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Original
Modeling and optimization of the consumption of a three-wheeled vehicle / Carello, Massimiliana; Bertipaglia, Alberto; Messana, Alessandro; Airale, Andrea Giancarlo; Sisca, Lorenzo. - In: SAE TECHNICAL PAPER. - ISSN 0148-7191. - ELETTRONICO. - 2019:(2019). (SAE World Congress Experience, WCX 2019 Cobo Center, usa 2019) [10.4271/2019-01-0164].

Publisher:
SAE International

Published
DOI:10.4271/2019-01-0164

Modeling and optimization of the consumption of a three-wheeled vehicle

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Abstract

In recent years, there is an increasing global interesting in alternative sources of energy. For this reason, Shell Company creates Shell Eco Marathon, a competition for fuel-efficient vehicles designed by student around the world. IDRAkronos is a fuel cell hydrogen prototype developed at the Politecnico of Turin. The vehicle races in prototype category with the task to complete ten laps of an urban circuit driving a total distance of 15 km in a maximum time of 39 min, then with an average speed of approximately 25 km/h, obtaining the less consumption. The vehicle is a three wheels vehicle based on a carbon fibre monocoque pushed by a hydrogen fuel cell with a high efficiency DC electric motor. The paper describes modelling and optimization of the powertrain design applicable to the development of fuel cell electric vehicles. A 1D-simulation model of the vehicle and its subsystems (fuel cell, electric motor, tires, aerodynamic, etc.) has been carried out in AMESim to analyse the behaviour of the vehicle during the race. The optimization leads to find the right combination of all parameters to achieve the least fuel consumption, considering the constraints of time, highest velocity, for example to perform a corner, and physical limit of the electric motor and fuel cell. Finally, the simulation results have been validated with the results obtained on the track during the competition.

Introduction

The dependence on liquid hydrocarbons as fuel and the emission of pollutants and greenhouse gases pushes to replace the internal combustion engine with different types of motors. Environmental problems due to pollutants, like carbon monoxide, nitrogen oxides, particulates, all substances not necessarily produced by combustion, have already been reduced with success by modern internal combustion engines. But carbon dioxide, on the contrary, is the result of the type of fuel used and can be reduced only by using fuels with lower carbon content or eliminated by using hydrogen.

Fuel cells are electrochemical devices able to generate pollution-free electric energy by electrochemical reaction of hydrogen with atmospheric oxygen, producing water as a by-product. Due to the absence of a combustion process the efficiency can be, theoretically, higher than that of thermal engine, even if it is limited by losses of various kinds.

This paper reports the results obtained by the vehicle IDRAkronos, a prototype designed at the Politecnico of Turin (Italy) to face the challenges posed by sustainable development with a vehicle that minimizes fuel consumption and emissions. IDRAkronos vehicle (evolution of IDRA*pegasus* [1, 2. 3, 4. 5]) is a fuel cell hybrid electric vehicle pushed by a 500 W Proton Exchange Membrane Fuel Cell (PEMFC), which feeds a high efficiency 250 W DC electric motor.

The methodologies used for the energy management optimization to have the lowest possible consumption of hydrogen have been shown. The developed 1D mathematical model has been used to predict the behaviour of the vehicle in operating conditions (during the competition or tests on track). In particular, the model joins, in a specific way, the equations contained inside software's blocks (in the following only equations inserted explicitly by user are explained). Thanks to the simulations, it is possible to select the best solution from a set of suggested solutions, also considering the ratio between feasibility, reliability and gain of each design. For this purpose, the characteristics of the competition track have been considered in the optimization of each lap. The fuel consumption obtained during the real competition (831 km/m^3 equivalent to 2466 km/L with the equivalent energy of one Liter of gasoline) was compared to the simulation-based optimization procedure (834 km/m^3 and equivalent to 2474 km/L) obtaining only a difference of 0.4%.

The results allow to validate the model and to propose it for a next development of similar vehicles.

Scenario

To illustrate the method used to create the 1D model of IDRAkronos and to optimize the energy management strategy of its fuel cell the representative case of the Shell Eco Marathon Europe 2017 in London has been chosen.

This competition is made for low energy consumption vehicles with the objective to complete 10 laps of an urban track by covering a total distance of 15 km in a maximum time of 39 minutes, with an average speed of approximately 25 km/h, according to the rules of the competition [6]. In addition, each participant must adhere to special constraints related to: body, safety, power, electronics, mechanical braking, visibility, ergonomics, tires, wheel dimensions and steering. The aim for the team is thus clear: to minimize energy consumption in given racing conditions.

Vehicle Architecture

IDRAkronos is a three wheels vehicle based on a carbon fibre monocoque, with two wheels in front part and one rear, which is the driving's one. This configuration requires attention in dimensioning the track and the wheelbase to keep the vehicle stable and safe. The curb mass is 41.5 kg despite the dimension of the vehicle (3500 mm x 580 mm x 650 mm) with an aerodynamic coefficient of 0.143. The attempt to eliminate all the resistive forces suggest the use of a Davis steering systems which allows to fullfil Ackerman condition [7,8] at every angle reducing sideslip in curves that can wear the tire and consequently increasing the rolling resistance of the latter. Obviously, the presence of more sliding members in the steering mechanism involves an increase of friction and so of the wear of components. The usage progressively eliminates the accuracy of the system, not allowing a mass usage of the system, nevertheless it can be very useful for a prototype which travel few kilometers each year. IDRAkronos architecture is shown in Figure 1. Thanks to a chemical reaction between hydrogen and oxygen, the fuel cell (500 W produced by Horizon) feeds the electric motor (250 W, 36 V DC RE55 produced by Maxon), with electrical energy needed for traction. The hydrogen is stored in a tank at 200 bar (20 MPa), that is connected to the fuel cell by means of two stage pressure reducer that reduce the pressure from 200 bar (20 MPa) to 0.5 bar (0.05 MPa), the value effectively required to supply the fuel cell.

To capture and analyse the dynamics behavior of IDRAkronos during the race and subsequently find the optimal race strategy, that provides the lower fuel consumption, a mathematical 1D model has been realized using the software LMS Imagine.lab AMESim. It's a simulation platform for multi-domain systems simulation and consequently predict the performance of systems. The software chosen is based on the C language, the standard language for the construction of computationally efficient simulations and has a wide range of already built libraries inside, which allow to facilitate the construction of the 1D models. The libraries implement the differential equations that govern the physics of the vehicle, the mechanical motion, the thermodynamics of the engine, the reactions of the cell. The software is provided with a series of integrators, software owners that solve the same equations and provide values estimated, in every instant of the race, the characteristic parameters of the different components of the vehicle (Figure 1).

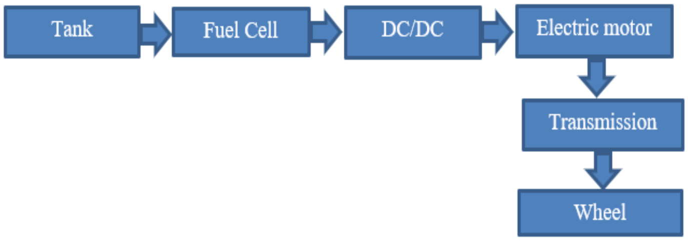


Figure 1. Scheme of the powertrain of IDRAkronos

Vehicle Modelling

The dynamic study of the vehicle, performed with the developed model, gave the possibility to simulate the vehicle itself on track in conditions complying with challenge regulations and to evaluate the impact of all the loads, forces applied on it and different drivetrain configuration.

A multi-module simulation model is created, but it's noticeable that the simulation model, which is constantly being evolved, is linked to the degree of vehicle development, and to the level of knowledge concerning both the vehicle and the race [9, 10]. Therefore, the model is subjected to continuous improvement and refinement.

The following phases can be highlighted:

1. Creation of a basic model

It is just the creation of each module of the model followed by their joint in a unique working model. Special measuring is made for the transmission module which requires a more accurate model despite the increasing computation time.

2. Computation of the strategy

The model is refined according to data recorded during test drive in racing track. The strategy is then computed.

Creation of the model

The vehicle model is composed of some subcomponents, each one representing some characteristics of the vehicle. This model is organized around five main blocks, as visible from Figure 2: vehicle dynamics, powertrain, transmission, environmental condition and strategy. This dynamical model is oriented towards the optimization and must be solved quickly. Thus, all the hypothesis and simplification are done to achieve this goal.

The simplification hypothesis of build a 1D model, ignoring the losses in curve, is due to the need of make several simulations in few times to optimize the race strategy. Even if the software gives the possibility to create more sophisticated model, for instance using a 15 dofs vehicle block, the configuration of the race, the quite low value of speed in corner, the usual configuration of track, the presence of few corners suggests the team to gain simulation speed at the expense of a low advantage in accuracy.

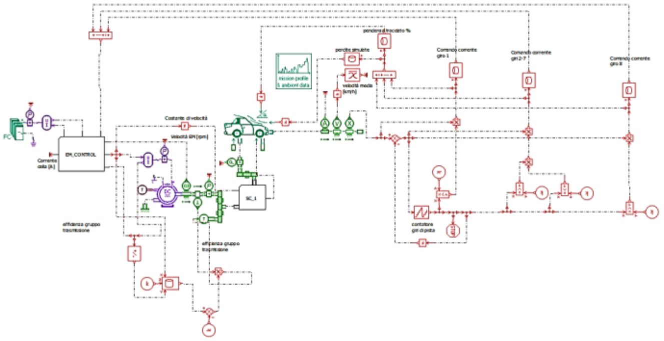


Figure 2. IDRAkronos model in AMEsim.

Table 1 shows all the parameters necessary to insert in the model. The parameters not known a priori are computed experimentally during the track tests.

Table 1. Input for the model

Input parameters	Value	Unit of measure
Actuation and Fuel cell		
Actuation consumption	0.05	A
Sampling period	0.008	S
PWM step size	0.001	N/A
Initial voltage	41.9	V
Maximum current	22	A
Polarization curve	N/A	N/A
Consumption curve	N/A	N/A
Vehicle and driver		
Curb mass	41.5	kg

Driver's mass	55	kg
Race strategy	N/A	N/A
Rolling resistance	0.0025	N/A
Wheel inertia	0.1056	kg•m^2
Width of wheel	45	Mm
Height of wheel	75%	N/A
Diameter of wheel	16	In
Frontal area	0.39	m^2
Cx	0.143	N/A
Track		
Length of the lap	1538	m
Number of laps	10	N/A
Altimetry	N/A	N/A
Transmission and Electric motor		
Pinion teeth	27	N/A
Crown teeth	360	N/A
Dynamics friction pinion crown	0.54	N/A
Friction resistance of freewheel	0.0022	N•m
Torque constant	84.4	m•Nm/A
Speed constant	113	rpm/V
Terminal resistance	0.174	Ω
Terminal inductance	0.076	mH
Rotor inertia	1380	g•cm^2
No load current	0.437	A

Vehicle Dynamics

The vehicle dynamic model is built around the constant load vehicle, the car block (Figure 2). Both front and rear axles are modelled, and the road configuration has been chosen: rolling friction, road slope and aerodynamic drag considered. Due to the low torque involved and the good characteristic of the tire, no slip between tire and ground is considered. The wind speed and the road slope are defined in the "mission profile and ambient" block, which is described in the model part "Environmental Condition" [11].

To obtain the dynamical behaviour of the vehicle, the mechanical equations are solved. To run, the vehicle must overcome the efforts due to the aerodynamic, the slope and the rolling resistance due to friction between the wheel and the road (the biggest resistance for the IDRAkronos vehicle). Finally, the vehicle linear acceleration is given by the equation 1:

$$a = \left[\frac{Fdr-(Fb+Fres)*Cstat-Fext}{\text{vehicle mass}}\right] \qquad (1)$$

Where:
a = Acceleration;
Fdr = Driven force;
Fb = Resistance force due to brakes;
Fres = Sum of all resistance forces (Rolling resistance, climbing, aerodynamic drag);
Cstat = Stiction coefficient, used only when the vehicle is stopped;
Fext = External resistance force (Wind, someone pushes the car).

Powertrain

The developed model (Figure 3) of the powertrain is divided into three parts: fuel cell, electric motor and its control [12, 13, 14, 15, 16]. The models presented in the literature are usually complex and therefore not suitable to analyse the principal aspects of vehicle dynamics owing to long simulation time.

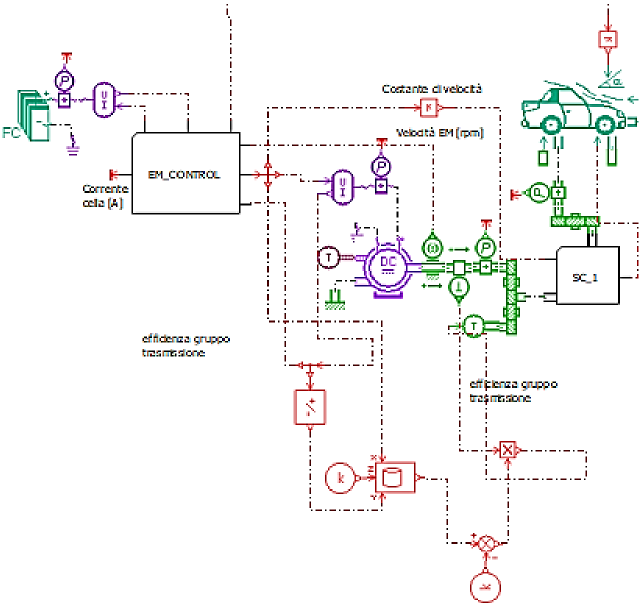


Figure 3. The powertrain model

The fuel cell is represented by the simple block (present in the AMEsim library) and it calculates the fuel consumption from a data map (fuel consumption as a function of current). The output voltage is calculated from the input current and a data map voltage in function of current.

The efficiency of the fuel cell is calculated from fuel low heating value of hydrogen and consumption map. The two text parameters have been obtained from the real fuel cell in the "Hysylab" laboratory in Turin. From the experimental polarization curve, it is noticeable that the fuel cell at the contrary of a battery provide current not at a constant voltage. This difference is fundamental to compute the limit speed of the vehicle that is the maximum speed that the prototype can reach in full throttle conditions. It's important to notice that the fuel cell after some period of work need to have a purge to throw all the water away composed in the process. In the model, the purge is not represented even if it is an inevitable operation in the race, also useful

to maintain the polarization curve as it was at the beginning. During the operation, the valve is open to throw away the water but together with it also some hydrogen goes away, influencing the fuel consumption. The period of the operation depends on many parameters like temperature, current, humidity (which is not predictable, and for this reason since this operation is made few times during the run, it has been decided not to represent it).
The electric motor (Figure 4) is modelled thanks to a simple block taken from the Amesim library, the current which absorbs the block is controlled by the electric motor control itself.
The parameters, which characterize the model, are taken from the datasheet of the motor. During the simulation, the temperature of the electric motor is supposed to be constant, even if it's not very true, the mistake due to this assumption is little enough to be considered negligible. This assumption can be done due to the fact the DC motor is not overloaded however in the opposite case it is advisable to make further study on the heat propagation, due to the dangerousness of the event beyond the loss in efficiency. The control submodule has the task to compute the current which is supplied to the motor, it's connected to the strategy block. It represents the model of all the electronic system of the car, so it controls when the fuel cell needs to supply energy to the electric motors, that's why it's colligated with the strategy. At the same time, it computes how much current is absorbed by the electronic cards. The PID (Proportional Integrative Derivative) controller works as a PWM (Pulse Wide Modulation) to control the current profile trend and at the same time, it helps to maintain the profile closer to the reality in an empirical way. It is possible also to make more realistic power electronics model, but they will oblige to use a smaller integer step which involves slower simulation.

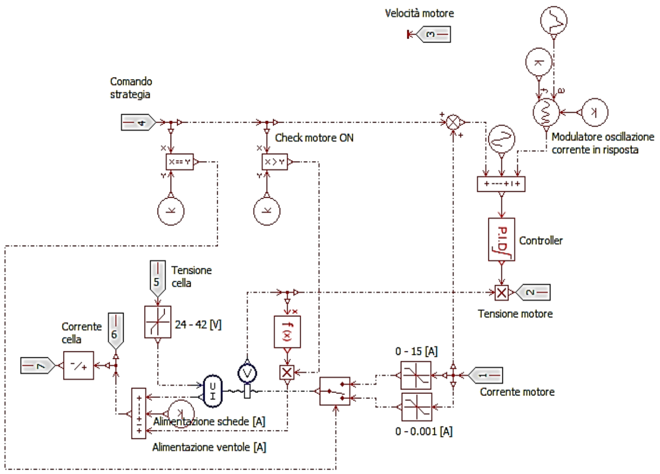


Figure 4. The electric motor control model

Transmission

The transmission system is designed to be as efficient as possible, so it's based on a pinion and crown. The pinion is directly splined on the motor shaft, while the crown is mounted on the wheel rim. Inside the pinion is mounted a freewheel, a device which can disengage the driveshaft from the driven shaft when the driven shaft rotates faster than the driveshaft. The condition of the wheel spinning faster than the pinion occurs a lot of times during the race because the limited velocity of the electric motor is lower than the velocity that the car can reach during a run. In a fixed-gear, without a freewheel, the rear wheel would drive the motors thus spending more energy and decreasing the time employed in a coast down. So, it has a double function, one when the electric motor is pushing and another when the electric motor isn't pushing. The model of the transmission is structured as follow:
1. Free wheel,
2. Gear ratio.
The free wheel (Figure 5) is modelled in a mathematical way and with a certain simplification (neglecting the inertia of the motor). The mathematical model works with a series of switch that are open or closed, following the commands of rotational speeds coming from the wheel on one side and from the motor on the other side. The switches present problem of discontinuity in the simulation which can block the optimization of the strategy with automatic algorithm of machine learning or create issues when the model is made running during the race to change in real time the strategy adopted for the competition. For these reasons, the team substitute the switch whit a table which make the same work but slower and in a continuous way. The accuracy of the model, after having tested the solution, doesn't present a noticeable decay while the generation of discontinuity decrease a lot making possible the use of machine learning algorithm for the strategy optimization.
Freewheel presents two different efficiency when it is engaged and when not due to its way of working: when it's engaged freewheel works as a solid body united with pinion, so it doesn't present inefficiency, while it's disengaged it seems to slip so it is useful to compute this inefficiency of the system. Considered the dual face of the efficiency, the submodel send a signal to the brake of the car when the freewheel is disengaged which slows the car.

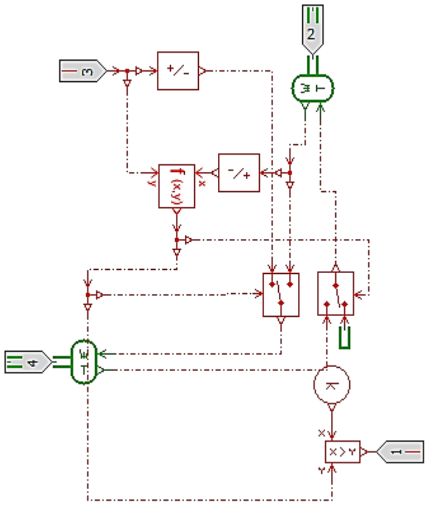


Figure 5. The freewheel model

The value of gear ratio can be modified according to what pinion (the number of teeth could be change) is mounted in the car, the choice of the pinion is very important to find the best strategy during the race so it's one of the main parameters to analyse during the optimization phase. The computation of the efficiency is made through the formula (2) and due to the use of the material choice it reaches the value of 98,53%.

$$\eta = \left[\frac{1}{1 + \pi \bullet \rho \bullet \left(\frac{1}{z1} + \frac{1}{z2}\right)}\right] \quad (2)$$

where:

η = efficiency of transmission gear;
ρ = friction coefficient between crown and pinion;
Z1= number of teeth of pinion;
Z2 = number of teeth of crown.

Strategy

This model is different from a common model because the input is represented by the intensity of current profile requested by the electric motor to powers the vehicle during the race instead of the desired velocity profile. In this way the reference profile for the model is the current supplied to the motor, while the velocity profile is a result of the race strategy adopted. The strategy of the race is inserted in the model thanks to the use of three tables, one for each race phase. The model (Figure 6) knows what lap it is because in the below part is represented the system which counts the lap knowing the distance travelled by the vehicle. The overall track has been divided in three segment categories:

1. First lap: indicates the first lap where the first acceleration of the vehicle is considered.
2. Central lap: indicates all laps that present the same conditions.
3. Last lap: indicates the remaining lap which is considered differently due to entry in pit line which must be undertaken safety.

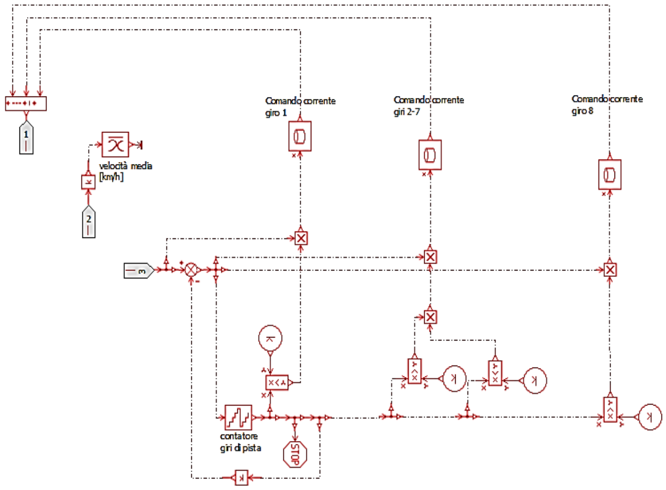


Figure 6. The strategy model

The characteristic of the race suggests that the behaviour of the vehicle is divided into three different phases, considering:

- Acceleration: In this first phase, the electric motor provides power to the vehicle, and the fuel cell is ON. Generally, the vehicle accelerates before every climb.
- Cruise: In this phase, when the vehicle has reached the cruising speed, the vehicle has finished to climb. The fuel cell is ON.
- Coast – down: During this important phase, the vehicle has completed the climb. The fuel cell is OFF, and the vehicle proceeds thanks to the inertia forces. In this phase the motor is disengaged and there is a deceleration, direct consequence of resistances forces like aerodynamics, rolling and slope.

A typical velocity profile in race conditions is represented in Figure 7, where it is possible to distinguish these three phases.

Velocity [km/h]

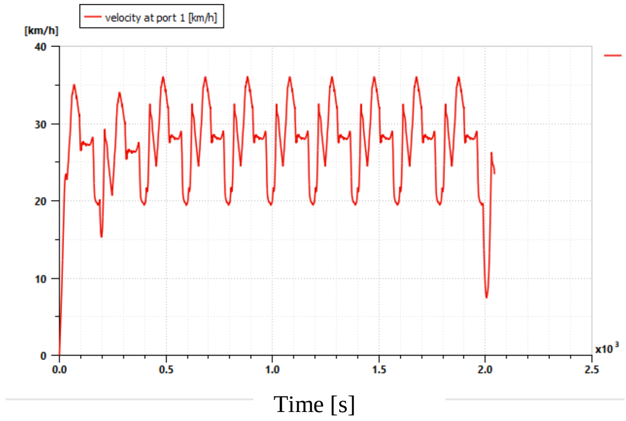


Figure 7. Velocity profile vs. time in race conditions

Environmental conditions

For prototype, the computation of perfect road profile sloppiness is fundamental to have a valid model, Shell gives the team the race track on a map, then starting from those data, a MatLab script has been created which can obtain the altitude of the point belonging to the track. This work is useful to verify the truthfulness of the altitude supplied by the Shell. The work starts from the data obtained through a query to Google Elevation API, starting from a drawing of the coordinates of the circuit on Google Earth, following the map provided by the Shell. Google Elevation API is a service offered by Google that allows you to get the information of the elevation of a circuit by visiting a web page and entering in the URL a key and a pair of latitude and longitude coordinates. Unfortunately, in correspondence of the bridges, one of which is the main climb to be tackled, the data are incorrect, as Google's altimetry is that of the water below the bridges and not that of the road. In addition, the data appear unreliable due to the presence of other overpasses at the track. All these unluckily events oblige the team to trust of the data supplied but at the same time they give the opportunity to make a comparison when the GPS altitude is not stopped by bridges.

Computation of the race strategy

The search for the best race strategy for the Shell Eco Marathon 2017 depends strongly on the path to be tackled for the race. Since it is not possible to test the route before the week of competition and during the same week the test possibilities are very limited, so it is necessary to do several simulations. To be able to do simulations you need a vehicle model and a model of the circuit, in particular of the circuit altimeters.

Constraints

The constraints that must be respected in the simulation are summarized in Table 2. The constraints related to displacement are fixed by the geometry of the track, while the maximum speed reachable in the track and the maximum time available to complete the race distance are set by the competition rules. As previously mentioned, each prototype must complete 10 laps (15380 m) in less than 35 minutes with an average speed of 25 km/h, never exceeding a speed of 40 km/h. Not only the competition rules must be respected but also the physical limits of the vehicle must be taken in consideration to define a feasible strategy. Among the dynamic manoeuvres a motor vehicle can experience, rollover is one of the most serious and threatening to the vehicle driver. It may occur on flat and level surfaces when the lateral accelerations on a vehicle reach a level beyond which can be compensated by lateral weight shift on the tires [17].

Table 2. Race constraints

Parameter	Target
Displacement [m]	15380
Total time [s]	2100
Maximum speed [km/h]	40

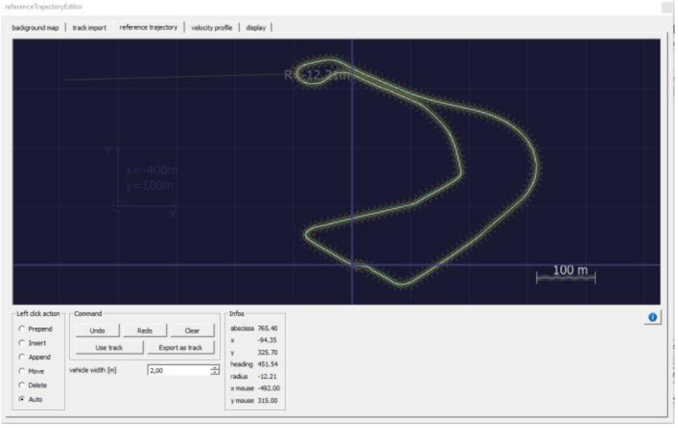
The dynamic stability of a vehicle is of profound significance, which has led three-wheel vehicles to be used for only low speed application. For this reason, even if the model created is longitudinal it's necessary to find a way to define the maximum speed the prototype can take every corner of the track. To fulfil these necessities there is an application present inside the vehicle dynamic library of AMEsim, which can be used (reference trajectory editor). Figure 8 defines the trajectory the vehicle probably will follow on the track. The trajectory created has no discontinuity in curvature and this guarantees that, for reasonable speeds, the driver can follow it using a continuous steering angle. Specifically, the trajectory is built from a collection of clothoids segments (Euler spiral). Now the application knows the radius of each corner so, after the data entry of maximum speed, max lateral acceleration sustainable, weight and power of the vehicle it computes the limiting speed to take each corner safely during the race. To compute the maximum lateral acceleration of the vehicle a particularized formula for the Static Stability Factor SSF of a three wheel-vehicle will be used. SSF is chosen because it represents the most crucial factors that determine the vehicle rollover resistance, almost in 95% of rollovers [18].
A modified formula, equation 3, for SSF of a three-wheel vehicle is derived for equivalent roll over resistance:

$$SSF = \frac{T}{2 * CGz} * \frac{(b - CGx)}{b} * cos\alpha \quad (3)$$

Where:

T = track width of vehicle,
CGz = height of centre of gravity from road surface,
b = wheel base of vehicle,
$\alpha = \arctan\left(\frac{T}{2*b}\right)$

Equation (3) includes the effect of position of CG in X direction as well as wheel base. These two parameters are not necessarily considered in a four-wheel vehicle's case, and these two parameters have effect on stand still stability during lateral slopes for vehicle. The rollover threshold is defined by the peak value of lateral acceleration that is needed to bring the vehicle to the point of initiating roll instability.
The results obtained by the application are collected in the figure 9, where the only curve which is necessary to pay attention is indicated with number 1, which show a maximum safety speed of 30 km/h.



○ Prepend
○ Insert
○ Append
○ Move
○ Delete
● Auto

vehicle width [m] 2,00

abscissa 765.40
x -94.35
y 325.70
heading 451.54
radius -12.21
x mouse -492.00
y mouse 315.00

Figure 8. London's track in the "Reference trajectory editor app"

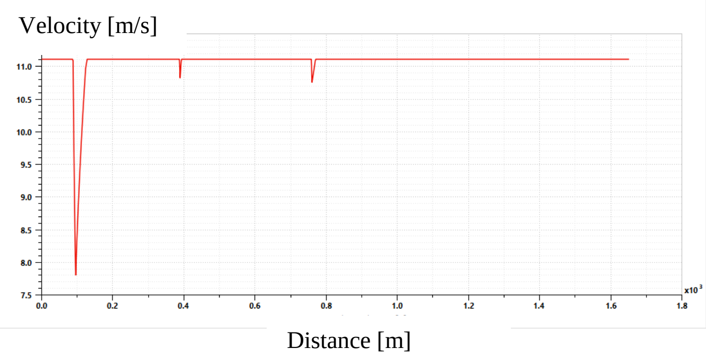


Figure 9. The maximum safety speed reachable by IDRAkronos in London's track.

Optimization of the strategy

The simulations must be based on a solid software infrastructure, that allows quick and accurate simulations from the modelling point of view and at the same time allows the development of a control in an interactive way, to easily study and modifying towards improvement, an optimal strategic plan.
After designing a model adherent to reality, to study the limit to which the vehicle can be brought from the point of view of consumption, it is necessary to study the optimal competition strategy for that model. Studying the optimal race strategy means building an optimal control for the vehicle. The study of the optimal competition strategy given a model is also important for guiding project choices in an appropriate manner. In summary, the steps for vehicle improvement are as follows:

1. building a vehicle model, focusing on adherence to the experimental reality, based as much as possible on the track tests;
2. bring the vehicle to the limit by studying the optimal race strategy;
3. observe the result, positive and negative aspects;
4. study new project choices to improve vehicle performance;
5. make adherent the vehicle model to the new project choices;
6. study a new optimal strategy for the obtained model.
7. Iterate improving at every step.

It is evident that, for a human operator, the search for an optimal strategy is very complex with a scheme of this kind, due to the many parameters to be taken into consideration. To approach sufficiently the optimum, i.e. the consumption limit of a model, many simulations are needed. This is the reason why the model has been built searching the maximum simulation speed: it is reached an average of 1 s for the simulation corresponding to 70 s. This peculiarity allows the model to be used for an automatic way to search the optimum. For instance, the first approach to increase the chances of approaching it is to reproduce automatically the changes made by a human operator to improve the competition strategy. It is a "brute force" approach that needs to precisely code the possible improvements that can be adopted on a given strategy. One of the easiest ways to implement is the "hill climbing" method. It is a method of looking for the minimum of problems with many dimensions, the least expensive and the most direct from the theoretical point of view. Further developments, however, can be found starting from the Reinforcement Learning RL algorithms, artificial intelligence algorithms that try to reproduce the learning methods of a human individual.

The methods applied up to now do not allow a fast-enough interaction with the AMESim model, therefore the "hand" solution is still the first available but in the long run it does not ensure to reach the optimal.

Before starting the optimization, a basic race strategy is computed attending the following rules:

- The car must finish the run at least 30 s before the total allowed time to have a safety coefficient during the first run and further to build a working window for strategy optimization.
- The pinion must allow the vehicle to reach a maximum speed in flat land greater than the required average speed, than the optimization will go to reduce the number teeth because in general less number of teeth with similar strategy lead to a slower but more efficient strategy.
- The number of acceleration must be among 1-5 in a lap depending on the length of it, then, optimization reduces the period of acceleration because lower accelerations imply lower time with all electronics boards sucking energy.
- Each acceleration must have a length of at least 100 m because shorter accelerations are difficult to experimentally replicate.
- The strategy tries to reach a smooth velocity profile avoiding throats and consequently peaks of speed which imply higher resisting power, especially aerodynamic drag which has a cubic trend. Furthermore, due to design choice the efficiency of the car reaches peak at a speed about 25km/h.

The basic strategy usually is not only the starting point of the optimization process but also the strategy used in the first run of the race because it has higher safety coefficient. The previous rules allow to reach a strategy easily implemented in the race track and with a sufficient margin of time to face the unexpected. In general, the optimization process goes to improve the strategy of 15%. For what concern the analysed case of London, the first valid run with the basic strategy had a result in track of 692 km/m^3 which has been improved in track of 16.73% thanks to the optimization process. This percentage clearly explains the importance and relevance of the optimization.

For London's track is particularly easy the search for the optimum due to the altimetry road profile which presents a big hill followed by a rapid downhill which allows the vehicle to accelerate only one time for lap. The engine thanks to its high torque constant allows to face the climb easily but the low constant of speed (113 rpm/V) joint the most advantageous pinion which has 24 teeth limits the maximum speed reachable in acceleration. It is equal to 23.85 km / h, lower than the minimum average speed of 25 km / h to have by regulation. Finally, the best strategy is to perform a single acceleration (verifying that there is the possibility of accelerating at least two other points on the circuit for precaution) from 12 A on the uphill, facing the second part almost at constant speed and almost at 20 km / h. The strategy, the speed profile and the current profile are reported in Figure 10.

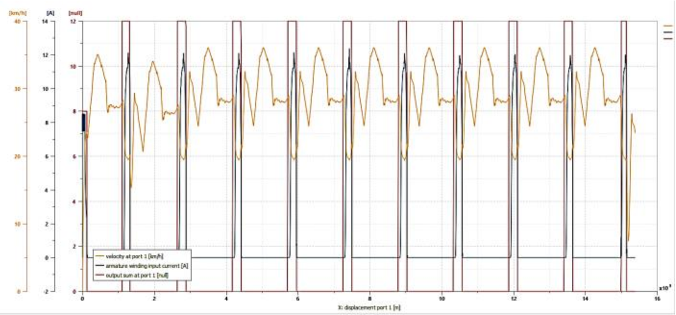


Figure 10. Strategy profile (red), current profile in ampere (blue) and speed profile km/h (yellow)

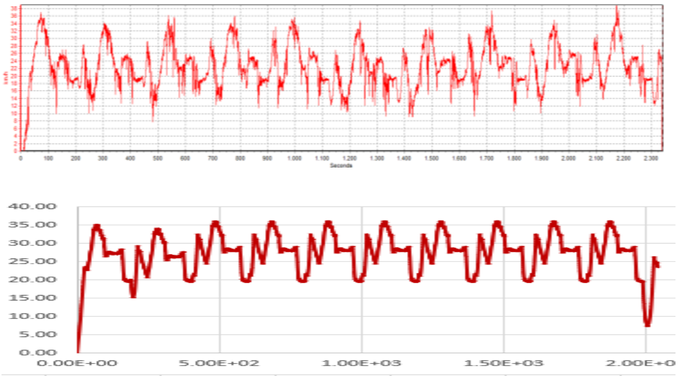


Figure 11. Speed profile:[km/h] vs. time [s]: above real results and below the simulated results

Analysing the difference of the simulated speed profile and the real one (Figure 11) it's possible to observe that the loss of speed uphill (where the efficiency of the mechanical affects more) is very similar to that of the model. So, the problem was not the inefficiency of the mechanics computed on track test but other losses, deriving from track conditions (such as bends and changes in asphalt) and from purely accidental factors. For example, the slope of the track doesn't consider the ramps that are superimposed on the London road surface only during the days of competition to mitigate the slowing down bumps. Furthermore, there are also factors to be considered purely accidental (contrary wind and overtaking) that obviously are present in the race. So, to take account of these losses, it is decided to consider them by inserting a table called the "simulated losses": it represents a force, which slow down the vehicle in correspondence with the speed losses on the Racelogic acquisition system due to overtaking, change of asphalt and wind.

Conclusions

The purpose of this paper was is to develop a model to predict the fuel consumption and prepare the energy management race strategy for the fuel cell vehicle IDRAkronos. For this purpose, a 1D model of the vehicle has been created and optimized to minimize the hydrogen consumption during the race. The model presents three concatenate strong points: simplicity, versatility and simulation speed.

Its simplicity requires few power computations allowing every student to run the simulation on their computer respecting the target of the team as an educational project. At the same time simplicity means also versatility, the model can be used for different purposes along the year: at the beginning can be used in the pre-design process to direct the development of the vehicle saving the time and money of track test, while at the end of the season it's able to compute the best strategy for the vehicle. The ability to make several simulations in few times, allowing the use of various design improvement techniques like design of experiments, response surface modelling, local and global optimization algorithms. Furthermore, its speed allows its use also during the competition, allowing the team to change race strategy in real time. Despite of the simplicity the accuracy is proved by the results obtained. The result of the optimization strategy has identified a vehicle setup, which is able to reach an estimated hydrogen consumption of 834 km/m^3, given the constraints and conditions relative to the Shell Eco-Marathon 2017. This outcome is substantially confirmed by the results obtained during the real race, where fuel consumption of 831 km/m^3 has been measured. This is an outstanding result considering that the vehicle has been tested just 1 month. The difference between the predicted result and the achieved result is below 0.4% and is due to environmental conditions (temperature, humidity, etc.) and not perfect condition of fuel cell. Thanks to the power optimization and the race strategy IDRAkronos classified 2nd in the hydrogen prototype category during the competition, the improvement of the simulation models represents an item for future work as the developments of reinforcement learning algorithms, artificial intelligence algorithms that try to reproduce the learning methods of a human individual.

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Acknowledgements

The authors would like to thank Hysylab - HYdrogen SYstem LABoratory; BSim and MSC Software (technical support and software licenses), and all the Team members.
The vehicle IDRAkronos are financially supported by the ‘‘Committee on Contributions and funds for students’ projects’’ of the Politecnico of Turin and other sponsors and partners (see also: www.polito.it/h2polito).