

# Rule-Based Optimization of Intermittent ICE Scheduling on a Hybrid Solar Vehicle

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## ABSTRACT

In the paper, a rule-based (RB) control strategy is proposed to optimize on-board energy management on a Hybrid Solar Vehicle (HSV) with series structure. Previous studies have shown the promising benefits of such vehicles in urban driving in terms of fuel economy and carbon dioxide reduction, and that economic feasibility could be achieved in a near future.

The control architecture consists of two main loops: one external, which determines final battery state of charge (SOC) as function of expected solar contribution during next parking phase, and the second internal, whose aim is to define optimal ICE-EG power trajectory and SOC oscillation around the final value, as addressed by the first loop.

In order to maximize the fuel savings achievable by a series architecture, an intermittent ICE scheduling is adopted for HSV. Therefore, the second loop yields the average power at which the ICE is operated as function of the average values of traction power demand and solar power. Expected solar contribution can be estimated starting from widely available solar databases and by processing past solar energy data measured on the vehicle. Neural Networks predictors, previously stored data and/or GPS derived information are suitable to estimate average power requested for vehicle traction.

Extensive simulation analyses were carried out to test the performance of the RB algorithm, also comparing it to Genetic Algorithms-based optimization strategies previously developed by the authors. The results confirm the high potentialities offered by the proposed RB control strategy to perform real-time energy management on hybrid solar vehicles.

The proposed rule-based optimization is currently under-implementation in an NI® cRIO control unit, thus allowing to perform experimental tests on a real HSV prototype developed at University of Salerno.

## INTRODUCTION

In the last years, there is an increasing awareness about the need to achieve a more sustainable mobility, allowing meeting the mobility needs of the present without compromising the ability of future generations

to meet their needs [1]. The most pressing arguments towards new solutions for personal mobility are the following:

- fossil fuels, largely used for car propulsion, are doomed to depletion, and their price is subject to large and unpredictable fluctuations (see Figure 1);

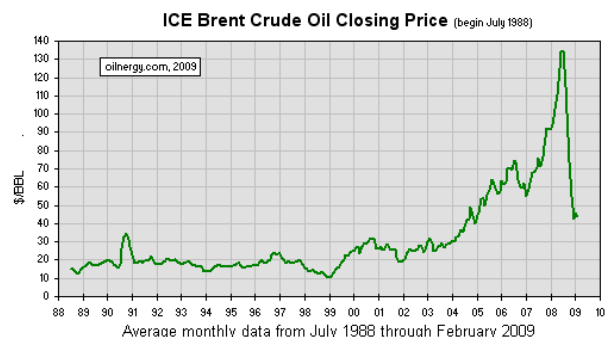
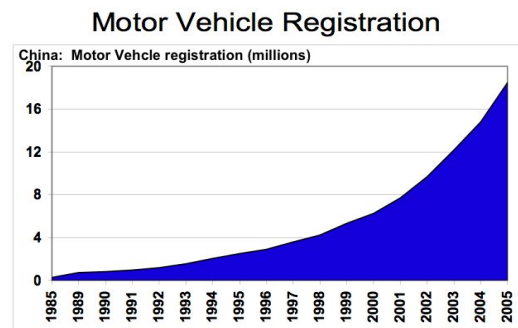


Figure 1 - Trends in oil price  
(<http://www.oilnergy.com/1obrent.htm>).

- the CO<sub>2</sub> generated by the combustion processes occurring in conventional thermal engines contributes to the greenhouse effects, with dangerous and maybe dramatic effects on global warming and climatic changes;
- the worldwide demand for personal mobility is rapidly growing, especially in China (see Figure 2) and India; as a consequence, energy consumption and CO<sub>2</sub> emissions related to cars and transportation are increasing;



Source: China Statistical Yearbook 2006

Figure 2 - Motor vehicle registration in China (Millions).

One of the most realistic short term solutions to the reduction of gaseous pollution in urban drive, as well

as the energy saving requirements, is represented by Hybrid Electric Vehicles (HEV). These vehicles, that have evolved to industrial maturity, allow achieving significant benefits in terms of fuel economy, but still using fossil fuels. On the other hand, in recent years increasing attention is being spent towards the applications of solar energy to electric and also to hybrid cars. But, while pure solar vehicles do not represent a practical alternative to cars for normal use, the concept of a hybrid electric car assisted by solar panels appears more realistic. The reasons for studying and developing a Hybrid Solar Vehicle (HSV) can be therefore summarized as follows:

- solar energy is renewable, free and largely diffused, and Photovoltaic Panels are subject to continuous technological advances in terms of cell efficiency; their diffusion is rapidly growing, while their cost, after a continuous reduction and an inversion occurred in 2004, again shows a decreasing trend [2];
- solar cars, in spite of some spectacular outcomes in competitions as World Solar Challenge, do not represent a practical alternative to conventional cars, due to limitations on maximum power, range, dimensions and costs;
- possibility of fruitfully combining HEV- and solar power-related energetic benefits.

In next chapters, the potentialities and problems associated to Hybrid Solar Vehicle technology are presented, and some specific control issues of such vehicles discussed, based on previous work of the authors. Then, a new implementable rule-based approach for energy flow management is proposed, and the results obtained by a dynamic model are compared with those deriving by an optimal strategy obtained via Genetic Algorithms. Finally, some preliminary experimental tests are presented and discussed.

## HYBRID SOLAR VEHICLES

In principle, Hybrid Solar Vehicles (HSV) could sum up the advantages of HEV and solar power, by the integration of Photovoltaic Panels in a Hybrid Electric Vehicle. But it would be simplistic to consider the development of an HSV as the simple addition of photovoltaic panels to an existing Hybrid Electric Vehicle. In fact, the development of HEV's, despite it was based on well-established technologies, showed how considerable research efforts were required for both optimizing the power-train design and defining the most suitable control and energy-management strategies. Analogously, to maximize the benefits coming from the integration of photovoltaic with HEV technology, it is required performing accurate re-design and optimization of the whole vehicle-powertrain system. In these vehicles, in fact, there are many mutual interactions between energy flows, propulsion system component sizing, vehicle dimension, performance, weight and costs, whose connections are much more critical than in conventional as well as in hybrid cars.

Another difference between HEV and HSV regards with their structure. In fact, the prevailing architectures for HEV are parallel and parallel-series, while in case of HSV the series structure seems preferable [3]. Despite some known disadvantages (higher efficiency losses due to more energy conversion stages), series structure is simpler and may offer some advantages:

- It is more suitable for plug-in and V2G applications [3] (the generator can be used as co-generator when the vehicle is parked at home).
- Due to absence of mechanical links between generator and wheels, very effective vibration insulation can be achieved, with less constraints for vehicle layout.
- Advanced techniques for noise reduction (i.e. active noise reduction) could be more easily applied, since the engine can work at fixed conditions.
- Engines specifically optimized for steady operation can be used (i.e. D.I. stratified charge engines, Micro gas turbine, and other solutions not suitable for classical vehicles due to lack of stability or low efficiency in the whole operating range).
- It is compatible with the use of in-wheel motors with built-in traction control and anti-skid.
- It will potentially act as a bridge towards the introduction of hybrid fuel cell powertrains.

A possible layout of an HSV with series structure is presented in Figure 3. The photovoltaic panels PV are usually mounted on or integrated with vehicle roof [3,4].

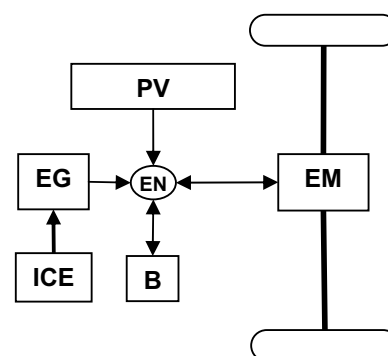


Figure 3 - Scheme of a series hybrid solar vehicle.

In spite of these encouraging perspectives, the use of solar energy on cars has been considered with a certain skepticism by most users, including automotive engineers. This may be due to the simple observation that the net power achievable in a car with current photovoltaic panels is about two order of magnitude less than maximum power of most of today cars. But a more careful analysis of the energy involved demonstrate that this perception may be misleading. In fact, there is a large number of drivers utilizing daily their car for short trips and with limited power demand. For instance, some recent studies conducted by the

UK government report that about 71 % of UK users reach their office by car, and 46 % of them have trips shorter than 20 minutes, mostly with only one person on board, i.e. the driver [5].

In those conditions, the solar energy collected by solar panels on the car along a day may represent a significant fraction of the energy required for traction [6-8].

Despite their potential interest, solar hybrid cars have received relatively little attention in literature [3], particularly if compared with the great effort spent in last years toward other solutions, as hydrogen cars, whose perspectives are affected by critical issues, such as production, distribution and storage.

Some prototypes have been developed in last decade in Japan [9], at Western Washington University [10], at the Queensland University [11] and, more recently, by the French company Venturi.

A prototype of Solar Prius has also been recently developed by Solar Electric Vehicles, equipped with a PV panel of 16% nominal efficiency [4]. It has been estimated that the PV Prius can have a range based on solar power alone between 5 and 8 miles per day, and that it can consume between 17% and 29% less gasoline than the standard Prius.

## CONTROL ISSUES FOR HYBRID SOLAR VEHICLES

Although HSV share many common features with HEV, for which numerous studies on energy management and control have been presented in last decade [12-15], there are also some significant differences between these kind of vehicles. In particular, the presence of solar panels and the adoption of a series structure may require to study and develop specific solutions for optimal management and control of an HSV.

As it is known, in most HEV a charge sustaining strategy is adopted: at the end of a driving path, the battery state of charge should remain unchanged. With an HSV, a different strategy should be adopted as battery is charged during parking hours as well. In this case, a different goal can be pursued, namely restoring the initial state of charge within the end of the day rather than after a single driving path [8].

Moreover, the series configuration suggests to operate the engine in an intermittent way at constant operating conditions, i.e. corresponding to the minimum fuel consumption. In such case, the ICE-EG system may be designed and optimized to maximize its efficiency, emissions and noise at design point, while in current automotive engines the maximum efficiency is usually sacrificed to the need of assuring stable operation and good performance in the whole operating range. In case of ICE intermittent operation, the effects exerted on fuel consumption and emissions by the occurrence of thermal transients in engine and catalyst should be considered [8,16,17]. These effects are neglected in most studies on HEV [15] and on HSV [18], where a

steady-state approach is usually preferred to evaluate fuel consumption and emissions.

In order to address the afore-mentioned control issues, in the last years the authors have performed several off-line analyses aimed at individuating optimal energy management strategies for series HSV [8,17,19,20]. Specifically in this work, the research interests and aims turned towards the development of an RB control strategy to perform quasi-optimal on-board energy management for a series HSV powertrain.

## RULE-BASED CONTROL STRATEGY FOR A SERIES HYBRID SOLAR VEHICLE

The RB control architecture consists of two loops, external and internal respectively:

- external loop: defines the desired final state of charge  $SOC_f$  (see Figure 4), to be reached at the end of the driving cycle to enable full storage of solar energy capted during the following parking phase (i.e.,  $E_{PV,p}$ ).
- internal loop: estimates the average power delivered by ICE-EG and SOC deviation ( $dSOC$ ) from  $SOC_f$  as function of average traction power  $\bar{P}_{tr}$  and  $E_{PV,p}$ .

Figure 4 provides a qualitative description of the start&stop strategy enabled by the above-described control loops. For sake of simplicity, in Figure 4 it is assumed that  $SOC_0 = SOC_f$  and  $\bar{P}_{tr}$  does not vary with time. The battery is initially depleted until SOC becomes lower than  $SOC_{lo} = SOC_f - dSOC$ . At this point ICE-EG is turned on at the assigned power level and switches off when the maximum threshold  $SOC_{up} = SOC_f + dSOC$  is reached. The procedure is repeated until the end of the driving cycle. It is worth mentioning here that effective final state of charge may differ from the desired  $SOC_f$  due to the difficulty of precisely predicting the end of the driving phase. This consideration entails satisfying the following energetic constraint:

$$SOC_{up} + \Delta SOC_p < 1 \quad (1)$$

where  $\Delta SOC_p$  represents the state of charge increase subsequent to battery recharging performed by PV panels during parking phases.

The described control strategy relies, on one hand, on the online estimation of current SOC level and, on the other, on predicting or properly estimating  $\bar{P}_{tr}$  over an assigned driving route. The following sub-sections go through a detail description of the rules defined in both external and internal loop.

## EXTERNAL-LOOP RULES

As explained above, the objective of the external loop is to ensure all the available  $E_{sun,p}$  be stored in the battery pack once the driving phase is over. This can be obtained imposing  $SOC_f$  always be safely lower than 1. This constraint can be expressed as follows: