Power Source to Wheel Model of a High Efficiency Fuel Cell Based Vehicle

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Abstract—**This paper presents a fuel cell to wheel model that has been developed to design and optimize a high efficiency fuel cell based vehicle. This prototype car runs energetic races where the main objective is to go the furthest with the lowest energy. The main subsystems of the vehicle are the fuel-cell, the power converter, the motor and the mechanical train. Each subsystem has a best operating point which can not be obtained when all subsystems are linked together. The fuel-cell to wheel model is then used to reach the best efficiency and the results are compared with experimental measurements.**

Keywords-component; fuel cell; power train; DC/DC converter, energetic race, energy optimization

I. INTRODUCTION

Regarding new economic and ecological issues, specially related to the limitation of oil resources, engineers must consider alternatives such as electric vehicles powered by a fuel cell. This innovative solution is highly promising but remains difficult to develop. Compared to a classical urban diesel vehicle, the fuel cell structure has a higher efficiency (typically 30% against 22% [1][4][5]). In addition, as the output energy of the fuel cell to achieve propulsion is electric, a more flexible power train with a high efficiency can be obtained [2][6].

For several years, Polytechnic School of the Nantes University in association with the Joliverie School, work together on the Polyjoule project to develop a vehicle with a very low consumption which participate to the Shell Eco-Marathon Race (Fig. 1). The car is powered by a PEMFC (Proton Exchange Membrane Fuel cell). The purpose of this competition is to achieve the maximum distance with the energetic equivalent of a liter of gasoline SP95. This year (2010), the competition takes place on the EuroSpeedway Lausitzring (Germany). The vehicle must travel a distance of 25 km at a minimum average speed of 30 km/h. The project objectives are the design and implementation of the different elements of the vehicle, from the fuel cell and its subsidiary elements (assembly of elementary cells, air supply, cooling,…) to the power train and control (power converter, control laws and regulations) [3]. As the objective of the competition is to realize the best performance in term of fuel consumption, a special attention must be paid on the global energy consumption of each sub-system, i.e. the fuel cell, the power converter, the motor, the mechanical train and the accessories. Each sub-system has a best operating point which can not be always obtained when all sub-systems are linked together. It is then necessary to optimize the whole structure of the vehicle regarding external conditions such as the profile of the circuit, the acceleration time, the wind and the temperature.

This paper presents a fuel cell to wheel model developed to design and optimize the vehicle in order to obtain the highest efficiency in term of kilometers done with the equivalent of one liter of fuel.

Figure 1. Polyjoule car on the race track

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II. RACE AND PROTOTYPE CAR DESCRIPTION

A. Presentation of the race rules

The prototype car and its associated power train have been both designed and build to participate to the Shell Eco Marathon energetic race (Lausitzring, Germany). The principle of such a competition is very simple: drive a vehicle with one pilot the furthest with the lowest quantity of fuel at a minimum average speed of 30 km/h. A minimum weight of 50kg is imposed for the pilot. Each competitor will have to travel eight turns of the race track corresponding to 25 km in less than 50 minutes (corresponding to a minimum average speed of 30 km/h). To evaluate prototype car efficiency, the fuel quantity carried on board is measured before and after the attempt. Wide range of fuels can be used (Unleaded gasoline (petrol) 95; diesel fuel; LPG; GTL; fatty acid methyl ester; ethanol E100 and hydrogen). In our fuel cell category, an official flow meter is used to measure the volume of hydrogen consumed during the test. This amount of energy is converted into a petrol volume and then an extrapolation is made to estimate the amount of kilometers that would have been travelled with the energetic equivalent of one liter of petrol. It is important to notice that in the fuel cell category, battery is not allowed in the car except for safety purposes, i.e. to power the car-horn and the hydrogen detector.

B. Presentation of the different elements of the vehicle

The figure 2 shows the structure of the vehicle. The power energy is supplied by a 500W PEM fuel cell. To operate, the stack needs an air feeding system and a cooling regulation. The consumption of these elements is not negligible compared to the needed energy for propulsion. In this case, the model developed must include these accessories.

The electrical ironless DC drive is powered by a DC/DC converter (asynchronous buck). The global efficiency of the vehicle is directly linked to the efficiency of this converter. The evaluation of the losses in the buck must then be calculated with a precise model which takes into account the commutations, conduction and command losses.

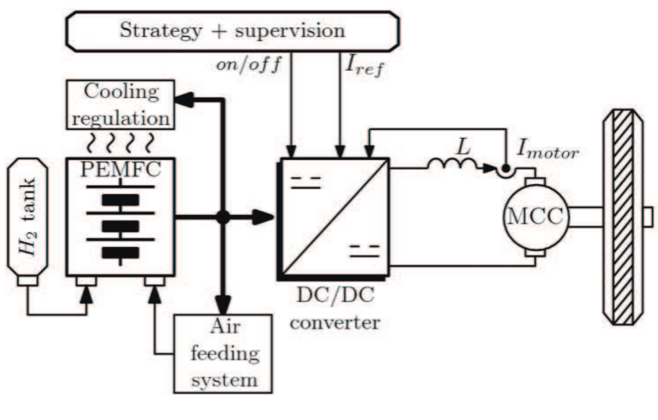


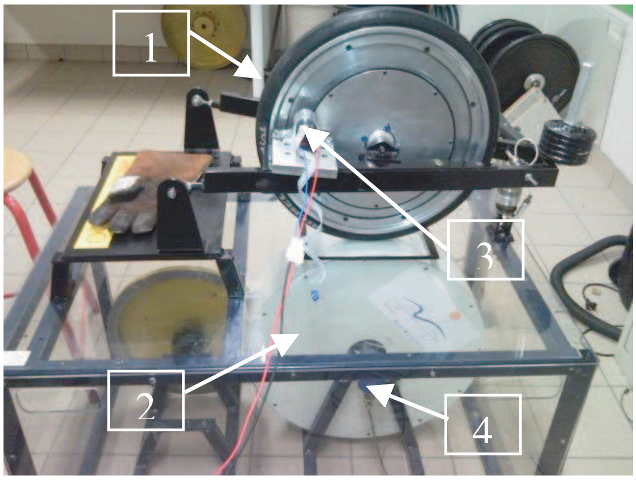
Figure 2. Structure of the vehicle

The supervision of the vehicle is done by a controller with a constant consumption during the entire race.

The motor to wheel adaptation is done by a mechanical power train. Using this system the motor can operate close to his optimal point and the car can run at the required speed.

C. Presentation of test bench

The figure 3 shows a picture of the test bench. The test bench consists of a driving wheel coupled with the electric motor via a gear. The driving wheel entrains an inertial wheel that has the car inertia. A resistive component has been added on the inertial wheel to represent the aerodynamic drag of the car. Additional rotational parts have been added on the inertial wheel to match the deceleration time of the wheel with the deceleration time of the car. Then, when the electric motor entrains the driving wheel on the test bench, it is equivalent to the entrainment of the car travelling on the race track.



1: Driving wheel　　3: electric motor

2: inertial wheel　　4: coder

Figure 3. Picture of the test bench to measure the efficiency of the ensemble (electric motor-gear-tires)

An optical coder is placed on the inertial wheel to acquire its rotational speed. Knowing its rotational momentum, the kinetic energy received by the inertial wheel can be deduced. The incoming current intensity and voltage of the electric motor is simultaneously acquired. The efficiency of the ensemble electric motor-gear-tires can then be deduced comparing the kinetic energy received by the inertial wheel during the acceleration and the electric energy consumed by the electric motor.

The electric motor has been chosen to supply the maximum power needed to launch the car on the race track (which is about 150 W). Once such an electric motor has been found, its nominal rotational speed is given by the manufacturer. As the target speed for our application is 30 km/h, the gear between the motor and the driving wheel has been chosen to match the nominal rotational speed of the motor to the target speed of the driving wheel.

III. MODEL DESCRIPTION

To optimize the vehicle, a global model is needed. This model must be a balance between the precision and computation time. Moreover, all the subsystem models must take into account the significant losses. Using this global model, one will be able to optimize each part of the vehicle and to determine the optimal strategy for the race.

The mechanical part of the model is based on the fundamental law of dynamics:

$$\sum \Gamma = J\frac{d\omega}{dt} \tag{1}$$

The previous equation is numerically solved by an integral representation, as shown on figure 4, where J is the inertia of the car, R is the radius of the wheel, R_{red} is the reduction ratio, k_a is the aerodynamic gain, k_i is the torque constant of the motor and η_n is the reducer and free wheel efficiency. The input of this mechanical model is the motor current (I_{motor}), controlled and imposed by the DC/DC power converter. The output is the angular speed ω. The current I_0 is the no-load current given by the constructor. The resistive torque (Γ_{res}) is obtained by the summation of the aerodynamic effects (F_{aero}) and the dry friction of the wheel (F_{wheel}).

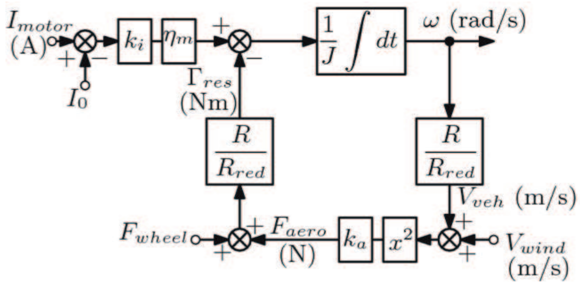


Figure 4. Mechanical part of the dynamical model

The aerodynamic resistance force is given by:

$$F_{aero} = k_a\left(V_{veh} + V_{wind}\right)^2 \text{ with } k_a = \frac{1}{2}\rho_{air}C_xS \tag{2}$$

With ρ_{air} the air density (1.2 kg.m^{-3}), C_x the drag coefficient of the car (0.11), S the frontal surface (0.31 m^2), V_{veh} the car velocity (m/s) and V_{wind} the wind velocity (m/s).

The wheel friction resistance force is given by:

$$F_{wheel} = mg\left(K_r\cos(\tan^{-1}(p)) + \sin(\tan^{-1}(p))\right) \tag{3}$$

With m the mass of the vehicle (40kg), g the acceleration due to gravity (9.81ms^{-2}), K_r the friction factor (1e-3) and p the slope of the track.

The DC motor is ironless, thus without iron loses and with a small internal inductance (20µH). The used electrical model is then only composed of a m.e.f. (E) proportional to the motor speed ($\omega = k_v$ E), a serial resistor (R_s) and the voltage drop in the brushes (V_{brush}). The motor voltage (V_{motor}) and the power consumption (P_{motor}) can be easily calculated by the next equations:

$$V_{motor} = E + R_sI_s + V_{brush} \text{ and } P_{motor} = \left(E + R_sI_s + V_{brush}\right)I_s \tag{4}$$

The k_v parameter is given by the motor manufacturer and Rs and V_{brush} are measured according to a locked-rotor test as described in figure 5.

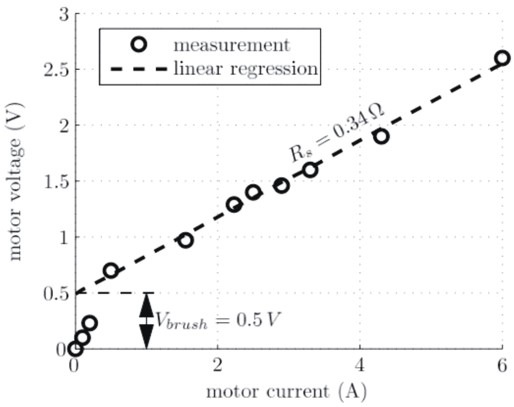


Figure 5. Mechanical part of the dynamical model

To control the car acceleration, a DC/DC converter is used to impose a constant motor current I_{motor}. The converter used is a classical asynchronous Buck. In this kind of structure, losses came from:

- The diode and the MOSFET conduction. The current waveform used to calculate losses in our model is described in figure 6. Where α is the duty cycle of the converter, ΔI is the current ripple and T is the switching period.
- The commutations of the MOSFET. Figure 7 shows the model used to evaluate the losses. Where t_r is the rising time of current and t_f is the falling time of current.
- The consumption of the command. This consumption includes a constant part (driver and oscillator) and a current depending part (current measurement devices).
- The smooth inductance and wires. In our model only the Joule's losses are taken into account. Due to the small frequency of our converter, hysteresis losses can be neglected at this step.

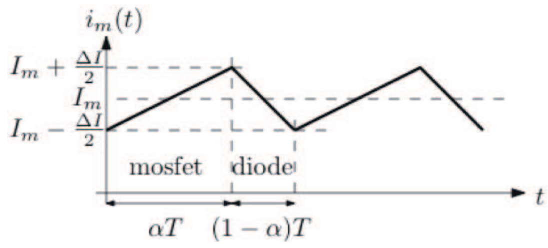


Figure 6. Conduction current in the asynchronous buck

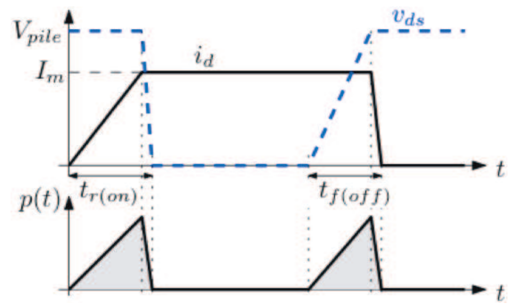


Figure 7. Commutations losses in the asynchronous buck

Concerning the PEMFC, due to the complexity of the electrical model of a fuel cell, a simple lookup-table based on experimental tests is proposed. The figure 8 shows the measurement done and used in our model for a stack with 24 cells.

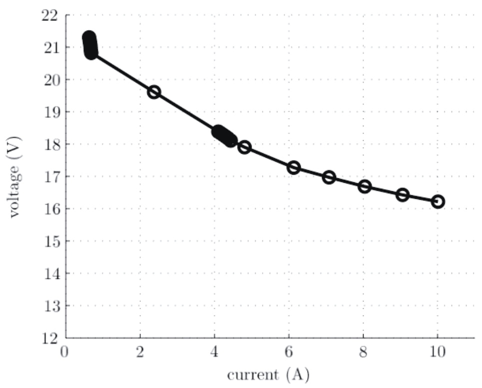


Figure 8. Polarization curve for a stack with 24 cells

This table permits to find the fuel cell voltage and current from the supplied power, and then to deduce the efficiency of the stack. Indeed, the hydrogen flow consumption (Dm) is directly given by the current and the stack efficiency (η_{fc}) by the output voltage:

$$D_m = n_{cells}\frac{I_{fc}}{1000f}\left(kg.s^{-1}\right) f = 9.65\times10^4\left(C.mol^{-1}\right) \quad (4)$$

$$\eta_{fc} = \frac{V_{fc}1000f}{n_{cells}PCI_H}, PCI_H = 119.9\times10^4\left(J.kg^{-1}\right) \quad (5)$$

At this point a hydrogen to wheel model is established and implemented in a Matlab Simulink workspace. In the next step some validations and exploitations will be presented.

IV. Experimental Results

The experimental and model results presented in this section are based on the vehicle which has ran in 2009 at the Shell eco-marathon.

A. *Validation of the power converter model*

An important part of the power train is the DC/DC converter used to supply the motor. The model of this converter is complex and a special attention must be paid on his validation.

In this validation, the efficiency of the power converter has been evaluated for different velocities of the car and for different motor current settings. The figure 9 shows the comparaison between measurment and model. A very good agreement can be observed.

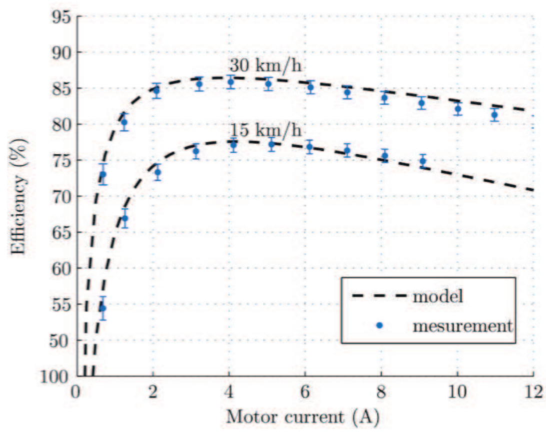


Figure 9. DC/DC converter efficiency for various car speeds.

These results show an optimal operating point around 4.4 Amperes. A current motor close to this value will be used for other experiments.

B. *Validation of the tank to wheel model*

In order to validate the whole model presented in section III, measurements for a complete race are performed using the test bench described in figure 3. To launch the car from 0 to 32.5 km/h, the DC motor is supplied by a constant current of 12 A (i.e. a constant torque). During the race, the strategy consists on periodic acceleration and free wheel phases with a constant current of 4.4 A. In order to maintain an average speed of 30 km/h, the acceleration speed range is from 28 km/h to 32.5 km/h.

Figure 10(a) shows the stack current measure during the whole race. The launch of the vehicle needs a current of 14A and a current of around 5A is needed for each acceleration.

Figure 10(b) shows the decomposition of the losses in the different elements of the power converter according to time.

This result is very useful for further optimizations. A special attention must be done on the inductance and wire design.

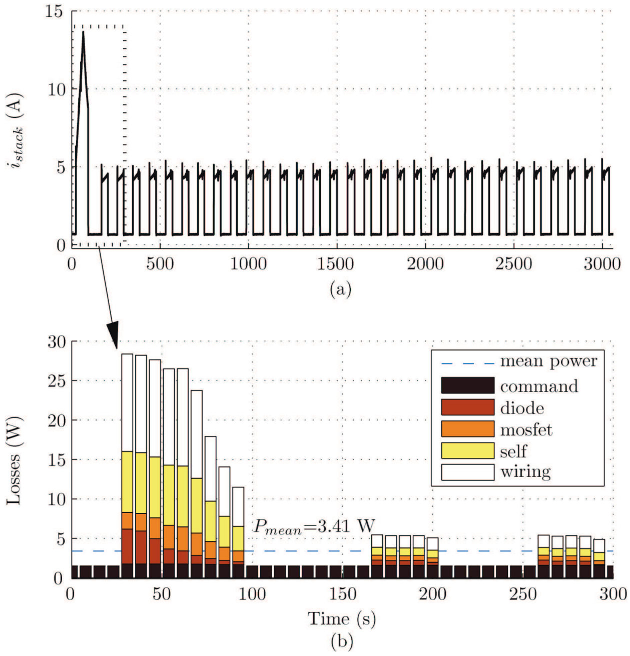


Figure 10. (a) Stack current during a complete race. (b) Losses in the asynchronous buck.

Figure 11 shows the comparison between the measured and simulated voltage and current of the fuel cell stack during an acceleration phase. The agreement between the model and the measurement is satisfactory.

Figure 12 presents the simulated and measured power supplied by the fuel cell during an acceleration phase. A good agreement is observed. However, the time-lag between simulated and measured results is only due to a different time origin.

Figure 13 shows the comparison between the measured and calculated voltage and current of the motor. The modelling does not include the free wheel during the deceleration phase. However, neglect the free wheel does not affect the energy consumption and improves the computation time.

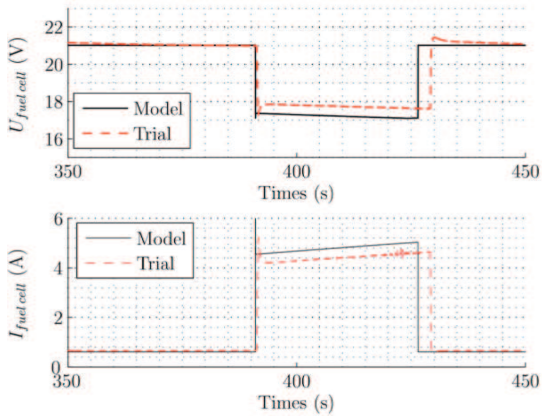


Figure 11. Voltage and current of the fuel cell comparison

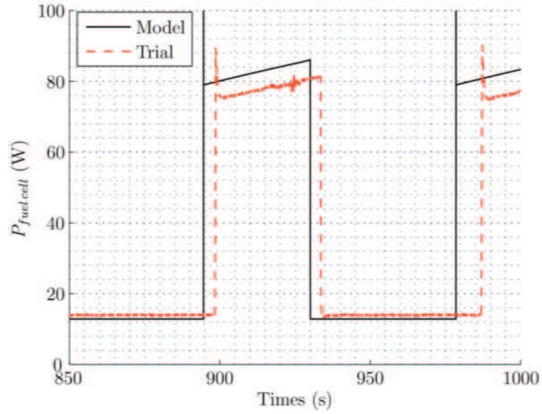


Figure 12. Simulated and measured power of the stack

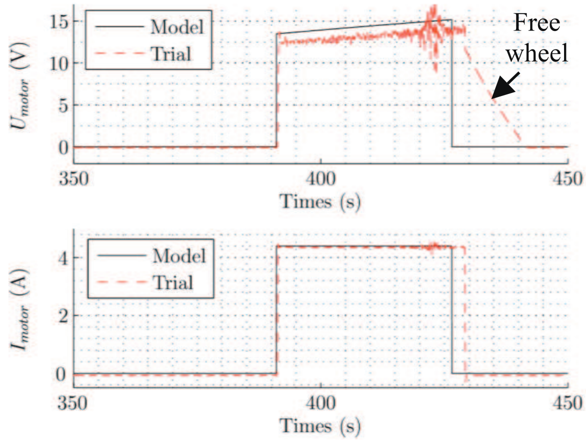


Figure 13. Voltage and current motor comparison

The measured and simulated energies of each subsystem are in a good agreement as shown in table I. The "propulsion" energy includes the car propulsion and losses in the DC/DC converter, the motor, the inductance and the mechanical power train. The energy called "command" is the energy supplied by the fuel cell stack to feed the cooling system, the air feeding system, the supervision and the command of the DC/DC converter. The "hydrogen" energy corresponds to the global energy from the stack to the wheel.

TABLE I: ENERGY CONSUMPTION FOR A COMPLETE RACE

	Energy consumption (J)		
	Model	***Trial***	***Error (%)***
Propulsion	81 576 J	80 002 J	1.9
Command	46 869 J	46 575 J	0.7
Hydrogen	219 970 J	217 533 J	1.3
Performance	3710 km/l	3752 km/l	1.2

The energy balance between the different parts of the car is more detailed in the flow energy diagram of Figure 14. This diagram allows to highlight the subsystem which must be improved.

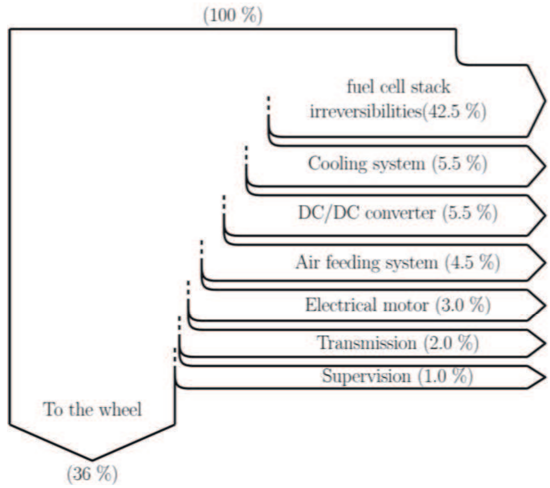


Figure 14. Power flow diagram

C. *Parameters influence of the power train*

The separate optimization of each element of the power train is not enough to obtain the most efficient system. For example figure 15 shows that the most efficient current value is a balance between the best current operating current of the power converter (around 4A) and the stack (close to 0A). Moreover, external constraints such as average speed or wind influence the optimization result and thus must be taken into account.

At this step, the developed model is a powerful and unique tool to analyze the parametric influence of settings on the global performance of the vehicle.

Table II shows some results on the influence of parameters on the global performance. In this table, the results are calculated for the increasing of one parameter from its nominal value.

TABLE II : PERFORMANCE IMPROVEMENT ACCORDING TO PARAMETERS VARIATIONS

Parameters	Nominal value	Performance Improvement
V_{max}-V_{min}	4 km/h	-0.14 %/(km/h)
V_{mean}	30 km/h	-1.88 %/(km/h)
m	90 kg	-0.33 %/kg
V_{wind}	0 km/h	-2.38 %/(km/h)
$P_{auxiliaries}$	15 W	-2.56 %/W
i_{launch}	12 A	-0.04 %/A
$i_{acceleration}$	4 A	-2.27 %/A
n_{cells}	24	+0.14 %/Cell

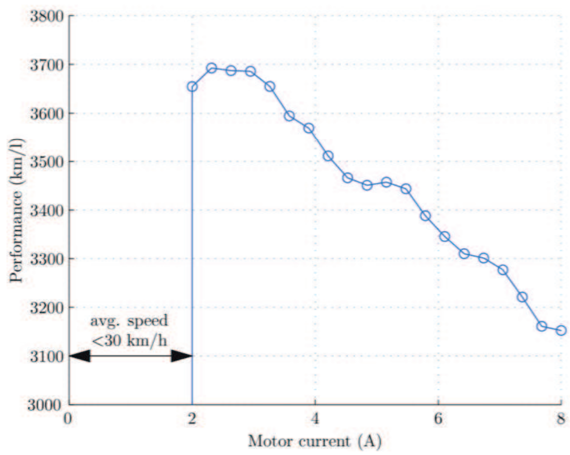


Figure 15. Distance performance versus motor current

Some parameters have a poor influence on the global performances (speed range variation, launch current), other are very influent (mass, average speed, motor current). Using these results, a more efficient optimization process can be done.

V. CONCLUSION

In this paper, a global model of a high efficiency vehicle was proposed. The model is fast and gives a satisfactory accuracy concerning the different losses evaluation. A good agreement between the measured and simulated results is observed. This model is then used to evaluate the repartition of the losses in the different subsystems and allows to focus on poor efficiency elements for an optimization. This optimization procedure permits to improve the performance from 3451 km/l in 2009 to 4896 km/l in 2010.

VI. AKNOWLEDGEMENT

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