hybrid Electric Vehicles **(HEVs)** are the best compromise perceived positively by customers
  - No need for battery charging
  - Long-distance travel capabilities comparable to those of conventional vehicles



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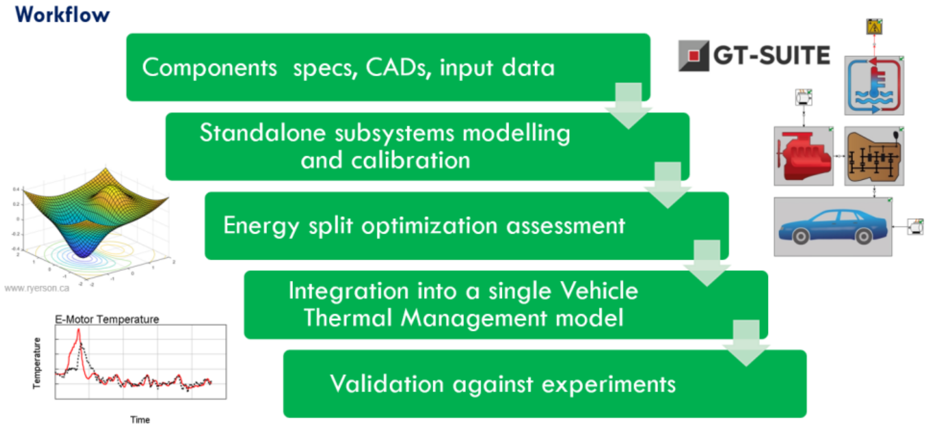

Workflow

1. Components specs, CADs, input data
2. Standalone subsystems modelling and calibration
3. Energy split optimization assessment
4. Integration into a single Vehicle Thermal Management model
5. Validation against experiments

- **HEVs Powertrain design** cannot rely only on testing and prototyping
  - Intermediate design challenge between conventional cars and Plug-in Hybrid Electric Vehicles (PHEVs)
  - Coexistence of an internal combustion engine (ICE) and a medium-sized electric powertrain
  - CAE simulation emerges as a powerful tool for optimizing complex systems → focus on **thermal and energy management**

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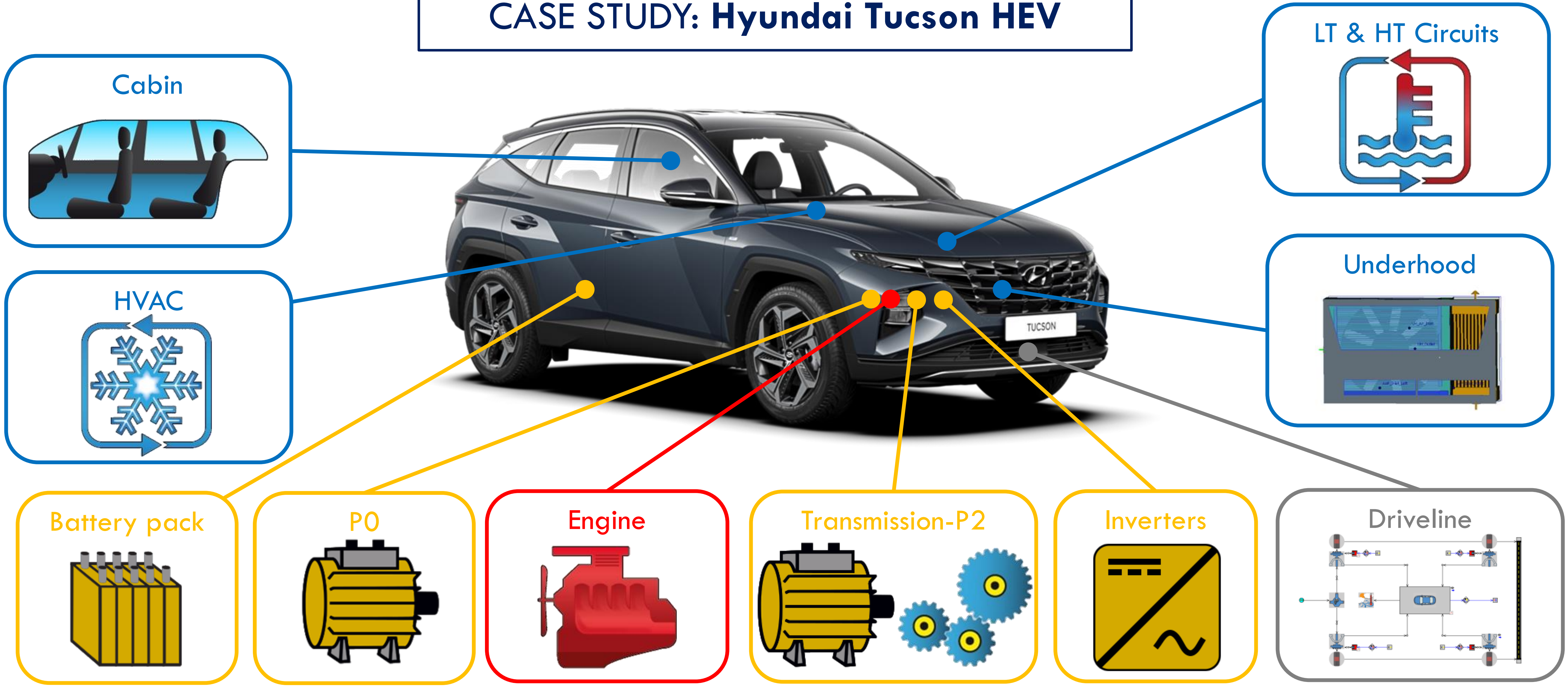
2. Hyundai Tucson Digital Twin Model

CASE STUDY: **Hyundai Tucson HEV**



Cabin

HVAC

LT & HT Circuits

Underhood

Battery pack

P0

Engine

Transmission-P2

Inverters

Driveline

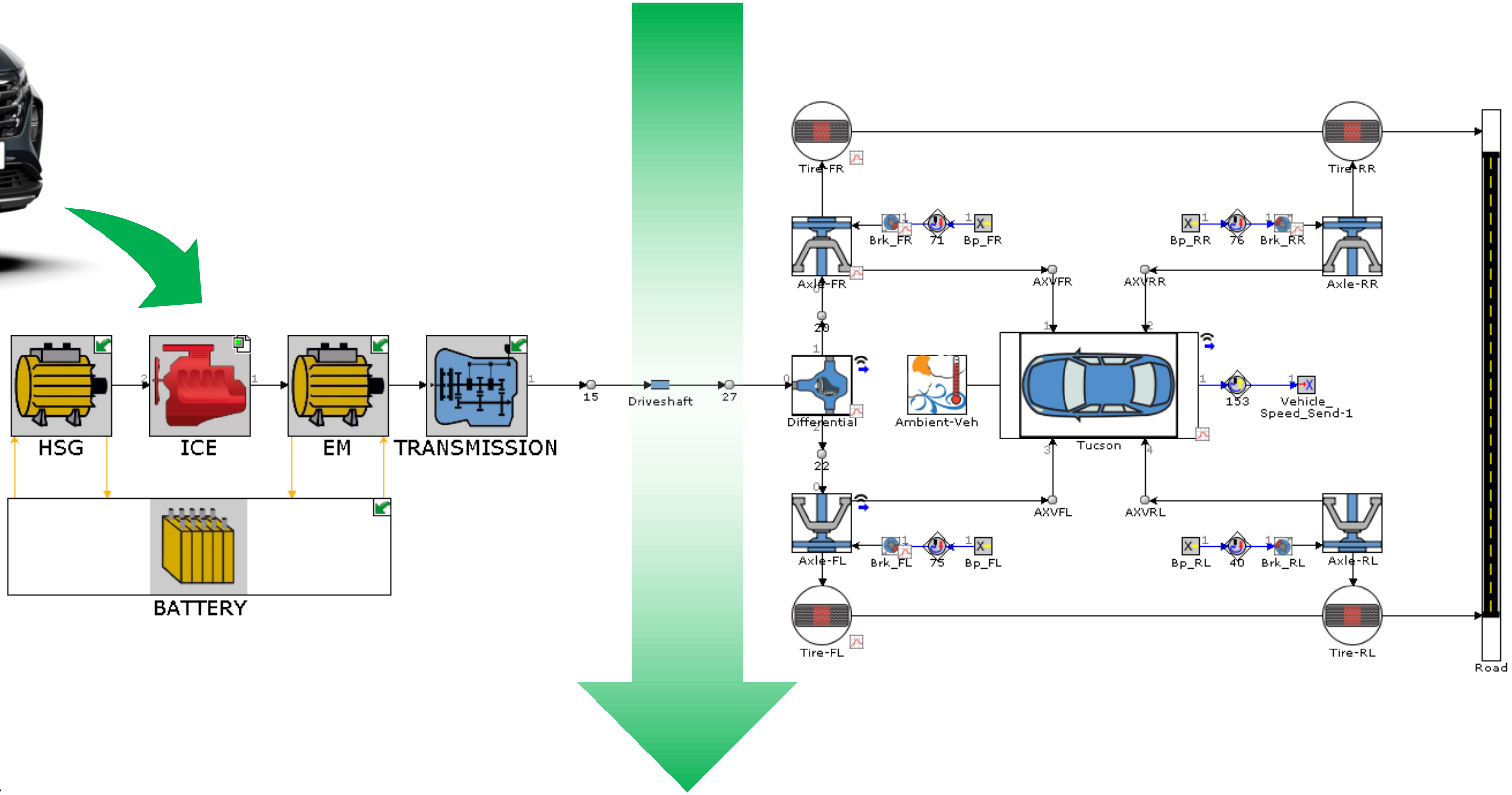
2. Hyundai Tucson Digital Twin Model

Vehicle

The **vehicle** model included information on:

- Vehicle dimensions and weight
- Coast-down coefficients
- Brakes characteristics
- Driveline and gearbox efficiency
- E-drive performance and efficiency (P2/P0 e-motor and inverter)
- Electrical circuit (HV battery pack, 12V battery, DC-DC, auxiliaries)
- Engine performance and consumption

INPUTS: Vehicle speed target profile, road grade, payload



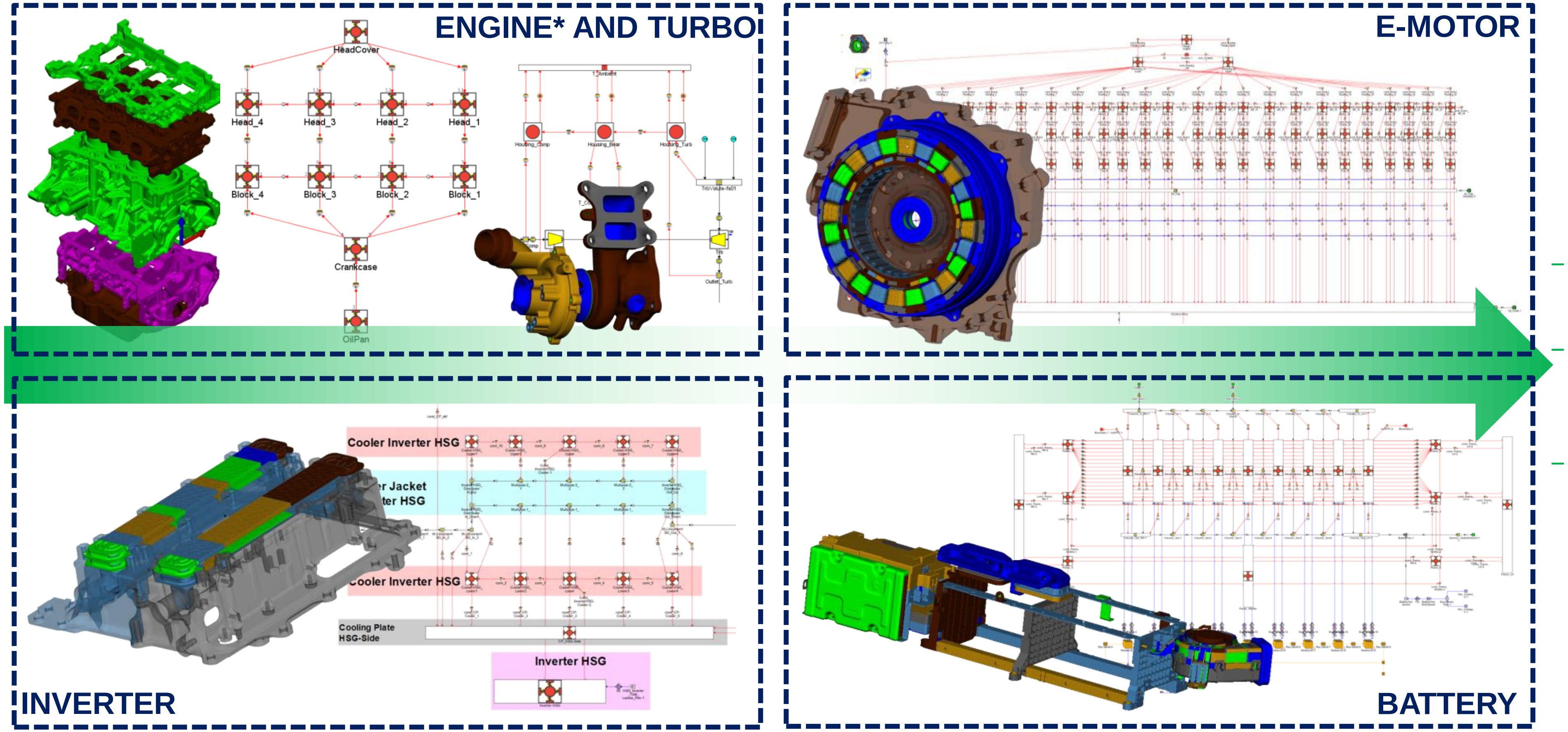
OUTPUTS: Engine and e-motor requested power, fuel/energy consumption, dissipated heat…

2. Hyundai Tucson Digital Twin Model

Powertrain Components Models

INPUTS

- Instantaneous operating conditions (speed/load, absorbed current)
- Dissipated heat
- Hydraulic-side boundaries (coolant/air inlet flow rate, temperature…)



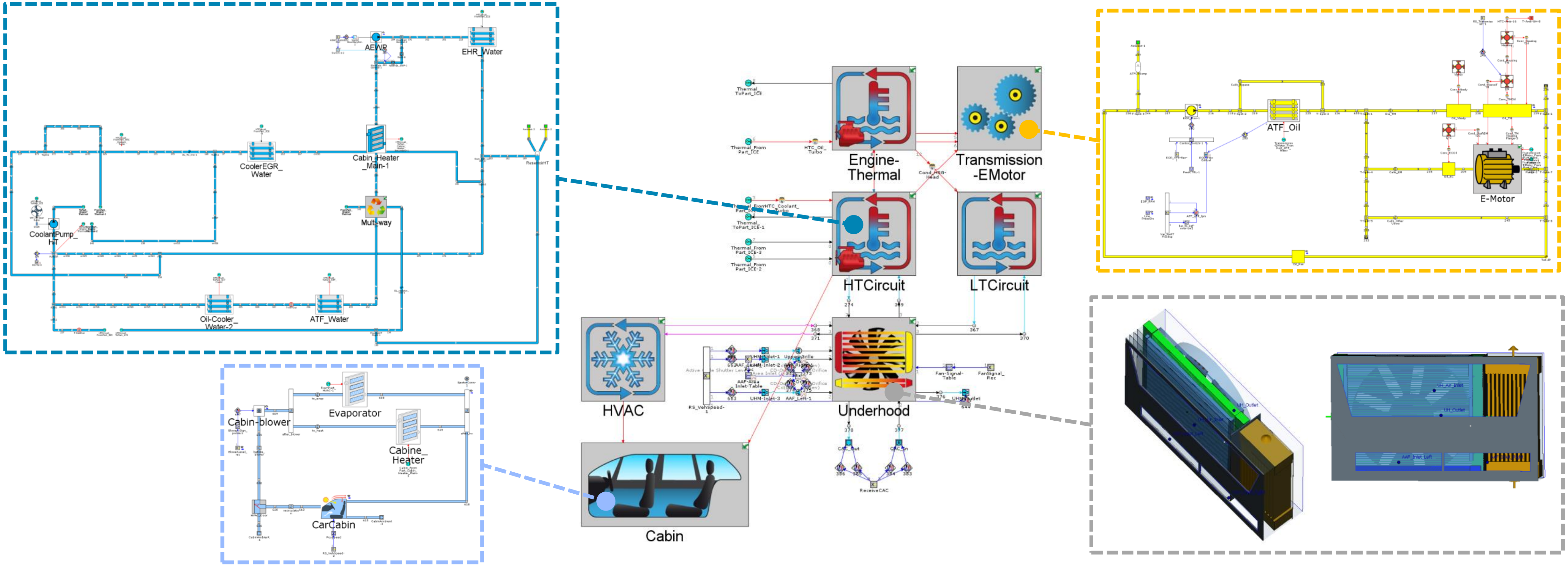
OUTPUTS

- Engine/electrical-side wall temperatures
- Hot spots temperatures (coil, IGBTs, battery cells)
- Heat rejection to air/coolant

- **Computationally-efficient thermal models** (based on thermal masses) for heat rejection prediction and local temperatures calculation → Good level of detail/accuracy with a low computational effort
- *Engine thermal model receives the heat rejection from gas to structure from the corresponding engine performance model, which can be **performance model to maximize predictivity** or **map-based model to optimize runtime**

2. Hyundai Tucson Digital Twin Model

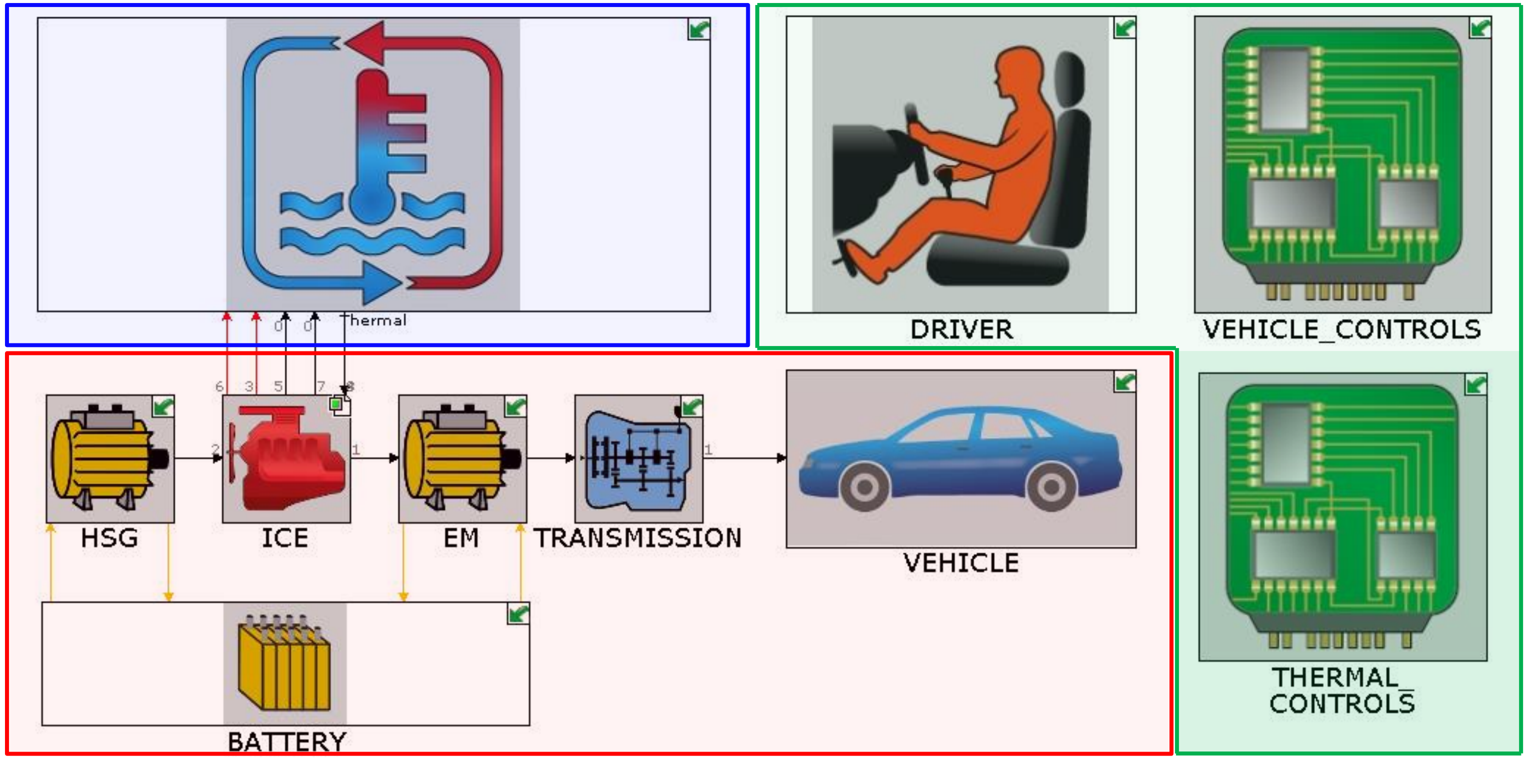
Thermal Circuits Models



- Fully-physical hydraulic and thermal representation of **cooling circuits**
- All the sub-systems were integrated and thermally connected to each other to enable the exchange of information (heat transfer, flow rates, temperatures…)

2. Hyundai Tucson Digital Twin Model

- The integrated GT-SUITE **VTM model** obtained at the end of the activity was characterized by the following inter-connected mechanical, electrical and thermal sub-domains:



THERMAL

- High- and low-temperature coolant circuits, oil circuit
- Heat distribution models for: engine, turbocharger, e-motor, inverter, battery
- HVAC refrigerant loop and cabin
- Cooling module and underhood compartment

VEHICLE

- Vehicle and driveline
- E-motor and inverter
- Hybrid-starter-generator (HSG) and inverter
- Battery pack
- 12V Battery
- Turbocharged internal combustion engine
- Gearbox

CONTROLS

- Driver and powertrain controllers
- **Energy management strategy***
- Cooling system control logic

* Constituted by:

- High-level supervisory controller imposing rules extracted from experimental tests
- Low-level controller employing **map-based ECMS** to compute optimum power split between ICE and P2

2. Hyundai Tucson Digital Twin Model

Controls

Several **controllers** were built to manage the vehicle operations:

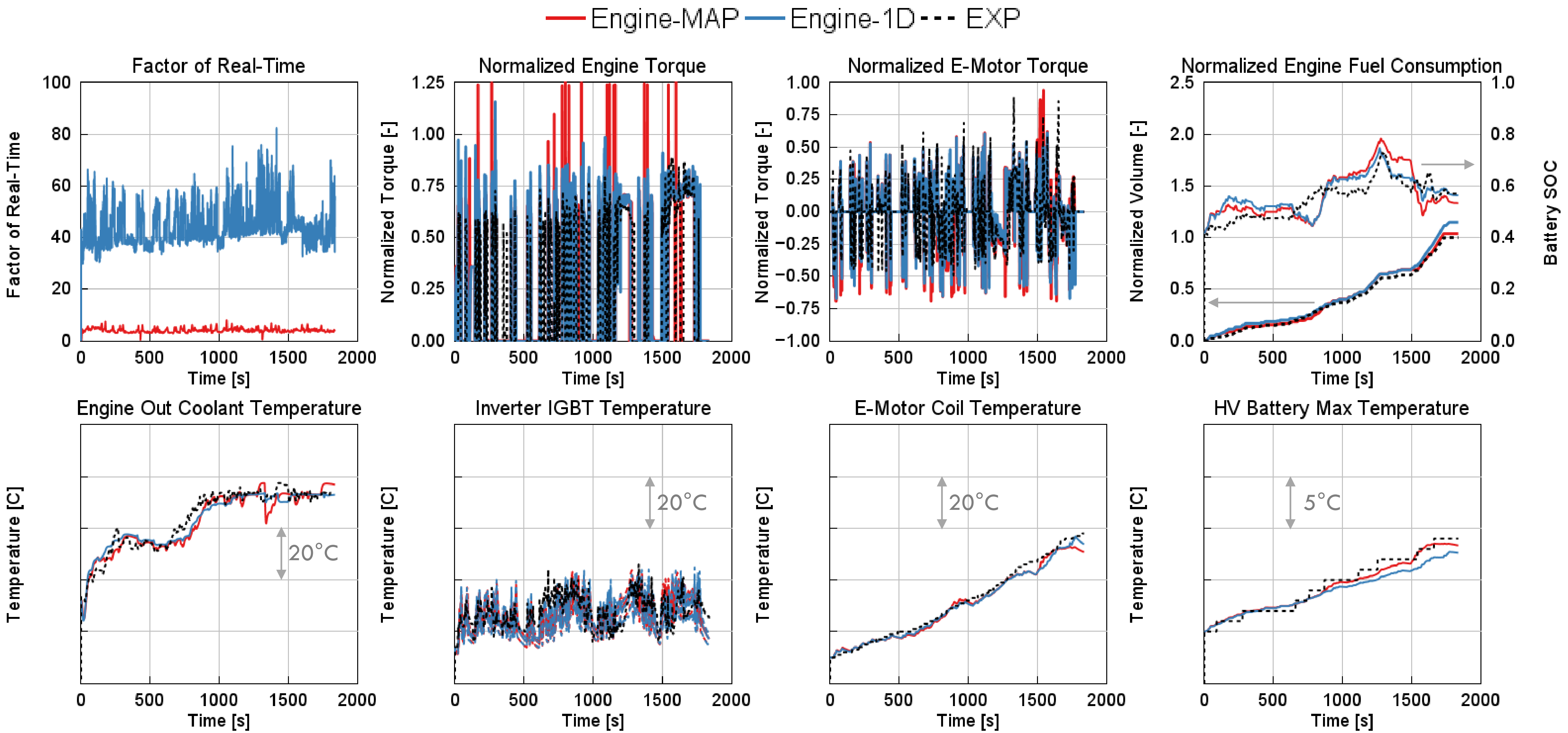
	Control	Description
Vehicle/ICE Controls	**Coasting**	Manages the vehicle deceleration when no pedal is pressed
	Regenerative Braking	Manages the Braking Torque split between E-Motor, front and rear mechanical brakes
	Start & Stop	Switches off the ICE when the vehicle is standstill or when required by the Supervisory
	Cut-Off	Inhibits the fuel injection when no power is required to the ICE
	ICE Start-Up	Manages the starting of the ICE both from vehicle standstill and in motion
Hybrid Controls	**Supervisory Control**	Defines ICE status (ON or OFF) and Generator Mode
	Torque Split	Manages torque split between ICE and E-Motor
	BMS	Series of controls to keep SOC in a safe range
Thermal Controls	**ITM Valve**	Regulates engine oil HT coolant temperature values
	LT Pump Speed	Actuates LT pump speed to cool e-drive components
	Battery Fan Speed	Actuates battery fan speed to cool cells
	Rad. Fan Speed & AGS	Regulates radiators fan speed and Active Grille Shutter position to achieve cooling targets
	Cabin Cooling/Heating	Determines if the cabin must be operated in cooling or heating mode and it regulates blower speed and compressor speed/e-heater power to attain the cabin temperature setpoint

The majority of these controllers were built by reverse-engineering of experimental measurements.

They can be used in a predictive way to operate the VTM model under arbitrary vehicle speed profiles and boundary conditions, triggering performance derating to guarantee the compliance with safety limits (if needed).

2. Hyundai Tucson Digital Twin Model

VTM Model Correlation Over WLTP Cold Start



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3. Energy Management Optimization Techniques

- Energy Management System (EMS) defines the HEV mode and the power split:
  - **Supervisory Controller:** high level control of powertrain
  - **Energy Management:** splits power demand (from supervisory) between ICE and EM(s)
- EMS based on Dynamic Programming (DP):
  - Minimization of a global cost function:

$$J_k(x^i) = \min_{u_k \in U_k} \{L_k(x^i, u_k) + p_k(x^i) \ldots + J_{k+1}(f_k(x^i, u_k))\} \ldots$$

- EMS based on Equivalent Consumption Minimization Strategy (ECMS):
  - Minimization of an instantaneous cost function:

$$\dot{m}_{eqv} = \dot{m}_f + \dot{m}_{batt} = \dot{m}_f + s \cdot \frac{P_{batt}}{H_i}$$

Battery power

Equivalent fuel consumption

Actual fuel consumption

Virtual fuel consumption from battery

Equivalence factor

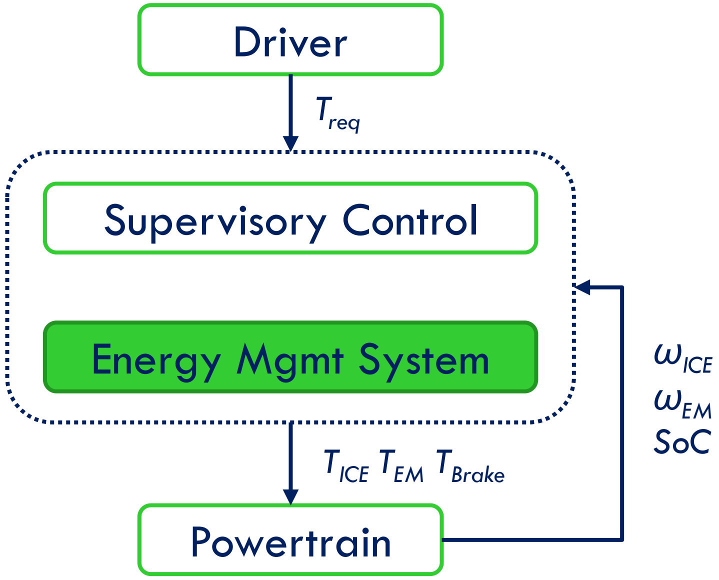
Fuel LHV

Option 1: **Map-Based ECMS**

Option 2: **Simulink Online ECMS**

Option 3: **Adaptive ECMS (SOC-feedback)**

Option 4: **Adaptive ECMS (DPR)**



3. Energy Management Optimization Techniques

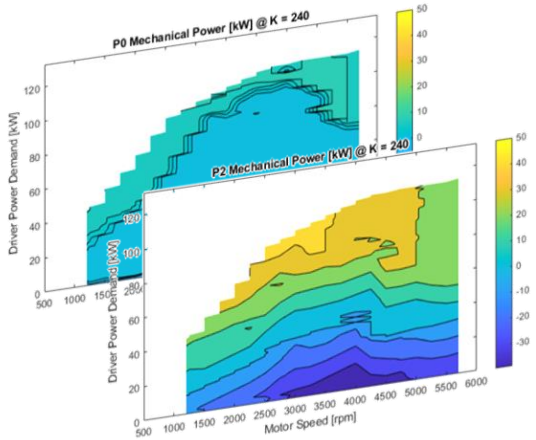
Simulink Online ECMS (+GT and Map-Based ECMS (GT

Simulink Online ECMS *(Co-simulation GT-SUITE/Simulink)*

- Online ECMS control built in MATLAB/Simulink
- M/S and GT-SUITE will co-simulate via the *SimulinkHarness* template
  1. Instantaneous variables (i.e., driver power demand, ICE speed, EM speed) sent from the GT plant to M/S controller
  2. A matrix of possible combinations of ICE and EMs is built
  3. For any combination, the equivalent fuel consumption is computed
  4. The coordinates corresponding to the minimum equivalent consumption (for a given equivalence factor) are identified and applied to the GT-SUITE dynamic vehicle model

Map-Based ECMS *(GT-SUITE only)*

It differs from the Simulink version in that optimal power split maps are computed offline by a MATLAB routine as a function of equivalence factor, power demand and ICE/e-motor speed and integrated into GT-SUITE



3. Energy Management Optimization Techniques

Equivalence factor adaptation using SOC feedback (GT)

- Several Energy Management Strategies in HEVs aim to find the optimal power split through ECMS → Equivalent Consumption Minimization Strategy:

Engine Fuel Flow

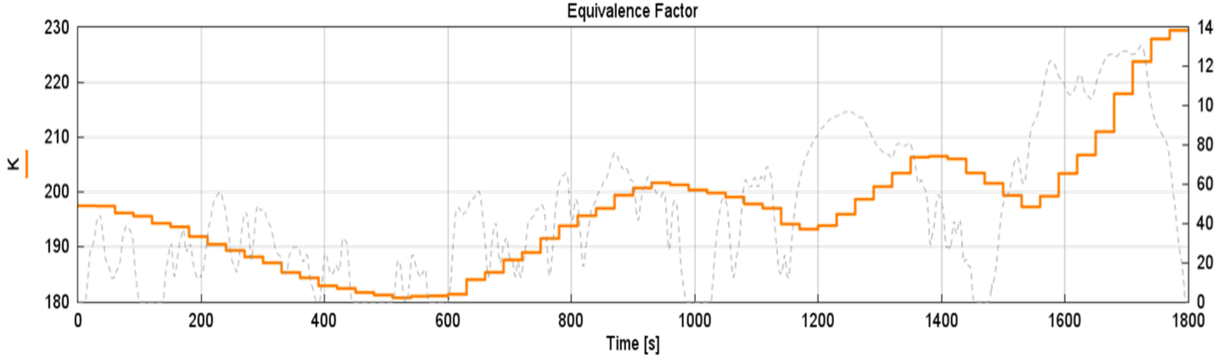
Fuel Flow 'equivalent' Electric Power

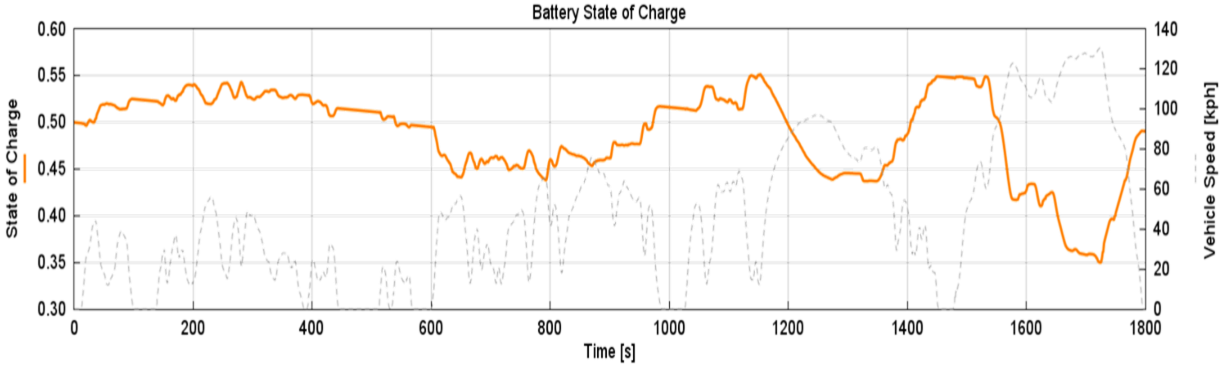
$$\dot{m}_{fuel\ eqv} = \dot{m}_{fuel} + s \cdot \frac{P_{batt}}{Hi}$$

s → Equivalence Factor

- Factor **s** is a value lumping the efficiency chain of a certain powertrain, which depends on operating conditions → having **s** fixed may not work for off-nominal conditions.
- Adaptation of **s** exploiting SOC feedback:

$$s_k(SOC,T) = \underbrace{\frac{s_{k-1} + s_{k-2}}{2}}_{\text{'Memory' term}} + \underbrace{k_P^d \left(SOC_{ref} - SOC(T)\right)}_{\text{Proportional correction}}$$



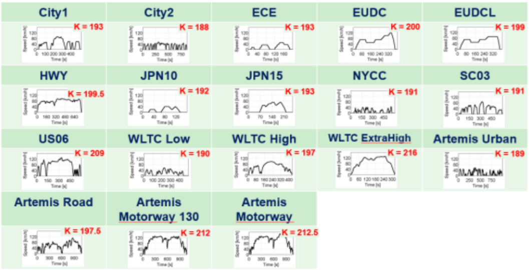


3. Energy Management Optimization Techniques

Equivalence factor adaptation using DPR + GT

- Adaptation of s exploiting DPR (Driving Pattern Recognition): the aim is to obtain a better estimation of the equivalence factor in different driving conditions:

Controller set-up

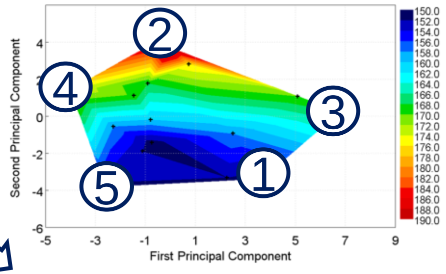


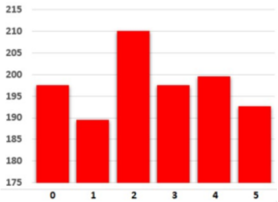
18 Type Approval driving cycles

⇩

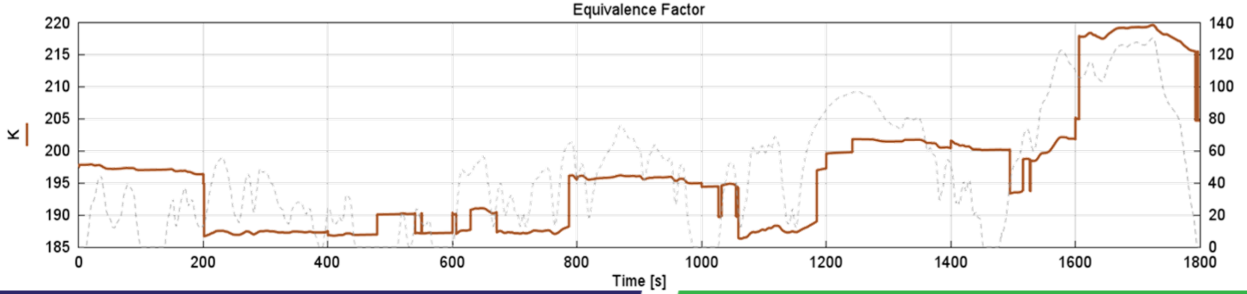
Assessment of **charge sustaining K**

Definition of **5 Driving Pattern cluster** by means of **statistical analysis** of several driving metrics



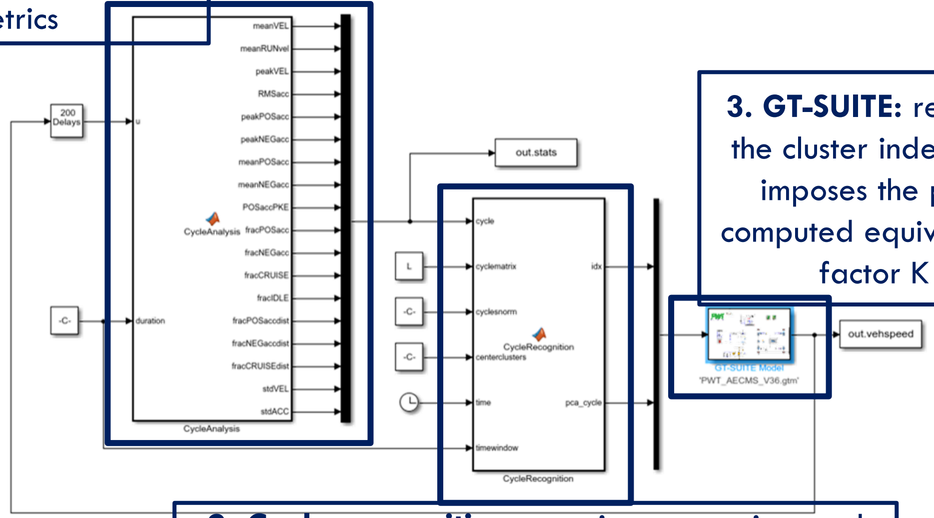


Attribution of **average K** for each DP cluster



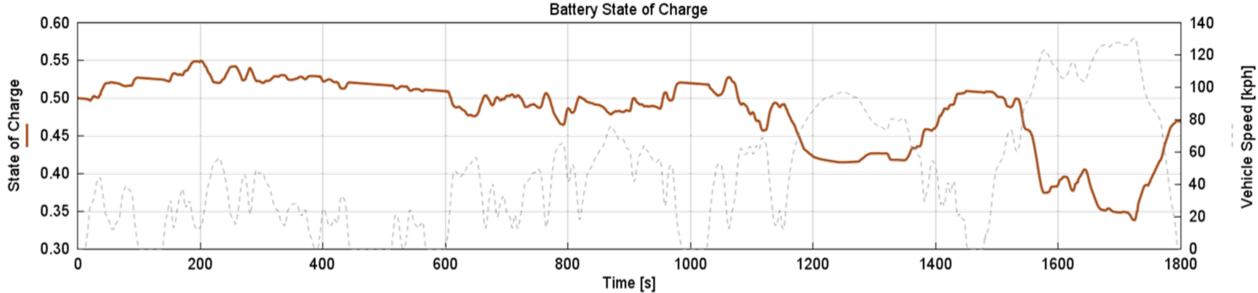
Controller operation

1. Cycle analysis: computation of statistical metrics



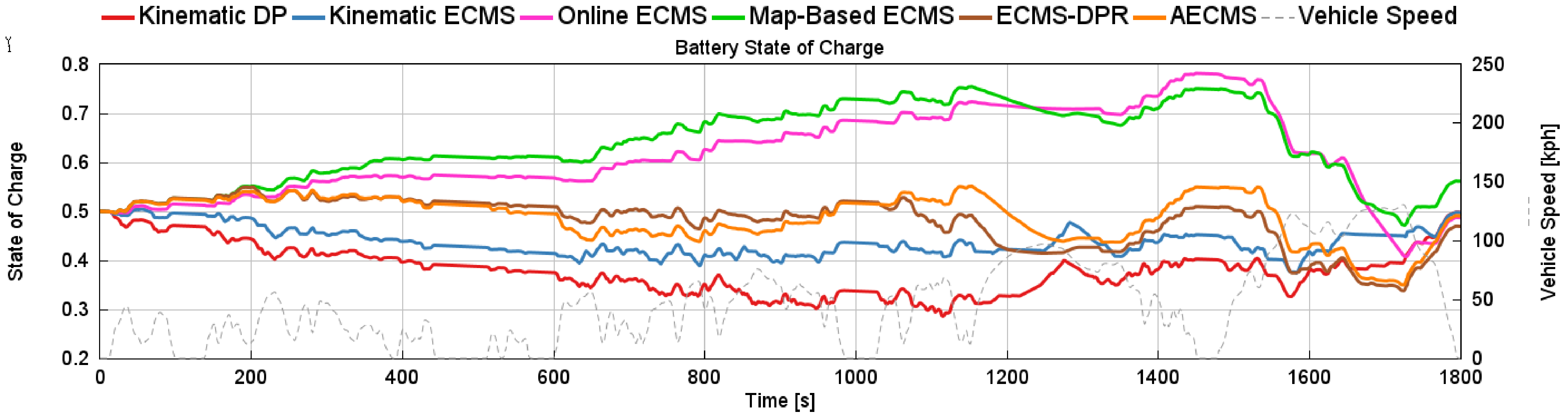
3. GT-SUITE: receives the cluster index and imposes the pre-computed equivalence factor K

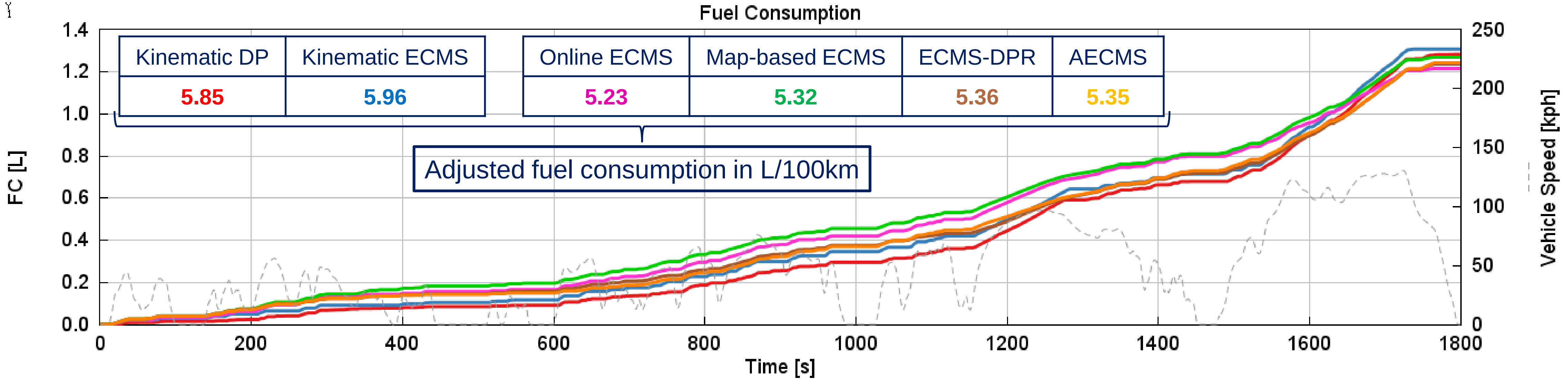
2. Cycle recognition: metrics processing and association to cluster number



3. Energy Management Optimization Techniques

Results comparison on WLTC





Kinematic DP	Kinematic ECMS	Online ECMS	Map-based ECMS	ECMS-DPR	AECMS
5.85	5.96	5.23	5.32	5.36	5.35

Adjusted fuel consumption in L/100km

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4. Conclusions

A comprehensive **Vehicle Thermal Management** model of the Hyundai Tucson HEV (NX4) was built in GT-SUITE. All the individual vehicle subsystems were modelled and integrated for system-level analyses, achieving a satisfactory **correlation** level against experimental data.

A **flexible control logic** was implemented to run the model over any arbitrary maneuver, taking into account limits and constraints.

Various HEV **power split optimization strategies** and methods were assessed.
Kinematic model optimizations can be used in the early stages of a vehicle development for the assessment of global benefits (Dynamic Programming) or the optimal power split using ECMS technique.
Online ECMS can be used alongside the VTM for advanced energy management strategies.

This kind of VTM model provides a valuable support on the **powertrain and vehicle development,** shortening time-to-market and contributing to reducing costs by means of virtual analyses.

Future developments can be the set-up of a VTM real-time variant for ECU validation and verifications purposes, or coupling with the real hybrid supervisory controller (in Simulink) to improve model accuracy.

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