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IDRA*pegasus*: a fuel-cell prototype for 3000 km/L

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ABSTRACT
High performances and low consumptions: this is the challenge for the Team H_2politO's members from Politecnico di Torino -Italy. Different technologies have enabled to design and manufacture the vehicle IDRA*pegasus*, a hydrogen prototype, for the Shell Eco-marathon (SEM), an international competition for low consumption vehicles. The target is very sophisticated: to achieve over 3000 km with the energy equivalent of 1 L of petrol, using a 200 W electric motor to move a vehicle of 33 kg. In order to win this challenge, students have used innovations in every technical field: mechanics, aerodynamics, electronic and powertrain.

KEYWORDS
Fuel-cell; hydrogen; carbon fiber

1. Introduction

The first important innovation has been focused on optimizing the tribological properties using materials with the lowest coefficient of friction. The prototype has a rear steering wheel, with a system that integrates rim, motor hubs and brakes in a space as small as possible. All mechanical parts are made of a lightweight alloy such as aluminum and titanium.

IDRA*pegasus* is a one-seat carbon fiber monocoque reinforced with honeycomb. The structural design of the monocoque has been done by means of numerical simulations in order to optimize the mechanical resistance, the total mass and the ply of carbon fiber definition.

To obtain a further reduction of fuel consumption and to improve the overall efficiency of the vehicle, the car has the front wheels inside the monocoque in order to reduce the frontal area and the wetted surface. This reduction is the result of an accurate study of the powertrain packaging and driver ergonomy. The optimization process has been carried out using a CFD software.

As far as electronics, to minimize the vehicle's fuel consumption it was developed a customized ECU for the fuel cell. It was also implemented a GPS tracking system allowing to know exactly where the vehicle is on the track (during the competition) and adapting the driving strategy according to it. The electronic architecture optimization, consisted of introducing a CAN BUS communication system to connect various elements of the vehicle's network, as used in automotive applications.

As regards powertrain, the Team efforts were concentrated to improve and develop the fuel-cell efficiency. This is why IDRA*pegasus* was equipped by a 1 kW fuel cell made with the newer technology advancements. In order to optimize the stack, the Team did some tests to investigate the effects of all important parameters on fuel cell efficiency, such as: temperature, reaction air flow rate and humidity. The car has been equipped with a 200 W high efficient electrical motor.

As result, IDRA*pegasus* was ranked 3rd place at SEM [9] with a consumption of 3023 km/L and it is the first Italian vehicle in its category.

2. Vehicle body and aerodynamic

For low consumption vehicle [8], drag is responsible for approximately half of the power demanded. The aerodynamic is clearly essential for the prototype success. A fuel-efficient vehicle shape is limited by certain qualitative and quantitative parameters that are considered as design constraints. These constraints come from race regulation, ergonomics and aerodynamics (Fig. 1).

The preliminary design phase consisted of a certain number of choices about the vehicle architecture and finished with the definition of the vehicle's topological model. Starting from this model, a series of modifications were carried out to improve the prototype's aerodynamics, using the computational fluid dynamics software CD-Adapco StarCCM+. The goal was to obtain the lowest

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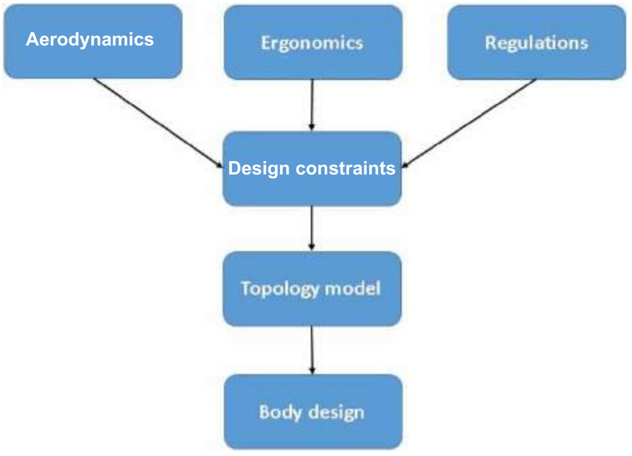

Figure 1. Optimization workflow used to develop the prototype's external shape.

product between frontal section (Sx coefficient) and drag (Cx coefficient), with a lift force close to zero. So the solutions studied for IDRA*pegasus* (Fig. 2) consisted of:

- Integration of front wheel inside monocoque;
- Front negative camber of 8°;
- Rear steering wheel.

Starting from the design constraints, it was defined the body shape. The analysis led to the definition of:

Table 1. Aerodynamics parameters.

C_x	0,093
F_x	0,991 N
F_z	0,694 N
C_xS_x	0,024

- ground clearance;
- camber;
- nose shape;
- body top curvature;
- pitch angle.

A basic profile was drawn by Autodesk Alias, and it was possible to define the external shape by CFD analysis, in order to optimize the variables of interest (Fig. 3).

Finally, after several simulations the results are the ones summed up in Tab. 1 while the final shape is represented in Fig. 4.

2.1. Ergonomy and driver position

A great attention was paid to driver ergonomy and visibility. A wood made mock-up (Fig. 5) was done in order to define the overall dimensions that allow to draw, with metric references, the first guidelines of the body.

The scale model of IDRA*pegasus* allowed to define the right positioning of seat belts and optimize the entrance

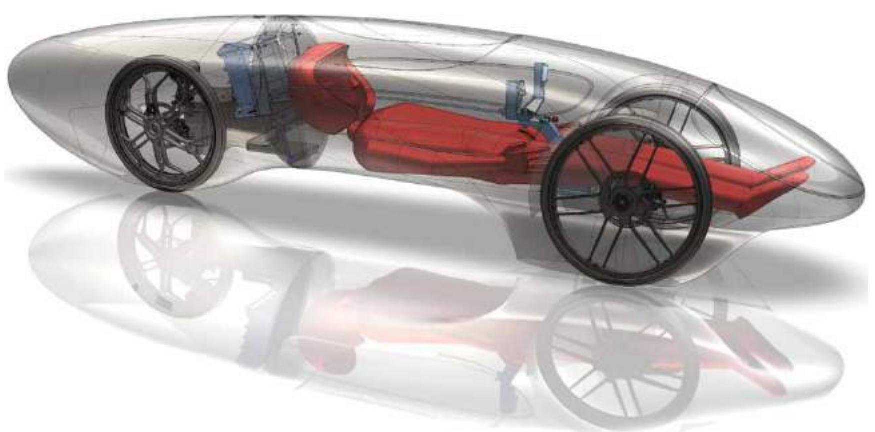

Figure 2. IDRA*pegasus* main feature.

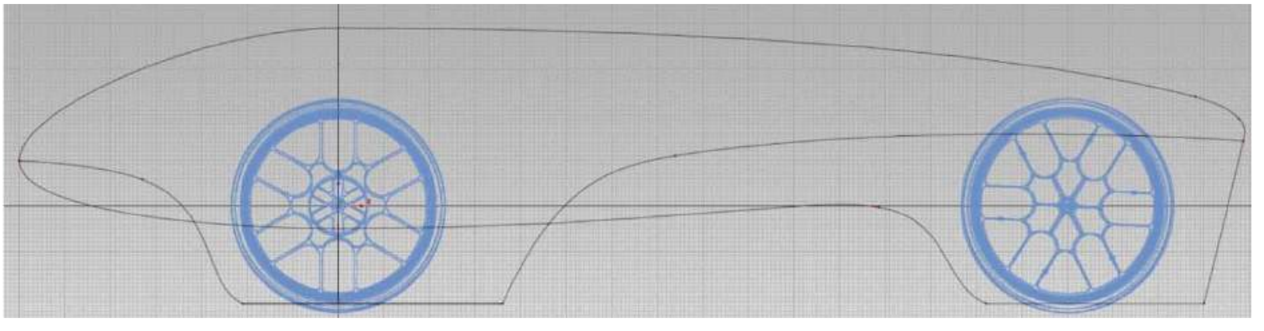

Figure 3. First shape of IDRA*pegasus* for CFD analysis.

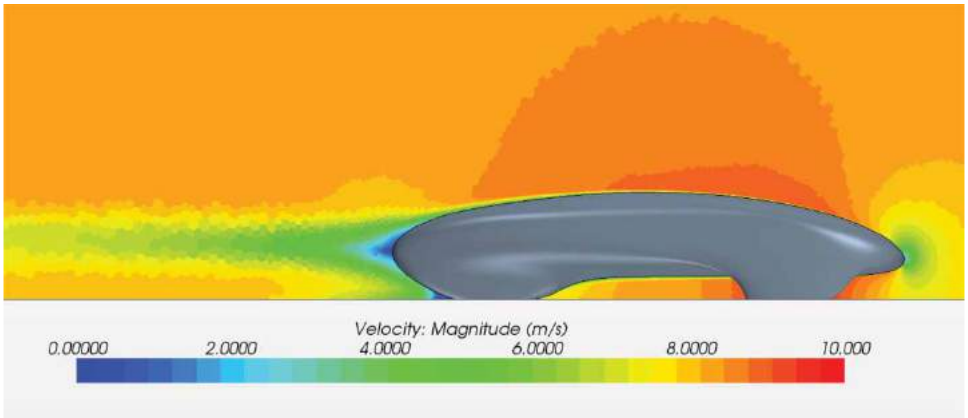

Figure 4. Final shape of IDRA*pegasus*.

Figure 5. Wood made mock-up.

side of the driver, in order to define the removable part of the vehicle body.

According to the Shell Eco-marathon rules that impose to pass the check visibility (Fig. 6), and in order to guarantee in the same time, high structural performance, a properly glass made part was used.

3. Mechanics and monocoque

Cutting-edge technologies were used in IDRA*pegasus*'s components as composite material (in particular carbon fiber) and lightweight alloy [2, 5, 6]. Moreover, the optimization of internal volume represented the main feature in order to achieve the best results in terms of consumption.

By Autodesk Inventor, it was possible to analyze the internal layout and design with high precision all mechanical assemblies of the car. Fig. 7 shows the three principal mechanical systems:

- Front wheels assembly;
- Rear steering system;
- Monocoque.

3.1. Front wheels assembly

To include the front wheels and the rear steering wheel into the monocoque, it was necessary to study new technical solutions. First of all, it was adopted a fixed 8° negative camber to the front wheels in order to reduce the frontal area of the vehicle and increase the aerodynamic efficiency. As shown in Fig. 8, the front wheel assembly is mainly composed by three macro components: rims, hubs and brakes. The increment of the strains, due both to the negative camber and the new type of the track for the competition, required the use of special materials that would have provided high strength, stiffness and lightness; in fact, the hubs and the housing were made of

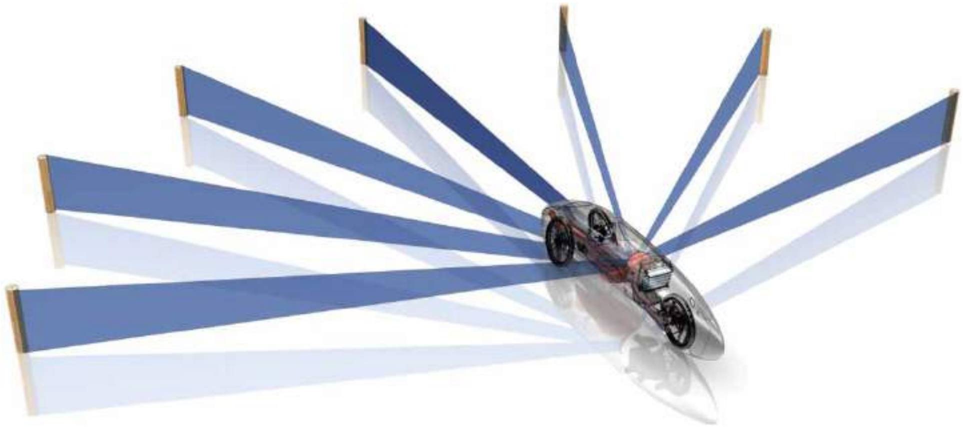

Figure 6. Visibility test as required by Shell Eco-marathon rules.

Figure 7. Main mechanical assembly of IDRA*pegasus*.

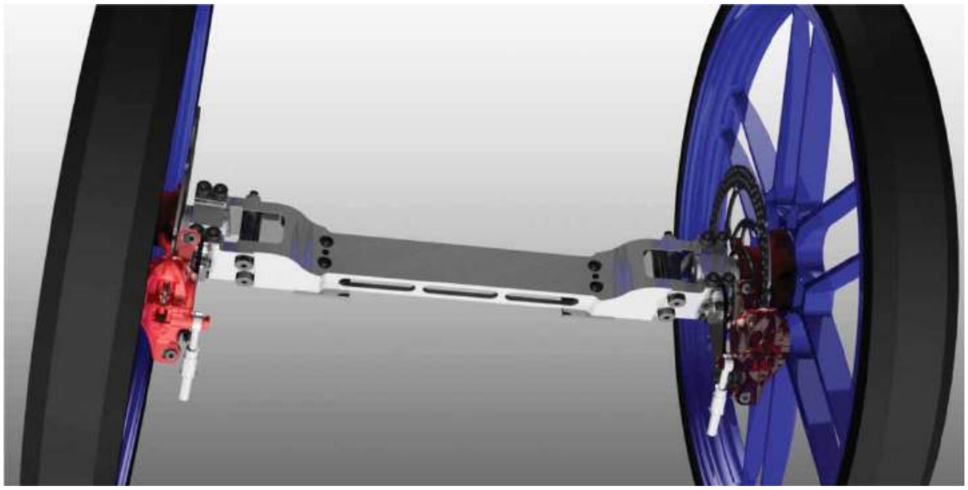

Figure 8. Front wheel assembly.

aluminum (7075 – T6 ERGAL), and the shaft was made of titanium.

3.2. Rear steering system

The rear steering is very difficult to set, because in no configuration of the steering axle it is possible to have concordant the three forces acting on the tire. This is due to: the trail, the gravity and the centrifugal force. This is why the goal of the design was to identify the configuration that would have prevailed the action of two forces on the third.

The first considered parameters were the *king-pin* and the *caster* angles. These angles define the trajectory of the contact point wheel-soil during the rotation of the tire. The non-zero value allows to obtain a downward trajectory oriented under the road. As a result, during the steering, the vehicle would have tended to rise and its own weight would have determined a moment of re-alignment. After several tests, the solution adopted for the prototype was the one represented in Fig. 9.

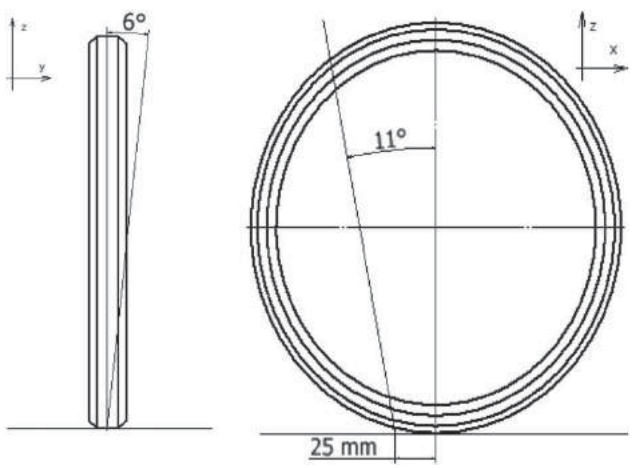

Figure 9. Steering parameter.

3.3. Rear wheel assembly

As far as the rear wheel assembly, the wheel hub had to have a fixing point for the motor assembly that during the steering had to rotate with the rear group assembly. It was determined the motor position in order to mount an internal meshing transmission with the crown mounted directly on the rim. Due to the dissipation caused by the dragging of the pinion that remained meshed to the crown, it was designed a system with a small spring allowing the detachment / attachment of the electric motor, as shown in Fig. 10. In so doing, it is possible to increase the overall efficiency of the race strategy during the coast down phases.

3.4. CAE Solutions for wheels and monocoque

An important engineering study was carried out during the rims designing. In particular, as regards the rims, a topological optimization was done by using Altair Optistruct solver v11.0.

The analysis was based on defining a target and a constraint: the target was the minimum mass possible, while the constraint was the maximum displacement allowed. The topological analysis gave as output the geometry to be achieved.

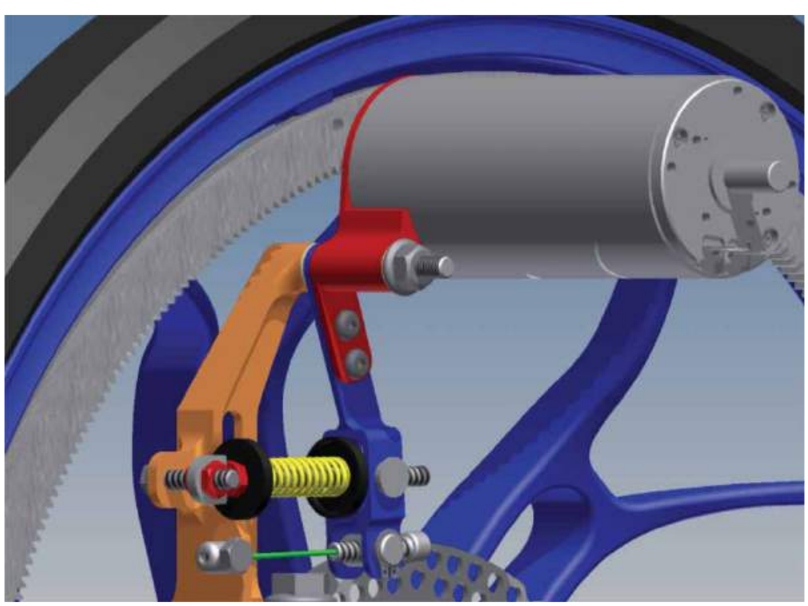

Figure 10. Rear wheel assembly.

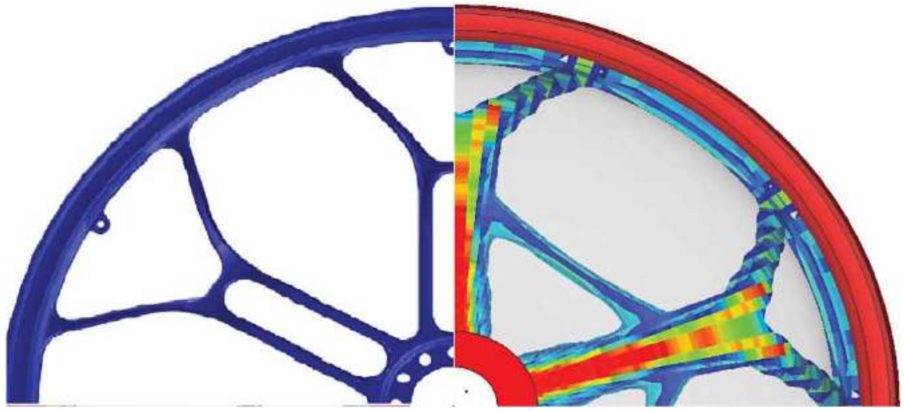

Figure 11. Optimization with different index of material density for the rear wheel.

Particular attention was paid to the study of the rear wheel, because it had a profile visibly rounded. Thanks to this analysis, it was possible to observe where the material was necessary (Fig. 11).

Figure 12. Removable parts of the monocoque in Dynamo Tex.

The aim was the chassis had to reach the lowest weight maintaining the structural resistance and stiffness.

The monocoque is the only structural element of the whole vehicle. For this reason, it was made by a sandwiched structure of Nomex honeycomb and pre-preg T-800 carbon fiber. In particular, in the rear area, in proximity of the single arm, it was used a pre-preg T1000G as reinforcement. The external layer of the vehicle was made by Dynamo Tex that also gave it an particular look (Fig. 12).

The monocoque was designed according to the following load cases:

- Vehicle equipment, driver mass and loads set by Shell Eco-marathon regulations;
- Rapid entrance and exit of the driver from the vehicle;
- Steering of the vehicle in the curve.

The simulations were carried out using Altair Radioss Linear v11.0. Fig. 13 shows the torsional simulation results.

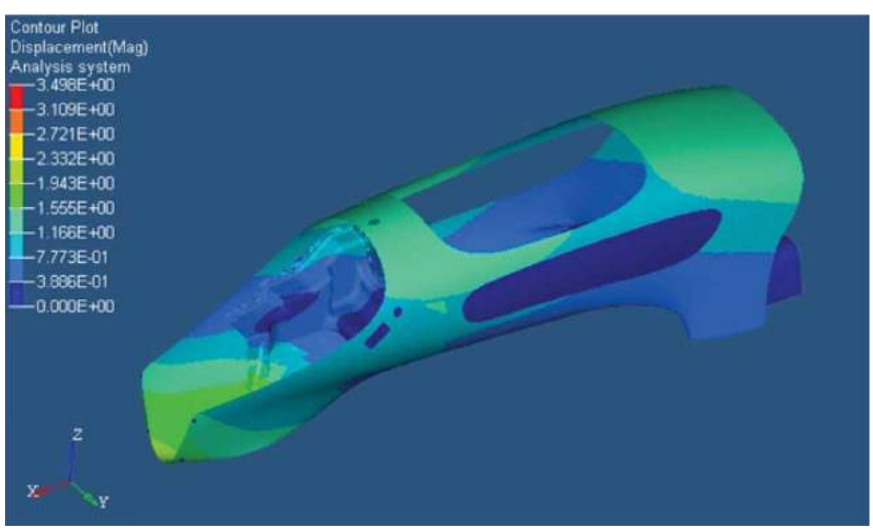

Figure 13. Torsional simulation results on IDRA*pegasus* monocoque.

4. Powertrain and electronics

4.1. Fuel-cell system

The IDRA*pegasus* powertrain was performed by a 1 kW fuel-cell PEM (Proton Exchange Membrane) combined with a 200 W high efficiency brushed electric motor.

The PEM-FC is particularly appropriate in automotive applications because the technology works at low temperature in comparison with other similar kind of fuel cell.

However, the hydrogen system required high safety strategy and IDRA*pegasus* was equipped with hydrogen sensor and safety valve in order to control the leakage and

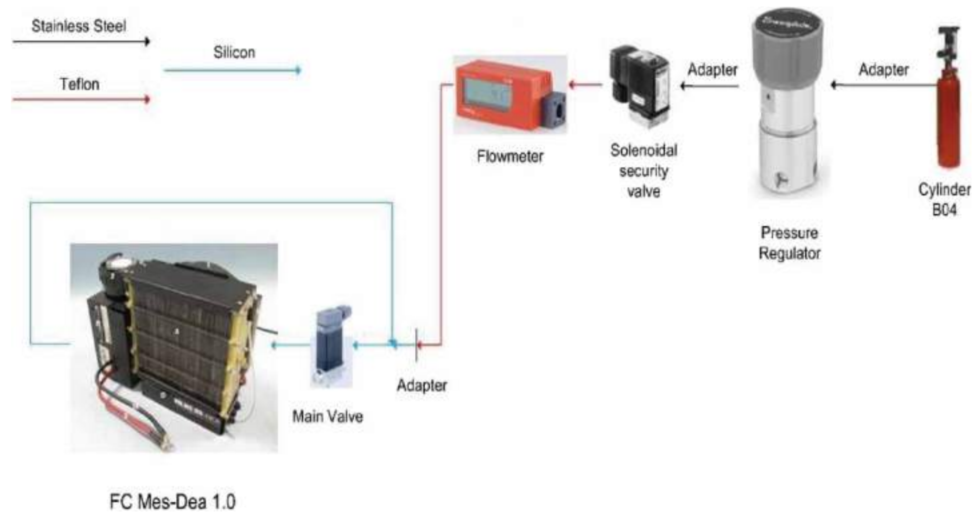

Figure 14. Hydrogen circuit with safety systems.

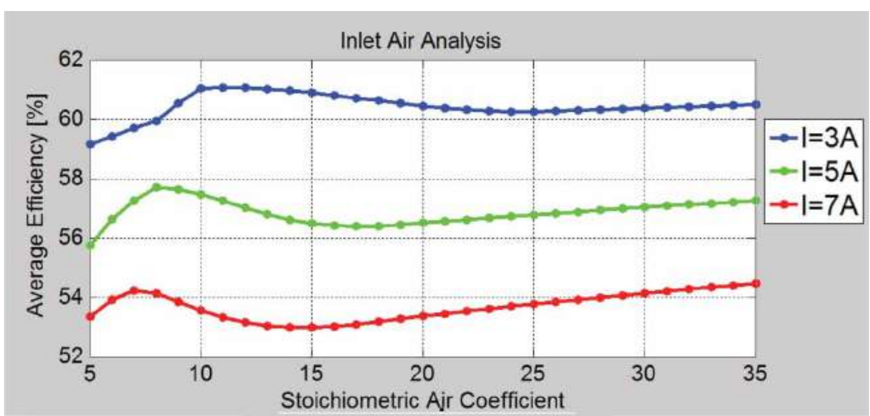

Figure 15. The influence of stoichiometric air coefficient in fuel cell efficiency.

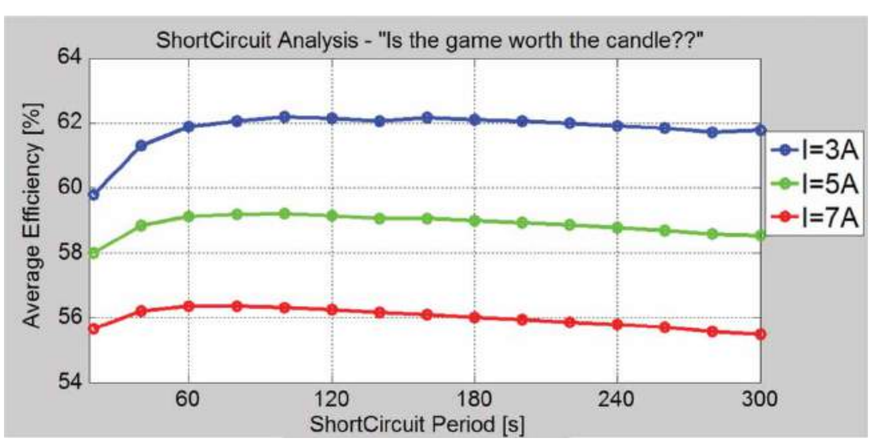

Figure 16. Influence of short circuit period in fuel cell efficiency.

an involuntary shot down of the ECU. Fig. 14 represents the hydrogen circuit used for the prototype.

An important development was done to set the mathematical model of the Fuel cell, in order to simulate it as in competition conditions [3].

The aim of the mathematical model is to optimize the fuel cell control [7, 4] in order to assure high efficiencies at any working condition. Three control parameters were analyzed:

- inlet air stoichiometric coefficient;
- short-circuits frequency;
- time cooling.

These, from the experimental data, are the most influencing parameters for the specific application.

The model was used to decide the best stoichiometric coefficient as a compromise between its cooling effect and drying effect. Then it was thought to implement into the control system, a step function that changes this coefficient so that the fan rotational speed changes at every temperature interval of 5°C. (Fig. 15)

Many studies show that the extra humidification of the reactant gases is essential in PEM fuel cells, so in particular it was studied, experimented and applied two methods, called “filling technique” and “short-circuits method” in order to increase the electrolyte membrane humidity. (Fig. 16).

These two methods avoid the use of a complex humidification system and allow a high increase of the electrolyte membrane humidity. These techniques have been performed with extreme caution to avoid the flooding problem.

4.2. Electronic devices

From the electronic point of view, the architecture of the vehicle can be summarized in four macro-blocks (Fig. 17):

- powertrain control;
- sensors;
- HMI (Human Machine Interface);
- Telemetry.

Powertrain control manages both the electric motor and the fuel cell. The electronic board (Fig. 18), entirely developed by the Team, is responsible for the flow of current from the fuel cell to the engine, the airflow

Figure 18. Actuation Board.

Figure 17. IDRA*pegasus* macro-blocks.

that allows the reaction and finally the cooling of the cell.

IDRA*pegasus* is equipped by several sensors in order to monitor the most important vehicle parameters. In fact, it is possible to measure the temperature and humidity in different points of the fuel cell to optimize its efficiency. It is also used a sensor to detect the vehicle speed and a GPS device for the position.

The human machine interface (HMI), it was developed with a LCD touch screen (Fig. 19) that allow the driver both to interact with the vehicle and to send useful information to the box during the race (e.g. vehicle speed and fuel cell voltage).

Thanks to the telemetry system (Fig. 20) it is possible to transmit vehicle information to the paddock in a real-time mode. This data are essential to the strategy that compares the simulated race profile with the real one.

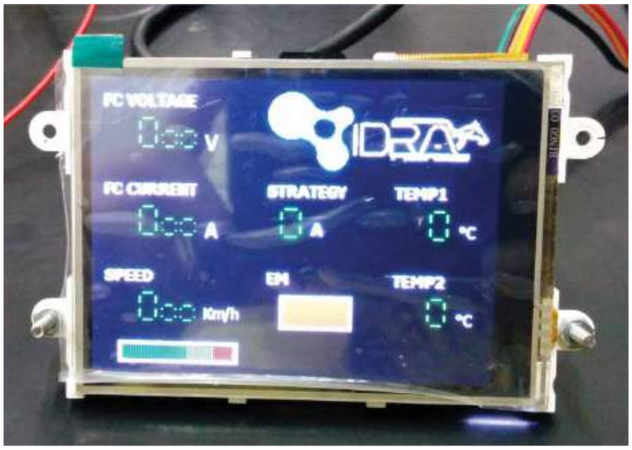

Figure 19. HMI LCD screen.

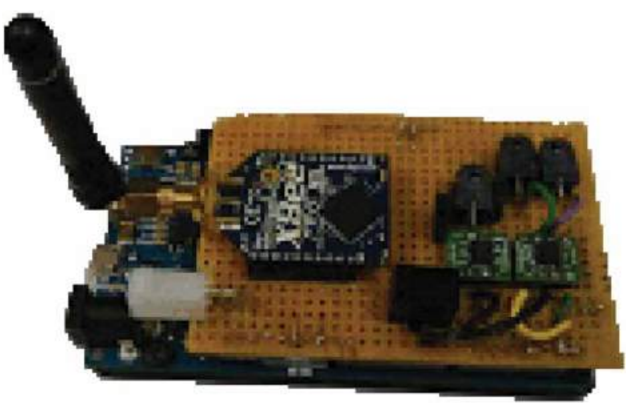

Figure 20. Telemetry board.

5. Strategy and modeling

The best way to decrease the consumption is to simulate the vehicle behavior during the race, by a mathematical model. This has been possible thanks to LMS-Siemens AMEsim software.

The IDRA*pegasus* model is composed by subcomponents, representing the main characteristics of the vehicle. The sub-components are:

- Vehicle Dynamics;
- Fuel Cell;
- Electric Motor;
- Transmission.

Through the interaction of this subcomponents, it has been possible to simulate the behavior of the prototype under the race conditions.

The vehicle dynamic study, performed with this model, gave the possibility to evaluate all the loads acting on the vehicle and the forces opposing to the drive considering Shell Eco-marathon track in Rotterdam

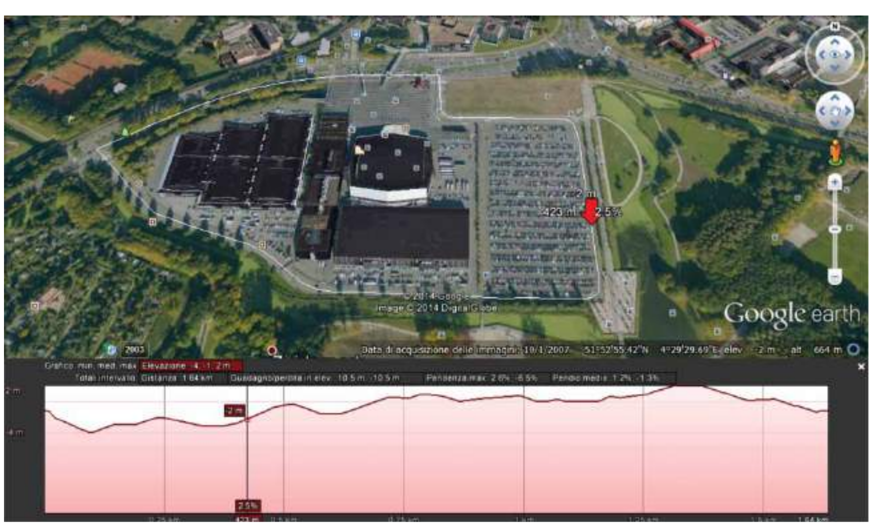

Figure 21. Track profile and slope.

(Fig. 21). These data were very important during the IDRA*pegasus* designing phases.

Moreover it was included in the main model, a dynamic fuel cell sub-model (Fig. 22). Thanks to this implementation, it was possible to simulate the state of fuel cell considering also the weather race conditions. The model was also validated through laboratory tests.

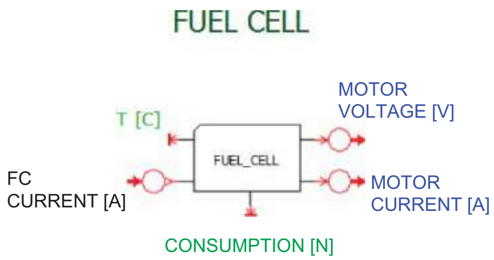

Figure 22. Customized fuel-cell block for AMEsim.

An important step was represented by the final overall optimization process. Using the software Noesis Solutions Optimus, it was possible to define the best type of power management (Fig. 23). The aim was to design through the definition of some principal parameters, such as torque, speed, fuel-cell condition, track slope and others to the external environment. The software output gave several important data in order to set the main blocks of the vehicle, such as the transmission ratio or the current intensity for the speed profile. In this way, it was possible to achieve the best results in terms of consumption.

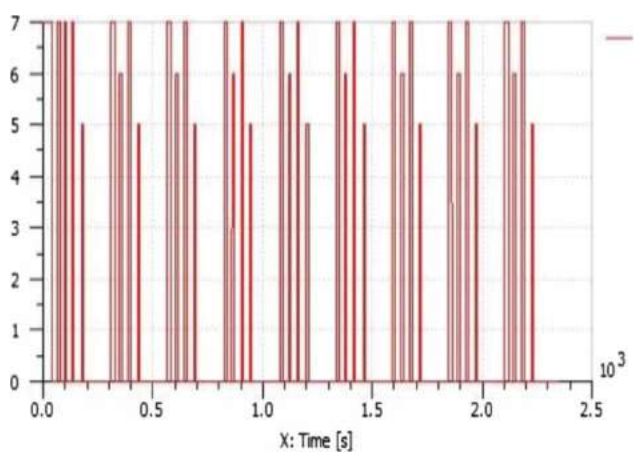

Figure 23. Plot of current profile [A] vs time [s].

6. Conclusion

The reduction of the masses is the key factor for the engineering of a prototype intended to participate in competitions for low consumption, like the Shell Eco-marathon.

The optimization work carried out, involved several different areas of research: the characterization of carbon fiber to obtain a light monocoque, the aerodynamics efficiency, the mechanics parts designed to reduce the weight also using new metallic materials, the fuel cell and electronic parts. For some parts of the vehicle a computational calculation and mathematical models have been pointed out and have been used for the strategy throughout the race, to obtain the best performance in terms of low consumption, first of all during the last competition in May 2014 at the Shell Eco-marathon.

The simulation result (3000 km /L) obtained by the vehicle model has been validated by t result obtained during the competition (3023 km/L).

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For further informations: www.polito.it/h2polito

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