Optimal Design of a Hybrid Electric Car with Solar Cells

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ABSTRACT: A model for the optimal design of a solar hybrid vehicle is presented. The model can describe the effects of solar panels area and position, vehicle dimensions and propulsion system components on vehicle performance, weight, fuel savings and costs for different sites. It is shown that significant fuel savings can be achieved for intermittent use with limited average power, and that economic feasibility could be achieved in next future considering expected trends in costs and prices.

Keywords: Hybrid Vehicle, Solar Energy, Photovoltaic Panel

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 [1][2][3] and demonstrative purposes [4][5][6], also to stimulate young students toward energy saving and automotive applications [7].

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 (FIG. 1). 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 [8][9][10][11]. In fact, in the last decades Hybrid Electric Vehicles (HEV) have evolved to industrial maturity, after a relevant research effort [12][13][14][15]. These vehicles now represent a realistic solution to the reduction of gaseous pollution in urban drive and to energy saving, thanks to the possibility of optimizing the recourse to two different engines and to perform regenerative braking. 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. Therefore, the feasibility of a hybrid vehicle where solar energy can provide a significant contribution to propulsion is of course questionable. 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 [16].

In spite of their potential interest, solar hybrid cars have received relatively little attention in literature. An innovative prototype (Viking 23) has been developed at Western Washington University [10][11] in the 90's, adopting advanced solutions for materials, aerodynamic drag reduction and PV power maximization with peak power tracking. Another study on a solar hybrid vehicle has been presented by Japanese researchers [8], with PV panels located on the roof and on the windows of the car: fuel consumption savings up to 90% could be achieved in some conditions. A further prototype of solar hybrid car powered with a gasoline engine and an electric engine has been proposed and tested by other Japanese researchers [9]. In this case, a relevant amount of the solar energy was provided by PV panels located at the parking place, while only a small fraction was supplied by PV panels on the car. The hybridization lead to a significant weight increase (350 kg), due to the adoption of lead batteries. A very advanced prototype (Ultra Commuter) has been recently developed at the Queensland University, adopting a hybrid series structure [17].

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. Moreover, cost and prices are also subject to rapid variations, thus requiring the development of a general model considering both technical and economic aspects related to the design and operation of a HSV. 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. A study on energy flows in a HSV has been recently developed by the authors [18]. In the following, a more detailed study on the optimal sizing of a solar hybrid car, including weight and costs, is presented.

FIG. 1 – A PROTOTYPE OF SOLAR CAR

II. STRUCTURE OF THE SOLAR HYBRID VEHICLE

As it is known, two different architectures can be applied to HEV's. In the Series Hybrid Vehicles the ICE powers an electric generator (EG) for recharging the battery pack (B), while the vehicle is powered by an electric motor (EM). The ICE is sized for a mean load power and works at constant load with reduced pollutant emissions, high reliability and long working life. On the other hand, in this configuration the energy flows through a series of devices (ICE, generator, battery pack, electric motor, driveline) each with its own efficiency, resulting in a reduction of the power-train global efficiency [15]. In the parallel architecture, both ICE and EM are mechanically coupled to the transmission and can simultaneously power the vehicle. This configuration offers a major flexibility to different working conditions, but requires more complex mechanical design and control strategies. In this paper, due to its greater simplicity and to recent advances in electric motor and generator technology, we assumed a series architecture for the Solar Hybrid Vehicle, as in the prototype recently developed at the Queensland University [17].

In this case (FIG. 2), the Photovoltaic Panels (PV) concur with the Electric Generator EG, powered by the ICE, to recharge the battery pack B both in parking mode and in driving conditions, through the electric node EN. The electric motor EM can both provide the mechanical power for the propulsion and restore part of the braking power during regenerative braking (FIG. 2). 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}:

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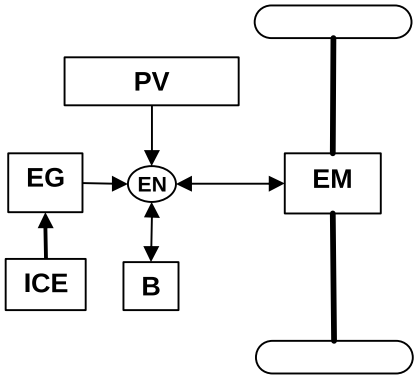
$$P_{\max} = qP_{av} \qquad (1)$$

The adoption of a peak factor q greater that unit is essential to reach acceptable values of power to weight ratio. On the other hand, too large values could result in unacceptable vehicle power decay when battery is depleted. In the following computations, a peak factor of 2 has been assumed.

Although developed for a series structure, this study could be adapted to a parallel architecture with minor changes, and the conclusions seem not strictly limited to the particular structure considered.

FIG. 2 - SCHEME OF THE SERIES HYBRID SOLAR VEHICLE (SEE NOMENCLATURE)



III. ENERGY FLOWS AND PV PANELS LOCATION

In order to estimate the net solar energy captured by PV panels in real conditions (i.e. considering clouds, rain etc.) and available to the propulsion, a solar calculator developed at the US National Renewable Energy Lab has been used [20] [21]. In TAB. I the net average energy per month is reported for four different US locations, ranging from 21° to 61° of latitude, based on 1961-1990 time series. The data refers to a crystalline silicon PV system rated 1 KW AC at SRC, at horizontal and optimal (=latitude) tilt angles. 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. In TAB. II the yearly average energy values with five different panel positions are reported. The tracking technique corresponds to the highest values, with small differences between 2 and 1 axis. It can be also observed that, except at highest latitudes and during winter time, there is not a significant reduction in the captured energy assuming a horizontal position of the PV panel with respect the 'optimal' tilt angle, roughly corresponding to the latitude. In case of vertical position, the energy is about one third of the maximum energy, and ranges from 45% to 65% respect to horizontal position, depending on latitude. The energy captured at vertical position depends also on azimuth angle: the values reported in the table have been obtained as the mean of four different azimuth angles (North, East, South, West), since when the solar vehicle is running the orientation of solar panels is almost random.

TAB. I - AVERAGE NET SOLAR ENERGY [KWH] PER MONTH FOR FOUR DIFFERENT US SITES.

	Honolulu		San Antonio		Chicago		Anchorage	
Month	0	21.33°	0°	29.53°	0°	41.78°	0°	61.17°
1	108	137	85	120	50	95	2	23
2	117	139	100	125	71	106	21	60
3	150	161	136	152	108	132	63	115
4	155	154	144	146	136	143	99	124
5	176	164	165	154	167	157	139	139
6	173	156	169	153	168	149	140	125
7	179	164	185	170	172	157	132	121
8	175	170	170	169	140	140	95	102
9	160	168	138	151	111	131	60	88
10	136	157	124	154	85	123	22	53
11	110	137	93	130	48	81	4	40
12	104	135	79	117	38	70	0	16
Year	1742	1842	1589	1741	1294	1485	778	1004
Day	4.773	5.047	4.353	4.770	3.545	4.068	2.132	2.751

TAB. II - AVERAGE YEARLY NET SOLAR ENERGY [KWH/m^2] WITH DIFFERENT PANEL POSITION.

Latitude [deg]	21.33	29.53	41.78	61.17
2 axis tracking	2547	2279	1963	1384
1 axis tracking	2468	2216	1906	1326
Tilt=Latitude	1842	1741	1485	1004
Horizontal	1742	1589	1294	778
Vertical (average)	785	751	686	509

The most obvious solution for solar cars is the location of panels on roof and bonnet, at almost horizontal position. Nevertheless, a general model could consider at least two additional options: (i) horizontal panels (on roof and bonnet) with one tracking axis, in order to maximize the energy captured during parking mode (this solution is obviously unfeasible during driving); (ii) panels located also on car sides and rear at almost vertical positions (the practical feasibility of this solution is questionable, also due to the limited reliability of panels in case of lateral impacts).

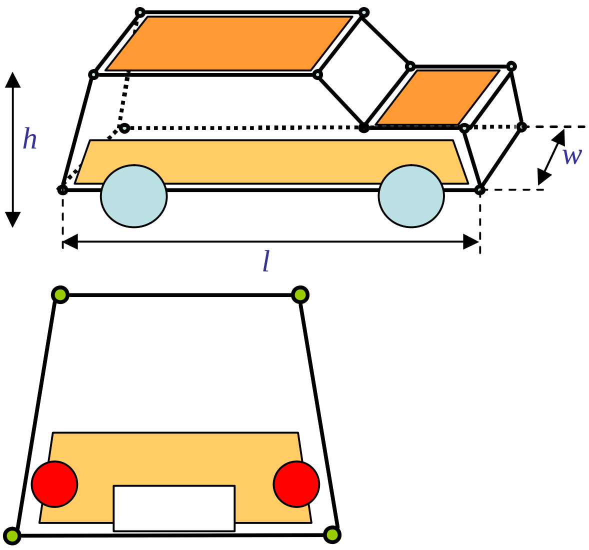


FIG. 3 - SIMPLIFIED SCHEME OF SOLAR CAR (LATERAL AND REAR VIEW).

The maximum panel area can be estimated as function of car dimensions and shape. For the following calculations this simple geometrical model has been used:

$$A_{PV,H,MAX} = lw - 0.30w - 0.05lw \qquad (2)$$

$$A_{PV,V,MAX} = (2l + w)(h - 0.9) - 0.1 \qquad (3)$$

The energy from PV panels can be obtained summing the contributes during parking (p) and driving (d) periods (for simplicity, it is assumed that both parking and driving occur during daytime). While in the former case it is reasonable to assume that the PV array has an unobstructed view of the sky, this hypothesis could probably fail in most driving conditions, where shadow can be due to the presence of trees, buildings and other obstacles. Therefore, the energy captured during driving can be reduced by a factor $\beta<1$, that of course depends on the specific route. 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 (h_{sun} =10). Anyway, this hypothesis does not affect the total energy to the PV panel, which is provided on daily basis.
The values reported in TAB. I take into account the efficiency of the devices (i.e.inverter, cables) to produce AC current, but do not consider the further degradation due to charge and discharge processes in the battery. A factor $\alpha<1$ is then introduced to account for this effect for energy taken during parking. The incident solar energy is computed considering the previously described options for panel positions: horizontal, tracking, vertical. The net solar energy available to the propulsion taken during parking and driving modes can therefore be expressed as:

$$E_{s,p} = h_p A_{PV} e_{sun} \frac{h_{sun} - h_d}{h_{sun}} a \qquad (4)$$

$$E_{s,d} = h_p A_{PV} e_{sun} \frac{h_d}{h_{sun}} b \qquad (5)$$

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:

$$E_d = \frac{1}{3600} \int_{h_d} P(t) \cdot dt = \frac{1}{3600} h_d P_{av} \qquad (6)$$

The instantaneous power can be computed starting from a given driving cycle, for assigned vehicle data, integrating a simplified 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, as shown in the next paragraph.
The contribution of solar energy to the propulsion can be therefore determined:

$$j = \frac{E_{sun}}{E_d} = \frac{E_{s,p} + E_{s,d}}{E_d} \tag{7}$$

The fuel consumption for the conventional vehicle (ICE) and of HSV can be then computed:

$$m_{f,ICE} = \frac{3600 E_d}{h_{ICE} H_i} \tag{8}$$

$$m_{f,HSV} = \frac{(1-j)3600 E_d}{h_{HEV} H_i} \tag{9}$$

In case of HSV, fuel consumption is reduced thanks both to solar energy contribution and to higher efficiency of the hybrid propulsion system: an increase in fuel economy up to 40% has been reported in literature [14]. A precise evaluation of the efficiency of both conventional and hybrid vehicle depends on several variables [13][19], including control system, not yet considered in this model. Average values of 30% and 40% have been assumed respectively for ICE and HEV efficiency.

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.

IV. WEIGHT MODEL

A parametric model for the weight[1] 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, including some "microcars". 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, as shown in TAB. III.

Three cases have been considered (TAB. IV). The best results have been obtained considering as independent variables vehicle power P and the product of car dimensions V (case #3), while in the case #2, even if characterized by the highest R^2 value, too large confidence intervals for coefficients k_4 and k_5 have been obtained, with poor statistical significance of the results. The analysis of the ratio between real and predicted weight for case #3 shows that these values range from 0.91 to 1.06. Therefore, it is realistic to assume that, with proper choice of components and materials and with careful design, the car body used for a HSV can reach a weight corresponding to 90% of the "average" value predicted by the model, for given power and dimensions.

In order to use these data to estimate the base weight of the HSV ($W_{body,HSV}$), it has to be considered that the commercial cars used in the above analysis include also some components not present in the series hybrid vehicle (i.e. gearbox, clutch). Their contribution, estimated as function of power, has been therefore subtracted. The car body also includes other components (thermal engine, electric generator, battery) that would 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. III – POWER, MASS AND DIMENSIONS OF COMMERCIAL CARS

Model	Mass [Kg]	P [KW]	L [mm]	w [mm]	h [mm]
FIAT Panda	840	40	3538	1589	1578
FIAT Seicento	735	40	3337	1508	1420
Ford KA 1.3	900	51	3620	1827	1368
Suzuki Alto	875	46	3495	1475	1455
Ford Fiesta	1050	55	3917	1683	1420
Renault Clio 1.2	910	55	3812	1940	1417
Bingo	400	9.8	2530	1430	1540
Aixam 500 Kubota Diesel	400	9.5	2885	1450	1380
Smart Fourfour 1.1	895	55	3750	1680	1450
Smart Fortwo Brabus	800	55	2500	1515	1549
Opel Agila	965	44	3540	1620	1695
Mini One	1115	66	3626	1688	1416
Mazda 2	1050	55	3925	1680	1545
Nissan Micra	935	48	3726	1595	1540
FIAT 500 D	425	16.2	2970	1322	1325

TAB. IV – 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 further subtractive term (DW) has been introduced, to consider possible weight savings due to use of aluminium instead of steel for chassis: in this case, of course, additional costs would be considered in the cost model [22].

Thus, the mass of the car body for HSV can be expressed as:

$$\begin{aligned} W_{body,HSV} &= \\ W_{body,CV}&(P_{\max}, V) - m_g(P_{\max}) \\ &- m_{ICE}(P_{\max}) - \Delta W \end{aligned} \tag{10}$$

The mass of the HSV can be therefore expressed in the following way:

[1] Although the model deals with the mass of the components, the term "weight" is also used due to its large diffusion in vehicular technical literature.

$$W_{HSV} = W_{body,HSV}\left(P_{\max}, V, \Delta W\right) + \\ + dP_{av}\left(m_{ICE} + m_{EG}\right) + \\ + P_{\max} m_{EM} + A_{PV} m_{PV} + C_B m_B \qquad (11)$$

The mass of the electric motor EM is considered as function of the maximum power, while the mass of internal combustion engine ICE and electric generator EG are proportional to average power. The factor δ=1.5 is due to the assumption that the maximum power of ICE is 50% greater than its average power, corresponding to maximum efficiency. A peak factor θ=2, ratio between vehicle maximum power and average power, has been assumed. The mass of PV panels depend on their area. The mass of the battery, finally, 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 (λ=2).

$$C_B = l E_p \qquad (12)$$

Of course, many of these assumptions need to be refined and validated both by simulation and optimization and also by experiments on prototypes.

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

$$PtW_{HSV} = \frac{P_{\max}}{W_{HSV}} \qquad (13)$$

V. 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, whose values are reported in Nomenclature:

$$C_{HSV} = dP_{av}\left(c_{ICE} + c_{EG}\right) + \\ + A_{PV} c_{PV} + P_{\max} c_{EM} + C_B c_B + \\ + \Delta W c_{al} - \Delta C_{ICE} \qquad (14)$$

The last two terms account for: i) possible weight reduction in chassis due to use of aluminum [22] and ii) the cost reduction for Internal Combustion Engine in HSV (where it is assumed $P_{ICE}=d\,P_{av}$) with respect to conventional vehicle (where $P_{ICE}=P_{max}$).

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

$$S = \left(m_{f,CV} - m_{f,HSV}\right) c_f \qquad (15)$$

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

$$PB = \frac{C_{HSV}}{n_D S} \qquad (16)$$

VI. OPTIMIZATION APPROACH

The models presented in 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 respect to commercial car.

$$\min_X \; PB(X) \qquad (17)$$

$$G_i(X) \le 0 \qquad i = 1, N_G \qquad (18)$$

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 (19).

ii) Car dimensions, length to width and height to width ratios within assigned limits, obtained by the database of commercial vehicles (the maximum values for l,w,h have been augmented by a factor 1.5, while the minimum values of l,w,h and the limit values of l/w and h/w coincide with their corresponding values in the database of TAB. III). The satisfaction of the constraints (21-22) assures that the resulting dimensions are almost compatible with the major requirement of a car, in terms of space and stability.

iii) PV panels area compatible with car dimensions, according to the given geometrical model (22).

$$\frac{PtW_{HSV}}{PtW_{CV}} \ge y \qquad \textbf{(19)}$$

$$l_{\min} \le l \le l_{\max} \qquad \textbf{(20)}$$

$$w_{\min} \le w \le w_{\max}$$

$$h_{\min} \le h \le h_{\max}$$

$$\left(\frac{l}{w}\right)_{\min} \le \frac{l}{w} \le \left(\frac{l}{w}\right)_{\max} \qquad \textbf{(21)}$$

$$\left(\frac{h}{w}\right)_{\min} \le \frac{h}{w} \le \left(\frac{h}{w}\right)_{\max}$$

$$A_{PV,H} \le A_{PV\max,H}(l,w) \qquad \textbf{(22)}$$

$$A_{PV,V} \le A_{PV\max,V}(l,w,h)$$

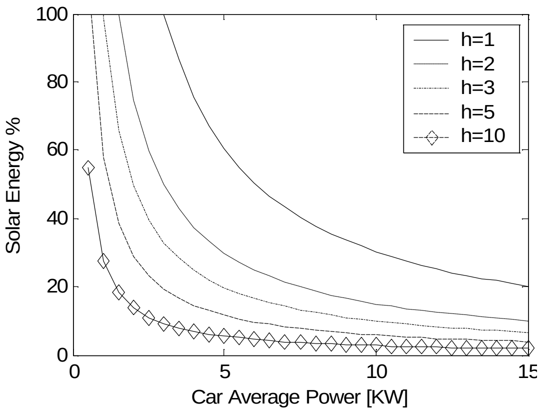
The mathematical programming problem has been solved by routine FMINCON of Matlab®.

VII. Results

A. Solar fraction

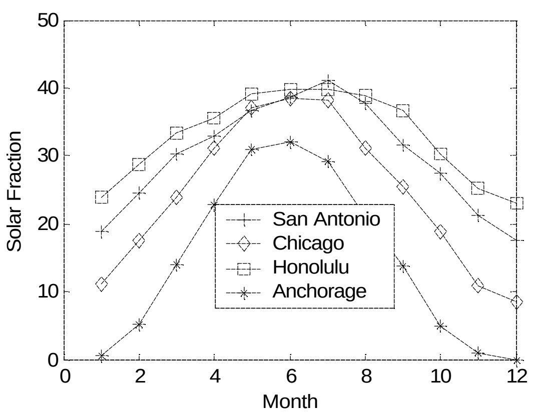
A simple energy balance allows estimating the relative contribution of solar energy to propulsion, during a typical day. Their values have been estimated by varying the number of driving hours per day (from 1 to 10), and for a range of average power (0-20 KW), considering the average yearly net solar energy obtainable in San Antonio (TAB. I), 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 satisfy completely 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. 4 - Solar energy contribution vs. average power



The relative solar contribution obtainable for various locations and months are reported in
Fig. 5. It may be observed that the solar contribution can raise up to 40% during summer time, at lowest latitudes, while is negligible in Alaska during winter time, as expected. These values agree with the results obtained by other researchers for solar hybrid vehicles [8].

Fig. 5 – Solar fraction in various locations and months (P_{av}=5 KW, h_d=2)



The range of power and driving hours (5-10 KW, 1-2 hours/day) is compatible with the use of a small car as the ones described in TAB. III in a typical working day, in urban conditions [16]. But, unlike the "microcars", the HSV should sustain the additional weight due to hybridization, including a battery of adequate capacity to store the energy during parking time, and of solar panels, that impose further constraints on vehicle dimensions and weight.

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. 6, for a HSV with 6 m^2 of panels in horizontal position. The dimensions of HSV have been selected as the ones corresponding to the minimum dimension product (i.e. minimum car body weight), by solving the following constrained minimization problem:

$$\min_{lwh} V = lwh \tag{23}$$

$$A_{PV,V} = (2l + w)(h - 0.9) - 0.1 \tag{24}$$

$$A_{PV,H} = lw - 0.30w - 0.05lw \tag{25}$$

Fig. 6 – Power to weight vs. peak power – A_{PV}=6 m^2

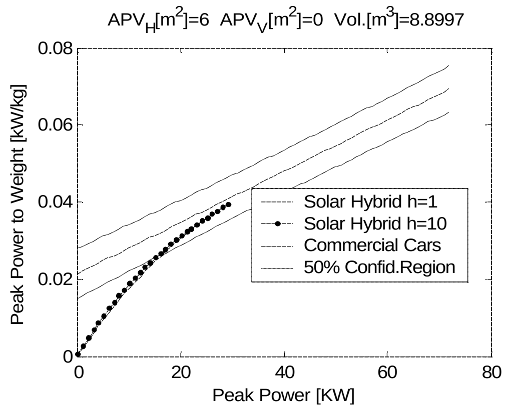
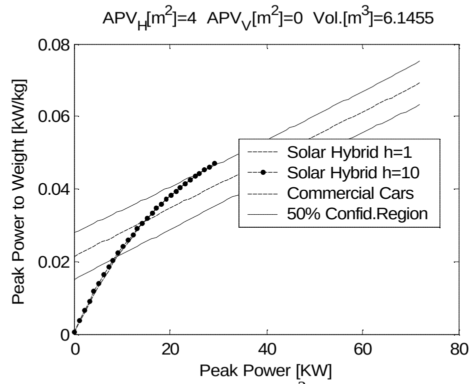


Fig. 7 – Power to weight vs. peak power – A_{PV}=4 m^2



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), while for 4 m^2 of panel area this result is achieved starting from peak power of about 10 KW (Fig. 7), thanks to the reduction in weight for panels, car body and battery (of course, also solar fraction decreases with panel area).

C. Sensitivity analysis

A sensitivity analysis has been also carried out, in order to study the effects of design variables on vehicle performance, weight and costs. It can be observed that a 50% increase in peak factor results in about 40% increase in power to weight ratio and in a 10% increase in vehicle weight, due to weight increment in electric motor, inverter and car body (Fig. 8).

Fig. 8 – EFFECTS OF PEAK FACTOR

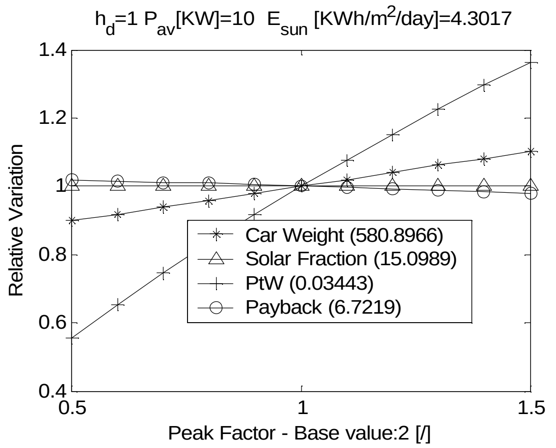


Fig. 9 – EFFECTS OF PV EFFICIENCY

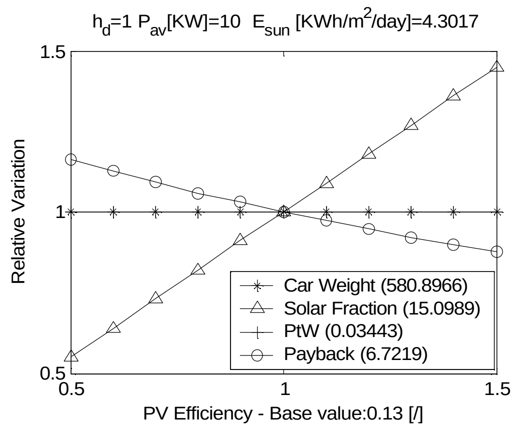
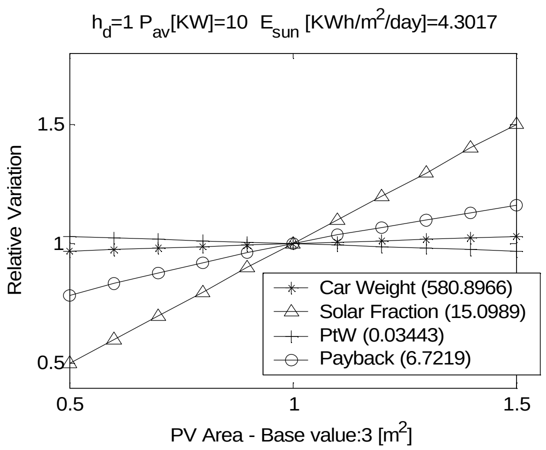


Fig. 10 – EFFECTS OF PV AREA



The effects of PV efficiency (Fig. 9) and PV area (Fig. 10) can be also analyzed. In both cases, their increment result in an almost equal variation in solar fraction, but, while an improvement in panel efficiency results in shorter payback (Fig. 9), an increment in panel area produces higher payback and a slight increment of car weight (Fig. 10).

D. Optimization analysis

Finally, the results achieved by optimization analysis for 36 different cases are presented in appendix (from Tab. V to Tab. X). All the results have been obtained considering the average yearly solar energy for San Antonio (TAB. I), with one hour driving per day ($h_d=1$). For each case, design variables, solar fraction, payback, cost, saving and the weight distribution among single vehicle components are shown. The default values of the missing variables are reported in Nomenclature, while only their variations are indicated in the tables. Although an exhaustive analysis of this large amount of data is beyond the space constraints of this paper, the most relevant outcomes are discussed in the following.

Case 1 (Tab. V) describes a hybrid vehicle with average power of 10 KW, without solar panels. It exhibit a payback of 3.13 years. The addition of 3 and 6 m^2 of solar panels (cases 2-3) increases solar fraction up to 30% but also payback to 8.7 years, since the greater daily saving do not compensate the higher vehicle additional costs. A similar result is obtained in cases 5-6, where the optimization algorithm puts average power to its upper limit (20 KW) to reduce payback. Solar fraction is halved with respect to cases 2-3. This result has been obtained considering up to date unit mass and costs for vehicle components.

The effects of latitude and of vertical panels are investigated in cases 7-12 (Tab. VI). Latitude variation from 30 to 60 degrees produces an increment in payback from 6.7 to 7.9 years, using 3 m^2 of horizontal panels, and from 8.9 to 10.6 years adopting also 2 m^2 of vertical panels (solar fraction of course increases in cases 10-12 with respect to cases 7-9, particularly at high latitudes). The increments in payback with latitude are significant but not dramatic.

The benefits achievable by adopting one axis tracking technique for PV panels in parking mode has been investigated in cases 13-15 (Tab. VII), using 3 m^2 of horizontal panels at different latitudes. The comparison with cases 7-9 shows that solar fraction increases from about 30% at low latitudes to more than 50% at higher latitudes, and payback is reduced of about 10% (but the additional costs and weights for tracking mechanism have not been modelled).

The effects of simultaneous reduction in panel cost and increase in fuel cost and panel efficiency have been analyzed in the cases from 16 to 36 (Tab. VII to Tab. X). It can be observed that HSV represents the optimal solution in many cases, with solar fraction approaching 30% (i.e. #23-25): i.e. PV cost=400 and

PV efficiency=0.26 (#25), PV cost=200 and PV efficiency from 0.13 up (#23-25), PV≤ 200 and PV efficiency≥0.26 (#26, 29-36). The combined effect of latitude has been also analyzed: if at PV cost of 400 the HSV represents the optimal solution only at low latitudes (case 26), by halving the PV cost the solar hybrid vehicle becomes optimal also at high latitudes (25, 29, 30), with little payback variations from 30 to 60 degrees. Also optimal panel area increases with latitude (from 1.97 to 2.80 m^2).

In order to compensate for the additional weight for solar panels and hybridization, in most cases a reduction in chassis weight respect to commercial cars has been adopted, by using aluminium (the variable X(7) is in many cases at its lower value=0.7).

The constraint on power to weight ratio (19) is usually respected (except in cases 8 and 9) and the ratio is often close to unit, while in some few cases (i.e. case 4, 27, 28) PtW is much higher than in commercial car. These aspects should be further investigated in the future, as the distribution of vehicle dimensions and the effects of the constraints (20, 21, 22) on the results.

It can also observed that in some cases the optimal value of solar fraction is invariant respect to panel efficiency and panel unit cost (i.e. cases 23-25, 31-36): this result, that may be related to the linear nature of the model, is worth closer examination too.

VIII. CONCLUSIONS

A comprehensive model for the study and the optimal design of a solar hybrid vehicle with series architecture has been presented, including energy flows, vehicle weight and costs. It has been shown that significant savings in fuel consumption and emissions, up to 40% with respect to hybrid electric vehicles depending on latitude and season, can be obtained with an intermittent use of the vehicle at limited average power, compatible with typical use in urban conditions during working days. The fuel saving with respect to conventional vehicles can be even more impressive, considering that a HEV can save about 40% with respect to actual cars.

This result has been obtained with commercial PV panels and with realistic data and assumptions on the achievable net solar energy for propulsion. The future adoption of last generation photovoltaic panels, with nominal efficiencies approaching 35%, may result in an almost complete solar autonomy of this kind of vehicle for such uses.

By adopting up to date technology for electric motor and generator, batteries and chassis, power to weight ratio comparable with the ones of commercial cars can be achieved, thus assuring acceptable vehicle performance.

Future developments may concern more accurate description of energy flows, the effects of control strategies and more careful analysis of powertrain sizing. More detailed models for component weights and costs, including non-linear effects, can be also necessary, as well as further studies on the interactions between vehicle and propulsion system.

In order to validate these studies, a prototype of HSV will be developed at DIMEC starting from next months, within a project funded by EU (Leonardo Program I05/B/P/PP-154181).

The results obtained by optimization analysis have shown that the hybrid solar vehicles, although still far from economic feasibility, could reach acceptable payback values if large but not unrealistic variations in costs, prices and panel efficiency will occur: considering recent trends in renewable energy field and actual geo-political scenarios, it is reasonable to expect further reductions in costs for PV panels, batteries and advanced electric motors and generators, while relevant increases in fuel cost could not be excluded.

Moreover, the recent and somewhat surprising commercial success of some electrical hybrid cars indicates that there are grounds for hope that a significant number of users is already willing to spend some more money to contribute to save the planet from pollution, climate changes and resource depletion.

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NOMENCLATURE

	Description	Unit	Value
λ	Ratio between battery capacity and daily stored energy	/	2
γ	Reduction factor respect to base car weight	/	0.90
θ	Peak factor (ratio between EM and EG power)	/	2
α	Energy degradation due to charge and discharge process	/	0.90
β	Solar energy reduction due to shadow during daytime driving	/	0.90
δ	Ratio from maximum ICE power and average power	/	1.5
h_{PV}	PV efficiency	/	0.13
A_{PV}	PV area	m^2	
C_B	Battery Capacity	KWh	
C_{HSV}	Additional cost in HSV respect to conventional vehicle	€	
c	Unit cost[2]		
c_b	Battery cost [28]	€/KWh	160
c_f	Fuel cost	€/Kg	1.77
c_{PV}	Solar Panels cost [28][29]	€/m^2	800
c_{EM}	Electric Motor and Inverter Cost [28]	€/KW	16.8
c_{ICE}	Internal Combustion Engine Cost [30]	€/KW	24
c_{al}	Cost for aluminum chassis [22]	€/Kg	5
c_{inv}	Electric Generator Cost [28]	€/KW	16
e_{sun}	Average net solar energy @ SRC rated power of 1 KW [21]	KWh/day	4.353
h_d	Daily driving hours	/	1-10
h_{sun}	Daily hours	/	10
m_{Batt}	Battery energy density (Lithium-Ion) [27]	KJ/Kg	366
m_{EM}	Electric Motor and Inverter Unit Mass	Kg/KW	0.81
m_{PV}	PV unit mass (crystalline silicon)	Kg/m^2	12
m_{ICE}	Internal Combustions Engine Unit Mass	Kg/KW	2
m_{EG}	Electric Generator Unit Mass	Kg/KW	0.83
n_D	Number of days per year of HSV use	/	300
PB	Pay-back in years	/	
PtW	Power to Weight Ratio	KW/Kg	
S	Daily Saving in HSV respect to conventional vehicle	€/day	

ACRONYMS / PEDICES

B	Battery
Body	Car Body
CV	Conventional Vehicle
EG	Electric Generator
EM	Electric Motor
EN	Electric Node
F	Fuel
H	Horizontal
HEV	Hybrid Electric Vehicle
HSV	Hybrid Solar Vehicle
ICE	Internal Combustion Engine
PV	Photovoltaic Panel
V	Vertical

2 A conversion ratio of 1.25 between € and US $ has been used.

APPENDIX – RESULTS OF THE OPTIMIZATION ANALYSIS

Tab. V – OPTIMIZATION RESULTS – CASES 1-6

Case	1	2	3	4	5	6
	P_av=10			P_av opt.		
	APVH=0	APVH=3	APVH=6	APVH=0	APVH=3	APVH=6
Payback	3.13773	6.72192	8.70347	3.13773	5.26075	6.72192
x(1):P_av	10	10	10	13.2199	20	20
x(2):APVH	0	3	6	0	3	6
x(4):l	4.09373	3.72295	4.02882	2.67598	2.5	4.5876
x(5):w	1.95104	1.71492	1.70516	1.322	1.45349	1.93611
x(6):h	1.43299	1.3783	1.325	1.325	1.325	1.41416
X(7):Car_W_f	0.7	0.813297	0.7	0.7	0.7	0.7
Cost	1136	3536	6005.7	1501.78	4672	7072
Savings	1.20682	1.75347	2.30012	1.5954	2.96029	3.50694
PtW/PtWcc	1.06499	1.012	1.0419	1.65159	1.30932	1.00024
Car W:total	530.492	558.274	542.254	401.14	618.425	809.522
Car W:chassis	422.676	414.457	358.152	258.608	366.792	521.889
Car W:hybrid.	107.817	143.817	184.101	142.532	251.633	287.633
PV_W	0	36	72	0	36	72
Batt_W	49.1803	49.1803	53.465	65.0157	98.3607	98.3607
EM_W	16.1364	16.1364	16.1364	21.332	32.2727	32.2727
EG_W	12.5	12.5	12.5	16.5248	25	25
ICE_W	30	30	30	39.6596	60	60
Car_W_sav	277.344	169.914	239.449	190.359	181.187	364.718
Fraz	0	15.0989	30.1978	0	7.54946	15.0989

Tab. VI – OPTIMIZATION RESULTS – CASES 7-12

Case	7	8	9	10	11	12
	P_av=10 APVH=3			P_av=10 APVH=3 APVV=2		
	Lat=30	Lat=45	Lat=60	Lat=30	Lat=45	Lat=60
Payback	6.72192	7.22464	7.91461	8.88344	9.58537	10.6288
x(1):P_av	10	10	10	10	10	10
x(2):APVH	3	3	3	3	3	3
x(4):l	3.72295	4.40061	4.01641	3.58012	4.30363	3.75246
x(5):w	1.71492	1.85719	1.91393	1.83183	1.81627	1.86315
x(6):h	1.3783	1.38603	1.40701	1.34166	1.34541	1.36506
X(7):Car_W_f	0.813297	0.702425	0.709833	0.7	0.7	0.7
Cost	3536	3536	3536	5136	5136	5136
Savings	1.75347	1.63145	1.48923	1.92718	1.78606	1.61072
PtW/PtWcc	1.012	0.894114	0.910462	1.09151	1.00009	1.0499
Car W:total	558.274	631.879	620.533	517.606	564.92	538.12
Car W:chassis	414.457	488.062	476.716	349.789	397.103	370.303
Car W:hybrid.	143.817	143.817	143.817	167.817	167.817	167.817
PV_W	36	36	36	60	60	60
Batt_W	49.1803	49.1803	49.1803	49.1803	49.1803	49.1803
EM_W	16.1364	16.1364	16.1364	16.1364	16.1364	16.1364
EG_W	12.5	12.5	12.5	12.5	12.5	12.5
ICE_W	30	30	30	30	30	30
Car_W_sav	169.914	206.818	195.788	234.537	262.312	246.585
Fraz	15.0989	11.7288	7.80042	19.897	15.999	11.156

Tab. VII – OPTIMIZATION RESULTS – CASES 13-18

Case	13	14	15	16	17	18
	P_av=10 APVH=3 1 axis tracking			P_av - APVH opt.		APVH=3
	Lat=30	Lat=45	Lat=60	PVuc=800	PVuc=400	
	EtaPV=0.13			EtaPV=0.13		
Payback	6.03058	6.47822	7.08522	3.13773	3.13773	3.90953
x(1):P_av	10	10	10	13.2199	12.8578	20
x(2):APVH	3	3	3	0	0	3
x(4):l	3.3989	3.61136	4.41114	2.67598	2.52734	2.5
x(5):w	1.70523	1.80411	1.86164	1.322	1.48185	1.45349
X(6):h	1.50487	1.35481	1.38701	1.325	1.5839	1.325
X(7):Car_W_f	0.814192	0.811714	0.7	0.7	0.989608	0.7
Cost	3536	3536	3536	1501.78	1460.65	3472
Savings	1.95448	1.81943	1.66356	1.5954	1.55171	2.96029
PtW/PtWcc	1.0156	1.01206	0.999926	1.65159	1.134	1.33717
Car W:total	556.294	558.238	565.014	401.14	575.545	605.546
Car W:chass	412.477	414.421	421.197	258.608	436.916	353.913
Car W:hybr.	143.817	143.817	143.817	142.532	138.629	251.633
PV_W	36	36	36	0	0	36
Batt_W	49.1803	49.1803	49.1803	65.0157	63.2353	98.3607
EM_W	16.1364	16.1364	16.1364	21.332	20.7479	32.2727
EG_W	12.5	12.5	12.5	16.5248	16.0723	25
ICE_W	30	30	30	39.6596	38.5735	60
Car_W_sav	168.495	171.137	276.409	190.359	61.4677	194.066
Fraz	20.6511	16.9209	12.6155	0	0	7.54946

Tab. VIII – OPTIMIZATION RESULTS – CASES 19-25

Case	19	20	21	22	23	24	25
	P_av - APVH opt. Fuel uc=3.54						
	PVuc=800		PVuc=400	PVuc=200			
	APVH=3	APVH opt.		EtaPV=0.13	EtaPV=0.16	EtaPV=0.20	EtaPV=0.26
Payback	2.63038	1.56886	1.56886	1.56886	1.53135	1.39623	1.2715
x(1):P_av	20	12.8418	12.3633	11.9546	8.1378	8.86128	7.14271
x(2):APVH	3	0	0	0	3.64924	3.17894	1.97109
x(4):l	2.5	2.62286	2.74133	2.72322	2.91798	2.76057	3.47546
x(5):w	1.45349	1.52359	1.65354	1.62841	1.63391	1.57911	1.64185
X(6):h	1.325	1.60151	1.71794	1.69797	1.50309	1.35784	1.43489
X(7):Car_W_f	0.7	0.966394	0.987439	1	0.749012	0.700004	0.772963
Cost	4672	1458.83	1404.47	1358.04	1654.3	1642.43	1205.63
Savings	5.92057	3.09955	2.98404	2.88539	3.60097	3.92112	3.16065
PtW/PtWcc	1.30932	1.12213	1.00532	1.00605	1.10998	1.21704	1.0101
Car W:total	618.425	581.24	635.405	623.168	447.139	430.756	450.404
Car W:chass	366.792	442.783	502.108	494.278	315.609	297.069	349.74
Car W:hybr.	251.633	138.456	133.296	128.89	131.53	133.687	100.663
PV_W	36	0	0	0	43.7909	38.1473	23.653
Batt_W	98.3607	63.1566	60.8029	58.7929	40.0219	43.5801	35.1281
EM_W	32.2727	20.7221	19.9498	19.2903	13.1314	14.2989	11.5257
EG_W	25	16.0523	15.4541	14.9432	10.1722	11.0766	8.92838
ICE_W	60	38.5255	37.0898	35.8637	24.4134	26.5838	21.4281
Car_W_sav	181.187	75.8373	70.5663	61.5033	171.684	145.675	168.492
fraz	7.54946	0	0	0	27.7778	27.7778	27.7778

Tab. IX – OPTIMIZATION RESULTS – CASES 26-30

Case	26	27	28	25	29	30
	P- APVH opt. Fuel cost=3.54 Eta_PV=0.26					
	PV_uc=400			PV_uc=200		
	Lat=30	Lat=45	Lat=60	Lat=30	Lat=45	Lat=60
Payback	1.46538	1.56886	1.56886	1.2715	1.23298	1.35822
x(1):P_av	8.3083	10.4092	11.2048	7.14271	7.04213	8.84358
x(2):APVH	1.6277	0	0	1.97109	1.67691	2.80204
x(4):l	2.53215	2.62516	2.62005	3.47546	3.74023	2.71379
x(5):w	1.47987	1.34503	1.322	1.64185	1.57857	1.64256
x(6):h	1.50842	1.34674	1.325	1.43489	1.43063	1.325
X(7):Car_Wf	0.856997	0.908913	0.80734	0.772963	0.757482	0.735236
Cost	1594.9	1182.48	1272.86	1205.63	1135.37	1565.04
Savings	3.62795	2.5124	2.70442	3.16065	3.06944	3.84091
PtW/PtWcc	1.18002	1.45039	1.65079	1.0101	1.00822	1.26787
Car W:total	426.308	399.013	366.035	450.404	446.893	412.963
Car W:chass	317.198	286.784	245.229	349.74	350.844	283.99
Car W:hyb.	109.11	112.228	120.806	100.663	96.0489	128.973
PV_W	19.5324	0	0	23.653	20.123	33.6244
Batt_W	40.8605	51.1927	55.1053	35.1281	34.6334	43.493
EM_W	13.4066	16.7966	18.0804	11.5257	11.3634	14.2703
EG_W	10.3854	13.0115	14.0059	8.92838	8.80267	11.0545
ICE_W	24.9249	31.2275	33.6143	21.4281	21.1264	26.5307
Car_W_sav	106.264	126.41	171.682	168.492	177.324	157.947
Fraz	26.972	0	0	27.7778	26.8619	26.6476

Tab. X – OPTIMIZATION RESULTS – CASES 31-36

Case	31	32	33	34	35	36
	P- APVH opt. Fuel cost=3.54 Batt_uc=80 EG_uc=5.6 EM_uc=9.6					
	Eta_PV=0.26			Eta_PV=0.35		
	PV_uc=200	PV_uc=100	PV_uc=50	PV_uc=200	PV_uc=100	PV_uc=50
Payback	0.702158	0.552606	0.47783	0.625245	0.51415	0.458602
x(1):P_av	9.78427	7.4845	8.06596	9.2552	8.27443	8.36476
x(2):APVH	1.91686	1.4663	1.58022	1.34695	1.20422	1.21736
x(4):l	2.51526	2.62809	2.68788	2.8742	2.99866	3.07153
x(5):w	1.32667	1.57282	1.60794	1.49357	1.54114	1.60424
x(6):h	1.32612	1.68649	1.63754	1.49343	1.49408	1.67633
X(7):Car_Wf	0.732627	0.731395	0.804944	0.865289	0.936435	0.7
Cost	899.981	541.812	504.894	758.065	557.312	502.527
Savings	4.27246	3.26822	3.52213	4.04143	3.61316	3.6526
PtW/PtWcc	1.51001	1.18927	1.10881	1.15896	1.10715	1.05106
Car W:total	369.228	394.837	445.022	464.867	453.164	480.717
Car W:chass	240.735	296.546	339.095	348.917	349.501	375.923
Car W:hyb.	128.493	98.291	105.927	115.95	103.663	104.794
PV_W	23.0023	17.5956	18.9627	16.1635	14.4506	14.6084
Batt_W	48.1194	36.809	39.6687	45.5174	40.6939	41.1381
EM_W	15.7882	12.0773	13.0155	14.9345	13.3519	13.4977
EG_W	12.2303	9.35562	10.0824	11.569	10.343	10.4559
ICE_W	29.3528	22.4535	24.1979	27.7656	24.8233	25.0943
Car_W_sav	149.417	173.211	143.32	120.76	128.238	162.314
Fraz	26.972	26.972	26.972	26.972	26.972	26.972