Control strategy of fuel cell hybrid electric vehicle based on driving cycle recognition

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Abstract— **This paper describes a novel control strategy based on driving cycle recognition. A Driving Cycle Recognition Algorithm (DCRA) is firstly presented. It allows switching between three driving modes: urban, suburban and highway. A real-time control strategy is then defined based on fuzzy logic with DCRA. Results are drawn and compared to fuzzy logic controllers parametrized for urban or highway cycles.**

I. Introduction

Proton Exchange Membrane Fuel Cells (PEMFC) appear to be suitable for vehicular applications [1] due to their low operating temperature range (60-90 °C) [2] and their high power density. Fuel Cell Hybrid Electric Vehicle (FCHEV) based on PEMFC and Power Peaking Sources (PPS) (batteries, supercapacitor) lead to zero emissions and enable kinetic energy recovery during braking phases. The control strategy of the two sources of energy on this vehicule is directly linked to hydrogen consumption [3]. Two kinds of control are found in the litterature: On the one hand, offline control aims at optimizing the power split between the two sources for a known driving cycle which leads to optimal fuel economy. On the other hand, online control is based on a real time controller such as fuzzy logic [4], [5], neural networks [6] or predictive control [7], which allow the vehicle to do any driving cycle but without maximizing fuel/hydrogen economy. In addition, some authors based the control strategy on driving cycle recognition [8] by comparing the real cycle with known cycles [9] or training a learning algorithm with it [10]. Both of these methods are offline and cannot be applied in a real-time control strategy.

This paper describes a Driving Cycle Recognition Algorithm (DCRA) based on a statistical study of a time frame of a driving cycle and determines which mode is the most probable: urban, surburban and higway. A real-time controller is then designed to use as an input to DCRA results in order to improve fuel economy. Results are then drawn and compared to two other fuzzy logic controllers parametrized for urban or highway cycles only.

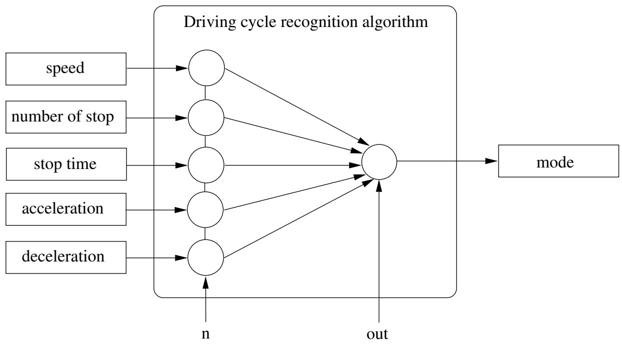


Fig. 1. DCRA principle

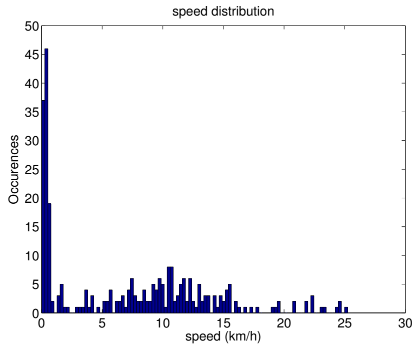
II. Driving cycle recognition algorithm

The driving cycle recognition algorithm used in this study is based on a statistical analysis of the driving cycle on a given time frame. Figure 1 describes the inputs/output of the DCRA: the *mode* output is composed of three states:

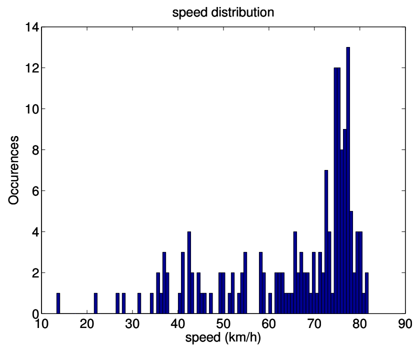
- *Urban*: The mean speed of the vehicle is low (around 30 km/h) but the dynamic is very high. There are a lot of start/stop, acceleration/deceleration phases. Nevertheless, due to long stop durations, the mean acceleration/deceleration is average;
- *Suburban*: The mean speed is medium/high (around 60 km/h) and the dynamic of the vehicle is average due to the low number of start/stop.
- *Highway*: The mean speed is high (up to 100 km/h) and the number of start/stop phases is zero. The dynamic is low because the vehicle is constantly running at high speed.

For each mode, a specific driving cycle is used to determine the limits of all inputs to determine the output.

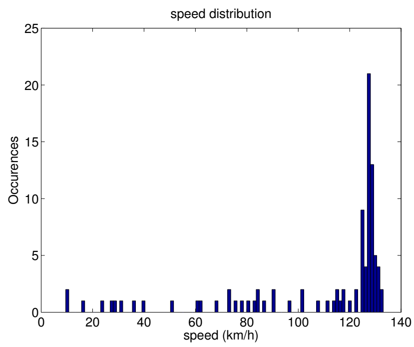
Figure 3 shows the speeds distribution of differents modes for the specific driving cycle. Each parameters (speed, acceleration, deceleration, stop time and number of stops) are statistically describe and each DCRA boundary is set to 70 % of the total occurences.



(a) Urban speeds distribution



(b) Suburban speeds distribution



(c) Highway speeds distribution

Fig. 2. Statistical distributions of speeds

The output is given by (1):

$$M = \sum_{k=0}^{4} n_k i_k \tag{1}$$

$$mode = 1 \quad \text{if} \quad 0 < M < out_1 \tag{2}$$

$$mode = 1 \quad \text{if} \quad out_1 < M < out_2 \tag{3}$$

$$mode = 3 \quad \text{if} \quad M > out_2 \tag{4}$$

where i_k is the input vector of the DCRA (average speed, number of stops, etc), n_k is the weight factor of the input vector, M is the sum of all input, out_1 , out_2 are the outputs triggers and $mode$ is 1 for urban, 2 for suburban and 3 for highway.

III. Results

Figure 3(a) shows the results of DCRA for a custom driving cycle. The driving cycle is composed of urban trips, highway roads and mixed parts. The DCRA switches between modes with a good reactivity, recognizing the type of the road. The algorithm has a window of time of 30 s, which is a good response time for this cycle. Reducing the time frame allows to increase the response time of the algorithm but decreases the precision.

IV. Real time control strategy

A. vehicle characteristics

1) Vehicle model: The vehicle considered for this study is a series hybrid electric vehicle based on a PEM fuel cell and batteries.

The PEMFC is connected to the DC bus via a DC/DC converter whereas the batteries are directly linked to the DC-bus [11]. Only one degree of freedom for the control strategy is possible: only the fuel cell current i_{FC} can be controlled. The vehicle power as a function of the speed is given by (5) [12]:

$$P_{mot}(t) = v\left(m_v(t)\frac{\mathrm{d}}{\mathrm{d}t}v(t) + F_a(t) + F_r(t) + F_g(t) + F_d(t)\right) \tag{5}$$

where F_a is the drag force, F_r the rolling friction, F_g the force caused by gravity when driving on non-horizontal roads and F_d the disturbance force that summarizes all other effects. The power split between the fuel cell P_{FC} and the batteries P_b is given by (6).

$$P_{mot}(t) = \eta_{FC}\, P_{FC}(t) + \eta_b\, P_b(t) \tag{6}$$

where η_{FC} is the fuel cell efficiency and η_b is the battery efficiency.

The simulated vehicle has the following characteristics:

- Weight: 570 kg;
- Front surface (A): 7 m^2;
- Drag coefficient (C_x): 0.8;
- Rolling coefficient (C_r): 0.015;
- Drivetrain efficiency: 0.72.
- Fuel cell power: 20 kW
- Battery capacity: 4 kW

2) Fuel cell model: The PEMFC is used as the primary source of energy and the objective of the strategy is to minimize the hydrogen consumption given by (7) [13], [14]:

$$m_{H2} = \int_0^t \frac{M_{H_2}\, n_c}{2\,F} I_{FC}(t)\,\mathrm{d}t \tag{7}$$

where m_{H_2} is the hydrogen mass, M_{H_2} is the hydrogen molar mass, n_c is the number of cells, I_{FC} the fuel cell current and F the faraday constant $(96,487\,\mathrm{C})$.

B. Fuzzy logic controller

The real time control strategy is based on a fuzzy logic controller [15]. The controller use on four states (membership functions) based on the battery's state of charge (SoC):

- *Low state of charge*: the state of charge of the batteries is low, the fuel cell needs to operate over its optimal operation point;
- *Optimal state of charge*: the fuel cell runs within its optimal power zone, the batteries absorbs the peaks of power;
- *High state of charge*: the batteries's state of charge is high, the fuel cell can work around its optimal running zone;
- *Very high state of charge*: the batteries state of charge is very high, the fuel cell is switched off and the vehicle runs using only the battery.

The DCRA is used to modify the optimal power zone (i.e, the fuel cell current working range) based on the value of mode:

$$mode = 1 \quad , \quad I_{FC_{\text{opt}}} \in [20\,, 30] \tag{8}$$

$$mode = 2 \quad , \quad I_{FC_{\text{opt}}} \in [40\,, 60] \tag{9}$$

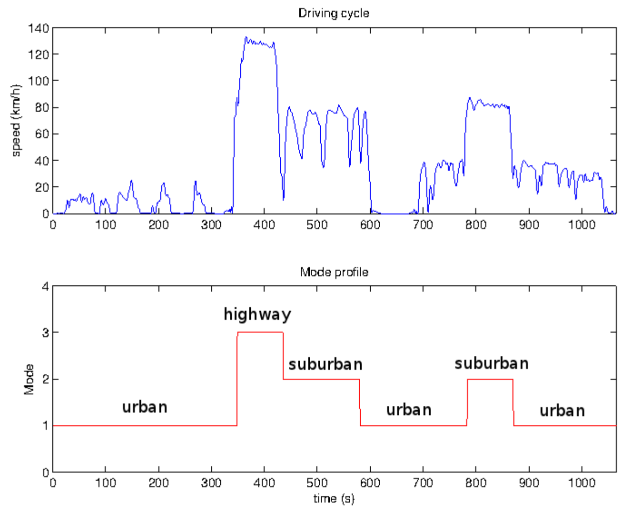
$$mode = 3 \quad , \quad I_{FC_{\text{opt}}} \in [80\,, 90] \tag{10}$$

V. Simulation of different scenarios with three parameters for the fuzzy logic controller

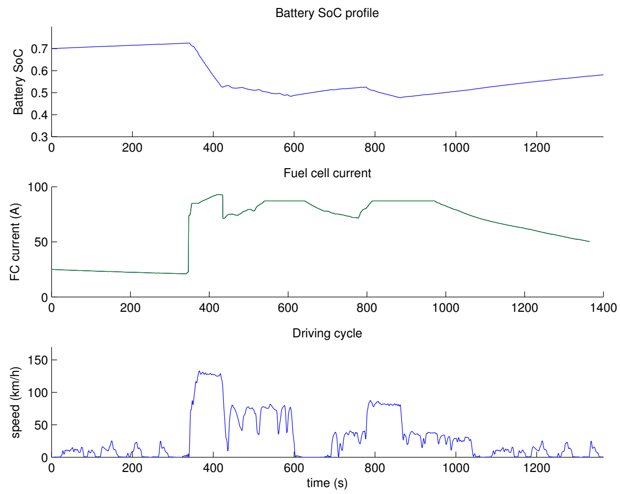
Figure 3(b) shows the fuzzy logic controller results for the same driving cycle used for the DCRA. The batteries's state of charge is kept in the optimal zone (around 70 %) during all the cycle due to the switch of mode. In order to compare results, two fuzzy logic controllers without DCRA are parametrized:

- Urban fuzzy logic controller: The fuel cell membership functions are parametrized for a specific urban driving cycle: LA92 [15].
- Highway fuzzy logic controller: The fuel cell membership functions are parametrized to run with a highway driving cycle.
- DCRA fuzzy logic: The results of DCRA mode are used to define the three types of fuzzy: urban, suburban and highway. The urban and highway parts have the same parameters as the previously defined fuzzy controllers.

A first simulation is carried out with LA92 driving cycle: Figure 4 shows the comparison for the fuzzy logic tuned for urban and highway. Since the driving cycle is urban, the DCRA fuzzy logic controller has the same results than fuzzy logic with urban parameters. The fuzzy controller with highway parameters aims to run the fuel cell at the optimal points for highway driving style: between 80 and 90 A, which is to high compare to the power needed by the vehicle. Consequently, the SoC increases and the fuel cell is switched off several times during the cycle in order to maintain the SoC in the optimal zone. Therefore, the urban fuzzy controller operates the fuel cell to the best running point for this driving cycle, allowing to keep the fuel cell current constant to save hydrogen consumption.



(a) DCRA results



(b) Fuzzy controller with DCRA results

Fig. 3. DCRA results

A second simulation is carried out to point out the interest of fuzzy logic with DCRA: Figure 5 shows the simulations of the mixed driving cycle presented in Figure 3(b) run ten times. Results are drawn for fuzzy logic with DCRA (with red color) and fuzzy logic with urban parameters (with blue color). The fuzzy logic controller with urban parameters aim to run the fuel cell in its optimal zone: between 20 and 30 A, but the power needed by the cycle is greater. The SoC decreases quickly and the controller response time is to low. After five cycles, the SoC goes under 20 %, and the simulation stops automatically (20 % SoC is the lower limit in order not to damage the batteries). Therefore, the fuzzy logic with DCRA anticipates the power needed during the highway phases and increases the fuel cell current, allowing to carry out the driving cycle ten time with a final state of charge of 40 %.
Table I shows the final SoC and hydrogen consumption of both simulations with different scenarios. On the one hand, the fuzzy controller with DCRA maintains the final SoC close

TABLE I

SIMULATIONS RESULTS

Driving cycle	Parameters of fuzzy controller	Final SoC	Hydrogen consumption (g)
LA92 cycle	Urban	0.72	73
	Highway	0.7	98
	DCRA	0.72	73
Custom cycle	Urban	0.56	168
	Highway	0.62	212
	DCRA	0.6	179
Custom cycle ran 5 times	Urban	0.28	1015
	Highway	0.6	1252
	DCRA	0.45	1143
Custom cycle ran 10 times	Urban	Not finished	Not finished
	Highway	0.6	2556
	DCRA	0.4	2365

to the initial during the custom driving cycle, allowing to carry out it ten times. On the other hand, the results of fuzzy with DCRA on urban cycle are the same as the optimised urban fuzzy logic, allowing to save hydrogen comsumption compared to the fuzzy tuned for highways.

VI. CONCLUSION

This paper describes a driving cycle recognition algorithm and its application to real time control strategy. The DCRA allows to predict the switch of driving style, for example urban to highway, and allows the fuzzy controller to be tuned for specific driving style in order to minimize hydrogen consumption during this driving cycle, while being able to carry out other types of cycles.

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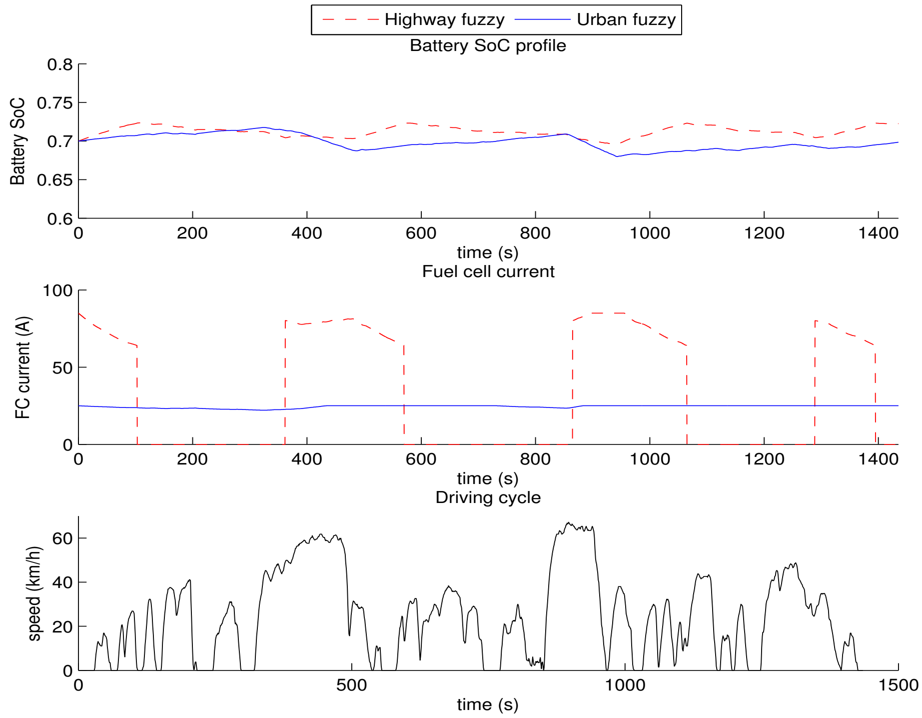

Fig. 4. Comparison of fuzzy logic controller with urban optimisation and highway

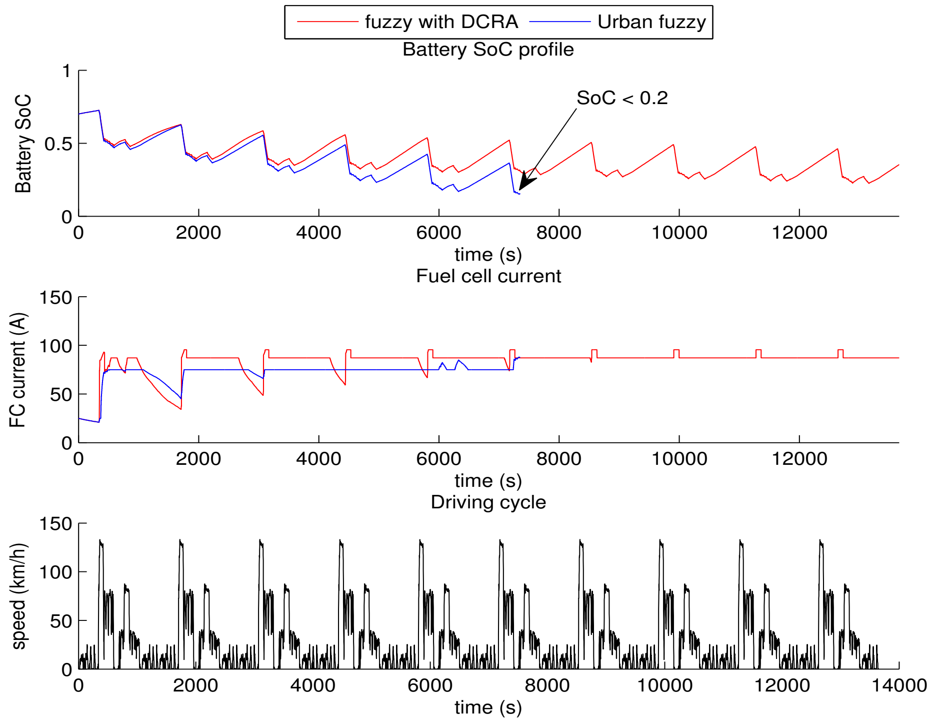

Fig. 5. Comparison of fuzzy logic controller with DCRA and urban for a custom mixed driving cycle