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Control Strategies for Hybrid Vehicles in Mountainous Areas

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Abstract

This paper presents control strategies for a Hybrid Electric Vehicle (HEV) aiming at fuel and battery consumption reduction in real life conditions. For years, car manufacturers have modeled and simulated control strategies using standardized driving cycles based on theoretical speed values such as the NEDC in Europe, leaving important external parameters out of the equation. Establishing driving cycles made out of GPS acquisitions and segmenting them into road sections, classified in different categories depending on the input parameters, including slope, allows the creation of logic rules defining the driving mode to adopt in each situation. Using Fuzzy Logic, those rules can be interpreted and used to adapt the control strategy to road conditions, resulting in many strategies covering every kind of road segment and offering different opportunities of energy savings.

Keywords: **Hybrid vehicle; Control strategies; Fuel Consumption; Driving Cycle; Mountainous terrain; Fuzzy Logic; Matlab/Simulink; Slope.**

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1. Introduction

In an effort to reduce the production of greenhouse gases of which emission standards are becoming increasingly strict, control strategies for HEV are put in place in order to optimize battery and fuel consumption. Considering input parameters such as torque demand or vehicle speed, the strategies are responsible for successively enabling each one of the motors or generator. Energy losses caused by delays or bad enabling decisions representing a non negligible part of the vehicle energy consumption, being able to implement a reactive and accurate control strategy becomes crucial.

Many studies have been written considering hybrid vehicles behaviors in both urban and extra-urban contexts [1,2], based on theoretical driving cycles which represent fictive road segments and estimate the vehicle consumption. Important potential energy savings can be generated by HEVs. In fact, hybrid vehicles and their control strategies [3] are a good solution to fight pollution and to respond to many important needs, such as maintaining driving performances, in order to make that kind of vehicle popular in the future. In this context, the use of Matlab and Simulink [4] in hybrid vehicle modeling and simulation is predominant and has shown its efficiency. However, other simulation tools such as PSIM [5], Modelica/Dymola [6] or Advisor [7,8] can be used to implement this kind of system. Furthermore, internal parameters such as powertrain configuration and energy storage systems such as super-capacitors [9] are crucial in the design and optimization of basic hybrid vehicles and to reduce the development effort of HEVs. The main aspect is to assimilate the use of a hybrid drive train in order to make the car components as efficient as possible. Other papers have already shown the benefits of different approaches, implementing strategies on a parallel hybrid vehicle working with a diesel engines [10] or Hybrid Solar Vehicles (HSV) [11]. Reducing fuel consumption and nitrogen oxides emissions is possible according to those studies. However, the hybrid systems showing the best consumption reduction results are the series-parallel ones, they are the center of the following study.

Using a fuzzy controller [12,13] to define the ideal rules regarding the engines control strategy already has proven its efficiency. But there is still room for improvement in regard to the scope of the parameter domain, usually limited to the battery State Of Charge (SOC) and the torque demand, when establishing control strategies [14,15]. The adaptability of the strategy to the model studied, the type of energy saving wanted [16,17] and the driving cycle encountered [18] are also varying parameters that shall be taken in account by a polyvalent control strategy. Benefiting from regenerative braking [19,20] , the strategies implemented can be adapted to fit different types of usages and the necessity of preserving the battery integrity and maximal state of discharge. Control strategies can then be derived and adapted to the kind of trajectories encountered, principally using adaptive [21] and evolutionary [22,23] fuzzy logic based strategies. This eventually leads to the development of genetic-fuzzy control strategies [24,25,26], aiming to balance the energy savings between battery charge and fuel consumption while maintaining the HEV driving performances .

Based on this observation, the study will focus on control strategies aiming to reduce fuel consumption and battery usage using drive cycles made out of GPS measures made in mountainous regions and urban or semi-urban areas. Taking in account parameters such as intensity of road slope, state of battery charge or vehicle speed and acceleration at any given time, the strategies will determine the best driving mode to adopt in each unique situation based on logic rules.

We will focus on adapting the control strategies to external road conditions and the need to adopt the most economically viable behavior. To obtain relevant results, the use of a robust model of simulation for hybrid electric vehicle is necessary. Therefore, using a model made accessible on the website of Mathworks, developed by Steve Miller, allowed us to start on a common basis, tried and tested by a community. Adding a variable ratio gear box and implementing the action of slope on the vehicle dynamics led us to obtain a more realistic model on which we implemented five control strategies described further.

2. Results

2.1 Matlab/Simulink model and driving cycles

Measuring the fuel consumption of a vehicle when choosing a conventional cycle is inconvenient because it is not representative of real trajectories, omitting traffic conditions or variations in terrain elevation. Study of consumption in a most realistic way according to the trajectory represents an important stake, hence the interest of measuring real values of slope and speed in the mountains using a GPS. From an 83 km long drive, two driving cycles which characteristics can be found in Table 1 have been defined.

Table 1.Characteristics of the driving cycles employed.

Characterisic	Cycle 1	Cycle 2
Total distance (km)	42.8	40.1
Average speed (kph)	63	59
Maximum speed (kph)	111	110
Minimum slope (%)	-6.3	-6.3
Maximum slope (%)	4	9

The two cycles have been used as inputs in the existing Matlab/Simulink model of a Toyota Prius Hybrid vehicle which architecture is series-parallel, providing the best potential in terms of control. Integrating the slope values in the model allows to take into account the influence of the road inclination on the system operation. Modifications applied to the model, including the integration of a variable ratio gear box or complexification of the decision algorithm based on a larger set of parameters were the first step before the use of fuzzy logic to establish control strategies.

Next step consists in implementing a control strategy considering four major entry parameters : intensity of slope, state of battery charge, vehicle speed and acceleration.

Considering the road as a set of segments, defined by key parameters that are slope, speed, SOC and acceleration values, the strategy will classify the type of segment being crossed and take the decision associated with this precise situation. The choice of these four parameters provides largest manifold of trajectories to be covered. Any driving cycle can be defined by a table containing arrays of the four parameter values for each system cycle step.

Conducting tests linking the evolution of each entry parameter with fuel consumption and final battery state of charge allows to find the ideal driving mode to fit every unique situation. The sample data obtained can be refined using linear interpolation/extrapolation to better approximate the vehicle behavior for each parameter variation in each driving mode.

Figure 1.a and 1.b represent two examples of results obtained with the original Matlab model, displaying respectively the evolution of the fuel consumption as a function of the vehicle acceleration and the evolution of the battery SOC as a function of a constant speed, depending on the driving mode adopted. Acceleration mode, consisting in the simultaneous use of the two engines, is represented in blue and cruise mode, where the generator is employed, in red.

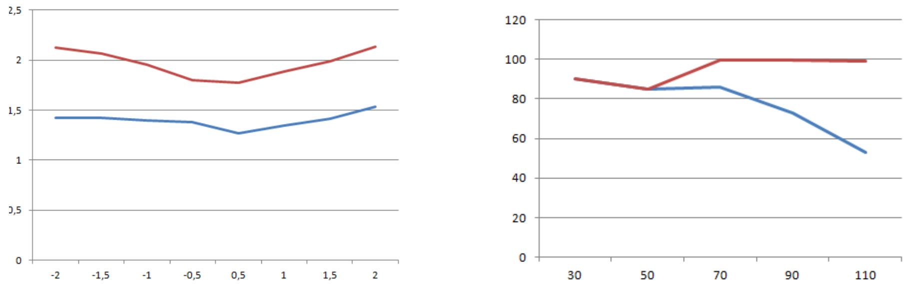

Fig. 1. (a) Test results linking fuel consumption in L/100km to acceleration in km.h^-1.s^-2; (b) Linking SOC in % to constant speed in km.h^-1

Based on initial model behavior and test results, membership functions qualifying the evolution of the vehicle consumption in terms of each entry parameter are established by simulation of each driving cycle with selected range of parameter value.

Defining the different possible states of each input variable using membership functions in a Fuzzy Logic controller and linking them using logical rules allows the expression of a single output value based on an unlimited number of possible states for the four input variables. Starting with simpler strategies based on a limited set of basic logic rules and only two entry parameters such as the vehicle speed and the slope, we implemented gradually more complex strategies taking in account up to four entry parameters and more than 40 logic rules actualized and checked at each system iteration.

This increase in rules complexity allows more trajectories to be covered and a better precision regarding the zones of transition between driving modes that can be hard to determine in very specific situations. The aim of the control strategies being to cover the entirety of the scope of trajectories encountered by a driver, from basic logic rules and a limited set of entry parameters we had to expand the resolution of the membership functions and the parameter domain in order to cover every kind of driving cycle or variation of road metrics.

2.2 Implementation of Control Strategies Using Fuzzy Logic

The Fuzzy Logic Toolbox available via Matlab/Simulink and employed in a lot of implementations related to the current subject, allows the consideration of a great number of entry parameters to which will be assigned different states defined by elaborating membership functions .

Simple membership functions such as the one displayed in Figure 2 allow fast simulations and the ability to consider multiple entry parameters.

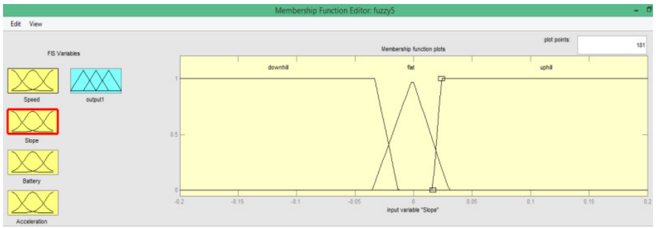

Fig.2. Membership Function of slope input parameter for strategy N°1

Next step consists in elaborating logical rules associating one or more logical states of one or more input variable to an unique output that will decide of the best corresponding driving mode according to the current vehicle situation. The output value ranks between 0 and 1, a value under 0.5 corresponding to the Acceleration mode, during which only the electric motor and the thermic engine will be enabled, and a value over 0.5 to the Cruise mode, during which the two motors and the generator will be enabled.

Concrete rules such as the combination of a low SOC and a high speed resulting in the activation of the Cruise mode can be found in Figure 3. Multiple rules can be true at any given time, resulting in the weighting of each rule and their level of completion while determining the final output.

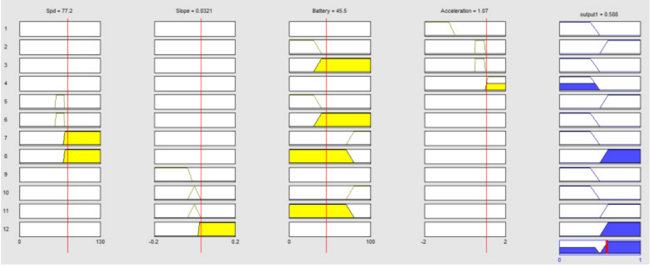

Fig.3. Example of a set of logical rules composing a control strategy.

Different strategies can be defined to fit a greater spectrum of situations, allowing predictive behaviors algorithms to select a strategy based on the type of road currently being crossed. For example, based on the system behavior in uphill increasing slope, and in the case of higher SOC than predefined threshold representing "acceptable" charge, an economically viable strategy favors simultaneous use of the two engines so as to reduce or maintain vehicle fuel consumption. Employing those strategies leads to a better reactivity in the decision making and a better usage of the battery charge by soliciting the generator in favorable situations such as downhill segments or high speed flat sections. It appears that charging the battery when meeting those kind of situation, even for a limited amount of time can cause a significant reduction of battery usage in the long run.

The strategies are modeled accordingly to few general principles which can be derived from the unitary tests described previously. Benefiting from high and constant speeds, negative slopes and low battery charge states to activating the generator is one of them along with the combination of the two engines in situations generating moderate to strong torque demand such as an increasing inclination met with a positive acceleration.

Results given by five of the strategies implemented using Fuzzy Logic can be found in Table 2. Decrease in fuel consumption being directly linked to battery charge, strategies focusing on energy recuperation tend to give lowest results regarding fuel economy. A strong correlation can be found between the order of magnitude of the energy economy and the intensity of the cycle slope, greater inclines leading to smaller savings.

Table 2. Energy savings realized using five strategies relying on different complexity levels of fuzzy logic.

Strategy	Cycle 1		Cycle 2	
	Battery Charge	Fuel Consumption	Battery Charge	Fuel Consumption
1	17.93%	1.38%	0.68%	2.53%
2	18.05%	1.45%	0.99%	2.53%
3	-7.4%	7.2%	2.64%	2.28%
4	11.92%	3.56%	2.17%	2.53%
5	1.67%	4.98%	2.42%	2.47%

Suffering from the lack of a gearbox ratio based on the engine speed demand and the vehicle speed, the hybrid vehicle model has been updated to take this part into account. Realizing the control strategies on the improved system is important to make a comparison which will show if the approach stays viable even if the system is upgraded. Table 3 shows the obtained results after implementation of the new gearbox.

Table 3. Energy savings realized using five strategies adding the implemented gearbox.

Strategy	Cycle 1		Cycle 2	
	Battery Charge	Fuel Consumption	Battery Charge	Fuel Consumption
1	19.36%	0.81%	2.63%	1.80%
2	18.54%	0.9%	1.07%	1.76%
3	-7.15%	3.4%	2.62%	1.65%
4	18.49%	0.63%	3.16%	2.13%
5	3.93%	3.13%	2.64%	2.02%

Energy savings amounts while not being exactly the same with and without gearbox stay consistent and show that the control strategies can be adapted to system modifications. Therefore, the implemented control strategies are viable for a high level use, no matter the variation in terms of technical conception. Implementing a cost function in order to expose the economical viability of the results is an interesting way to prove the validity of the study. Based on the current prices of gas in the EU as of the 15 February 2015 and on the average price of the KWH in the EU for the year 2013, establishing a cost function allows to determine which one of the five strategies obtained is the most economically viable.

At 1.19€/L and 0.2€/KWH with a battery requiring 4.4 KWH to be charged at 100%, the following equation is obtained:

$$G = \alpha X + \beta Y$$

With G the total amount of money gained during the cycle in euro, α the cost of gas in euro per liter, β the cost of electricity in dollar per % of battery consumed, X and Y respectively the gas economy during the cycle in liter and the economy during the cycle in % of battery gained. Hence the following equation. The cost gain for all the control strategies in Euro cents is calculated for the two cycles and is computed in Table 4.

$$G=1.19X+0.0088Y$$

Table 4. Gain in Euro cents for each driving cycle.

Strategy	Cycle 1	Cycle 2
	G	G
1	17.97c	3.59c
2	17.34c	2.51c
3	6.86c	3.78c
4	16.96c	4.68c
5	6.99c	3.59c

Calculating the gain on a full gas tank and a full battery charge with the previous data given V the 45L volume for the tank gives the following equation. The cost gain for all the control strategies in Euro is calculated based on a full gas tank and a full battery charge in Table 5.

$$G = V\alpha X + 4.4\beta Y$$

Table 5. Gain in Euro based on a full gas tank and battery charge.

Strategy	Cycle 1	Cycle 2
	G	G
1	0.6€	3.27€
2	0.64€	1.88€
3	1.76€	3.19€
4	0.5€	3.92€
5	1.71€	3.4€

The most complex strategies based on a greater sample of logic rules and entry parameters show the best results with up to 3.92€ of savings on a full tank and battery charge. This is the direct consequence of expanding the scope of trajectories covered by the control strategies. Every situation that can be encountered, every given trajectory will contain a variation of those four entry parameters that are vehicle speed, acceleration, road slope and battery state of charge. This allows the determination of a fixed domain of parameters with known limit values, based on which the fuzzy logic rules will always be able to determine the best system state at any given time leading to the most economical decision.

This invariant parameter domain leading to potential energy savings can be exploited in every system independently of the internal parameters such as vehicle weight and aerodynamics or even external parameters such as driving style or road metrics since such variables do not impact the four parameters describe before that can be found no matter what the trajectory being followed.

3. Conclusion

Regarding the actual environmental and economic problematic, optimizing hybrid vehicles constitutes an interesting solution in order to reduce energy consumptions and gas emissions. Working on a Toyota Prius model to establish control strategies was a good way to start a constructive reasoning about this kind of optimisation.

This Matlab/Simulink simulation has been upgraded with an decisional algorithmic component using Fuzzy Logic which provides many analysis possibilities. This structure accurately optimizes the usage of each kind of engine during realistic driving cycles measured with a GPS in a mountain area. Due to the accuracy of this approach, the established control strategies offer an interesting energy consumption gain, the best fuel consumption decrease being equal to 3.16% and the maximum percentage of electricity saving reaching 19.36 %.

This approach offers an alternative to heavier control strategies monopolizing lots of computational power an offers possibilities regarding situational and predictive algorithms based on the evolution of the road characteristics.

Otherwise, the established strategies are robust and efficient independently of the possible systemic or environmental fluctuations as shown by the modified gear box and the different driving cycles tested, due to the invariant parameters domain studied and employed to obtain the final control decision .

Furthermore, the presented work opens the opportunity to base the choice of the current control strategies employed on the upcoming road profile acquired by GPS stored data for example. Adapting the control strategies to the future road geometry could again optimize the energy consumption reduction with little impact on the computational power required to the embedded systems.

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