Methodology applied to couple 1D & 3D models for electric vehicles thermal management design

- Use of high fidelity models for HPC smart coupling -

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ABSTRACT: The purpose of this article is to show a virtual methodology that simulates an electric vehicle, with its systems and subsystems, in different drive cycle scenarios and focusing on thermal management design. Vehicle FIAT 500e is taken as reference case to test the application study. This methodology is developed from a collaboration between Centro Ricerche Fiat and Siemens Industry Software, in the context of project OBELICS, that has received funding from the European Union's Horizon 2020 research and innovation programme.

KEY WORDS: **EV and HV system, energy control system, cooling/heat and temperature management,** 1D/3D Smart Coupling, High Performance Computing (A3)

1. INTRODUCTION

In the last decades, the design world has been deeply transformed by computer science. Many industries, including automotive, rely on this technology to develop new products and test processes virtually, thus the need of physical prototypes has been reduced.

Nowadays, car makers are making particular efforts to come up with new approaches to design, development and testing for EVs, where experience, standards and know-how has to be created more or less from scratch. By adopting and using model based system design, it will be possible to improve product development processes, reduce errors, and facilitate change management also for this new area. In fact model-based development enables engineers to test the system in early phases of the development within a virtual environment, when it is inexpensive to fix problems. Such model-based development is a process that enables faster, more cost-effective development of dynamic systems, including control systems, signal processing, and communications systems.

This paper aims to show a methodology based on coupling between 1D and 3D models, developing a high fidelity simulation on the thermal behaviour of full vehicle, systems and components.

1D-3D coupling is already widely used in different domains since the last 2 decades, especially in electronic domain [1], combustion [2] or hydraulic system [3]. Such approach is relevant for component design to enhance local behaviour which cannot be properly modelled in 1D. Almost all simulation tools propose strong coupling, meaning with small communication time. Some new approach has been developed by Siemens Industry Software, by using smart coupling between Simcenter Amesim and Simcenter Star-CCM+ [4]. Nevertheless, only one 1D model and one 3D model have been coupled up to now due to computation power. The novelty of the proposed methodology is to connect several 3D models with single one 1D model used as "variable boundary condition" supplier along some transient scenario by using smarter coupling strategy.

This virtual methodology is implemented in order to improve development of electric vehicles, analyzing all systems and subsystems in different drive cycle scenarios. In this work the focus is on thermal management design, because optimization of energy consumption has become of fundamental importance in electric vehicles, especially to increase autonomy.

As reference case to test the application study, pure electric vehicle FIAT 500e, sold in United States since 2013, has been considered (Fig. 1).

Fig.1 FIAT 500e

2. MODEL DESCRIPTION

2.1. 1D vehicle model

1D model is used to simulate components and subsystems of the electric vehicle (battery, inverter, electric motor, cooling system, HVAC and others), replicating how they work and which I/O are required or provided. They are mutually linked to simulate the behaviour of a whole vehicle in real driving conditions, as shown in Fig. 2 for FIAT 500e. Focusing on the thermal management, such numerical simulations can provide information about the temperatures of each component and therefore the influence of the AC system on the vehicle range, through the electric consumption of the compressor. Simcenter Amesim V17 has been used for the 1D modelling.

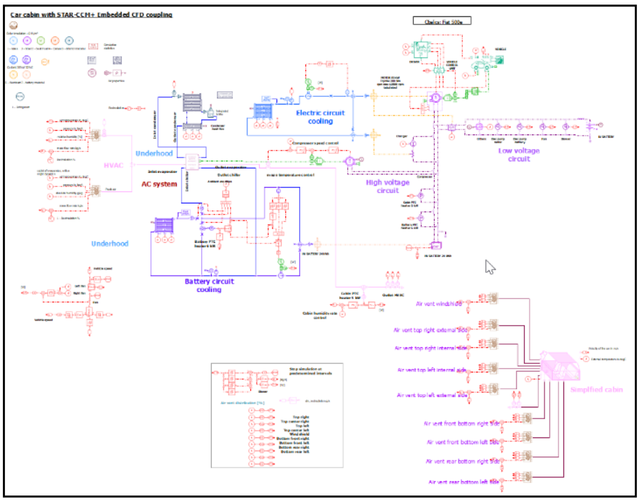


Fig. 2 Simcenter Amesim 1D for FIAT 500e

2.1.1. Electric powertrain

The electric powertrain consists of three main components which are the battery, the inverter and the electric motor as well as different other electric consumers.

In the context of coupling methodology, functional models have been used. So, motor and inverter have been merged by considering global losses, which are transferred to the thermal model. Functional information is given in Table 1. Nevertheless, this methodology can be applied with more details on electric components.

Table 1 Main characteristics of the motor

Motor characteristics	Value
Overall efficiency (-)	0.92
Maximum torque (Nm)	200
Maximum power (kW)	85
Maximum speed (rpm)	12800

Motor model calculates torque (Nm), heat loss (W) and output current (A) based on motor speed (rpm) and input voltage (V). The battery is a Li-Ion Ni-rich NMC-C and the corresponding model has been validated by IFP Energies Nouvelles [5].

Additionally, other electric components have been included, especially ones dealing with thermal management. Indeed blower, fan but also electric pumps must be accounted to have a better estimation of the vehicle range. These components are connected to the main electric circuit through a DC/DC converter from 390 V to 14.5V. Efficiency of the converter is also considered, and electric losses are transferred to the thermal model.

Finally, two Positive Temperature Coefficient (PTC) heaters are used for battery heating in one hand and cabin heating in other hand. All these electric powers consumed by these different components are summarized in Table2.

Table 2 Main electric consumption

Electric circuit consumer (W)	Low voltage	High voltage
Powertrain pump	25	
Battery pump	25	
Fan	600	
Blower	300	
Battery PTC heater		8000 max
Cabin PTC heater		5000 max
AC compressor		7000 max

2.1.2. HVAC and cabin

The 1D cabin model is used in complementary to the 3D cabin model. Indeed, in this model, thermal walls are considered as well as average air volume temperature. These temperatures are then used in the HVAC control. In the Table3 are listed all heat exchanges between cabin volume split in 10 areas and walls.

Table3 Heat exchange in cabin for each area

Areas	Glass	Panel	Roof	Floor	Internal
Windshield	Windshield				Dashboard
Top Front Right	Side glass		Roof		Dashboard & Front seat
Top Front Left	Side glass		Roof		Dashboard & Front seat
Top Rear Right	Side glass	Side panel	Roof	Floor	Front seat
Top Rear Left	Side glass	Side panel	Roof	Floor	Front seat
Bottom Front Right		Side panel		Floor	Front & rear seat
Bottom Front Left		Side panel		Floor	Front & rear seat
Bottom Rear Right					Front & rear seat
Bottom Rear Left	Rearshield				

Rearshield					Front & rear seat Rear shelf

Radiative heat transfer (W) is considered, especially in glass component where solar heat flux is partially absorbed and transmitted.

Roof and side panel are not only made with one material, but with several layers of materials and air gaps are modelled to calculate conductive heat exchange (W).

The Heat Venting Air Conditioning (HVAC) system is composed of the evaporator, which will be described in the thermal management paragraph and the cabin PTC heater, already described in the previous paragraph.

Blower position is controlled with cabin temperature at foot (recirculation temperature) as illustrated in Table 4.

Table 4 Blower position

Blower position	Low threshold (degC)	High threshold (degC)
0.5	T_1	T_2
0.75	T_2	T_3
1	T_3	T_4
1.5	T_4	T_5

2.1.3. Thermal management

The thermal management model is composed of three main subsystems, which are physically connected with the underhood (from the 3D vehicle model):

- Battery cooling circuit
- Powertrain cooling circuit
- AC system

The battery cooling circuit is composed of three different branches, according to the external temperature:

- Chiller branch if $Text > 30$
- Battery PTC heater branch $Text \leq 10$
- Battery radiator branch $10 < Text \leq 30$

In each case, coolant pump could be stopped at specific condition with hysteresis control as highligthed in Table 5.

Table 5 Battery cooling circuit stop condition

Branch	On condition (degC)	Off condition (degC)
Chiller	30	25
Battery PTC	10	15
Radiator	20	15

The powertrain cooling circuit is composed by powertrain radiator, electric pump and internal flow inside motor and inverter. Pump is working in function of the coolant temperature at motor outlet with hysteris control:

- on condition if $Tcool_{Motor} > 45$
- off condition if $Tcool_{motor} < 40$

The AC system is modelled with functional components:

- Condenser
- Evaporator
- Thermal expansion valve
- Compressor
- Chiller

The compressor speed target is controlled with evaporator air outlet temperature. Then compressor motor torque is controlled with this speed target.

The fan can be activated from different condition, as listed in Table 6.

Table 6 Fan activation

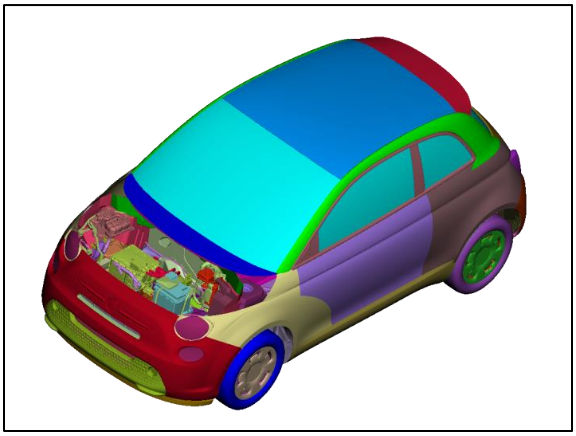
Inputs	On condition	Off condition
Motor coolant temperature (degC)	60	55
Condenser inlet pressure (BarA)	25	11
Vehicle speed (km/h)	40	50

2.2. 3D models

Even if 1D model can connect all these subsystems of the vehicle, it cannot reply properly some physical phenomena. This is the case of air flow and all its derivatives, which calculation needs very complex and expensive models. The only way to obtain a high-fidelity simulation is using 3D models, in particular Computational Fluid Dynamics (CFD).

For this methodology, air flow is calculated in two different domains, which makes two 3D models, as illustrated in Fig.3:

- Vehicle model: simulation of external flow around vehicle and under the hood
- Cabin model: simulation of internal flow for passenger comfort



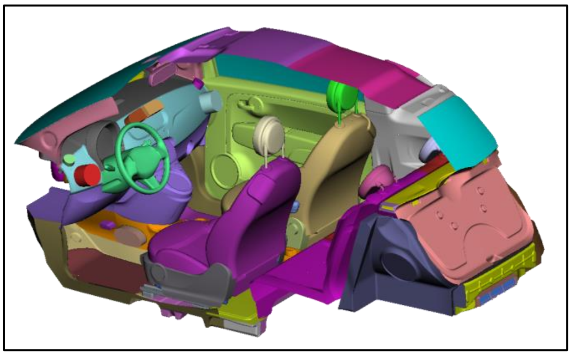


Fig. 3 External vehicle and cabin geometries of FIAT 500e

For both simulations, solver used has been Simcenter Star-CCM+ 12.06.011 and same procedure was applied with following steps:

- Watertight geometry definition
- Surface mesh generation
- Volume mesh generation
- Setting CFD model
- Running
- Post-processing

In the next paragraphs both 3D simulations are described in detail.

2.2.1 Vehicle model

Vehicle model simulates the air flow around the whole vehicle, while it is moving forward with a certain velocity. The domain is a big box that replicates open air condition as illustrated in Fig.4.

Basic information about model setup are:

- Solver: RANS
- Turbulence model: K-ε
- Trimmed volume mesh
- Number of elements: ~ 15M

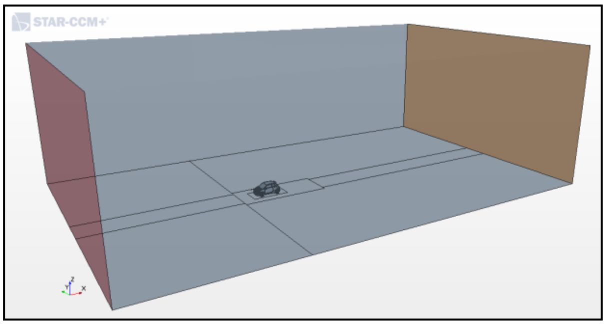


Fig. 4 External vehicle domain

For thermal management, heat exchangers behaviour becomes fundamental and therefore analysis is highly focused on mass flows, inlet velocities and inlet temperatures on them.

In Fig.5, FIAT 500e heat exchangers configuration is clearly showed:

- Battery radiator (brown colour)
- Condenser (grey colour)
- Powertrain radiator (green colour)
- Double fan (green and yellow colours)

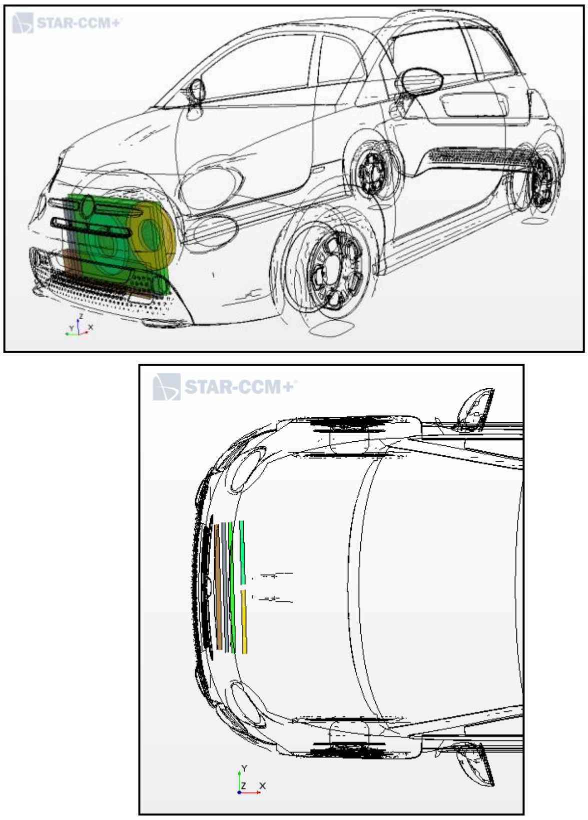


Fig. 5 Heat exchangers and fans

2.2.2 Cabin model

Cabin model (Fig.6) simulates the internal air flow, necessary to heat or cool down cabin for passenger's comfort, studying distribution of velocities inside the vehicle and the convection with internal walls.

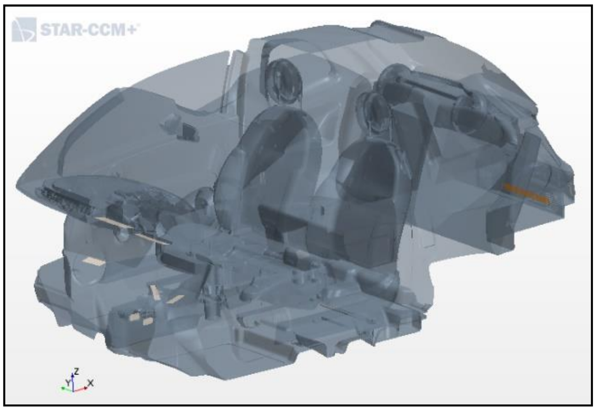


Fig. 6 Cabin domain

Basic information about model setup are:

- Solver: RANS
- Turbulence model: K-ε
- Polyhedral volume mesh
- Number of elements: ~ 1M
- Cool down mode

In order to exchange distribution of velocities, the cabin is split into smaller volumes divided by interfaces (orange faces shown in Fig.7). In this way, mass flows between volumes are calculated and provided to Simcenter Amesim.

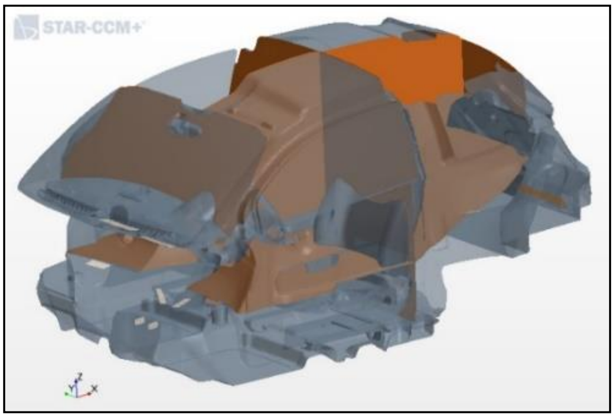


Fig. 7 Interfaces between cabin sub-regions

2.3. HPC

The aim of High Performance Computing (HPC) is to provide the computational power for the simulations needed for virtual design and validation phases. The use of HPC is limited to applications that require high computing performances; focusing the attention to the scope of this work, the main application that will need such amount of resources is the 3D simulation because it relies on data obtained from Computational Fluid Dynamics analysis. 3D models are launched separately on HPC server by specific scripts basing on call strategies, which are different for both models. But even so, there is still a significant gap between the time needed from 1D and 3D simulation. Anyway, entire simulation with all drive cycle becomes affordable in terms of time: using ~300 CPUs, whole simulation (1D model calling several 3D models) runs in a few hours, depending on driving cycle duration.

2.4. Coupling strategy

Coupling strategy applied in this project consists on running 1D model and calling 3D model only when it is necessary. Calling strategy are summarized in Table7.

Table7 Coupling strategies

3D model	Vehicle	Cabin
Vehicle speed Fan Blower	$\Delta V > 2,5\ m/s$ Fan on/off	 Blower position

A dedicated component is used in the 1D model to stop the simulation when one of these criteria is achieved. Then when CFD calculation is completed, different boundary conditions to the 3D models are transferred from1D model and vice versa, as illustrated in Fig.8.

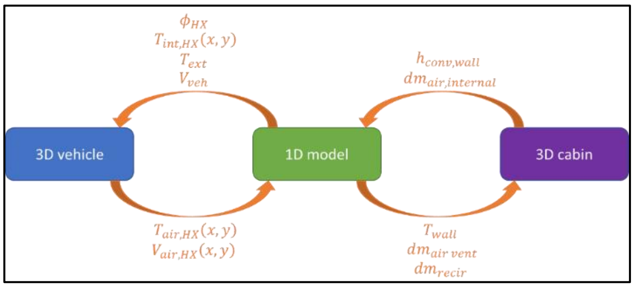


Fig. 8 Variables exchange between 1D model and 3D models

Heat exchanger heat fluxes, heat exchanger internal temperature, ambient condition and vehicle speed are transferred to 3D vehicle model and wall temperature, HVAC air vent and recirculation mass flows rates distribution are transferred to 3D cabin model. On the other hand, also 3D models transfer some results to 1D model: air velocity and air temperature maps of each heat exchanger from 3D vehicle model, and heat transfer coefficient and mass flows through cabin volumes from 3D vehicle.

3. RESULTS

Different driving cycles have been tested to validate the procedure. In this paper, main driving cycles are:

- WLTC
- Real driving cycle (Urban, Extra-urban)

3.1. 1D model

Methodology has been validated on different conventional driving cycle, like WLTC. It can be observed when 3D vehicle model has been called in Fig.9.

Each vehicle speed step of 5 m/s, except at low speed, generates a call. The number of calls can be modified by changing the vehicle speed step: lower is it, higher is the number of calls.

It can be observed minimal reference speed is not set at 0 km/h when vehicle is standstill, and therefore 3D model runs with a minimal velocity. Indeed 3D simulation with free convection will be investigated later.

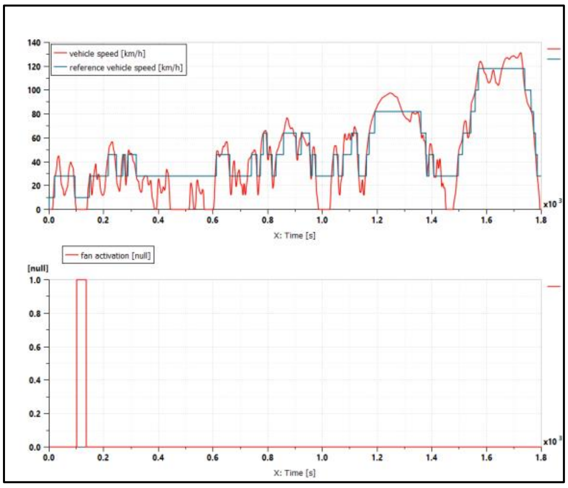


Fig. 9 3D vehicle model call during WLTC driving cycle

Real driving cycles have been perfomed at low speed (urban condition) and at higher speed (extra urban condition). It is used the same coupling mechanism, but with lower vehicle speed step (2 m/s instead of 5 m/s), as shown in Fig.10 and Fig.11.

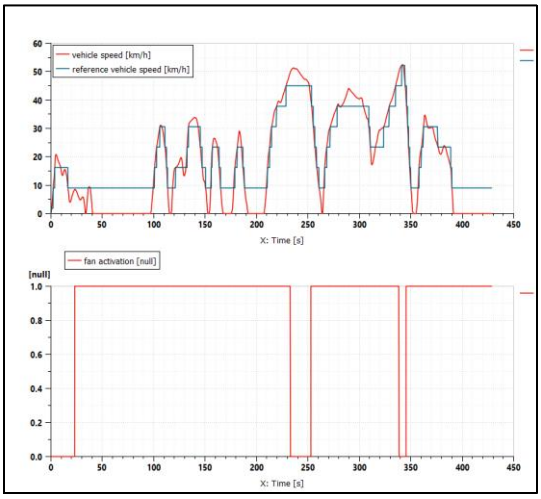


Fig. 10 3D vehicle model call during urban driving cycle

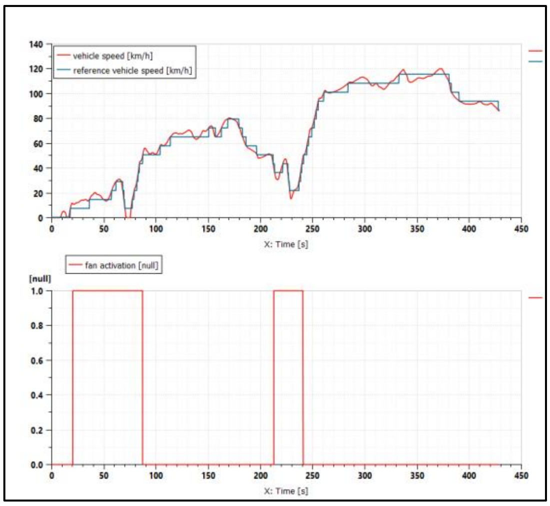


Fig. 11 3D vehicle model call during extra urban cycle

It can be observed that fan is activated because condenser inlet pressure increases up to 25 barA, as shown in Fig.12. Furthermore fan is deactivated due to vehicle speed higher than 50 km/h.

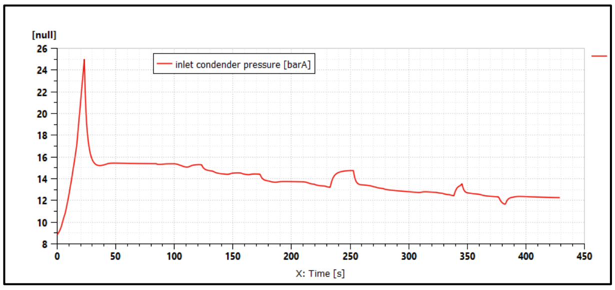


Fig. 12 Inlet condenser pressure during urban driving cycle

The AC compressor electric consumption is not negligible in comparison with other electric devices, as shown in Fig. 13.

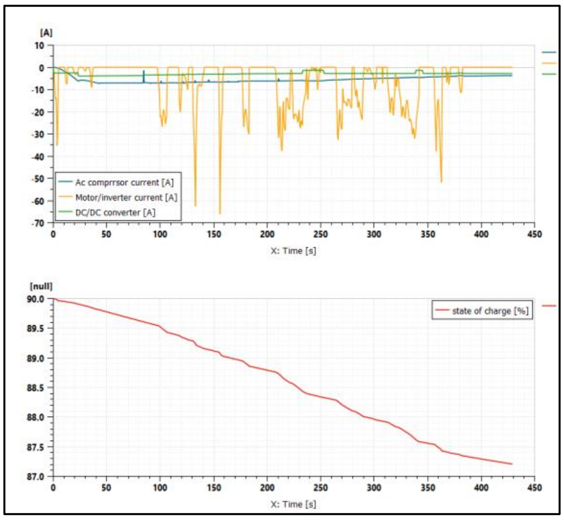


Fig. 13 Current balance during urban driving cycle

Powertrain cooling circuit is activated when coolant temperature achieves 45 degC, as shown in Fig.14.

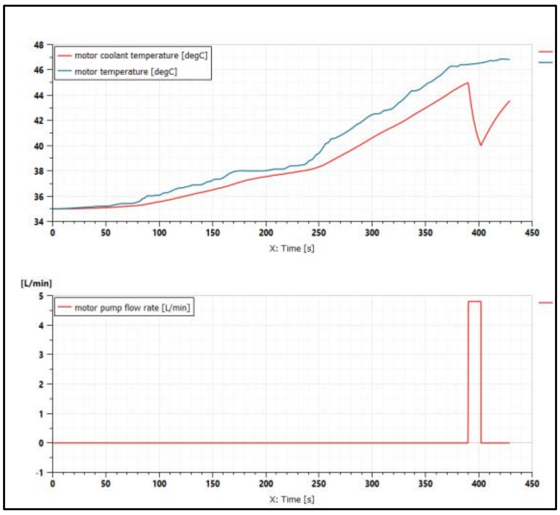


Fig. 14 Internal coolant, motor temperature (above) and pump flow rate (below) during extra urban driving cycle

During extra urban cycle, the blower position switches from high level to lower level with regards of the controled cabin tempertaure, as shown in the Fig. 15.

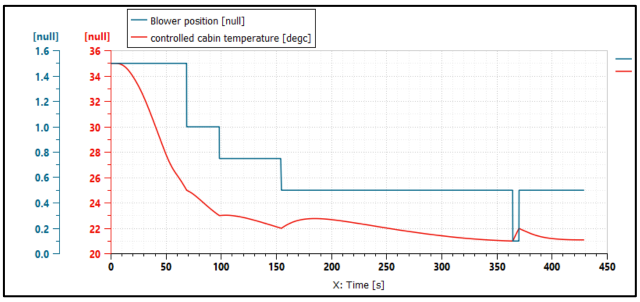


Fig. 15 Blower position during extra urban driving cycle

The influence of the blower air mass flow rate can be observed, as shown in Fig.16, especially between 365s and 370s, with an increase of average cabin temperature due to low blower air mass flow rate.

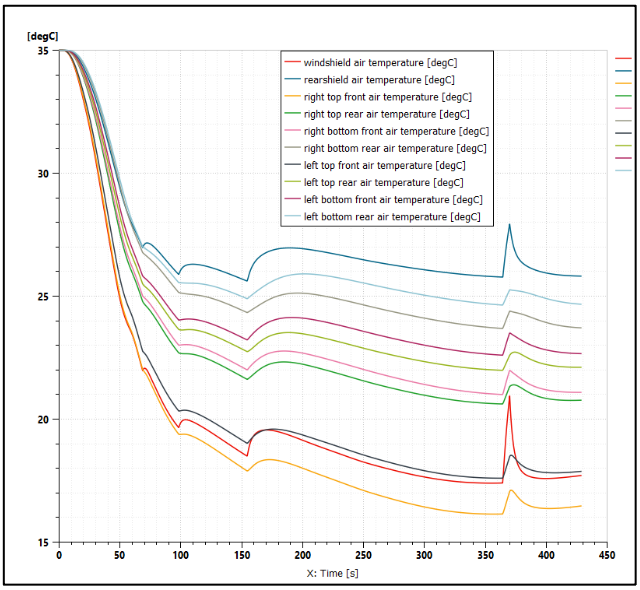


Fig. 16 Cabin tempertaures in different areas during extra urban driving cycle

3.2. 3D model

Simulating the flow field around a vehicle, under the hood and inside the cabin, CFD can provide every information that is needed. With this procedure, the great benefit is that boundary conditions are not anymore estimated but they are calculated by 1D Simcenter Amesim model. Therefore, potentially every interested instant or phase in a driving cycle can be studied in detail for each kind of application.

In the next figures, some 3D visualizations are shown, coming from WLTC simulation. In particular they focus on measures that Simcenter Star-CCM+ calculates in order to use in 1D model, for both vehicle model and cabin model.

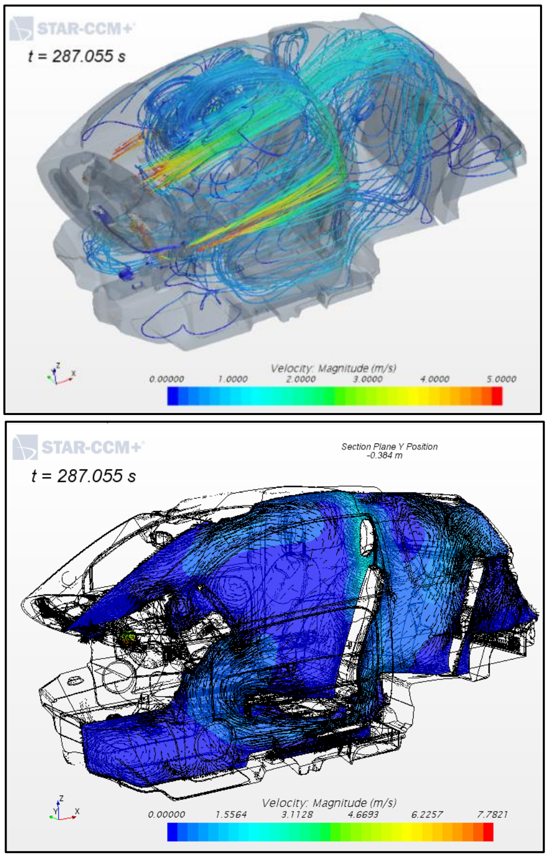


Fig. 17 Velocity streamlines and plane section with velocity magnitude

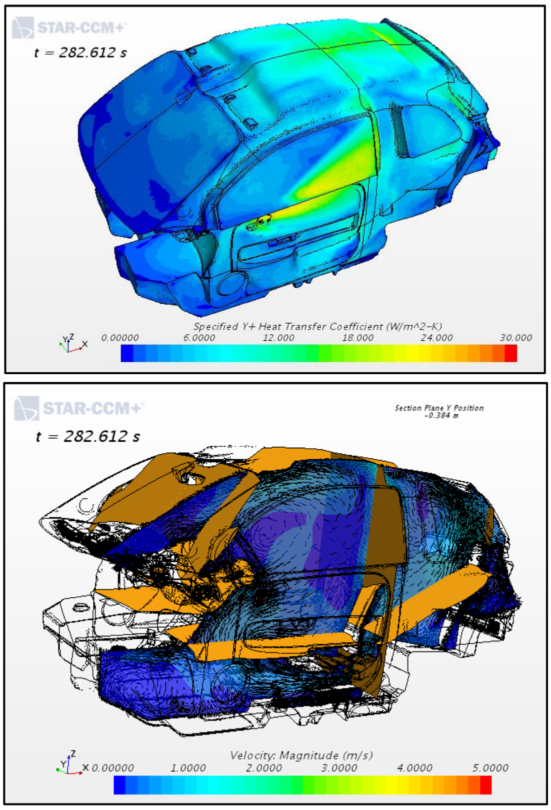


Fig. 18 Velocity streamlines and plane section with velocity magnitude

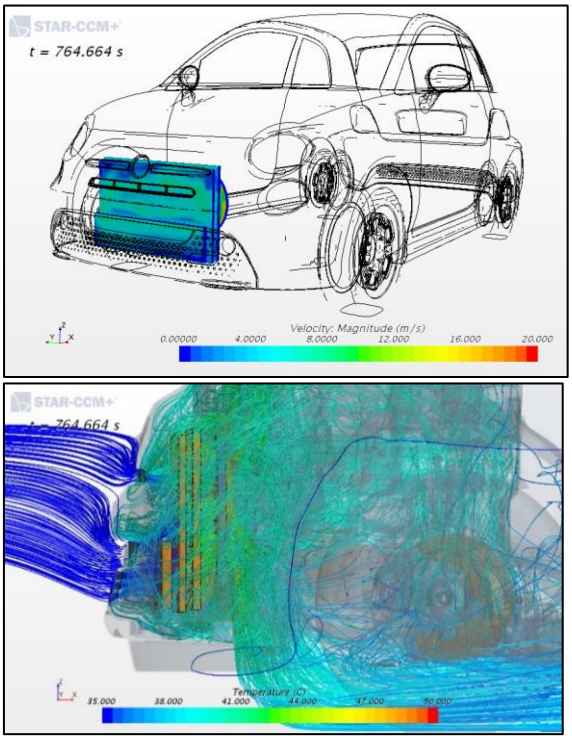


Fig. 19 Heat exchangers velocity maps and temperature streamlines

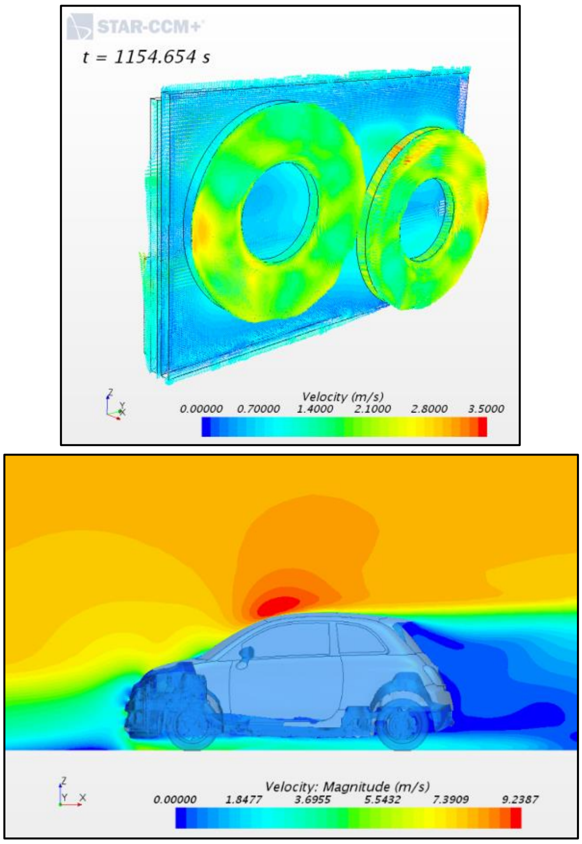


Fig. 20 Heat exchangers velocity vector and midplane velocity section

4. CONCLUSION

With such coupling approach, overall simulation, even for long transient scenarios like driving cycle, becomes affordable in terms of time and computational resources thanks to the use of HPC and smart coupling. 3D physical phenomena are still simulated with 3D model, but in a most efficient way with variable boundary conditions from 1D model, allowing a very high fidelity thermal system estimation for the electric vehicle and its components.

Furthermore, this methodology will be used to optimize the thermal management and energy consumption in the electric vehicle, by testing and assessing new different strategies in less than one day each.

AKNOWLEDGMENTS

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