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Energy Management in Parallel Hybrid Electric Vehicles Combining Fuzzy Logic and Equivalent Consumption Minimization Algorithms

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Abstract

This paper presents a hybrid algorithm combining fuzzy logic with equivalent consumption minimization strategy (ECMS) for energy management in parallel hybrid electric vehicles. The fuzzy control algorithm selects the mode of operation from 5 possible modes, i.e. electric motor (EM) only mode, internal combustion engine (ICE) only mode, EM + ICE mode, charging mode or regenerative mode. The solution provided by the fuzzy control algorithm is not optimal. Therefore, to obtain an optimal solution, the ECMS optimization method is applied when mode 3 (EM + ICE) and mode 4 (charging) are selected. The US06 or supplemental FTP driving schedule and the EPA highway fuel economy driving cycle have been used for highlighting the advantages of the proposed hybrid fuzzy + ECMS algorithm over the fuzzy-only and if-then-else rule-based control algorithms. Results attained reflect that the proposed hybrid fuzzy + ECMS improves fuel economy by around 27.6% in the case of US06 or supplemental FTP while it improves fuel economy by 16.3% in case of EPA highway fuel economy driving cycle. It is also shown that there is a minor increase in computational time and complexity in using this hybrid algorithm as compared to the other algorithms. The proposed hybrid fuzzy + ECMS algorithm does not require prior knowledge of the driving cycle, so it can be used for both online (when the driving conditions are unknown) and offline (when the entire driving cycle is known and predefined) strategies.

Keywords

Parallel hybrid electric vehicles, fuzzy logic, equivalent consumption minimization strategy, optimization, fuel economy.

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Introduction

With every passing year HEVs are gaining popularity. At present, HEVs seem to be the best replacement for pure gasoline vehicles. The main advantage of HEVs is their better fuel economy (Solano et al., 2011). Therefore HEVs provide one of the possible solutions to problems faced by the transportation sector, like risen oil prices or global warming among others (Li et al.,2012).

HEVs are characterized by including two power sources, i.e. an internal combustion engine (ICE) and an electric motor (EM) connected to a battery pack. Among the major advantages of HEVs, regenerative braking mode highlights, since it allows converting the kinetic energy into electric energy, which is stored in the battery pack for later use, thus increasing fuel economy and battery life (Chen et al.,2011).

HEVs are broadly classified into two major categories, i.e. parallel and series HEVs. This paper deals with energy management strategy in parallel HEVs since they are the most commonly used and manufactured at present. Parallel HEVs allow downsizing the engine while providing more freedom to satisfy the power demand because series HEVs are driven only by electric traction. In a parallel hybrid vehicle, both the ICE and the EM may work simultaneously, since they are coupled to a common axis. The EM may either provide extra power to the powertrain or recover the kinetic energy during braking. The EM is also used in operating regions where the ICE has low efficiency, thus increasing the fuel economy or applied as a generator when the SOC is below a threshold value.

This paper deals with the energy management strategy in parallel HEVs, which is based on sharing the load power demand between the vehicle's energy sources, while ensuring optimizing system efficiency. Control strategies used for energy management in hybrid vehicles may be broadly classified into three categories (Chen et al.,2011; Boukehili et al., 2012). The first category is classified as rule-based methods, the fuzzy logic method belonging to this category (Solano et al., 2011; Li et al., 2012; Solano et al., 2013), which shows appealing features as low sensitivity to component changes and measurement inaccuracies (Motapon et al., 2014). The second category uses the equivalent fuel consumption as a cost function. The equivalent fuel consumption comprises the fuel consumption of the ICE as well as that of the other energy sources (Motapon et al., 2014). Equivalent consumption minimization strategy (ECMS) is the main technique in this category. It is worth noting that the two first groups do not rely on the priori knowledge of the future driving cycle (Li et al., 2009) but they provide suboptimal solutions (Kermani et al., 2012). The third group of methods is based on dynamic programming optimization (Kum et al., 2012; Shams-Zahraei et al., 2012). However, although this technique provides optimal solutions, it is rather computationally demanding and requires prior knowledge of the driving cycle, which is frequently unknown. The idea of using fuzzy and ECMS based methods has been explored recently in (Chen et al.,2011).

In this paper a novel hybrid method which combines both fuzzy and ECMS control algorithms for energy management in parallel HEVs is proposed and its behavior is checked by analyzing two driving cycles. However, in this paper a different approach from that found in (Chen et al.,2011) is applied to combine fuzzy logic and ECMS algorithms to form a hybrid algorithm. First, the fuzzy algorithm is used to select among the five possible modes (1: EM only, 2: ICE only, 3: EM + ICE, 4: battery charging and 5: regenerative mode) the most appropriated operating mode at each time instant. Then for further optimizing the fuel consumption, the ECMS algorithm is applied only in modes 3 and 4.

Vehicle Modelling

To move a HEV, different forces must be overcome, including the rolling resistance (F_{rr}), the aerodynamic drag (F_{ad}), the grading resistance (F_{gr}) and the acceleration term. Therefore, the total force which an HEV has to overcome is shown in equation (1),

$$F_{wheel} = ma_{cc} + F_{rr} + F_{ad} + F_{gr} = ma_{cc} + \mu mg\cos\alpha + mg\sin\alpha + 0.5\rho_a C_D A_{frontal} v^2 \tag{1}$$

Where, m and a being, respectively, the mass and acceleration of the vehicle, μ the coefficient of friction, g the acceleration due to gravity and α the road grade. In addition, ρ_a is the air density, C_D the drag coefficient, $A_{frontal}$ is the frontal area of the vehicle and v the vehicle speed. Therefore Ma is the acceleration force term, $\mu Mg\ cos\alpha$ is the friction force, $Mg\ sin\alpha$ is the gravity force and $0.5\rho_a C_D A_{frontal} v^2$ is the air drag term.

The tractive torque at the wheels may be expressed as,

$$T_{wheel} = F_{wheel} \cdot r_{wheel} = [ma + \mu mg\cos\alpha + mg\sin\alpha + 0.5\rho_a C_D A_{frontal} v^2] \cdot r_{wheel} \tag{2}$$

Where, r_{wheel} is the radius of the tyre

The torque and power requested by the vehicle to overcome the different loads are calculated as,

$$T_{requested} = (T_{wheel} / \eta_{trans}) \cdot g_r \tag{3}$$

$$P_{requested} = T_{requested} \cdot (v / r_{wheel}) \cdot g_r \tag{4}$$

η_{trans} being the efficiency of the power train and g_r the gear ratio and v the speed of the HEV.

The values of the parameters used to model the HEV dealt with in this paper are shown in Table I.

Parameter	Value
$A_{frontal}$	2.16 m^2
r_{wheel}	0.29 m
m	1500 kg
η_{trans}	0.9
g_r (1^{st}, 2^{nd}, 3^{rd}, 4^{th}, 5^{th})	15.5, 10.1, 6.8, 5.0, 3.8
C_D	0.26
ρ_a	1.2 kg/m^3
α	0º
μ	0.01

Table I: Vehicle Modelling Parameters (Ngo et al., 2013)

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The vehicle has been modelled by using the Matlab®-Simulink platform.

Vehicle Structure

This paper deals with a two-shaft parallel hybrid drive train with speed coupling which allows adding both the speeds of the ICE and EM. This structure also enables both the ICE and EM propelling the vehicle alone. Figure 1 shows the parallel HEV drive train dealt with in this paper, in which the multi-gear transmission is placed between the speed coupling device and the drive shaft. It is worth noting that this multi-gear transmission system allows the engine operating close to its optimum region, so the overall drive train efficiency may be enhanced when compared to other designs.

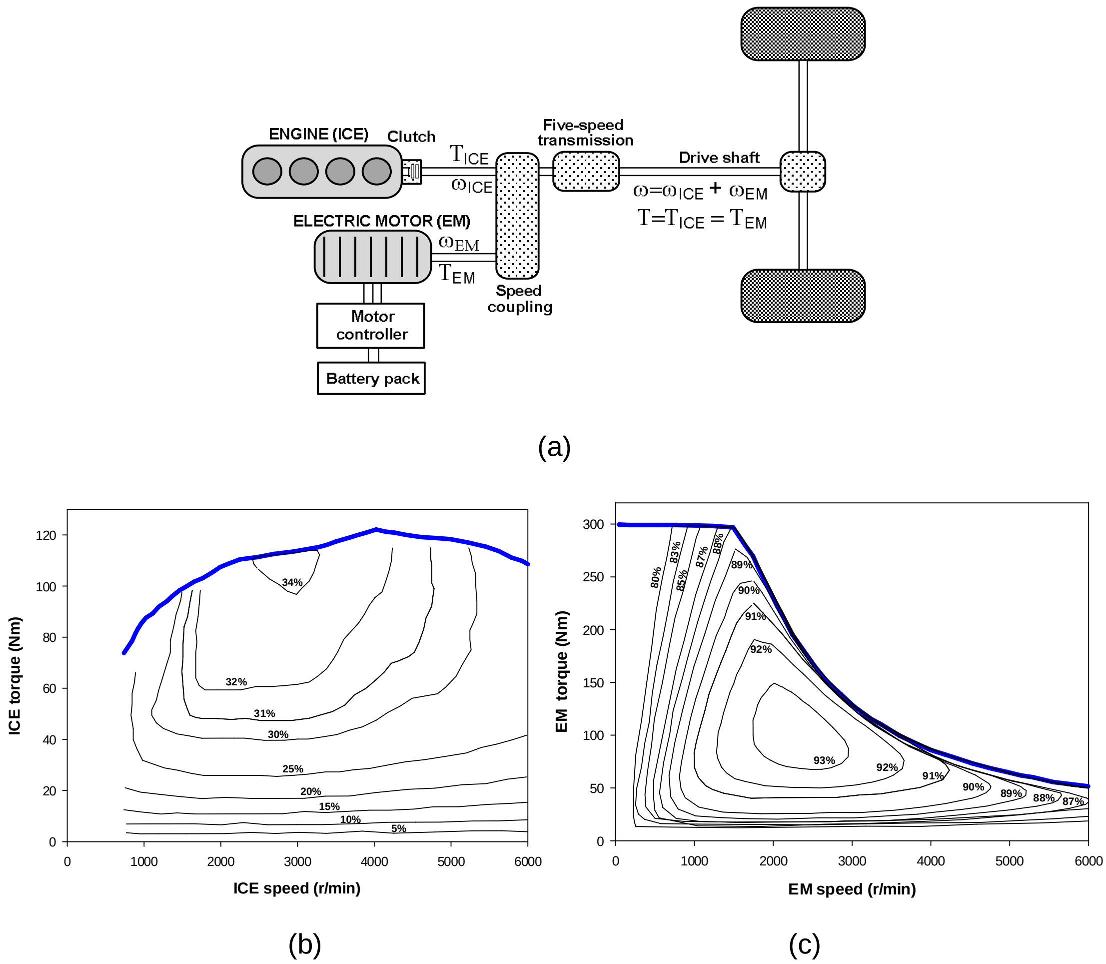

Figure 1: (a) Parallel hybrid vehicle analyzed with speed coupling. (b) Torque-speed and efficiency map of the 65 kW ICE. (c) Torque-speed and efficiency map of the 50 kW EM (permanent magnet synchronous motor).

As far as the battery is concerned, the battery model dealt with in this work is shown in Figure 2.

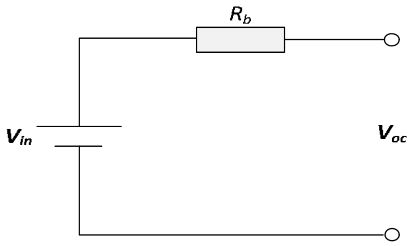

Figure 2: Battery model

The battery energy at any time instant *t* is calculated from the instantaneous battery power as,

$$E_{batt}(t) = E_{batt}(t_0) \pm \int P_{batt}(t)dt \tag{5}$$

Where, signs (+) and (-) are applied, respectively, during charging and discharging periods. The power of the battery may be calculated as in (Lin *et al.*, 2003),

$$P_{batt} = \frac{V_{oc}^2 - V_{oc}\sqrt{V_{oc}^2 - 4P_{inv,DC}R_b}}{2R_b} \tag{6}$$

where V_{oc} is the open circuit voltage, R_b is the equivalent battery resistance and $P_{inv,DC}$ is the power at the electronic inverter side.

The state of charge (SOC) of the battery, which plays a key role in the performance of HEVs, is calculated as the ratio between the current battery capacity and the nominal full capacity,

$$SOC = E_{batt}(t) / E_{batt,\ nom} \tag{7}$$

In any optimization problem some constrains have to be defined. Therefore, to ensure an adequate behavior, the following restrictions are imposed (Tulpule *et al.*, 2009),

$$P_{ICE}(t) \in [0, P_{ICE,\max}] \tag{8}$$

$$P_{EM}(t) \in [P_{EM,\min}, P_{EM,\max}] \tag{9}$$

$$P_{batt}(t) \in [P_{batt,\min}, P_{batt,\max}] \tag{10}$$

$$P_{requested} = P_{EM} + P_{ICE} \tag{11}$$

$$SOC(t) \in [SOC_{\min}, SOC_{\max}] \tag{12}$$

Where, subscripts EM and ICE stand for, respectively, electric motor and internal combustion engine.

If the acceleration or power requested $P_{requested}$ are negative, then the regenerative braking mode (mode 5) is selected and the energy produced during this mode is delivered to the battery pack, which is expressed as,

$$E_{regen} = \frac{1}{2} \cdot \eta_{bat} \cdot \eta_{gen} \cdot M \cdot (v_1^2 - v_2^2) \tag{13}$$

v_1 and v_2 being respectively, the initial and final speeds of the applied braking interval.

Values of different vehicle structural parameters required to assess the vehicle behaviour are shown in Table II.

Parameter	Value
[SOC_{min}, SOC_{max}]	[0.2, 0.8] p.u.
Battery type	Lithium-ion
Cell nominal voltage	3.30V
Cell nominal capacity	2.22 Ah
Energy capacity, $E_{batt, nom}$	4 kWh, 546 cells 91 in series x 6 sets in parallel
E_{batt} (t_0)	3.0 kWh
η_{bat}	0.9 p.u.
V_{oc}	300 V
R_b	0.37 Ω
P_{ICE}	[0, 65] kW
P_{EM}	[-50, 50] kW
η_{gen}	0.9 p.u.

Table II: Vehicle Structure Parameters (Ngo et al., 2013)

The Analysed Algorithms

This paper proposes a hybrid algorithm which combines a fuzzy control algorithm with ECMS (Equivalent Consumption Minimization Strategy) for energy management in parallel HEVs. However, for comparison purposes two more algorithms are analyzed, i.e. the fuzzy-only and the if-then-else rule-based algorithms.

The hybrid fuzzy + ECMS algorithm

This paper proposes a hybrid algorithm which combines a fuzzy control algorithm with ECMS (Equivalent Consumption Minimization Strategy) for energy management in parallel HEVs.

The fuzzy algorithm proposed in this paper deals with three input variables, namely actual vehicle speed, state of charge and acceleration. The output is the operating mode, which has five possibilities as detailed in the following paragraphs. The selection of the actual operation mode (output) is done by the fuzzy algorithm, which takes into account the actual values of the input variables, the fuzzy rules defined for this specific application and the defuzzification strategy adopted. The SOC is limited within the range 0.20 to 0.80 to avoid premature aging of the battery pack and improve battery performance, whereas the initial SOC is supposed 0.75.

Parallel HEVs may work in 5 operating modes,

- **Mode 1**. EM only mode. It is well known that ICEs are less efficient when operating at low speed. This mode (or EM only mode) is selected when the speed is less than or equal to 30 km/h, the SOC is between 0.55 and 0.80 and the acceleration is positive or zero. In this mode the battery drives the vehicle, no fuel consumption is considered, and consequently the SOC tends to decrease.

- **Mode 2**. ICE only mode. When the vehicle speed is between 30 km/h and 60 km/h, the ICE has high efficiency, so the ICE only mode is selected. In this mode the SOC is between 0.55 and 0.80 and the acceleration is positive or zero. To calculate the fuel consumed by the ICE, the actual power requested by the vehicle is divided by the engine efficiency, which depends on the operating condition according to the engine efficiency map. The SOC variation is calculated according to equations (5) to (7).

- **Mode 3**. Hybrid ICE+EM mode. The power requested in this mode is shared between the ICE and EM. At high speed operation the combination of ICE and EM provides better efficiency. In this mode the vehicle speed must be greater than 60 km/h, the SOC between 0.55 and 0.80 and the acceleration positive or zero. In this mode the total power request is shared between the ICE and EM. The SOC in this mode is calculated by applying equations (5) to (7). To further optimize the fuel consumption, the ECMS algorithm is applied in this mode.

- **Mode 4**. Charging mode. This mode is selected when the SOC is below 0.55 and the acceleration is positive or zero. In this mode only the ICE drives the vehicle, so the power requested by the driving cycle is fully delivered by the ICE. The ICE also moves the EM, which acts as a generator, thus charging the battery. The SOC increase in this mode is calculated by applying equations (5) to (7). To further optimize the fuel consumption, the ECMS algorithm is applied in this mode.

- **Mode 5**. Regenerative mode. This mode is selected when the acceleration is negative. In this mode only the EM is active, which acts as a generator. The electrical energy produced in the regenerative mode is delivered to the battery pack and is calculated by means of equation (13). The SOC increase in this mode is calculated by applying equations (5) to (7).

Table III shows the summary of the hybrid algorithm. It is shown that fuzzy is first used to select the operating mode to improve the overall efficiency. Then, the power requested $P_{requested}$ is calculated for each mode and the ECMS algorithm is applied in modes 3 and 4 to obtain a near-optimal solution for fuel consumption.

Mode	Optimization method
Mode 1 (EM only)	Fuzzy
Mode 2 (ICE only)	Fuzzy
Mode 3 (ICE + EM)	Fuzzy + ECMS
Mode 4 (Charging)	Fuzzy + ECMS
Mode 5 (Regenerative braking)	Fuzzy

Table III: Summary of the Hybrid Algorithm.

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Figure 3 shows a flow chart of the hybrid fuzzy + ECMS algorithm proposed in this paper.

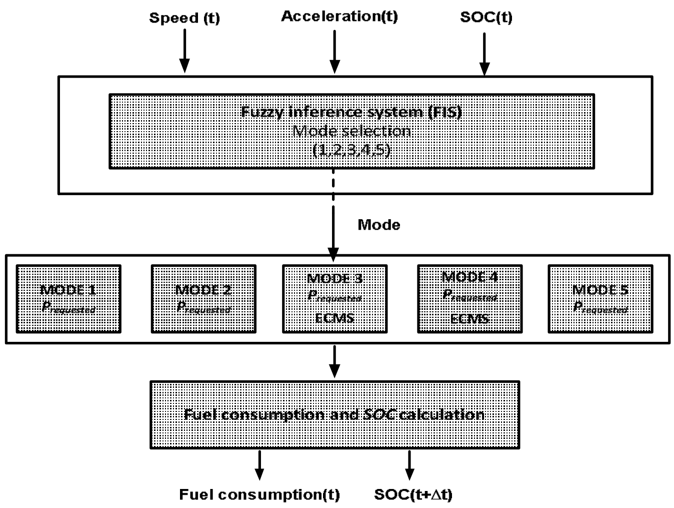

Figure 3: Flowchart of the hybrid fuzzy + ECMS algorithm proposed and evaluated in this paper.

Fuzzy logic is a set of mathematical techniques suitable to make complex decisions based on variables with a certain degree of variability or uncertainty. Figure 4 shows the triangular membership functions of the three fuzzy inputs i.e. speed, acceleration and SOC.

The output of the fuzzy strategy adopted is in the range 0-5 and includes five triangular fuzzy membership functions. Figure 5 shows the triangular membership functions of the five output modes provided by the fuzzy system. Each function is associated to one of the 5 operating modes as displayed in Table IV.

Output values	Max. value	Mode
0 - 1	0.0	1
1 - 2	1.5	2
2 - 3	2.5	3
3 -4	3.5	4
4 - 5	5.0	5

Table IV: Fuzzy rules to select the operating mode

Based on the features of each operating mode, 12 fuzzy rules are defined to select the most appropriate mode of operation according to the actual values of the three input variables (Motapon et al., 2014), i.e. the actual speed, SOC and acceleration. The 12 fuzzy rules included in the FIS are shown in Table V.

Complete FIS diagrams with all input and output variables are shown in Figure 6. The fuzzy inference system (FIS) allows assigning values to the output vector based on the values of the input fuzzy membership functions and the user-defined fuzzy rules. Triangular membership functions and center average defuzzification method are adopted in this work.

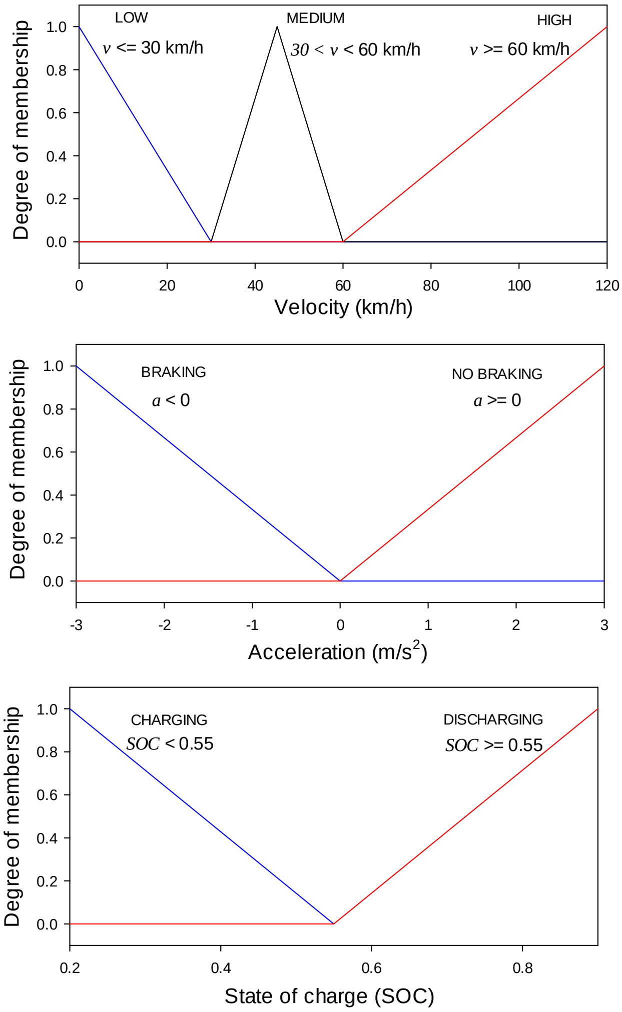

Figure 4: Inputs of the FIS (fuzzy inference system) and their membership functions. a) Speed input variable with three triangular membership functions. b) Acceleration input variable with two triangular membership function. c) State of charge of the battery with two triangular membership functions.

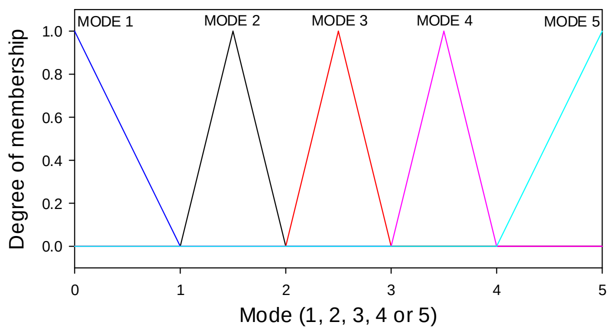

Figure 5: Output variable of the FIS containing five triangular membership functions.

Rule	Input values	Output mode
1	if (v low) and ($SOC \geq 0.55$) and ($a \geq 0$)	1
2	if (v med.) and ($SOC \geq 0.55$) and ($a \geq 0$)	2
3	if (v high) and ($SOC \geq 0.55$) and ($a \geq 0$)	3*
4	if (v low) and ($SOC \geq 0.55$) and ($a < 0$)	5
5	if (v med.) and $SOC \geq 0.55$) and ($a < 0$)	5
6	if (v high) and ($SOC \geq 0.55$) and ($a < 0$)	5
7	if (v low) and ($SOC < 0.55$) and ($a \geq 0$)	4*
8	if (v med.) and ($SOC < 0.55$) and ($a \geq 0$)	4*
9	if (v high) and ($SOC < 0.55$) and ($a \geq 0$)	4*
10	if (v low) and ($SOC < 0.55$and ($a < 0$)	5
11	if (v med.) and ($SOC < 0.55$) and ($a < 0$)	5
12	if (v high) and ($SOC < 0.55$) and ($a < 0$)	5

Table V: Fuzzy rules defined to select the operating mode

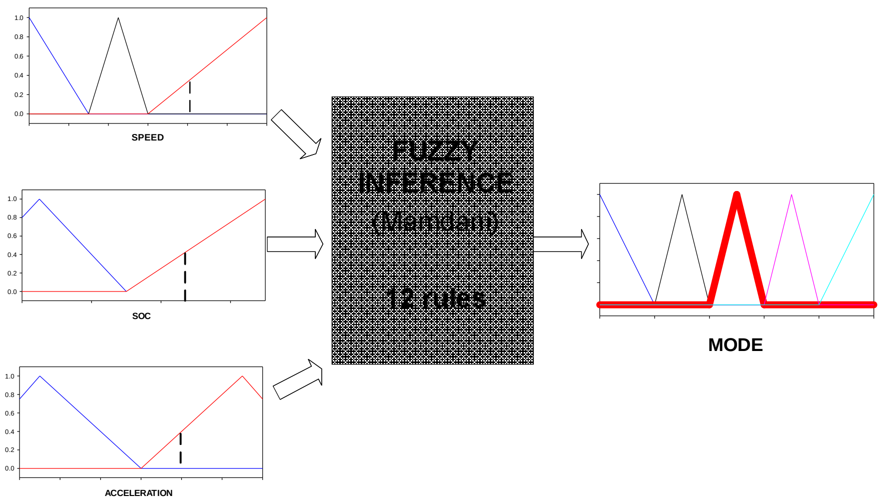

Figure 6: Diagram of the FIS with the three input sets and the fuzzy logic rules to select the most appropriate mode of operation.

Figure 7 shows the process to obtain an output value (operating mode) from the three inputs, i.e. speed, SOC and acceleration. Suppose, for instance, that a given speed v, SOC and acceleration a of the vehicle are reached. Figure 7 shows how the membership functions μ_v, μ_{SOC} and μ_a are selected for each row (rule).

Then the degree of membership of each rule (i = 1,…,12) for the output variable (operating mode) is calculated as:

$$\mu_{Mode,min,i} = \min(\mu_{v,i}, \mu_{SOC,i}, \mu_{a,i}) \quad i = 1, \ldots, 12$$

Next, the aggregation process is carried out, which consists of computing the maximum value within a fuzzy set [Garcia *et al*., 2008], i.e.,

$$Mode = \max(\mu_{Mode,min,1}, \ldots, \mu_{Mode,min,12})$$

The result of the former equation is shown in row 13 of Figure 6. Next, the defuzzyfication process is applied, which calculates a numerical value of the output variable by applying the centroid method. It is computed as the center of gravity of the resulting trapezoid, as indicated in row 13 of Figure 7.

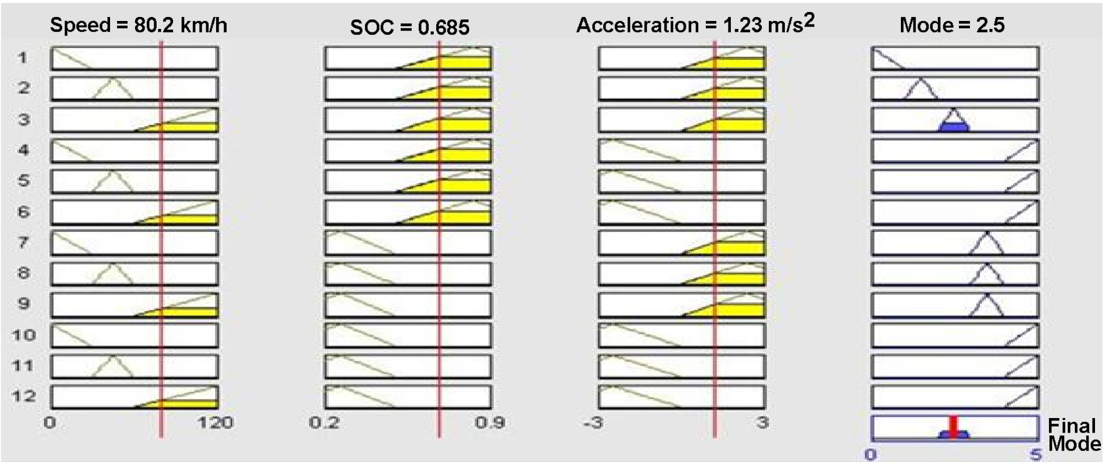

Figure 7: Rules application and defuzzification process to obtain the output operating mode

After selecting the operating mode, the power requested is calculated for each mode. Next, in modes 3 and 4 the power requested is further optimized by means of the ECMS algorithm, since the fuel consumption obtained by the fuzzy logic algorithm is not optimal. The ECMS algorithm is an on-line optimization method which attempts minimizing the fuel consumption at every time instance. ECMS is focused to determine the best power sharing between the ICE and the battery to cope with the power demand. To this end, ECMS defines an instantaneous cost function based on the equivalent fuel consumption. This is calculated as the fuel mass flow rate (it is a function of the power delivered by the ICE) plus the equivalent fuel flow rate due to the EM. This latter is a function of the equivalence factor (the factor applied to transform the electric power consumption into the equivalent fuel consumption) and the EM output power among others (Chen *et al.,*2011). The main objective of the ECMS algorithm is to optimize the overall fuel consumption by minimizing the fuel consumed by the ICE (Motapon *et al.,* 2014). A detailed description of the mathematical background of the ECMS algorithm is found in (Chen *et al.,*2011; Tulpule *et al.*, 2009).

Next equations present the mathematical details involved in the ECMS algorithm. The objective function to be minimized by the ECMS algorithm is given as,

$$J(t)=\int_0^t \dot{m}_{eq}(t)dt=\int_0^t \left[\dot{m}_{ice}(t)+\dot{m}_{battery}(t)\right]dt \quad (14)$$

where $\dot{m}_{ice}(t)$ is the fuel consumption of the ICE in kWh and $\dot{m}_{battery}(t)$ is the equivalent fuel consumed by the vehicle during battery charging or discharging.

For mode 4, i.e. when the battery is charging, the equivalent fuel consumed by the battery is,

$$\dot{m}_{battery}(t) = K_{eqf}\cdot P_{batt}\cdot \eta_{total}/Q_{lhv} \quad (15)$$

where K_{eqf} is the equivalence factor, which acts as a weighting factor for the electric energy. This factor affects the optimum power sharing between the engine and the motor. Q_{lhv} is the gasoline lower heating value and η_{total} is the drive train efficiency.

For mode 3, i.e. when the battery is discharging, the equivalent fuel consumed by the battery is,

$$\dot{m}_{battery}(t) = K_{eqf}\cdot P_{batt}/(Q_{lhv}\cdot \eta_{total}) \quad (16)$$

The SOC of the battery is not explicitly considered in the objective function, as described in (14). However, it must be taken into account since the SOC must be maintained within a predetermined range to ensure satisfactory vehicle behavior and adequate battery useful life. To take into account the current SOC value, a feedback adjustment is often applied to the weighting factor K_{eqf} in (16) and (17) as follows,

$$K_{eqf} = EQF\cdot K_p \cdot K_I \quad (17)$$

For a parallel hybrid configuration, the suggested value of *EQF* is 2.4 [Tuple *et al*., 2009], whereas K_p and K_I are the gains, whose values are calculated as follows,

$$x_1(t) = \frac{SOC(t) - SOC_{ref}/2}{\Delta SOC/2} \quad (18)$$

where SOC_{ref} is set to 27% and ΔSOC is set to 4% [Tulpule *et al.*, 2009]. In addition,

$$K_p = 1 - x_1^3 \quad (19)$$

$$x_2(t) = 0.01\left(SOC_{ref} - SOC(t)\right) + 0.99\cdot x_2(t-\Delta t) \quad (20)$$

$$K_I = 1 + \tanh(12\cdot x_2) \quad (21)$$

Δt being the time step taken during simulations.

The fuzzy-only algorithm

In the previous subsection the hybrid fuzzy + ECMS algorithm has been detailed. It has been explained that in modes 3 (ICE + EM) and 4 (recharging) the ECMS algorithm is applied to further optimize the fuel consumption.

The difference between the hybrid fuzzy + ECMS and the fuzzy-only algorithms lies in that the last one does not applies the ECMS algorithm in modes 3 and 4. Instead, in these modes the fuzzy-only algorithm operates as follows:

- **Mode 3**. The fuzzy-only algorithm assumes that the engine provides the amount of power required for driving the vehicle until 60 km/h, whereas the EM delivers the remaining extra power.
- **Mode 4**. In this mode it is supposed that the ICE delivers its rated power, which is divided into the amount of power required to run the vehicle according to the power requested by the driving conditions, the remaining extra power being sent to the battery pack.

Fig. 8 shows the power delivered by both the ICE and the EM in modes 3 and 4.

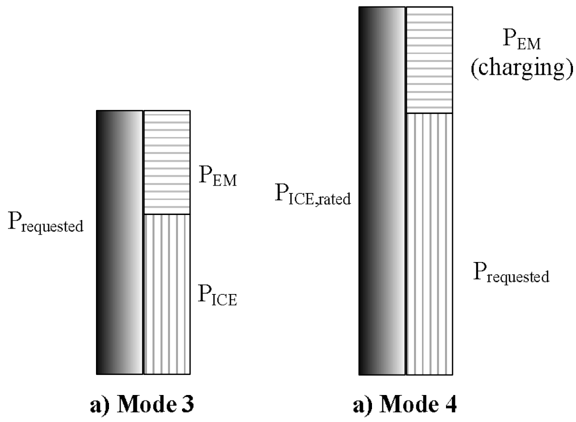

Figure 8: Power sharing in modes 3 and 4.

The if-then-else rule-based algorithm

The if-then-else rule-based algorithm is also considered in this work for comparison purpose. This algorithm selects the instantaneous operation mode according to the actual acceleration, SOC and speed values as follows,

IF $a > 0$
IF $SOC \geq 0.55$
IF $v < 30$ km/h **mode 1** (EM only) is selected
ELSE
IF $v < 60$ km/h **mode 2** (ICE only) is selected
ELSE **mode 3** (ICE + motor) is selected
IF $SOC < 0.55$ **mode 4** (battery charging) is selected
IF $a < 0$ **mode 5** (regenerative braking) is selected

When operating in modes 3 or 4, the power sharing strategy applied is the same as in the fuzzy-only algorithm, which is detailed in Fig. 8. The main problem of the if-then-else rules is that they provide suboptimal solutions.

Results

In this section the behavior of the proposed algorithm is evaluated. Two driving cycles with very different characteristics are analyzed, i.e. the US06 or supplemental FTP driving schedule (represents a driving style with fast speed changes) and the EPA highway fuel economy test cycle (represents highway driving conditions). Main features of both driving cycles are summarized in Table VI.

Parameters	**US06**	**EPA Highway**
Distance (km)	12.89	16.51
Sample period (s)	596	765
Time resolution (s)	1	1
Average speed (km/h)	77.9	77.7

Table VI: Main Features of EPA Urban and Highway Driving Cycles

Figs. 9 and 10 show the results for the both driving schedules. The results include the speed profile, the power requested, the power provided by both the ICE and EM, the SOC evolution provided by the hybrid algorithm as well as the instantaneous operating mode.

Note that the time resolution of both driving cycles shown in Figs. 9 and 10 is one second, which has been taken as the constant sampling time Δt in the calculations presented in next sections.

Results Summary

A summary of the results attained in this section are shown in Table VII. The behavior of the hybrid fuzzy + ECMS algorithm is compared with that of the other control algorithms, i.e. fuzzy-only and if-then-else rule-based. It is found that hybrid algorithm leads to 27.6% better fuel economy as compared to the fuzzy-only algorithm in the case of US06 supplemental FTP driving schedule. The hybrid algorithm provides 16.3% better fuel economy for EPA highway fuel economy driving schedule. These comparative results are a clear evidence of the better performance and strength of the proposed hybrid algorithm over the fuzzy-only and if-then-else rule-based methods for energy optimization in HEVs.

Fuel consumption (p.u.)		
Algorithm	US 06	EPA highway
If-then-else	1.013	1.008
Fuzzy-only	1.000	1.000
Fuzzy + ECMS	**0.724**	**0.837**

Table VII: Comparative fuel consumption of the different algorithms

Another interesting aspect of the analyzed algorithms is their computational burden. Table VIII shows the average time required for each analyzed algorithm to calculate each time step (1 second), for both studied driving schedules. The algorithms were programmed in Matlab® and an Intel® Atom™ Processor N450, 1.66 GHz CPU was used.

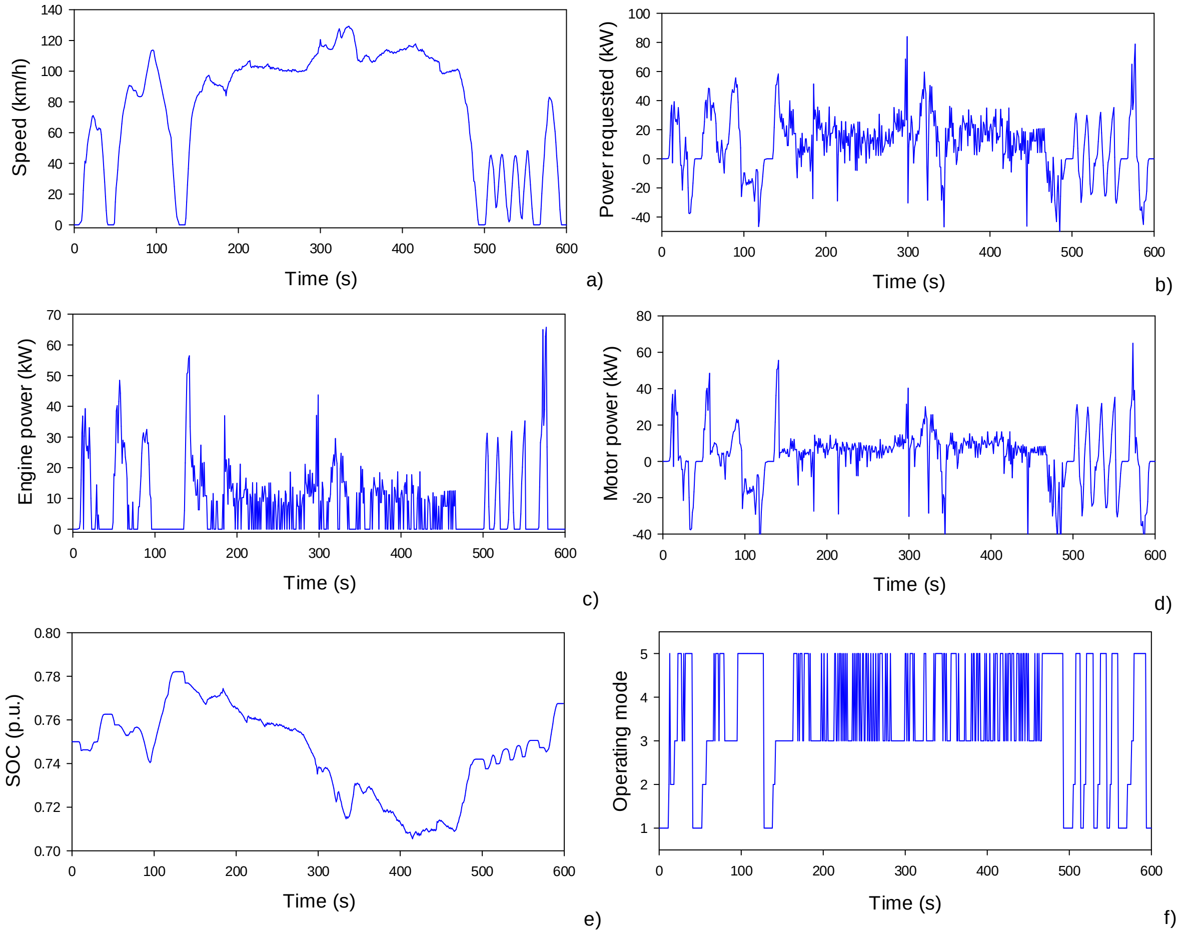

Figure 9: a) US06 supplemental FTP driving schedule applied to the vehicle modeled in this paper. b) Instantaneous power requested by the driving cycle. c) Instantaneous power delivered by the ICE. d) Instantaneous power delivered by the EM. e) Instantaneous SOC as calculated by the hybrid fuzzy + ECMS algorithm. f) Operating mode.

Computational time (ms)		
Algorithm	US 06	EPA highway
If-then-else	0.03	0.03
Fuzzy-only	3.61	3.55
Fuzzy + ECMS	**3.61**	**3.55**

Table VIII: Comparative computational burden of the different algorithms

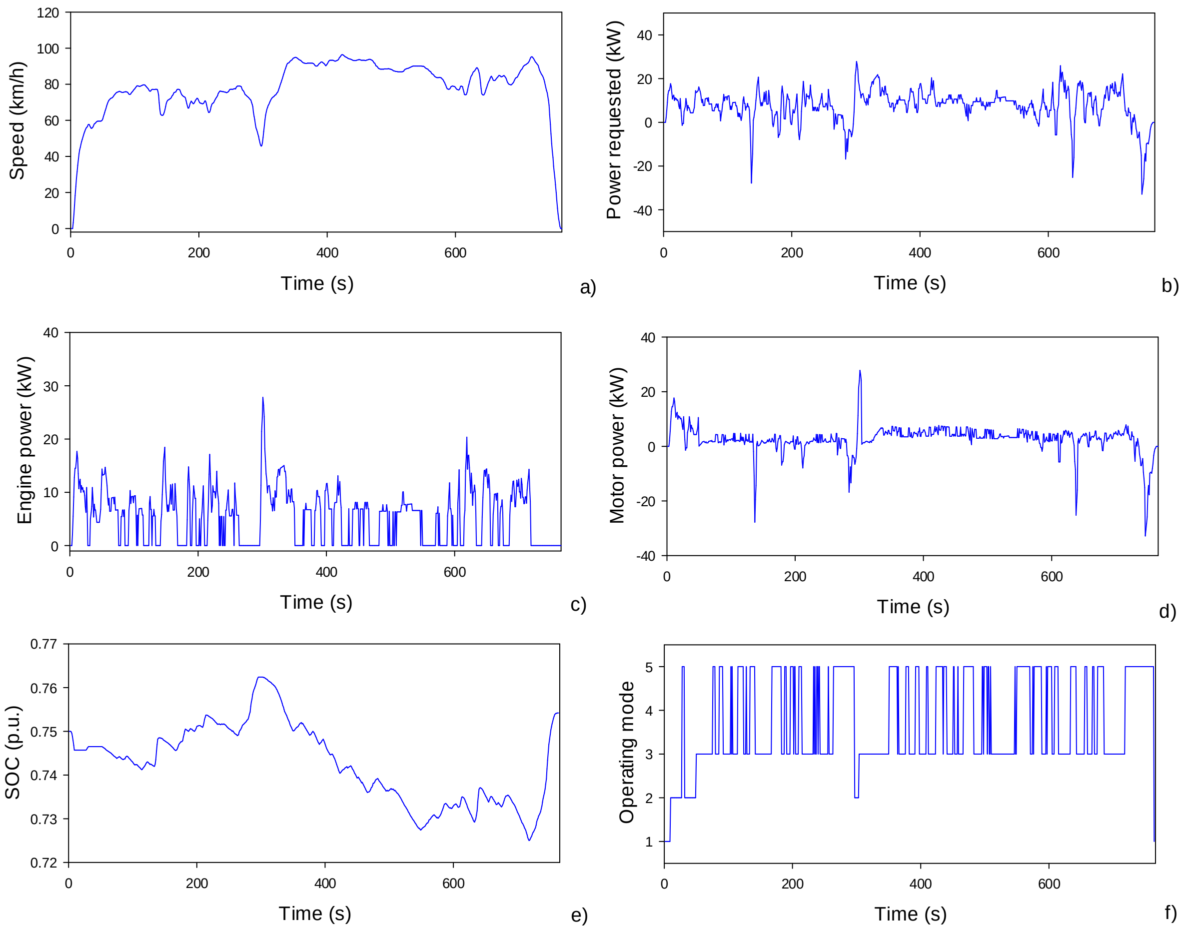

Figure 10. a) EPA highway fuel economy driving schedule applied to the vehicle modeled in this paper b) Instantaneous power requested by the driving cycle. c) Instantaneous power delivered by the ICE. d) Instantaneous power delivered by the EM. e) Instantaneous SOC as calculated by the hybrid fuzzy + ECMS algorithm. f) Operating mode.

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