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# Modeling and Control of the Energy Consumption of a Prototype Urban Vehicle

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*Abstract*—**This paper presents a model of an urban vehicle that was specifically designed for low energy consumption. It is the first but crucial step towards the installation of an automated energy management system on the vehicle. The powertrain of the vehicle consists of a fuel ($H_2$) cell system, an ultra-capacitor bank, a DC/DC converter, a motor controller and an electric motor. The overall system is modeled and simulated in MATLAB. Further, an energy management strategy is described and tested. It consists of two fuzzy logic controllers, which are responsible for the distribution of power needs between the fuel cell and the capacitors, aiming in maximizing the performance and improving the fuel consumption. Several test cases are presented and compared to the on-off control approach.**

## I. Introduction

In the last years, the energy and pollution crisis has led researchers to develop alternative powertrains for transportation systems. One of the alternative sources of electric power that used in these systems is the Proton Exchange Membrane Fuel Cells (PEMFC). A Fuel Cell (FC) is an electrochemical device that converts chemical energy into electrical energy. FCs present a lot of advantages compared to internal combustion engines, such as, higher efficiency, zero $CO_2$ emissions, less weight and lack of moving parts. On the contrary, main disadvantages of the FCs are the low response and the high cost [1], [2]. Rechargeable Energy Storage Systems (RESS) like Ultra-Capacitors (UC) used to increase the low response and the efficiency of the FC. In this paper a FC and an ultra-capacitors bank are combined [3]. The parallel operation of FC and UC can improve the efficiency of the FC in part loads. Furthermore, the UC bank can supply extra power for acceleration.

The paper is organized as follows. Section 2 initially describes the prototype vehicle and its power system. Then a mathematical model is presented based on the kinetic state of the vehicle and in fuel consumption. In Section 3 we present a fuzzy logic strategy in order to control the distribution of power needs between the fuel cell and the capacitors. The main aim is the maximization of the performance and the improvement of the fuel consumption. In section 4, the fuzzy logic control approach compared to the on-off control approach. Experimental results are presented and remarked. At last, a conclusion is derived.

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## II. Model Description and Methodology

### A. The TUCer prototype vehicle

The TUCer vehicle is a prototype fuel cell hybrid urban vehicle. It is fully designed and constructed by the Machine Tools Laboratory and the Intelligent Systems and Robotics Laboratory (IS&RL) of the Technical University of Crete, Greece. It is a research and development platform suitable for studying aspects regarding low consumption, driving safety and unmanned navigation. The TUCer vehicle, version ER10, is shown in Figure 1. It is 2.5m long, 1.25m wide, 1m high and its gross mass is 110kg. Its technical and other characteristics are summarized in Table 1. Initially it was developed to participate in international fuel economy competitions, such as, the Eco Shell Marathon which is held every year in Europe and around the world. Detailed info regarding the prototype, the research team, the scope, sponsors, awards etc., may be found on team's web site: www.tucer.tuc.gr.

### B. The powerplant of TUCer

The power system consists of a commercially available $H_2$ FC system, a set of rechargeable ultra-capacitors (UC), a DC/DC converter, a motor controller and an electric motor. The FC that used is the Nexa Power Module 1.2 KW and the UC bank consists of six Maxwell BPAK0052 P015 B01 modules. The FC generates the power of the system and the UC can be utilized when the electric motor demands extra power to overcome situations with increased energy needs.

Figure 1: TUCer fuel cell prototype vehicle, version ER11

The parallel operation of FC and UC enhance the driving performance and the fuel economy. A DC/DC converter is responsible for the simultaneous operation of the two energy sources.

| | |
|---|---|
| Mass | 110 kg |
| Dimensions (length×width×height) | 2.5×1.25×1 (m) |
| Frame | Aluminum |
| Body parts | Carbon Fiber |
| Energy Source | Hydrogen Fuel cell |
| Motor | Electric |

Table 1: Technical characteristics of TUCer, version ER10

### C. *Vehicle modeling*

The vehicle model and its' power system is fully realized in Matlab and Simulink. The Simulink model is shown in Fig.3. Road information is inserted into the model from Matlab's workspace. This information represents the inclination of the road. The road inclination and the vehicle's current velocity and acceleration are used as inputs in model. Then the current power demand is calculated, from the total force which acts on the vehicle, in order to maintain the vehicle's existing kinetics state. The exact amount of power that is offered from FC and UC is determined by two fuzzy logic controllers. It must be mentioned that in each simulation hydrogen tank has capacity equal to 200 liters and the initial UCs state of charge was equal to 50% of their maximum.

The total force $F_{tot}$ which acts on the vehicle is given by

$$F_{tot} = F_a + F_r + F_g, \quad (1)$$

where $F_a$ is the aerodynamic resistance, $F_r$ is the rolling resistance, and $F_g$ is the gravitational force. Analytically, the aerodynamic resistance is given by

$$F_a = \frac{1}{2} \cdot \rho \cdot A \cdot c_d \cdot u^2, \quad (2)$$

where $\rho$ is the density area, $A$ is the frontal area, $c_d$ is the air resistance coefficient and $u$ is the velocity. The rolling resistance is given by

$$F_r = m \cdot g \cdot c_r \cdot cos\gamma, \quad (3)$$

where $m$ is the vehicle mass, $g$ is the gravitation constant, $c_r$ is the rolling resistance coefficient and $\gamma$ is the road grade.

The gravitational force is given by

$$F_g = m \cdot g \cdot sin\gamma, \quad (4)$$

where $m$ is again the vehicle mass, $g$ is the gravitation constant, $\gamma$ is the road grade.

The numerical values of the above parameters for the ER10 version of TUCer are: $\rho$=1.29 kg/m$^2$, $A$=1m$^2$, $c_d$=0.3, $c_r$=0.005, $m$=180kg =(110kg mass of car) + (70kg driver's mass).

## III. FUZZY ENERGY MANAGEMENT

A fuzzy logic energy management strategy is introduced in order to control the distribution of the power among FC and UC [4], [5], [6]. Two fuzzy controllers of the Mamdani type have been designed and implemented in Matlab environment. The main fuzzy logic controller has four input variables and two output variables. The input variables are the power required for the vehicle, the ultra-capacitor SOC, the hydrogen level and the velocity error. This controller is responsible for achieving the desired speed. It reads the input variables and controls the power demand required from the FC and UC, in order to maintain the desired speed.

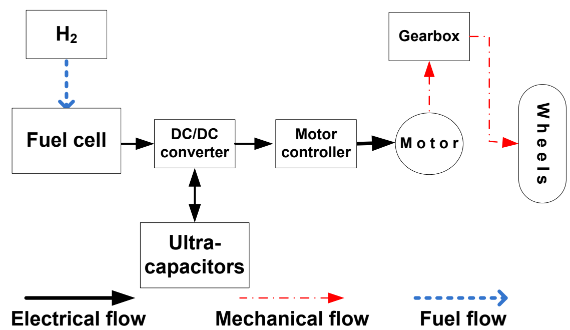


Figure 1: Main components and flows of vehicle's powertrain

The first input variable is calculated by the dynamic model of the vehicle. The dynamic model calculates the total force which acts on the vehicle and then converse it in power. The linguistic values that represent the power required for this input are: Too Small (*TS*), Small (*S*), Medium (*M*), Big (*B*), Too Big (*TB*). The linguistic values of the second and the third inputs variable are: Low (*L*), Normal (*N*), High (*H*). The fourth input variable represents the difference between the current velocity and the target velocity. The linguistic variations are: Negative (*N*), Zero (*ZERO*), Positive (*P*).

The output variables are the power required from the FC and the power required from the UC. The linguistic values for these variables are: Level_1 (*L1*), Level_2 (*L2*), Level_3 (*L3*), Level_4 (*L4*), Level_5 (*L5*).

The rules that used in this controller have the following type:

IF *energy demand-level* is $LV_i$ AND *SOC-level* is $LV_{i+1}$ AND *hydrogen-level* is $LV_{i+2}$ AND *velocity error-condition* is $LV_{i+3}$ THEN *power required from FC-level* is $LV_o$ AND *power required from UC-level* is $LV_{o+1}$,

where $LV_i$'s and $LV_o$'s represent the input and output linguistic variations respectively.

The second fuzzy logic controller has three input variables and one output variable. The input variables are the ultra-capacitor SOC, the hydrogen level and the output current of FC. The linguistic values for these variables are:

Low (*L*), Normal (*N*), High (*H*). The output variable is the fuel cell current which charge the UCs. The linguistic values again are: Low (*L*), Normal (*N*), High (*H*). The rules that used in this controller have the following type:

IF *SOC level* is $LV_i$ AND *hydrogen-level* is $LV_{i+1}$ AND *output current from FC-condition* is $LV_{i+2}$ THEN *the fuel cell current which charge UC –level* is $LV_o$.

## IV. SIMULATION RESULTS

The aim of this simulation process is the evaluation of two different energy management strategies. The target of these strategies is to maintain the average speed constant. The desirable value of the speed is 25km/h. This regulation is directed as the minimum average speed in the Shell Eco marathon competition. The main criterion of the comparisons we perform is the fuel consumption. We cross examine a fuzzy logic strategy and an on-off control policy. The fuzzy approach is based on the knowledge acquired during experimentation with the actual vehicle. The on-off/bang bang policy, although it is not gradual, offers implementation simplicity and fast response. Given the minimum speed requirement it may offer a consumption management solution that has to be examined.

In the fuzzy strategy two controllers were implemented. The first one decides the distribution of the power needed between the FC and the UCs. As the FC has a dual responsibility (giving power to motor and recharging the UCs), the second fuzzy controller determines the value of current provided by the FC to charge the UCs. In the on-off strategy two bang-bang controllers are used instead of the two fuzzy logic controllers. Their aim is the same as fuzzy logic controllers.

Two test cases were used in order to examine and compare the implemented control strategies. In the first case, a zero inclination track is used. In the second test case, a real test track with various degrees of inclination is reflected. It resembles the Eurospeed racing field at Lausitz, Germany. Figures 4 and 5 show the performance of the fuzzy logic and bang-bang approach, respectively, when tested in a zero inclination track. As may be seen, the hydrogen consumption of the vehicle is better when the fuzzy logic implementation is used. Another point that is worth to mention is that in fuzzy logic strategy the FC and UC power demand has small value range.

Similarly, figures 6 and 7 present the performance of the two control approaches when tested in real track. In both cases the speed is achieved. It can be observed that in the case of fuzzy logic control the range of the power demand from FC and UCs are smaller and as a result of this the hydrogen consumption of the vehicle is smaller when fuzzy logic is used.

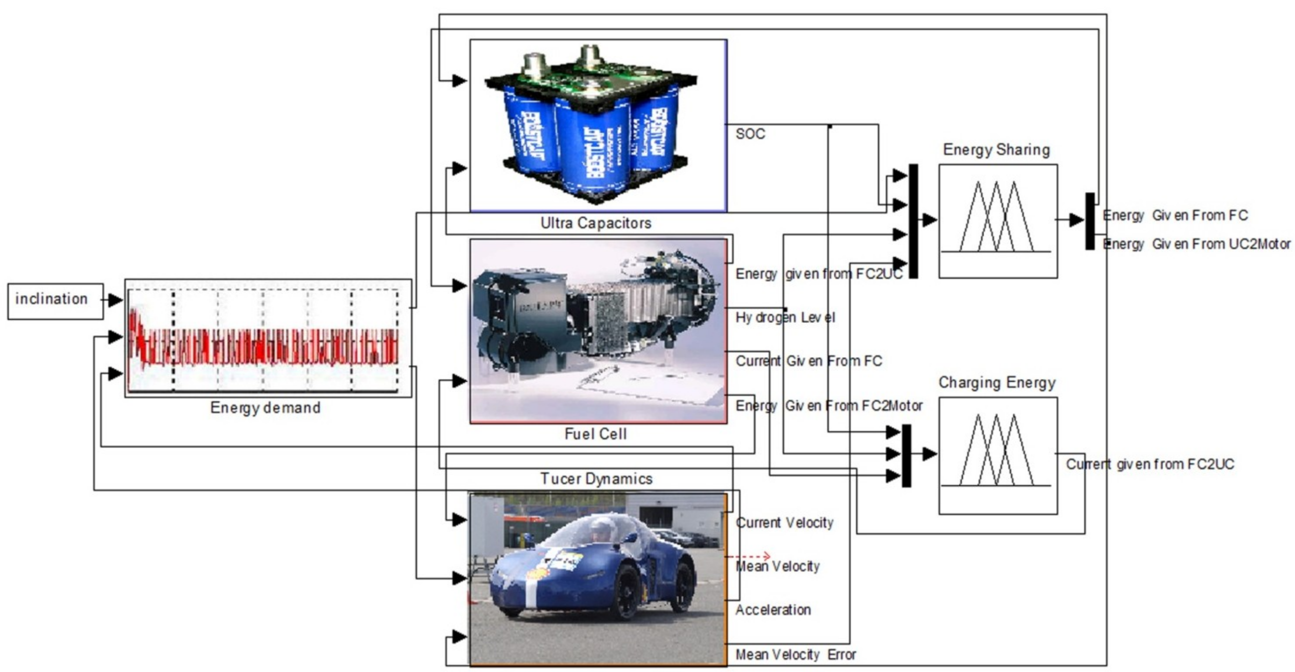


Figure 2: Simulink model of the suggested fuel management system

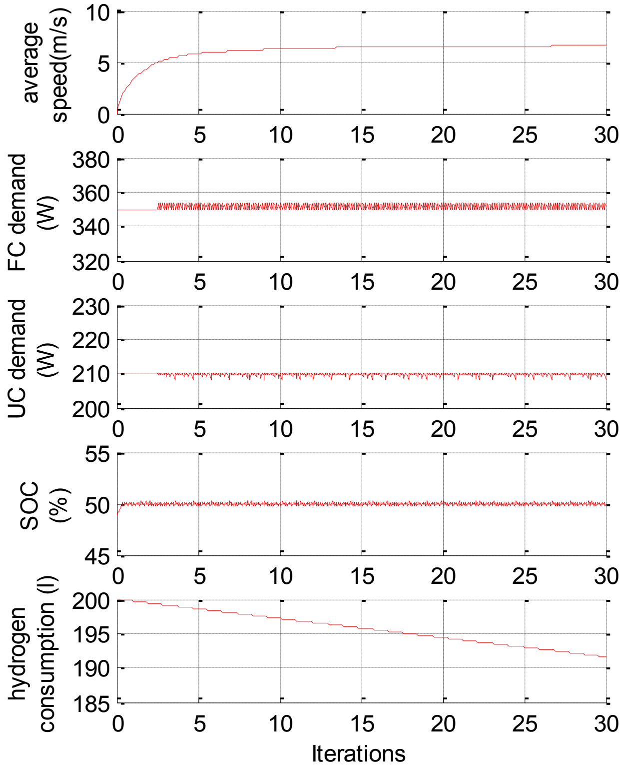


Figure 3: Fuzzy logic control in zero inclination track

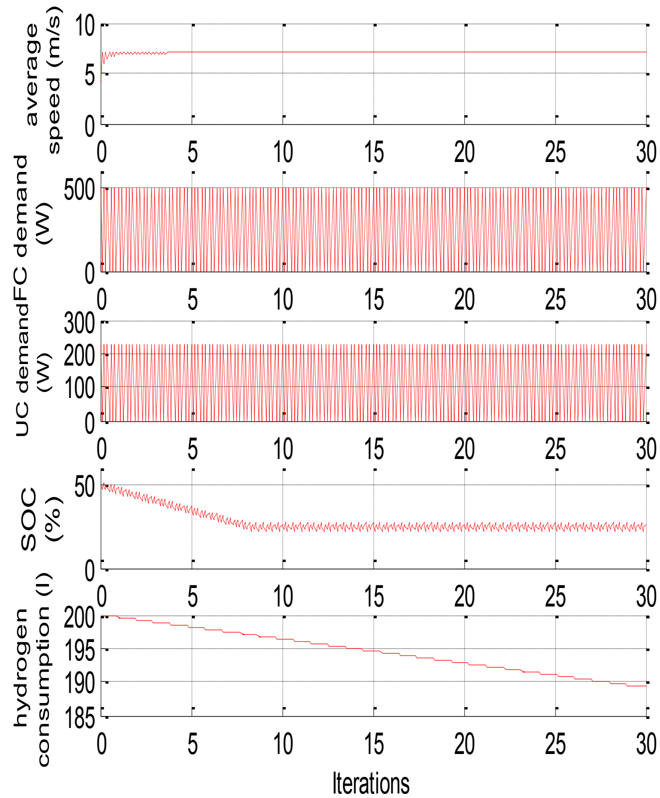


Figure 5: On-off control in zero inclination track

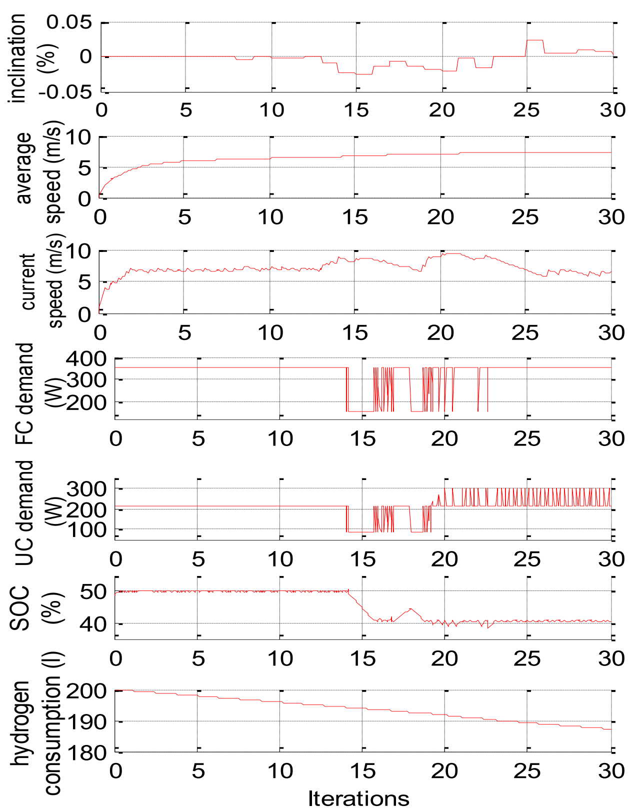


Figure 6: Fuzzy logic control in real track

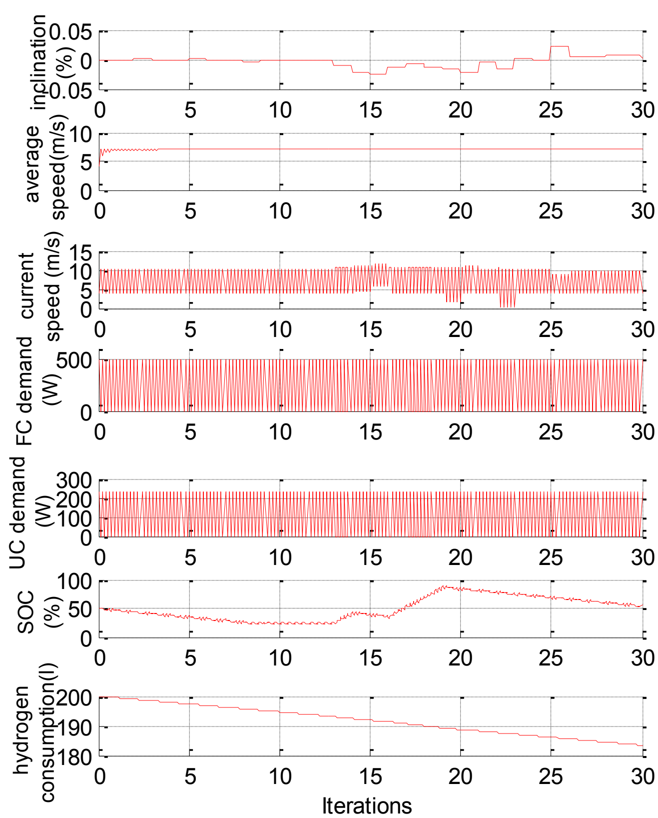


Figure 7: On-off control in real track

## V. Discussion

Fuzzy control is known for the gradual transition between states of operation, which in this case resulted in a smoother consumption curve compared to the bang-bang (on/off) controller. In all test cases (in zero and realistic inclination), the control objective was succeeded by both controllers. The bang-bang controller achieves the desired speed faster, which forced both FC and UCs to work more intensively between their limit values. This is the main reason for the slightly increased consumption of the bang–bang controllers in all test cases compared to the fuzzy ones for the same track. During the test case with zero ground inclination, the fuel level dropped to 189 liters with the bang-bang approach, while fuzzy kept 192 liters in the tank (about 6% better). Similarly, when the ground slopes (inclination pattern) were close to reality, the fuzzy controller needed about 8% less hydrogen to accomplish the mission by also keeping the average car speed within the desired levels.

## VI. Conclusion

In this paper, a FC/UC urban vehicle was simulated using Matlab. The simulation model is an important contribution towards the optimal setting of the vehicle, when it participates in fuel consumption competitions. Furthermore, an energy management strategy using two fuzzy controllers is presented and compared with an alternative strategy in which two bang-bang controllers are used. Two study cases examined in order to evaluate the performance and compared the two strategies. In first case a zero inclination track is used against a real multi value inclination track that used in the second test case.

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