Numerical analysis of the benefits achievable by after-market mild hybridisation of conventional cars

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Abstract: It is worldwide recognised how hybrid electric vehicle (HEV) currently represents a key technology to reduce automotive fuel consumption and related emissions. Nevertheless, since HEV market share is still insufficient to produce a significant impact on global energy consumption, also due to the recent global financial crisis, a substantial replacement of conventional vehicles is unlikely to occur in a short time. Therefore, a solution is proposed in this paper, consisting of a kit for after-market mild solar hybridisation of conventional vehicles. The mild hybridisation is obtained by replacing original rear wheels by in-wheel motors, on one hand, and, on the other, by adding a photovoltaic (PV) panel, a second battery pack and a dedicated control unit. The substantial benefits obtainable in terms of fuel consumption are evaluated by running a numerical analysis on different kit designs and original conventional cars converted via the kit.

Keywords: solar energy; solar cell; electric vehicles; hybrid vehicles; automotive control.

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1 Introduction

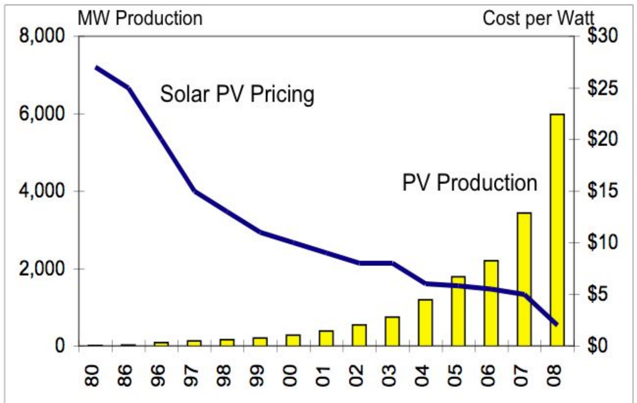
Transportation has a marked impact on acoustic and atmospheric pollution in urban areas, on fossil fuels depletion and on the greenhouse effect. Hybrid electric vehicles have emerged as one of the most effective and feasible alternatives to engine-driven vehicles, allowing significant reductions in fuel consumption and emissions (Sciarretta and Guzzella, 2007).

Further substantial benefits can be achieved by hybrid solar vehicles, obtained by the integration of HEVs with photovoltaic panels, particularly for urban driving (Letendre et al., 2003; Rizzo, 2010; Arsie et al., 2010; Rizzo et al., 2010, Singh et al., 2013, Giannouli and Yianoulis, 2012). The adoption of tracking solar roofs to maximise solar contribution during parking phases is also under study (Coraggio et al., 2010a).

In parallel, due to the pressing need for a renewable and carbon-free energy (REN21, 2009), the production of photovoltaic panels has been growing exponentially in recent years, while their price is significantly decreasing (Figure 1) and their efficiency improving. The industrial interest toward application of photovoltaic to cars is demonstrated by the recent launch of a new model of an HEV equipped with PV panels by a major automotive company.

But, despite the recent commercial success of HEVs, their market share is still insufficient to produce a significant impact on energy consumption on a global basis. Moreover, considering the current economic crisis, it is unlikely that, in next few years, PV assisted EVs and HEVs will substitute a substantial number of conventional vehicles, since relevant investments on production plants would be needed. This fact could of course impair the global impact of these innovations on fuel consumption and CO_2 emissions, at least in a short term scenario. Therefore, one may wonder if there is any possibility to upgrade conventional vehicles to PV assisted hybrid.

Figure 1 Solar PV production and cost (see online version for colours)



Source: Solar Buzz, Company Reports, Green Econometrics Research

Such a proposal has been recently formulated and patented at the University of Salerno. A research project aiming at the development of a kit for mild-solar-hybridisation of conventional cars, proposed by University of Salerno and University of Sannio, has been recently financed by the Italian Ministry of University and Research.

In the following, the peculiar features of the after-market kit here proposed to convert a conventional car into a mild-solar-hybrid vehicle is presented. Furthermore, the impact on vehicle drivability and the interaction between the driver and the additional control algorithm used to manage the hybridising kit are deeply analysed and discussed. Then, the details of the models used for simulation analysis are presented. Finally, the assessment of the benefits achievable with the proposal kit for after-market solar hybridisation are presented.

2 Vehicle structure

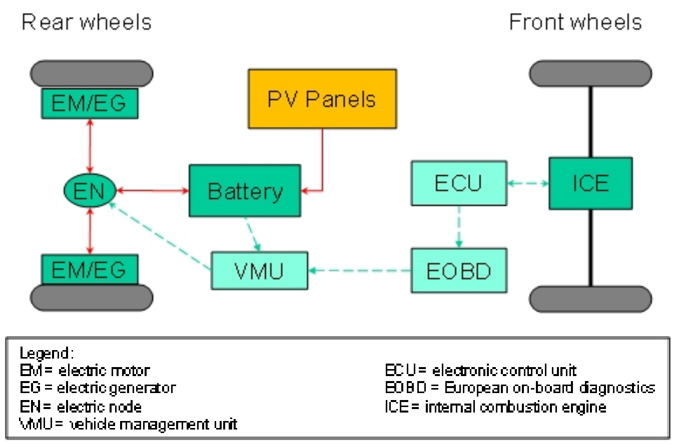
The vehicle structure is based on the conversion of a conventional vehicle, where the front wheels are propelled by an internal combustion engine (ICE) controlled by an engine control unit (ECU). The ECU, as a rule, is equipped by an on-board diagnostics (OBD) gate that enables the access to significant engine/vehicle operation data, such as pedal position, vehicle and engine speed, manifold pressure, thermal state, and environmental conditions. The mild parallel hybrid structure is realised by substituting/integrating the rear wheels with in-wheel motors and by including an additional battery pack and photovoltaic panels on the roof. The upgraded vehicle can operate in:

1 pure electric mode – when the ICE is switched off or disconnected by the front wheels

2 hybrid mode – when the ICE drives the front wheels while the rear wheels operate in traction mode or in generation mode, corresponding to positive or negative torque, respectively.

The battery can be recharged by both in-wheels motors, when operating in generation mode, and photovoltaic panels. Optionally, the battery could be recharged also by the grid, in Plug-In mode. A vehicle management unit (VMU) receives the data from the OBD gate and the battery (for SOC estimation) to drive the in-wheel motors, by properly acting on the electric node EN. A display on the dashboard may advise the driver about the actual system operation mode. Figure 2 depicts a scheme of the upgraded vehicle structure.

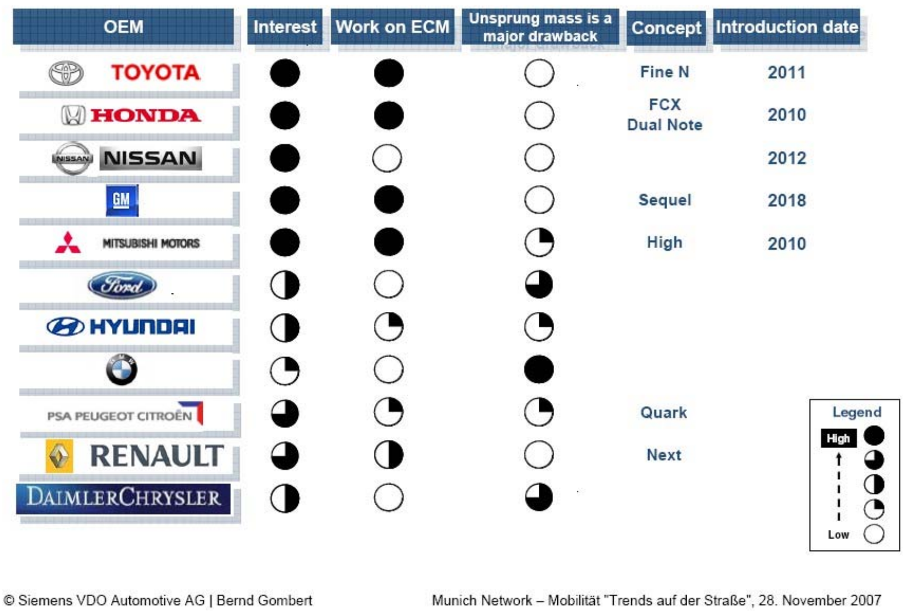
Figure 2 Scheme of a system to upgrade a conventional car to mild hybrid solar vehicle (see online version for colours)



2.1 In-wheel motors

One of the key aspects of this proposal concerns the possibility of replacing the rear wheels with in-wheel motors. This topic is very actual and of increasing industrial interest, as evidenced in Figure 3, being strongly related to the diffusion of electric vehicles. In this sense, it is considered as a 'disruptive technology' (Murata, 2010). Their use would also allow to integrate advanced techniques for vehicle control (Braghin and Sabbioni, 2010; Xiong at al., 2010) and to expand the applicable range of vehicle control (Murata, 2010). Anyway, the installation of a motor inside the wheel is made difficult by the standpoint of space constraints. Moreover, deterioration of ride comfort due to increase in unsprung mass occurs. The complexity of these problems tends to increase with motor power. Therefore, a parametric analysis of the influence of in-wheel motor power on the expected benefits of the hybridisation strategy will be performed in the following.

Figure 3 Activities of OEM’s in the in-wheel motor technology (see online version for colours)



Source: Gombert (2007)

2.2 Control strategies issues

The powerflow control in the HEV is particularly challenging because of the hybrid structure of the driveline and the conflicting performance objectives: driver power demand, fuel economy, SOC regulation, drivability. A flexible, model-based, decoupling control strategy for power split in mild hybridised vehicles would be suitable. In such case, the control strategy should be composed of three main tasks:

1 steady-state power management based upon consumption minimisation

2 dynamic regulation of battery SOC, also considering the energy contribution from PV panels during driving and parking

3 dynamic power split for energy efficiency and drivability.

Decoupling should be obtained in the sense that control of battery SOC and drivability neither does not affect the power demand nor does not influence each other in the nominal operating conditions.

As for to the operating modes enabled by the hybridising kit, it should be noticed that in some vehicles pure electric mode operation, with engine switched off, could not be compatible with normal operation of steering and braking systems. On the contrary, hybrid mode operation (with both engine and electric motors working) should be always possible, compatibly with driving behaviour, driveability and safety issues. The following analysis is therefore referred to the operation in hybrid mode only. In that case, the energy management and control in the proposed hybridisation system would differ from classical HEV by two main reasons.

The former is related to the addition of solar panels. 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. On the other hand, in case of solar hybrid vehicle, as in plug-in vehicles too, the battery can be 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 (Sorrentino et al., 2011). Moreover, advanced strategies could be necessary for the optimal management of vehicle and battery, even adopting on-board weather forecast to estimate the amount of solar recharge in next parking phase (Coraggio et al., 2010b).

The second reason is due to the fact that it would be advisable to develop a kit which does not require any modifications to the original ECU: in fact, the VMU would drive the electric motors deriving its data from OBD port (Figure 2), and not interfering with the operation of the original ECU. Of course, the need to design a control system coexisting with the original ECU poses some specific constraints in terms of driving requirements and driveability, which result in different control strategies vs. those implementable on a full hybrid vehicle. For instance, when the driver steps on the accelerator in the hybridised vehicle, so demanding higher vehicle power, an increase in the engine power will necessarily result; on the contrary, in a 'native' HEV, where the splitting between thermal and electric engine is managed by the control system, the increase in vehicle power could be achieved even by reducing the engine power and, in parallel, by increasing the electric motor power. Similarly, in the hybridised vehicle a reduction in engine power will be always achieved when the driver releases gas pedal.

Therefore, the achievement of a given level of power splitting between thermal and electric motor can be obtained by inducing the driver to modulate the pedal position until the desired vehicle power would be reached. In other words, the driver will act as the vehicle is running downhill. On the contrary, the hybridised vehicle can operate in recharging mode when the in-wheel motors absorb part of the power generated by the engine: in this case the driver will act on the pedal as the vehicle would run uphill. A detailed study of driver behaviour is therefore needed to develop implementable strategies for this kind of vehicle.

2.3 Vehicle model

Vehicle simulation, whose results are presented in the next section, was performed by means of a longitudinal vehicle model developed under the following hypotheses:

1. the drag force is considered acting on vehicle centre of gravity
2. vehicle inertia accounts for both vehicle mass (M_{HSV}) and rotational inertia of ICE, EM/EG and wheels into the term M_{eff}
3. the effects of elasticity in the mechanical transmission are neglected.

The resulting longitudinal model relates requested power at wheels P_w to the road load, as follows:

$$P_w = M_{HSV} \cdot g \cdot v \cdot \left[C_r \cos(\alpha) + \sin(\alpha) \right] + 0.5 \rho C_x A v^3 + M_{eff} \frac{dv}{dt} v \tag{1}$$

In case of non-negative P_w values, the mechanical power is supplied by the ICE (P_{ICE}) and/or the in-wheel motors (P_{EM}), depending on the control variable *PS* (Power Split) defined as:

$$PS = \frac{P_{EM}}{P_w} \quad \text{if } P_w \geq 0 \tag{2}$$

The control variable *PS* may range between negative values, in case ICE provides an extra power to be recovered into the battery, to unit (i.e., pure electric vehicle). In all cases the requested power is given as the algebraic sum of ICE and in-wheel motors power:

$$P_w = P_{ICE} + P_{EM} \tag{3}$$

In case of vehicle braking or deceleration ($P_w < 0$), the regenerative braking mode is active and the power is recovered into to the battery, according to battery power limitations and to in-wheel motors performance and efficiency. These latter are computed from static maps provided by the manufacturer as a function of torque and speed. Depending on in-wheel motors operation mode (motor or generator), the electric power (P_B) requested or supplied to the battery is given by the following relationships:

$$P_B = \frac{P_{EM}}{\eta_{tr}} \quad \text{if } P_w \geq 0 \tag{4}$$

$$P_B = P_w \cdot \eta_{EM} \quad \text{if } P_w < 0 \tag{5}$$

2.4 Lithium-ion battery model

The model considered for the lithium-ion battery pack consists of N_B cells. Thus the instantaneous battery power is related to the power of each cell as follows:

$$P_B = N_B P_c \tag{6}$$

Each cell is assumed to be modelled by means of an equivalent static electrical circuit characterised by an internal resistance R_{in} and the open circuit voltage V_0. Then the cell model will be:

$$V_c = V_0 - R_{in} I_c \tag{7}$$

and the power provided by each cell is given by

$$P_c = V_c I_c \tag{8}$$

By substituting equation (8) in equation (7), the instantaneous battery current can be written as

$$I_c = \frac{V_0 - \sqrt{V_0^2 - 4 R_{in} P_c}}{2 R_{in}} \tag{9}$$

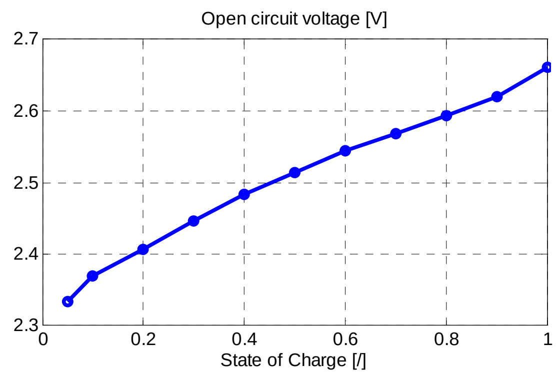
where only the solution corresponding to the lower current is considered. The other solution is not considered because the major cause for the battery power absorption is assumed to be the unknown load and the power dissipated on the battery internal resistance is much lower than the load power.

By assuming that all battery cells are equalised and that the battery is able to provide the requested power P_B, the evolution of the battery state of charge SOC can be obtained by considering a single cell and is represented by the following differential equation:

$$\frac{dSOC}{dt} = -\frac{1}{Q_{\max}} I_c = -\frac{V_0(SOC) - \sqrt{V_0(SOC)^2 - 4 R_{in} P_B / N_B}}{2 R_{in} Q_{\max}} \tag{10}$$

where t is the continuous time variable and $Q_{\max}$ is the maximum battery cell charge. The values of open circuit voltage, internal resistance, battery capacity, energy density and power to weight ratio were extrapolated from the experimental data provided by Nelson et al. (2007). Specifically in this paper, energy density and power to weight ratio were set to 150 Wh/kg and 300 W/kg, respectively, whereas the nonlinear characteristic relating the open circuit voltage to the state of charge is shown in Figure 4.

Figure 4 Battery open circuit voltage vs. state of charge (see online version for colours)



3 Scenario analysis

In order to assess the benefits associated to mild hybridisation of conventional cars, a simulation based scenario analysis was carried out. Table 1 describes the basic features and hypotheses of three selected scenarios. Case 1 is nothing but the reference one, in that it provides the conventional vehicle fuel economy. In case 2 the benefits achievable by only enabling regenerative braking through in-wheel motors are estimated. Finally in case 3 a PV roof is added to the mild hybrid powertrain, thus enabling the achievement of further benefits in terms of fuel consumption. The main difference between case 2 and case 3 energy management policy lies in the final state of charge to be reached at the end of the driving cycle, which in the current scenario analysis is the standard NEDC driving path. Charge sustaining strategy is adopted in case 2, whereas in case 3 the final SOC must differ from the initial one by the amount of energy supplied by the PV roof during the parking phase (Sorrentino et al., 2011). Particularly, it was assumed that driving time is 1.5 hour/day, while parking phase lasts for 8.5 hours on average during daytime (recharging with solar power), while for the remaining parking time it is assumed that the vehicle is not recharged. Considering the average daily solar power that impacts on Italy, the 300 Watts PV roof assumed in case 3 provides up to 1 kWh a day.

In both cases 2 and 3 the hybrid components are managed as follows:

$$P_b(t) = -P_{PV} + \min\left\{P_w \cdot \eta_{IWM} \cdot \eta_c, P_{\max,IWM}(\omega_w) \cdot \eta_{IWM} \cdot \eta_c\right\}, \quad P_w(t) < 0 \tag{11}$$

$$\begin{cases} P_b = -P_{PV} + \min\left\{\dfrac{PS \cdot P_w}{\eta_{IWM} \cdot \eta_c}, \dfrac{P_{\max,IWM}(\omega_w)}{\eta_{IWM} \cdot \eta_c}\right\}, & P_w(t) \geq 0 \text{ and } SOC(t) > SOC_{\min} \\ P_b = -P_{PV}, & P_w(t) \geq 0 \text{ and } SOC(t) \leq SOC_{\min} \end{cases} \tag{12}$$

where P is power [kW], η [/] is efficiency and the footers w, IWM, b, c and PV stand for, respectively: wheel, in-wheel motor, battery, converter and photovoltaic panels. Equation (11) highlights how the in-wheel motors are exploited to the extent of maximum available generator power; on the other hand, in drive phases [see equation (12)] in-wheel motors contribution can be limited either by the assigned power split (i.e., PS) or by the maximum power that can be supplied during motor functioning. Such a choice is justified by the need of recharging as much power as possible during recharging phases, whereas in-wheel contribution during drive phases must be carefully managed, to avoid both battery over-discharging and inappropriate use of electric energy in correspondence of highly efficient ICE operating conditions.

The term associated to photovoltaic panel power contribution [see equations (11) and (12)], which is actually minor during drive phases, already accounts for PV converter losses. In this preliminary numerical activity, the PS value was constantly set to 0.5. It is also worth mentioning here that when $P_w(t) \geq 0$ the remaining power demand is always met by the ICE. The parameter $SOC_{\min}$ in equation (12) has been found as function of the following variables: in-wheel motors power, size of battery pack and presence of the PV roof (i.e., different final SOC, i.e., SOC_f, to be reached at the end of the driving path).

Table 1 Description of analysed mild hybridisation scenarios

Case	*Regenerative braking*	*PV roof*
1	NO	NO
2	YES	NO
3	YES	YES

The impact of additional weight due to mild hybridisation on fuel consumption has been also considered.

In order to guide toward the proper design of the system considering both technical and economic aspects and to assess the practical feasibility of the proposed hybridisation technique, a study of additional costs and of the expected pay-back periods has been also performed. The cost of the kit components (battery, PV panels, in-wheel motors) has been described with the following model:

$$C = C_0 B^k \tag{13}$$

The parameters C_0 and k have been obtained by literature and market data (solarbuzz.com, www.alibaba.com). Scenario A is referred to the present situation, while in Scenario B a 20% decrease in unit costs has been considered. Fuel cost (gasoline) has been assumed 1.63 €/l and 1.96 €/l respectively for the two scenarios.

Table 2 Data and parameters of the cost model

Component	*B*	*C_0 (scenario A)*	*C_0 (scenario B)*	*k*
Battery	Capacity [kWh]	450 [€/kWh]	375 [€/kWh]	0,8
Wheel motors	Power [kW]	207 [€/kW]	172.5 [€/kW]	0,342
PV panels	Peak power [kW]	1,000 [€/kWp]	833 [€/kWp]	1

The study has been performed for different combinations of vehicle mass and power, as specified in Table 3.

Table 3 Data and parameters of the cost model.

Segment		*Car mass [kg]*	*Power [kW]*
A	Mini car	1,000	50
B	Small cars	1,075	77
C	Medium cars	1,215	90
D	Large cars	1,355	103
E	Executive cars	1,464	132
F	Luxury cars	1,835	225

4 Results

In this section the main outcomes of the scenario analyses described in the previous section are presented and discussed. Particularly, cases 2 and 3 were simulated varying the nominal in-wheel power ($P_{n,IWM}$), in the range [1, 12] kW (the nominal power of each wheel is therefore the half of such value). Table 2 lists the main specifications of the simulated vehicle.

Table 4 Conventional car specifications

Nominal ICE power [kW]	50
Fuel	gasoline
Coefficient of drag (C_d)	0.35
Frontal area [m^2]	2.24
Rolling radius [m]	0.294
Rolling resistance coefficient [/]	0.01
Base vehicle mass [kg]	1,000

Next figures illustrate the impact of in-wheel motor and battery size on fuel economy with and without PV roof. Figure 5 shows that energy benefits due to mild hybridisation always increase in case 2. On the other hand case 3 exhibits a maximum fuel economy between 5 and 7 kW, beyond which fuel savings with respect to the reference case tend to remain constant, mainly due to the weight increase, as shown in Figure 6, and to variations in average in-wheel motor efficiency. Furthermore, the comparison of cases 2 and 3 highlight the importance of coupling in-wheel motors to the PV roof to significantly enhance the energy saving effect achievable via mild hybridisation. The aforementioned optimal case 3 value corresponds with fuel savings as high as 18% as compared to the conventional car.

Figure 6 shows the variation of weight increase due to mild hybridisation in case 3. The curve is not perfectly linear since for $P_{n,IWM}$ < 4 kW, the battery pack size was fixed to that one corresponding to $P_{n,IWM}$ = 4 kW, thus ensuring the whole amount of solar energy be restored in the parking phase. On the other hand, higher values of $P_{n,IWM}$ correspond to higher battery power, which in turn results in higher energy storage capabilities. The simultaneous analysis of Figures 5 and 6 suggests once again the opportunity of selecting a reasonable maximum power for in-wheel motors. Higher power not only may not further increase energy savings, but also leads to unnecessary weight and inertia increase of the hybridised vehicle.

Starting from the fuel savings and the estimate of the additional costs due to hybridisation, the payback period has been then estimated. The best results range around 7–8 years for the base case, and are achieved at power of about 5 kW (Figure 7). This figure, incidentally, is not very different from the payback computed for some commercial hybrid vehicles, with respect to the reference conventional model. The payback decreases to about five years in case of scenario B, characterised by a 20% reduction in component cost and 20% increase in fuel cost. It is also interesting to notice that the payback is significantly influenced by vehicle mass and power, decreasing by about 37% passing from mini car to luxury car (Figure 8).

In a more recent paper (Marano et al, 2013a), the study has been extended to plug-in hybrid solar vehicles, considering the effects of real-world driving cycles and different recharging infrastructures and determining the optimal sizing of the vehicle components (Battery, solar panels, wheel motors). The analysis has evidenced that improvements in fuel economy up to 20–25% with respect to the base conventional vehicle can be achieved, and that the benefits due to solar panels are more significant with respect to the availability of recharging infrastructures during all the day. Moreover, it has to be noticed that the presence of a photovoltaic source on board is also helpful in mitigating the overcharge on electrical infrastructures, which is emerging as a critical factor for the diffusion of plug-in vehicles (Marano et al, 2013b).

Finally, it should be noticed that the presented analysis has not yet exploited all the potentialities of this system. For instance, in case that the vehicle requires low torque, corresponding to low engine efficiency, i.e., point A in Figure 9, which shows a typical efficiency contour plot for a spark-ignited ICE. In such a case, it could actually be convenient to operate the engine at higher torque, for instance corresponding to the maximum efficiency at the given engine speed (i.e., point B), and recovering the excess power by operating the electric motors in generating mode, as it happens in full hybrid vehicles. Of course, the convenience should be assessed considering the conversion efficiencies involved, also taking into account the maximum torque that in-wheel motor can deliver at the given speed. Preliminary studies have confirmed that fuel consumption can be improved with respect to the presented results by adopting such strategy. Anyway, some issues related to the implementability of this solution within the hybridisation strategy are in course (Arsie et al., 2013).

Figure 5 Variation of fuel economy as function of degree of mild hybridisation (see online version for colours)

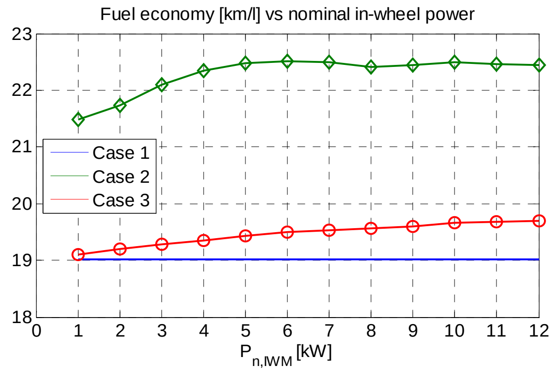


Figure 6 Weight increase due mild solar hybridisation (see online version for colours)

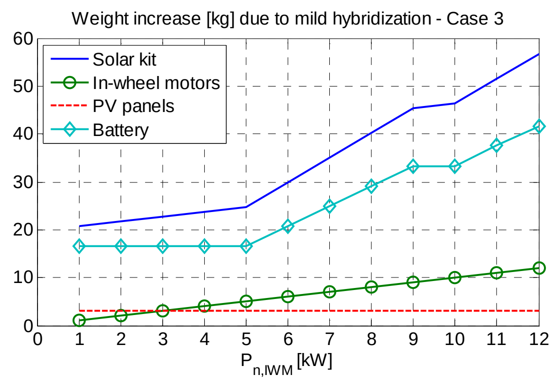


Figure 7 Payback vs wheel power for two different scenarios (see online version for colours)

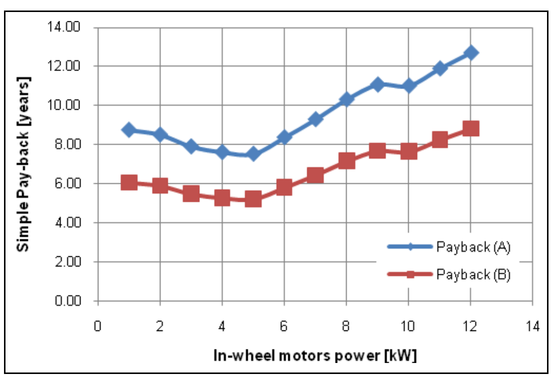


Figure 8 Payback for different cars (wheel power = 5 kW, scenario A) (see online version for colours)

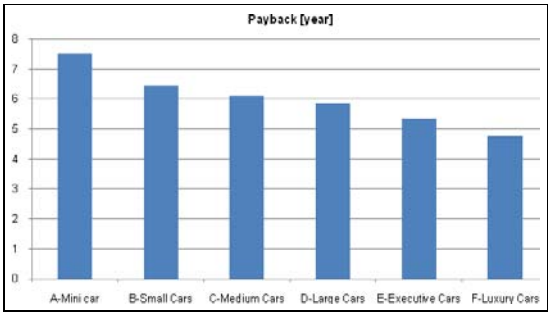
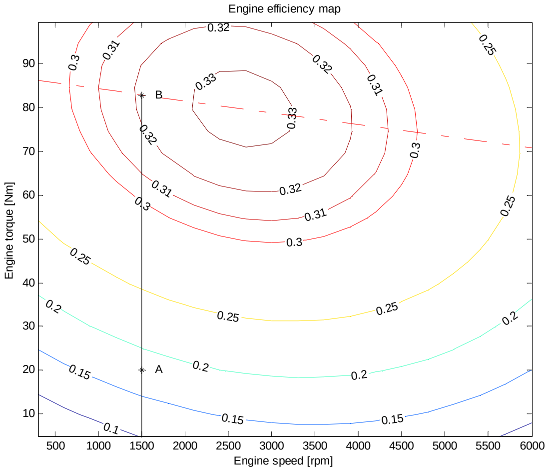


Figure 9 Engine efficiency map and possible operating points in recharging mode (see online version for colours)



5 Conclusions

The availability of a system to upgrade conventional vehicles to mild-solar-hybrid could have a relevant impact on fuel consumption and CO_2 emissions due to transportation, since it may potentially be applied to most of the today fleet, and without requiring expensive reconversion of production lines for cars. A discussion on the main features of such a system, on the open problems and on main control issues has been presented. A study by simulation analysis has confirmed that the proposed mild-solar-hybrid conversion can give significant benefits in terms of fuel consumption, up to about 18%, even adopting in-wheel motors with limited power and without fully exploiting the capability of the system in terms of control strategies. It also emerged that the photovoltaic panels significantly enhance fuel savings. Preliminary studies on economic feasibility show that the payback is around seven to eight years, comparable with the values of some commercial hybrid vehicles. This value is affected by in-wheel power and by vehicle mass and power, decreasing for large cars. Considering the present scenario of cost reduction for the main components of the kit and perspective fuel cost increase, the economic feasibility is expected to improve significantly in the near future.

Further work is in progress to:

1 develop optimal control strategies that are suitable for online implementation (i.e., real world application)

2 to address both safety and functionality issues associated to car retrofitting, mainly due to the need of addressing the interaction among driver action on acceleration and brake pedal and the additional VMU

3 finally, develop a prototype of the whole mild-solar-hybridisation system.

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Nomenclature

	Name	Unit
A	Frontal area	m^2
C_0	Unit cost	Euro/[reference variable]
C_r	Rolling resistance coefficient	/
C_x	Drag coefficient	/
I	Battery current	A
k	Exponent for cost model	/
M	Mass	kg
P	Power	W
PS	Power split index	/
R_{in}	Internal resistance	Ohm
SOC	State of charge	/
v	Vehicle speed	m/s
V	Voltage	Volt
Greek symbols		
α	Road grade	Deg
ρ	Density	Kg/m3
η	Efficiency	/
Subscripts		
c	Battery single cell	
B	Battery	
EM	Electric motor	
HSV	Hybrid solar vehicle	
ICE	Internal combustion engine	
IWM	In-wheel motor	
tr	Transmission	
w	Wheels	
Acronyms		
ECU	Engine control unit	
EN	Electric node	
EV	Electric vehicles	
HEV	Hybrid electric vehicle	
HSV	Hybrid solar vehicle	
ICE	Internal combustion engine	
PV	Photovoltaic	
SOC	State of charge	
VMU	Vehicle management unit	