TOWARD A SUPERVISORY CONTROL OF A HYBRID SOLAR VEHICLE

Ivan Arsie, Raffaele Di Martino, Gianfranco Rizzo, Marco Sorrentino

Department of Mechanical Engineering, University of Salerno, 84084 Fisciano (SA), Italy

Abstract: A study on optimal energy management on a hybrid solar vehicle (HSV) with series structure is presented. Previous results obtained by optimal design analysis for HSV have confirmed the relevant benefits of such vehicles with respect to conventional cars in case of intermittent use in urban driving (city-car), and that economical feasibility could be achieved in a near future. In order to develop a supervisory control for a HSV prototype now under development at University of Salerno, a study on the performance achievable by an intermittent use of the ICE powering the electric generator is presented. In particular, the effects of engine thermal transient on fuel consumption are studied and discussed. The optimal ICE power trajectory is found by solving a non-linear constrained optimization that suitably accounts for fuel mileage and state of charge, also considering solar contribution during parking mode.

Keywords: Engine Modeling, Engine Control, Optimization, Hybrid Vehicles, Solar Energy.

1. INTRODUCTION

In the last years, increasing attention is being spent towards the applications of solar energy to electric and hybrid cars. While solar cars 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 [1], [2], [3], [4], [5]. In fact, thanks to a relevant research effort [6], [7], [8], [9], in the last decade Hybrid Electric Vehicles (HEV) have evolved to industrial maturity, and represent now a realistic solution to important issues, such as the reduction of gaseous pollution in urban drive as well as the energy saving requirements.

The use of solar energy on cars has been considered with a certain scepticism 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 passenger (i.e. the driver) [10]. 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 [19].

In spite of their potential interest, solar hybrid cars have received relatively little attention in literature [5]. Some prototypes have been developed in last decade in Japan [1], [2], at Western Washington University [3], [4] and at the Queensland University [11]. Although these works demonstrate the general feasibility of such an idea, detailed presentation of results and performance, along with a systematic approach to solar hybrid vehicle design, seem still missing in literature. Therefore, appropriate methodologies are required to address both the rapid changes in the technological scenario and the increasing availability of innovative, more efficient components and solutions. A specific difficulty in developing a Hybrid Solar Vehicle (HSV) model relates to the many mutual interactions between energy flows, power-train balance of plant and sizing, vehicle dimension, performance, weight and costs, whose connections are much more critical than in either conventional or hybrid electric vehicles. Moreover, the control strategies for HSV cannot be simply derived from the solutions developed for HEV. In fact, the presence of solar panels requires to extend the SOC management strategies also to parking phases, while the study of suitable control techniques is needed in order to maximize the net power from solar panels (MPPT). Finally, many HSV prototypes tend to adopt a series structure, while most of today HEV adopt a parallel or series/parallel

approach. Series structure appears more suitable for plug-in hybrid applications [5], and is compatible with the use of in-wheel motors with built-in traction control and anti-skid [11], [24].
The current study focuses on the extension of the analysis methodologies presented in [12], [13], [19] to the control of a hybrid solar vehicle prototype, now under development at the University of Salerno. This activity is being conducted in the framework of the UE funded Leonardo project I05/B/P/PP-154181 "Energy Conversion Systems and Their Environmental Impact" [18]. The on going research is also extended to the study of real time control of solar panels (MPPT techniques and their implementation) and to the development of converters specifically suited for automotive applications [20].

2. THE SOLAR HYBRID VEHICLE MODEL

Different architectures can be applied to HEVs: series, parallel, and parallel-series. The two latter structures have been utilized for two of the more widely available hybrid cars in the market: Toyota Prius (parallel-series) and Honda Civic (parallel). Instead, for solar hybrid vehicles the series structure seems preferable [5], due to its simplicity, as in some recent prototypes of EV [24] and HSV [11]. With this approach, the Photovoltaic Panels (PV) assist the Electric Generator EG, powered by the Internal Combustion Engine (ICE), in recharging 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, corresponding to its optimal efficiency, while the electric motor EM is designed to assure the attainment of the vehicle peak power.

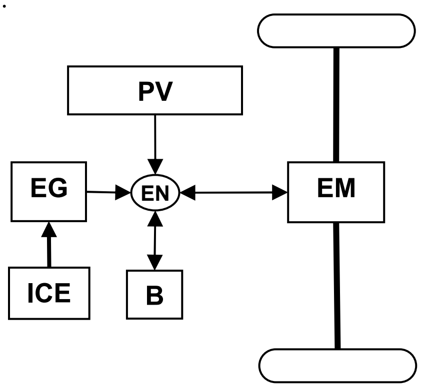


Fig. 1 - Scheme of the series hybrid solar vehicle.

2.1 Solar energy for vehicle propulsion

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 [13]. The maximum panel area can be estimated as function of car dimensions and shape, by means of a simple geometrical model. An analysis of the effect of panel position at different latitudes has been recently presented by the authors [12].
The instantaneous power (*P(t)*) is estimated for assigned vehicle data and driving cycle, integrating a longitudinal vehicle model based on a dynamic vehicle simulator developed by the authors [16]. The model allows estimating the drive torque and power requested by the vehicle to accomplish the imposed driving cycle, depending on transmission ratio and efficiency, aerodynamic losses (CX, cross section) and weight. Thus, the required driving energy depends on vehicle weight and aerodynamic parameters, which in turn depend on the sizing of the propulsion system components and on vehicle dimensions, related to solar panel area. Battery, electric motor and generator have been simulated by the ADVISOR model [17].

2.2 Vehicle weight

The parametric weight model of the HSV can be obtained adding the weight of the specific components (PV panels, battery pack, ICE, Generator, Electric Motor, Inverter) to the weight of the Conventional Vehicle (CV) equipped with ICE (W_{CV}) and by subtracting the contribution of the components resized or not present in the HSV (i.e. ICE, gearbox, clutch, as detailed in a previous work [12].
Thus, the body (i.e. $W_{body,HSV}$) and whole (W_{HSV}) mass of the HSV can be expressed as:

$$W_{body,HSV} = W_{CV} - P_{ICE,CV} \cdot \left(w_{ICE} + w_{gear}\right) \quad (1)$$

$$\begin{aligned} W_{HSV} &= W_{body,HSV} + \\ &+ P_{EG} \cdot \frac{w_{ICE}}{\eta_{EG}} + P_{EG} \cdot w_{EG} + P_{EM}\, w_{EM} \quad (2) \\ &+ A_{PV}\, w_{PV} + w_{B,u} \cdot N_B \end{aligned}$$

Considering the lay-out described in Fig. 1 , the required nominal battery power is:

$$P_B = P_{EM} - P_{EG} \quad (3)$$

Therefore the number of battery modules is evaluated as:

$$N_B = \frac{P_{EM} - P_{EG}}{P_{B,u}} \quad (4)$$

where $P_{B,u}$ is the nominal power of a single battery module.
The power of the electric machine (P_{EM}) is computed imposing that the HSV Power to Weight ratio (PtW_{HSV}), corresponds to a 1250 kg conventional vehicle (CV) powered by a 75 kW gasoline engine, as reported in *Tab. I.*

$$PtW_{HSV} = \frac{P_{ICE,CC}}{W_{body,CC}} \quad (5)$$

$$P_{EM} = PtW_{HSV} \cdot W_{HSV} \quad (6)$$

	CV	HSV
P_{ICE} [kW]	75	46
P_{EG} [kW]	0	43
P_{EM} [kW]	0	90
N_B [/]	0	28
A_{PVH} [m^2]	0	3
W [kg]	1250	1500

Tab. I – Vehicle Technical Data.

2.3 Cost estimation

In order to assess the benefits provided by HSV with respect to conventional vehicles, the additional costs due to both hybridization and solar panels, and the achievable fuel savings have to be estimated. The additional cost C_{HSV} can be expressed starting from the estimated unit cost of each component:

$$C_{HSV} = P_{EG} \cdot \frac{c_{ICE}}{\eta_{EG}} + P_{EG} \cdot c_{EG} + A_{PV} c_{PV} + P_{\max} c_{EM} + C_B N_B - P_{ICE,CV} \cdot c_{ICE} \quad (7)$$

The last term accounts for cost reduction for Internal Combustion Engine in HSV (where it is assumed $P_{ICE} = P_{EG}/\eta_{EG}$) with respect to conventional vehicle (where $P_{ICE} = P_{ICE,CV}$).
The unit costs c_{ICE}, c_{PV} and c_{EM} have been set according with the values estimated in a previous work [12].
The daily saving with respect to conventional vehicle can be computed starting from fuel saving and fuel unit cost:

$$S = \left(m_{f,CC} - m_{f,HSV}\right) \cdot c_f \quad (8)$$

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

$$PB = \frac{C_{HSV}}{n_D S} \quad (9)$$

For further details about the meaning and the values of some of the parameters introduced in eqs. 1 through 9, the reader is addressed to previous work [12], [19].

3. ENERGY FLOW MANAGEMENT AND CONTROL IN A HYBRID SOLARVEHICLE

Hybrid Solar Vehicles have of course many similarities with Hybrid Electric Vehicles, for which many studies on the optimal management and control of energy flows have been presented in last years [6], [7], [8], [9], [26], [27], [28]. Nevertheless, 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.

In fact, 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 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 [13] [19].
Moreover, the series configuration suggests quite an efficient solution, namely to operate the engine in an intermittent way at constant operating conditions. Of course, the maximum gain in terms of fuel consumption occurs when the ICE power corresponds to the most efficient value. In such case, the engine-generator 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. The techniques developed for HEV, mostly adopting parallel or series/parallel structure, tend to treat the engine as a continuous system working in the whole range of operating conditions. This approach is also followed in some recent studies to HSV, based on the application of Dynamic Programming and Model Predictive Control [24].
In case of engine intermittent operation, the effects exerted on fuel consumption and emissions by the occurrence of thermal transients in engine and catalyst should be considered. These effects are neglected in most studies on HEV, where a steady-state approach is usually used to evaluate fuel consumption and emissions.
A preliminary analysis of HSV energy management has been presented in previous papers by considering a single period for ICE operation within the driving cycle module, at specified position (i.e. at the end of driving cycle) [19], [23]. This approach allows to take into account the key aspects related to control, in a framework where the main target was to estimate the effects of different vehicle and powertrain variables on energy flows. This procedure has been integrated in the vehicle dynamic model, also considering weight and costs, and used to study optimal vehicle design.
In order to develop a supervisory control to be implemented on the vehicle, a more accurate analysis of the optimal ICE power distribution over an arbitrary driving cycle has to be performed.

4. EFFECTS OF ICE INTERMITTENT OPERATION

The intermittent operation of the ICE produces the occurrence of thermal transients both in engine and in catalyst, so influencing fuel consumption and emissions. These effects should be analyzed and taken into account for energy flow management and control, also in order to develop suitable solutions for vehicle thermal management. In this paper, the aspects related to engine thermal transients are

considered, while the effects on catalyst and emissions will be analyzed in future developments.
A study on the optimal ICE power trajectory has been performed by solving the following constrained optimization problem:

$$\min_X \int \dot{m}_{f,HSV}(X)dt \tag{10}$$

subject to the constraints:

$$\Delta SOC_{day}(P_{EM}, P_{ICE}(X), P_{SUN}) = 0 \tag{11}$$

$$SOC > SOC_{\min} \tag{12}$$

$$SOC < SOC_{\max} \tag{13}$$

The decision variables X include, for each ICE-on event, starting time, duration and ICE power level, while the number N of ICE-on phases has been assigned, in order to analyze its influence on the results.
The first constraint allows to restore the initial state of charge within the end of the day, also considering parking phases. It requires the integration of the vehicle dynamic model over the day. P_{EM} is known from the assigned mission profile, while also net power from sun is considered known. P_{ICE} depends on the decision variables X.
It is worth noting that the proposed control strategy is based on the knowledge of the vehicle route, thus being unsuitable for real-time control. Nevertheless the proposed approach is consistent with the purpose of the paper, that is aimed at analyzing the effects of engine operation on fuel efficiency. This task will be helpful for the future development of supervisory HSV control, extending to HSV the approach based on provisional load estimate recently applied by the authors to HEV real-time control [9].
The minimum and maximum allowed values for SOC are imposed considering battery reliability, while the limit on maximum SOC during driving phases is due to the exigency to assure a battery capacity sufficient to store the expected solar energy during parking time. Further constraints are introduced to limit the ICE power within the operating range and to avoid ICE operation phases overlapping.
The driving cycle is composed of 4 modules of ECE-EUDC cycle, as shown in Fig. 2.

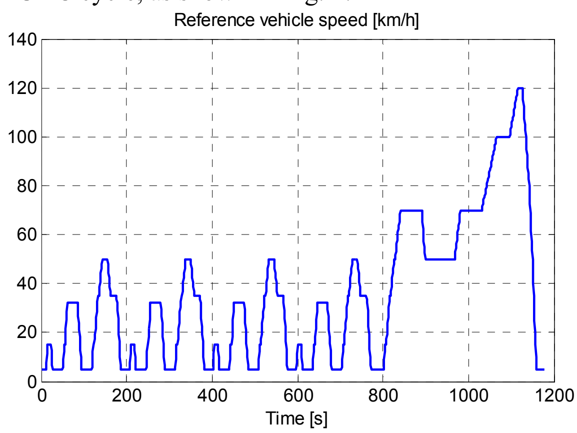


Fig. 2 – Module of the ECE-EUDC driving cycle.

A first series of results has been obtained by neglecting the effects of thermal transient on engine operation, so assuming that the ICE can operate at warmed up conditions (case A).
In a second series of results (case B) the effects of thermal transients have also been considered, assuming that (i) the ICE power does not reach instantaneously its reference value and (ii) the specific consumption depends not only on ICE power but also on the actual engine temperature.
The coolant temperature T has been assumed as engine reference temperature. The time variation of T has been estimated as a first order process by the following equation:

$$T(t) = T_{in} + (T_{ss} - T_{in})e^{-\frac{t}{K}} \tag{14}$$

The values of steady state temperature T_{ss} and of the time constant K have been assigned according to the following table, based on some experimental tests performed at DIMEC test bench:

ICE operation	T_{ss} [°C]	K [s]
ON	82	150
OFF	27	600

The estimation of fuel consumption (Eqs. 16 and 17) is obtained by correcting the steady-state values, corresponding to thermal equilibrium conditions, by a factor depending on the ratio between the actual and steady-state values of engine temperature.

$$P(t) = P_{ss} \cdot f\left(\frac{T}{T_{ss}}\right) \tag{15}$$

$$SFC(t) = SFC_{ss}(P) \Big/ f\left(\frac{T}{T_{ss}}\right) \tag{16}$$

In the following Fig. 3, the percent gains in fuel economy with respect to the reference conventional vehicle are presented. In case A (steady-state approach), the fuel economy gain increases with the number of ICE operation. In fact, the adoption of a larger number of ICE operation phases might allow to allocate them in the most convenient positions with respect to vehicle power demand and battery status.

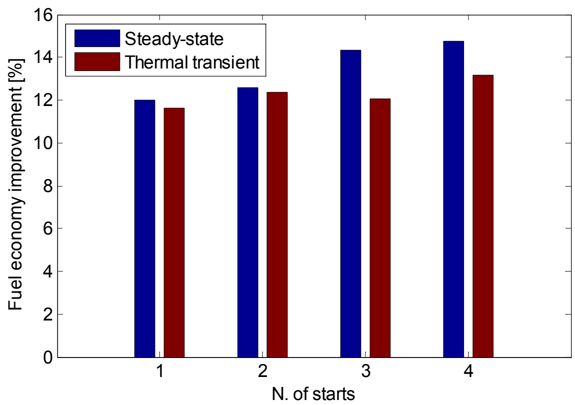
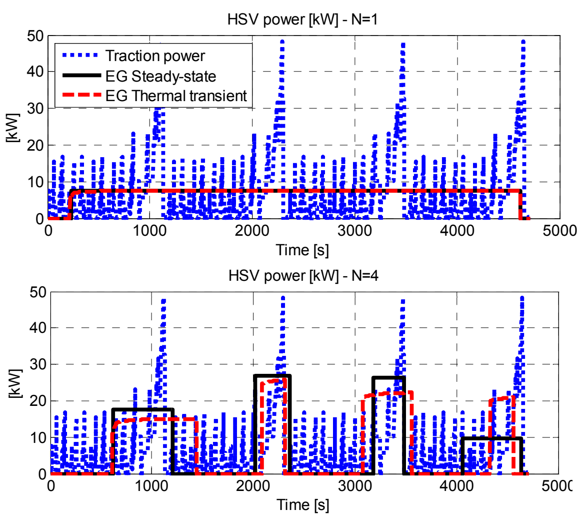


Fig. 3 – Impact of ICE-on events and thermal transient effect on fuel economy improvement.

When thermal transients are considered (Case B), the gain in fuel economy is lower, as a consequence of the lower efficiencies at which the engine operates during the warming up phase until the steady state temperature is reached.
The differences with respect to case A tend to increase with the number of start-stop phases, causing a higher incidence of thermal transients.

Fig. 4 shows the model outputs computed in case of 1 and 4 ICE-on events for both case A and case B. For the current work, the simulated HSV configuration corresponds to the one that maximizes fuel economy, as indicated by the authors themselves in a previous work [13].
The figure shows the power contributions from the electric generator (black line) to meet the traction power demand, whereas battery and solar panels (the latter being constant and quite negligible during driving phases) power trajectories were omitted for sake of clarity. It is interesting to note how for N=4 the constrained optimization analyses led to place the ICE-on events in correspondence of the highest power demands. This result, which holds valid independently of whether the thermal transient is accounted for or not (see Fig. 4 for N=4), can be explained by considering that it allows to reduce low-load, less efficient ICE operations. As expected, the delay with which the ICE reaches the regime in case B causes the optimal power levels and ICE-on duration to set at different values as compared to case A. This aspect significantly impacts the state of charge trajectories simulated for N=4, which denote a significant difference between case A and case B. On the other hand, in case of one ICE-on event the thermal transient has a much lower influence of optimal power levels and ICE-on duration, thus resulting in quasi-identical SOC trajectories in case A and B (see Fig. 4 N=1). It is also worth remarking that both in Fig. 5 N=1 and Fig. 5 N=4 the final state of charge differs from the initial one by the value corresponding to the energy storable during parking hours through the solar panels.



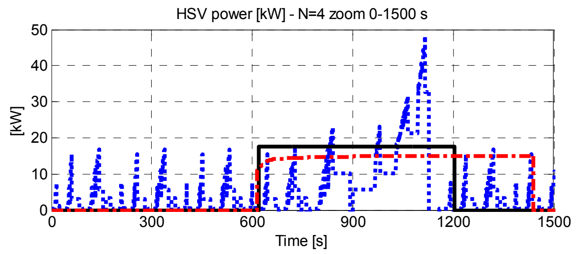


Fig. 4 – Power contributions for the selected driving cycle ($A_{PV,H}$ = 3 m^2, P_{EG} = 43 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).

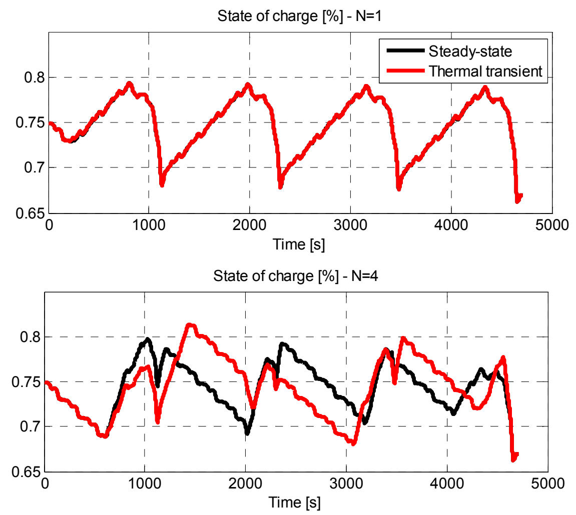


Fig. 5 – Battery state of charge ($A_{PV,H}$ = 3 m^2, P_{EG} = 43 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).

Fig. 6 shows the engine temperature trajectories simulated in case B. The comparison between N=1 and N=4 shows that, as expected, longer intervals between two active engine phases determine higher temperature decay and a longer ramp in next active phase (see Fig. 4 N=4 zoom, where a zoom in the time window 0-1500 s is shown). This effect, which is more evident for N=4 than N=1, determines higher fuel consumption during the power ramps shown in Fig. 4 N=4. Nevertheless, the availability of a higher number of decision variables when 4 ICE-on events were assigned allowed to compensate the negative impact of the above effect on fuel consumption, as confirmed by the bar-plot shown in Fig. 3.

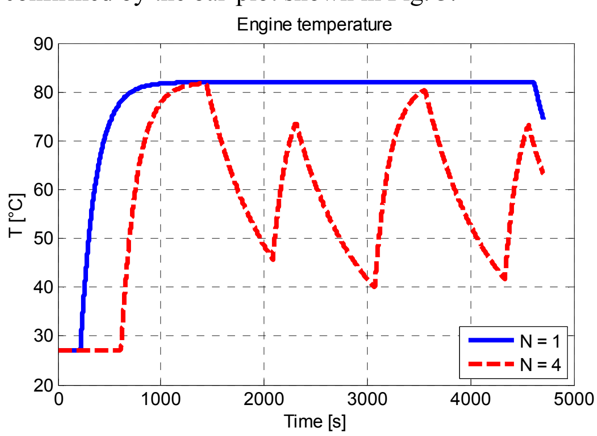


Fig. 6 – Engine temperature when thermal transient is accounted for ($A_{PV,H}$ = 3 m^2, P_{EG} = 43 kW, l = 4.2 m, w = 1.75 m, h =1.5 m).

5. HSV PROTOTYPE

A prototype of solar hybrid vehicle with series structure is being developed at the University of Salerno, within the EU supported Leonardo Program I05/B/P/PP-154181 “Energy Conversion Systems and Their Environmental Impact” (www.dimec.unisa.it/leonardo), starting from the Electric Vehicle *Piaggio-Micro-Vett Porter*, shown in Fig. 7.

Fig. 7 – The Hybrid Solar Vehicle Prototype.

5.1 SIMULATION OF HSV PROTOTYPE

In this section a simulation-based comparative analysis is performed to assess the potential fuel savings achievable by means of solar hybridization of conventional cars. Due to the lower power to weight ratio of the reference vehicle, i.e. the Porter commercialized by Piaggio, such an analysis has been performed over a driving route composed of 4 ECE modules, as shown in Fig. 8.

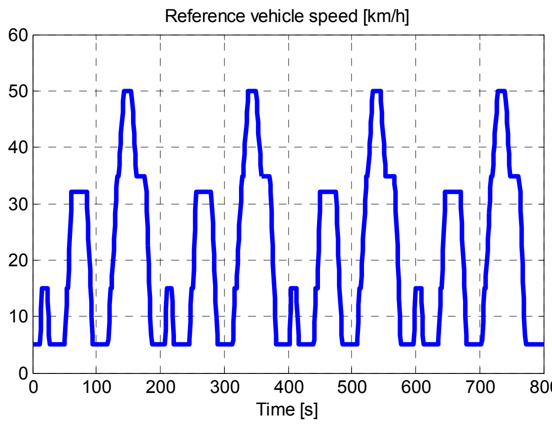


Fig. 8 – Module of the ECE-EUDC driving cycle.

The specifications of both reference and HS vehicle are reported in *Tab. II*. It is worth noting how HSV components were designed applying the weight model described in section 2.2, thus guaranteeing that the two vehicles have the same power to weight ratio.

	CV	HSV
P_{ICE} [kW]	48	32
P_{EG} [kW]	0	30
P_{EM} [kW]	0	51
N_B [/]	0	13
A_{PVH} [m^2]	0	1.44
W [kg]	1550	1644

Tab. II – Vehicles Technical Data.

Fig. 9 a-d show the model outputs computed for the HSV prototype over the selected driving schedule. Following the indications provided in the previous section, 4 ICE-on events were adopted to maximize fuel economy improvement. Fig. 9-b shows that such a strategy allows to operate the ICE mostly in the high-efficiency rpm range, whereas the CV ICE always operates in transient conditions and partial loads, with higher values of specific fuel consumption. The different behaviour of engine operation results in a significant improvement in fuel economy in case of HSV, as indicated in *Tab. III*, where fuel economy improvement is estimated considering that the vehicle is driven for 1 hour.

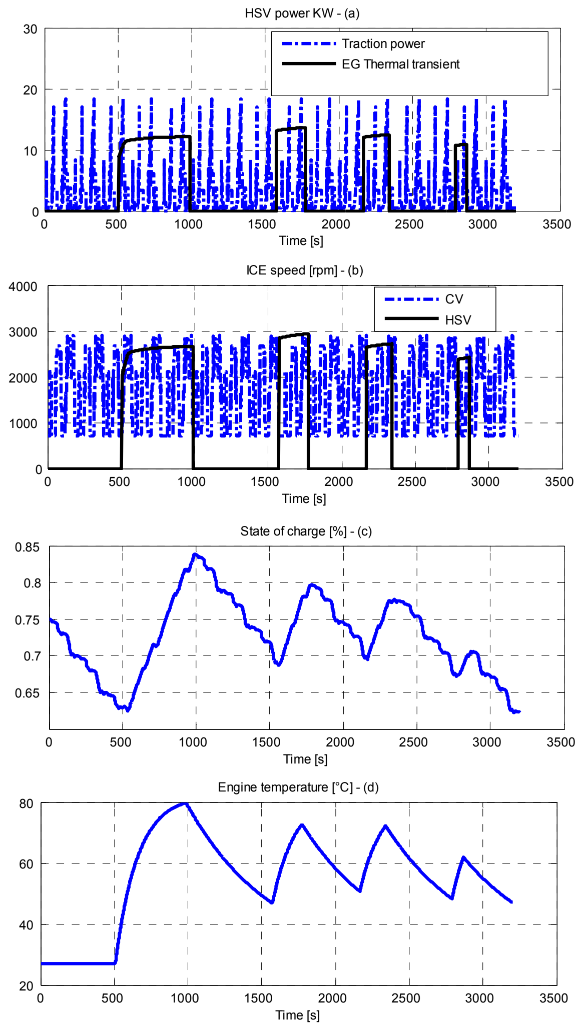


Fig. 9 – Simulation results for the HSV prototype over the selected driving route, composed of 6 ECE modules.

	HSV	CV
Fuel consumption (kg per cycle)	0.84	1.04
Fuel economy improvement (%)	19	/

Tab. III – Fuel saving associated with solar hybridization of the reference car.

6. CONCLUSIONS

A study on energy flow management in a hybrid solar vehicle with series structure has been presented. Previous results obtained by the integration of a comprehensive HSV dynamic model within an optimization approach have shown the relevant benefits of such vehicles with respect to conventional cars in case of intermittent use in urban driving, and that economical feasibility could be achieved in a near future. In spite of the many similarities, there are some significant differences between HSVs and HEVs: the presence of solar panels, contributing to recharge the battery also during parking phases, and the adoption of a series structure, more suitable with plug-in hybrid concept, instead of the prevailing parallel or series/parallel structure in HEVs. These differences suggest that HSV control cannot be simply borrowed by the solutions adopted for HEV. In order to develop a supervisory control for a HSV prototype, a study on the performance achievable by using the ICE at maximum efficiency in intermittent mode is presented, also considering thermal transient effects on engine power and fuel consumption. The optimal ICE power trajectory is found by solving a non-linear constrained optimization that accounts for fuel mileage and state of charge, also considering solar contribution during parking mode. The results show that the presence of engine thermal transients due to start-stop operation cause a non negligible reduction in fuel economy with respect to the results obtained in steady-state warmed-up case. Moreover, the distributions of ICE operation phases differ from steady-state case, indicating that such effects should be taken into account in HEV and HSV control where ICE start-stop operation can occur. Future developments will include the development of a supervisor control for a HSV prototype, the study of thermal transient in catalyst and their effects on vehicle emissions, and the adoption of strategies for vehicle thermal management.

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8. CONTACT

Ivan Arsie (iarsie@unisa.it)
Raffaele Di Martino (rdimartino@unisa.it)
Gianfranco Rizzo (grizzo@unisa.it)
Marco Sorrentino (msorrentino@unisa.it)
Tel. +39 089 964080 – Fax +39 089 964037
Web www.dimec.unisa.it

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10. DEFINITIONS, ACRONYMS, ABBREVIATIONS

A_{PV}: PV surface (m^2)
c: cost to power ratio (Eur/kW)
c_B: Single battery module cost (Eur)
c_f: fuel unit cost (Eur/kg)
c_{PV}: PV specific cost (Eur/m^2)
e: emissions (g)
$E_{s,d}$: Solar energy stored during driving hours (kWh)
$E_{s,p}$: Solar energy stored during parking hours (kWh)
k: correction factor for thermal transient effects (/)
n_D: number of days per year in the pay-back analysis
P: Power (kW)
S: savings (€/day)
T: temperature (K)
T_{Cat}: mean catalyst temperature (K)
T_{ICE}: mean cylinder wall temperature (K)
v: catalytic converter efficiency (/)
w: weight to power ratio (kg/kW)
w_{PV}: PV specific weight (kg/m^2)
X: decision (control) variables
ΔSOC_d: state of charge variation in driving phases
ΔSOC_{day}: state of charge variation over the whole day
ΔSOC_p: state of charge variation in parking phases (/)
η: efficiency
Subscripts
B,u: single battery module
EM: electric motor
EG: electric generator
gear: gearbox
ICE: internal combustion engine
in: initial
PV: photovoltaic panels
ss: steady state