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Optimal Design of a Hybrid Solar Vehicle

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I. INTRODUCTION

In the last years, increasing attention has been spent toward the applications of solar energy to cars. Various prototypes of solar cars have been built and tested, mainly for racing and demonstrative purposes [1] [2].

Despite of a significant technological effort and some spectacular outcomes, the limitations due to low density and unpredictable availability of solar source, the weight associated to energy storage systems, the need of minimizing weight, friction and aerodynamic losses make these vehicles quite different from the current idea of a car. But, while cars powered only by the sun seems still unfeasible for practical uses, the concept of an electric hybrid car assisted by solar cells appears more realistic [3][4][5][6][15]. In fact, in the last decades Hybrid Electric Vehicles (HEV) have evolved to industrial maturity, after a relevant research effort [7]. These vehicles now represent a realistic solution to the reduction of gaseous pollution in urban drive and to energy saving. Nevertheless, the need of mounting on-board both thermal and electrical machines and a battery of significant capacity makes these vehicles heavier than the conventional ones, at the same power, while solar cars are characterized by very limited power and weight. On the other hand, there is a large number of users that utilizes daily their car for short trips with limited power. Some recent studies of the UK government report that about 71% of UK users reaches their office by car, and 46% of them have trips shorter than 20 min., mostly with only one person on board [8].

In spite of their potential interest, solar hybrid cars have received relatively little attention in literature [15]. An innovative prototype has been developed at Western Washington University [5][6] in the 90’s, adopting advanced solutions for materials, aerodynamic drag reduction and PV power maximization with peak power tracking. Other studies and prototypes on solar hybrid vehicles have been presented by Japanese researchers [3][4] and at the Queensland University [9].

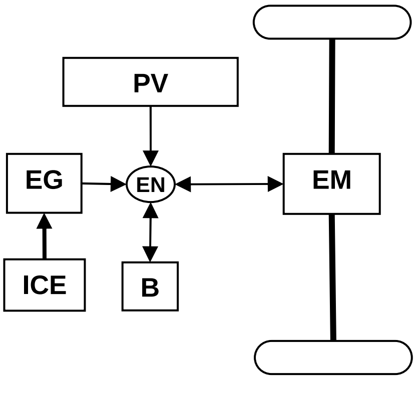
Although these works demonstrate the general feasibility of this idea, a detailed presentation of results and performance and a systematic approach to the design of a solar hybrid vehicle seems still missing in literature. Such a model is particularly necessary since the technological scenario is rapidly changing, and new components and solutions are becoming available or will be available in the next future. A specific difficulty in developing a HSV model is due to the 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 and also in hybrid cars. Preliminary studies on energy flows in a HSV has been recently developed by the authors [10][11]. In the paper, a more detailed study on the optimal sizing of a solar hybrid car, based on a longitudinal vehicle dynamic model and considering energy flows, control strategies, weight and costs, is presented.

II. STRUCTURE OF THE SOLAR HYBRID VEHICLE

Different architectures can be applied to HEV’s: series, parallel, and parallel-series. These two latter structures have been utilized for two of the most diffused hybrid cars in the market: Toyota Prius (parallel-series) and Honda Civic (parallel). Instead, for solar hybrid vehicles the series structure seems preferable [15], due to its simplicity, as in some recent prototypes of HSV [9]. With this approach, the Photovoltaic Panels (PV) concur with the Electric Generator EG, powered by the ICE, to recharge the battery pack B in both parking mode and driving conditions, through the electric node EN. The electric motor EM can either provide the mechanical power for the propulsion or restore part of the braking power during regenerative braking (FIG. 1). In this structure, the thermal engine can work mostly at constant power (P_{AV}), corresponding to its optimal efficiency, while the electric motor EM can reach a peak power P_{max}:

$$P_{\max} = \theta P_{av} \qquad (1)$$

FIG. 1 - SCHEME OF THE SERIES HYBRID SOLAR VEHICLE



In order to estimate the net solar energy captured by PV panels in real conditions (i.e. considering clouds, rain etc.) and available for propulsion, a solar calculator developed at the US National Renewable Energy Lab has been used [12], considering four different US locations, ranging from 21° to 61° of latitude, based on 1961-1990 time series. The calculator provides the net solar energy for different panel positions: with 1 or 2 axis tracking mechanism or for fixed panels, at various tilt and azimuth angles.

The most obvious solution for solar cars is the location of panels on roof and bonnet, at almost horizontal position. Nevertheless, two additional options have been considered: (i) horizontal panels (on roof and bonnet) with one tracking axis, in order to maximize the energy captured during parking mode; (ii) panels located also on car sides and rear at almost vertical positions. The maximum panel area can be estimated as function of car dimensions and shape, with a simple geometrical model [11].

The energy from PV panels can be obtained summing the contributes during parking (p) and driving (d) periods. While in the former case it is reasonable to assume that the PV array has an unobstructed view of the sky, this hypothesis could fail in most driving conditions. Therefore, the energy captured during driving can be reduced by a factor $\beta<1$. In order to estimate the fraction of daily solar energy captured during driving hours (h_d), it is assumed that the daily solar energy is distributed over h_{sun} hours. A factor $\alpha<1$ is then introduced to account for further degradation due to charge and discharge processes in the battery for energy taken during parking. The net solar energy available for propulsion taken during parking and driving modes can therefore be expressed as:

$$E_{s,p} = \eta_p A_{PV} e_{sun} \frac{h_{sun} - h_d}{h_{sun}} \alpha \qquad (2)$$

$$E_{s,d} = \eta_p A_{PV} e_{sun} \frac{h_d}{h_{sun}} \beta \qquad (3)$$

The energy required to drive the vehicle during the day can be expressed as function of the average power P_{av} and the driving hours h_d:

$$E_d = \frac{1}{3600} \int_{h_d} P(t) \cdot dt = \frac{1}{3600} h_d P_{av} \qquad (4)$$

The instantaneous power can be computed starting from a given driving cycle, for assigned vehicle data, integrating a vehicle longitudinal dynamic model. Required driving energy E_d depends therefore on vehicle weight and on vehicle cross section, that in turn depend on the sizing of the propulsion system components and on vehicle dimensions, related to solar panel area. The contribution of solar energy to the propulsion can be therefore determined:

$$\varphi = \frac{E_{sun}}{E_d} = \frac{E_{s,p} + E_{s,d}}{E_d} \qquad (5)$$

The fuel consumption for both conventional vehicle (ICE) and HSV can be then computed and compared. Of course, in parallel with fuel saving, corresponding reduction in the emissions of pollutants and CO_2 with respect to the conventional vehicle is also achieved.

III. WEIGHT MODEL

A parametric model for the weight of a HSV can be obtained summing the weight of the specific components (PV panels, battery pack, ICE, Generator, Electric Motor, Inverter) to the weight of the car body. This latter has been obtained starting from a statistical analysis of small commercial cars. A linear regression analysis has been performed, considering weight W ($W_{body,CC}$), power P and vehicle dimensions (length l, width w, height h and their product $V=lwh$) for 15 commercial cars, with power ranging from 9.5 KW to 66 KW [11]. In order to use these data to estimate the base weight of the HSV ($W_{body,HSV}$), the contribution of the components not present in the series hybrid vehicle (i.e. gearbox, clutch) has been subtracted. The car body also includes other components (thermal engine, electric generator, battery) that will be considered separately for the hybrid car model; the weight of ICE is estimated as function of peak power, while the influence of electric generator and battery has been neglected (their weights are of course much lower than the corresponding components needed on the hybrid car).

TAB. I – REGRESSION ANALYSIS FOR COMMERCIAL CAR BODY MASS.

#	Variables	R^2
1	$W=k_1+k_2P$	0.894
2	$W= k_1+k_2P+k_3l+k_4w+k_5h$	0.973
3	$W= k_1+k_2P+k_3V$	0.946

A subtractive term (ΔW) has been introduced to include weight savings achievable through the use of aluminium instead of steel for chassis: in this case, additional costs have been considered in the cost model [12]. Thus, the mass of the car body and of the entire HSV can be expressed as:

$$\begin{aligned} &W_{body,HSV} = \\ &W_{body,CV}\left(P_{\max}, V\right) - \\ &P_{\max}\left(m_g + m_{ICE}\right) - \Delta W \end{aligned} \qquad (6)$$

and

$$\begin{aligned} W_{HSV} &= W_{body,HSV}\left(P_{\max}, V, \Delta W\right) + \\ &+ \delta P_{av}\left(m_{ICE} + m_{EG}\right) + \\ &+ P_{\max} m_{EM} + A_{PV} m_{PV} + C_B m_B \end{aligned} \qquad (7)$$

The mass of the battery depends on its capacity C, related to the energy to be stored during parking mode E_P. In order to assure efficient charge and discharge processes, it is assumed that capacity is greater that the average yearly value of the energy stored during parking mode ($\lambda=2$).

$$C_B = \lambda E_p \qquad (8)$$

The ratio between peak power and car weight, related to vehicle performance, can be then computed:

$$PtW_{HSV} = \frac{P_{\max}}{W_{HSV}} \qquad (9)$$

IV. COST ESTIMATION

In order to assess the real feasibility of solar hybrid vehicles, an estimation of the additional costs related to hybridization and to solar panel installation and of the fuel saving achievable with respect to conventional vehicles are necessary. They can be expressed starting from the estimated unit costs of each component:

$$C_{HSV} = \delta P_{av}\left(c_{ICE} + c_{EG}\right) + \\ + A_{PV} c_{PV} + P_{\max} c_{EM} + C_B c_B + \\ + \Delta W c_{al} - \Delta C_{ICE} \qquad (10)$$

The last two terms account for: i) possible weight reduction in chassis due to use of aluminum [12] and ii) the cost reduction for Internal Combustion Engine in HSV (where it is assumed $P_{ICE}=\delta\, P_{av}$) with respect to conventional vehicle (where $P_{ICE}=P_{max}$).

The daily saving with respect to conventional vehicle can be computed starting from fuel saving and fuel unit cost:

$$S = \left(m_{f,CV} - m_{f,HSV}\right) c_f \qquad (11)$$

The pay-back, in terms of years necessary to restore the additional costs respect to conventional vehicle, can be therefore estimated:

$$PB = \frac{C_{HSV}}{n_D S} \qquad (12)$$

V. OPTIMIZATION APPROACH

The models presented in the previous chapters allow to achieve the optimal design of the HSV via mathematical programming, considering both technical and economic aspects. The payback is assumed as objective function, while design variables X are represented by Car Average Power P_{av}, horizontal and vertical panel area $A_{PV,H}$ and $A_{PV,V}$, car dimensions (l,w,h) and by the weight reduction factor of car chassis with respect to commercial car.

$$\min_X \; PB(X) \qquad (13)$$

$$G_i(X) \le 0 \qquad i = 1, N_G \qquad (14)$$

The inequality constraints G_i (18) express the following conditions:

i) Power to Weight ratio comparable with the corresponding values for the conventional vehicle, at the same peak power.

ii) Car dimensions, length to width and height to width ratios within assigned limits, obtained by the database of commercial vehicles.

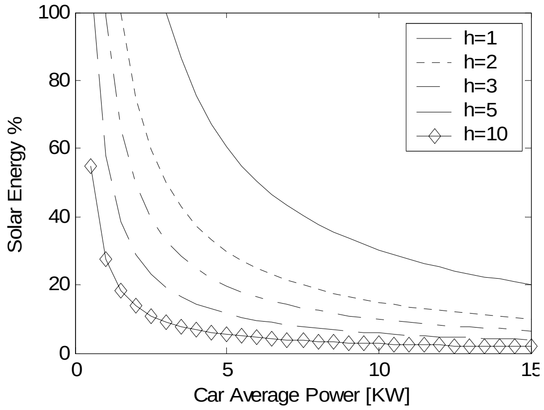
iii) PV panels area compatible with car dimensions, according to the given geometrical model.

VI. RESULTS

A. Solar fraction

A simple energy balance allows to estimate the relative contribution of solar energy to propulsion, during a typical day. Their values have been estimated by varying the number of driving hours per day (from 1 to 10), and for a range of average power (0-20 KW), considering the average yearly net solar energy obtainable in San Antonio, TX (about 30° of latitude) with 6 m^2 of PV panels in horizontal position. It may be observed that, in case of “continuous” use (h_d=10), the solar energy can completely satisfy the required energy only at very low power (about 1 KW), of course not compatible with “normal” use of a car. It also emerges that if the car is used in intermittent way and at limited average power, a significant percent of the required energy can be provided by the sun. For instance, a car operating for 2 hours a day at 5 KW or for 1 hour at 10 KW can save about 30% of fuel.

Fig. 2 - SOLAR ENERGY VS. AVERAGE POWER

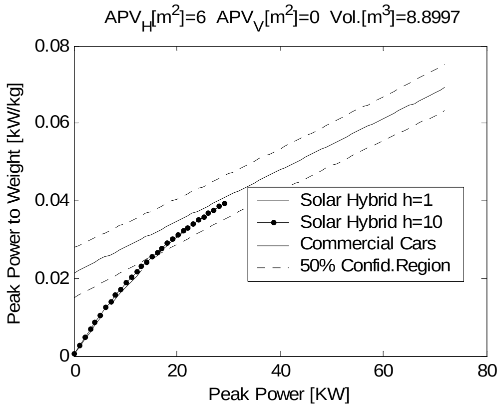


The range of power and driving hours (5-10 KW, 1-2 hours/day) is compatible with the use of a small car in a typical working day, in urban conditions [8].

B. Power to weight

An analysis of power to weight ratio versus peak power and a comparison with the values corresponding to commercial cars is presented in Fig. 3, for a HSV with 6 m^2 of panels in horizontal position.

Fig. 3 – POWER TO WEIGHT VS. PEAK POWER – A_{PV}=6 m^2



The results show that, for 6 m^2 of panels, the HSV exhibit PtW values comparable with commercial cars (i.e. within confidence region) starting from peak power of about 20 KW (and then to average power of 10 KW).

A sensitivity analysis also has been carried out, in order to study the effects of design variables on vehicle performance, weight and costs [11].

D. Optimization analysis

In a previous paper [11], a large set of results have been obtained by applying the presented optimization approach, also analyzing the effects of latitude, costs, prices and layout on optimal vehicle structures, in terms of panel area, vehicle dimension and weight. Some significant results are summarized in the following table:

#	Latitude [deg]	Fuel Cost [€/kg]	PV cost [€/m^2]	PV eff. [/]	PV Area [m^2]	Pay back [yrs]	Solar Fract. [/]
1	30	1.77	800	0.13	0	3.14	0
2	30	1.77	800	0.13	3	6.72	15.1
3	30	3.54	200	0.16	3.65	1.53	27.8
4	60	3.54	200	0.26	2.80	1.36	26.6

Case 1, representing a series HEV without solar panels, is considered as reference, with a payback of 3.14 years respect to the conventional vehicle. The addition of solar panels allows to use 15% of solar energy, but results in a higher payback (from 3.14 to 6.72 years), at the actual costs for fuel and panels. The HSV can represent the optimal solution considering a simultaneous reduction of PV costs (by a factor 4) and an increase in fuel cost (by a factor 2) and in panel efficiency (from 0.13 to 0.16). The variations in prices and costs are significant but not unrealistic, considering actual trends of reduction of solar component costs and increase in oil prices. Case 4, finally, shows that, with further increase in panel efficiency (to 0.26), the HSV can represent the optimal solution also at higher latitudes.

VII. VEHICLE DYNAMIC MODEL

The results presented have been obtained by computing the fuel saving of the HSV with respect to the conventional vehicle with a simplified approach, assuming average values for fuel consumption in the two cases [11], and average yearly solar data. This approach, although sufficient to assess the general feasibility of this solution and to understand the role of the main variables on costs and energy saving, does not allow an accurate evaluation of the effects of vehicle weight and dimensions on inertial and aerodynamic forces during the driving cycle. Moreover, a more precise analysis is required to analyze the effects of control strategies on energy flows, also considering seasonal effects on solar energy. In order to overcome these limitations, a longitudinal vehicle model has been developed to simulate the dynamic behaviour of both HSV and conventional vehicle over a driving cycle. Battery, electric motor and generator have been simulated by the ADVISOR model [14].

VIII. ENGINE CONTROL STRATEGY

In most electric hybrid vehicles, a charge sustaining strategy is adopted: at the end of a driving path, the battery state of charge should remain unchanged. With a solar hybrid vehicle, a different strategy should be adopted, since battery can be charged during parking hours too. In this case, a suitable strategy can try to maintain the state of charge during a whole day.

In order to minimize fuel consumption, the internal combustion engine is operated whenever possible at maximum efficiency, corresponding to power P_{opt} .If the energy required to restore battery charge is lower than the amount corresponding to a continuous use at P_{opt} during the driving time h_d (case B), an intermittent operation can be adopted (cases A1-A2), in order to avoid low efficiency part-load operation. In case that more energy respect to case B is required, the internal combustion engine is operated at constant power between P_{opt} and $P_{\max}$ (case C). The different operating modes can be described by the variable ϕ , ranging from 0 to $\phi_{\max} = P_{\max} / P_{opt}$, as described in the table below.

A1	$\phi < 1$	$P_{ICE} = P_{opt}$	$0 < t < \phi h_d$
A2		$P_{ICE} = 0$	$\phi h_d < t < h_d$
B	$\phi = 1$	$P_{ICE} = P_{opt}$	$0 < t < h_d$
C	$1 < \phi < \phi_{\max}$	$P_{ICE} = \phi P_{opt}$	$0 < t < h_d$

The value of ϕ is found by imposing that the energy provided by ICE and by PV panels must equate the energy required for driving, so that the State of Charge (SOC) remains unchanged over a day:

$$\Delta SOC(\phi) = \int dSOC(\phi) dt = 0 \tag{15}$$

This non-linear equation is solved by iterative techniques.

Other strategies are also possible, for instance in case that the ICE could run during parking mode too: in that case, the engine could restore battery charge by operating always at its maximum efficiency.

RESULTS

Some results obtained by the vehicle dynamic model are shown in next figures. It is assumed that the driving module (in this case an ECE cycle) is repeated continuously N_{cycles} times during the driving time h_d , and that the solar power is constant during the h_{sun} hours. Therefore, the increment of state of charge ΔSOC_{park} during parking time $h_{park} = h_{sun} - h_d$ can be computed, and the corresponding increment during each driving cycle estimated as:

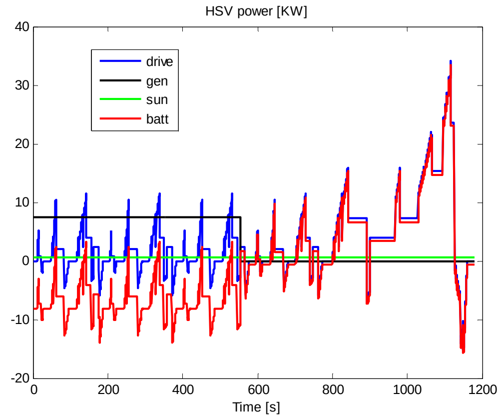
$$\Delta SOC_{cycle} = \frac{\Delta SOC_{park}}{N_{cycles}} \tag{16}$$

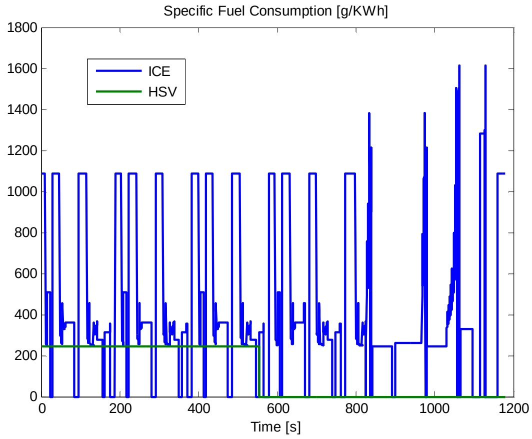
With HSV, the thermal engine works at its highest efficiency for the first part of the cycle (green line), recharging the battery, while is off in the second part. In case of conventional vehicle (blue line), instead, the ICE works in most cases at partial loads, with higher values of specific fuel consumption. The resulting variation of the state of charge (SOC) of the battery is also shown.

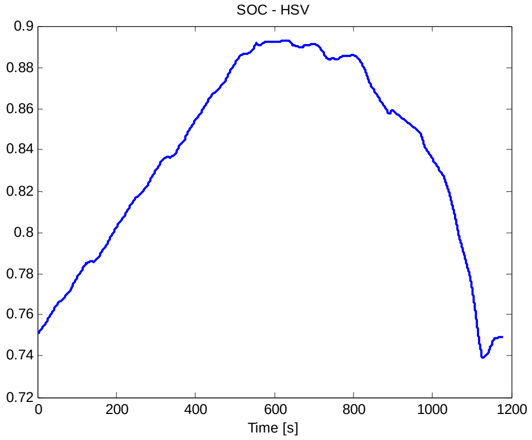
The undergoing activity is finalized to integrate the vehicle model with weight and cost models and to obtain the optimal vehicle configuration by means of the optimization approach, in order to analyze in a comprehensive framework performance, energy saving and costs.

In order to validate these studies, a prototype of HSV with series structure is being developed at DIMEC, within a project funded by EU [16].

CONCLUSIONS







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