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A Prototype Mild-Solar-Hybridization Kit: Design and Challenges

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Abstract

This paper deals with the development of an automotive hybridization kit (equipment, along with associated techniques and methodologies), aimed at converting conventional cars into hybrid solar vehicles (Mild-Solar-Hybrid). The main aspect of the projects consists into the integration of state-of-the-art components (in-wheel motors, photovoltaic panels, batteries), and into the development of an optimal controller for the power management.

A prototype of the hybridizing equipment – patented by the University of Salerno (Italy)- is installed on a FIAT Grande Punto. A mild parallel hybrid structure is obtained by substituting/integrating the rear wheels with 7kW in-wheel motors and adding a lithium battery to manage on-board energy. Thus, the vehicle can operate in electric mode (when ICE is switched off or disconnected by the front wheels) or in hybrid mode (when the ICE drives the front wheels and the rear in-wheel motors operate in traction mode or in generation mode, corresponding to a positive or negative torque). The battery can be recharged both by rear wheels, when operating in generation mode, and by photovoltaic panels.

The vehicle is also equipped with an EOBD gate (On Board Diagnostics protocol), which allows accessing data such as pedal position, vehicle speed, engine speed, manifold pressure and other variables. The Vehicle Management Unit (VMU), which is part of the invention and implements control logics compatible with typical drive styles of conventional-car users, receives the data from OBD gate, from battery (SOC estimation) and drives in-wheel motors by properly acting on the electric node.

The paper, focused on the main aspects of prototype design and realization, also provides insights on control issues related to the integration of the above-mentioned components, drivability and safety.

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Keywords: automotive hybridization kit; hybrid solar vehciles (HSV); vehicle electrification; HSV prototype;

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1. Introduction

Road transport contributes about one-fifth of the EU total emissions of carbon dioxide (CO_2), the main greenhouse gas. CO_2 emissions from road transport increased by nearly 23% between 1990 and 2010, and without the economic downturn growth could have been even bigger. Passenger cars are required by law to become more efficient and environment-friendly. EU legislation adopted in 2009 mandatory emission reduction targets for new cars: the fleet average to be achieved by all new cars is 130 grams of CO2 per kilometer (g/km) by 2015 – with the target phased in from 2012 - and 95 g/km by 2020. The 2015 and 2020 targets represent reductions of 18% and 40% respectively compared with the 2007 fleet average of 158.7g/km [1].

Emission limits are set according to the mass of vehicle, using a limit value curve. The curve is set in such a way that a fleet average of 130 grams of CO2 per kilometer is achieved by 2015. The limit value curve means that heavier cars are allowed higher emissions than lighter cars while preserving the overall fleet average, thus vehicles with emissions above the limit value curve are still allowed, provided these are balanced by vehicles below the curve [1].

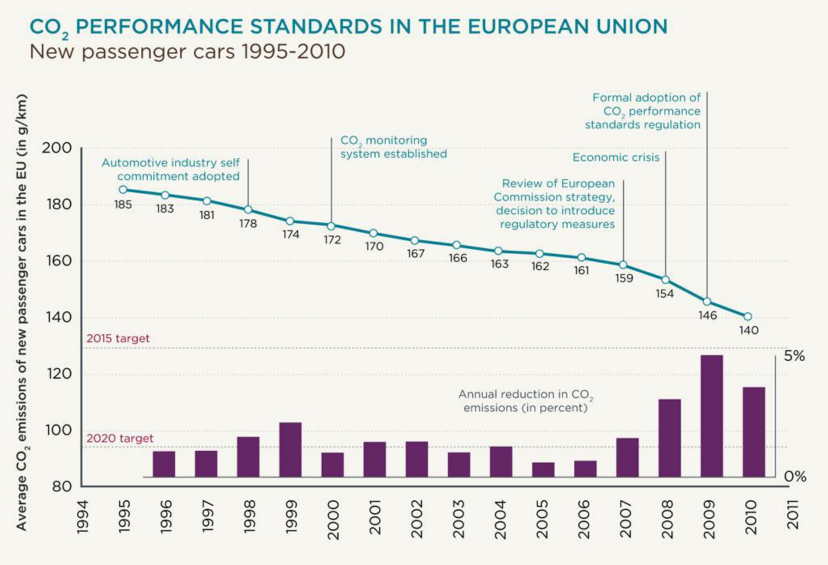

Fig. 1. CO_2 performance standards in European Union (new passenger cars 1995-2011), [2].

The EU fleet average target of 130g CO_2 per km will be phased in between 2012 and 2015. In 2012, an average of 65% of each manufacturers newly registered cars must comply with the limit value curve set by the legislation. This will rise to 75% in 2013, 80% in 2014, and 100% from 2015 onwards. Such regulations do not involve only environmental effects, but also come with significant direct economic impact for the automotive industry. In fact, if the average CO_2 emissions of a manufacturer fleet exceed its limit value in any year from 2012, the manufacturer has to pay an excess emissions premium for each car registered. This premium amounts to €5 for the first g/km above the limit, €15 for the second g/km, €25 for the third g/km, and €95 for each subsequent g/km. From 2019, the cost will be €95 from the first gram of exceedance onwards.

Recent studies [2] show that while the annual reduction rate was usually lower than 2.2% before 2007, the EU efforts in terms of mandatory CO2 limits for passenger cars resulted in a strong acceleration in emission reduction (up to 5% annual). Also, current trends suggest that the 2015 target could be met without major investments, while the 2020 target will likely require a more aggressive recourse to innovative solutions.

Today, viable options include fuel economy improvements in conventional vehicles (engine downsizing and boosting, direct injection and variable valve actuation, weight reduction), fuel-cell vehicles, non-electric hybrids (pneumatic, for instance), vehicle electric hybridization, Plug-in Electric Vehicles (PEVs, including renewable-based hybridizations and/or recharging), natural gas and bio-fuel vehicles. Among the current available options for alternative propulsions, electricity is the only potential energy source for transportation that addresses the simultaneous need for fuel diversity, energy security, reductions in greenhouse gas emissions, and improvements in air quality that is widely available and produced domestically. However, nowadays electricity has a share of transportation energy that is well below 1%. Despite the recent commercial success of HEVs, their market share is still insufficient to produce a significant impact on global energy consumption [3].

1.1. Integration of photovoltaic energy into passenger vehicles

The use of photovoltaic in cars has some unique features that make it different from every other alternative. In fact, in all the other cases (fossil fuels, biofuels, electricity, and hydrogen) an energy carrier is needed and energy is somehow stored in the vehicle (with related conversion and transportation/ distribution issues). This generates energy losses and, in most cases, emissions, but also profits and, in turns, tax revenues. The direct use of photovoltaic on the vehicle is then a way to realize a short circuit from primary renewable energy directly to the wheels, by cutting emissions, transportation and distribution losses [4],[5].

A practical and promising opportunity is the integration of solar PV on hybrid or plug-in electric vehicles, in order to increase energy saving and cope with environmental issues. This integration would be fostered by current trends toward increasing fleet electrification, increase in fuel costs, advances in PV panel technology, and reduction in PV cost [6],[7]. Moreover, it is unlikely that, in the next few years, EVs and HEVs will substitute for a substantial number of conventional vehicles, since relevant investments would be needed. Therefore, the possibility of upgrading conventional vehicles is gaining interest. Among the hybridization options, the electrification of rear wheels in front-wheel-drive vehicles appears particularly attractive, for the trade-off between cost and benefits. In such a way, the vehicle is transformed into a Through-The-Road (TTR) parallel hybrid electric vehicle. In some cases, photovoltaic panels are also introduced [8].

Nonetheless, the benefits in terms of fuel savings are lower than on a native hybrid, due to the constraints posed by the TTR structure, and by the absence of downsizing. On the other hand, the addition of the electric propulsion may offer further advantages:

- Enhancement of vehicle power and performance, in particular acceleration
- Increase in vehicle reliability, due to presence of two propulsion devices
- Better driveability, due to the possibility of exploiting advanced vehicle control schemes.

On the other hand, the use of PV technology for vehicle electrification triggers further layers of complexity in terms of control, as discussed in the following sections.

This paper deals with the development of an automotive hybridization kit (equipment, along with associated techniques and methodologies), aimed at converting conventional cars into hybrid solar vehicles (Mild-Solar-Hybrid). The main aspect of the projects consists into the integration of state-of-the-art components (in-wheel motors, photovoltaic panels, batteries), and into the development of an optimal controller for the power management. A mild parallel hybrid structure is obtained by substituting/integrating the rear wheels with 7kW in-wheel motors and adding a lithium battery to manage on-board energy. A prototype of the hybridizing equipment – patented by the University of Salerno (Italy)- installed on a FIAT Grande Punto, will be briefly described.

2. HySolarKit (HSK): overview

The hybridizing equipment (Fig. 2), installed on a FIAT Grande Punto (Tab. 1), consists of:

- in-wheel motors;
- auxiliary Lithium-ion battery pack;
- flexible photovoltaic panels installed on vehicle roof and hood;
- additional control system that interacts with existing vehicle components and optimizes energy flows.

The vehicle is also equipped with an EOBD gate (On Board Diagnostics protocol), which allows accessing data such as pedal position, vehicle speed, engine speed, manifold pressure and other variables. A mild parallel hybrid structure is obtained by substituting/integrating the rear wheels with in-wheel motors.

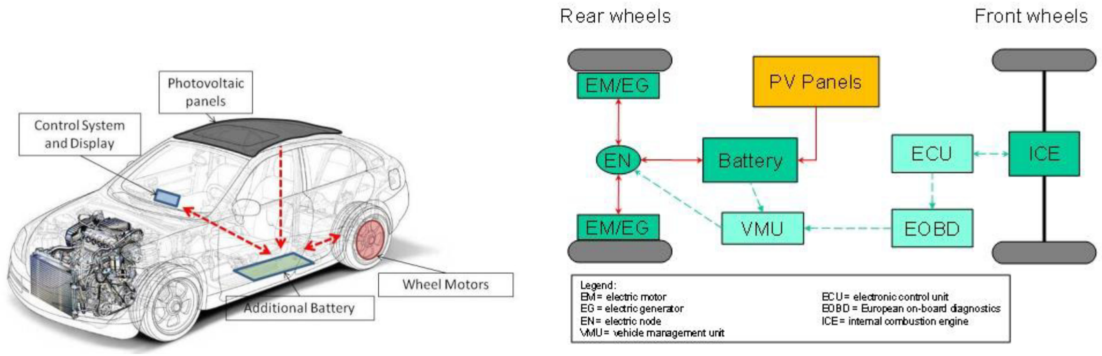

Fig. 2. Hybridization kit and vehicle integration – system schematics.

In this way, the vehicle can operate in pure electric mode (when ICE is switched off or disconnected by the front wheels) or in hybrid mode (when the ICE drives the front wheels and the rear in-wheel motors operate in traction mode or in generation mode, corresponding to a positive or negative torque).

The VMU implements control logics compatible with typical drive styles of conventional-car users, receives the data from OBD gate, from battery (SOC estimation) and drives in-wheel motors by properly acting on the electric node. The battery can be recharged by:

- rear wheels, when operating in generation mode;
- photovoltaic panels;
- a regular electric power outlet, when the vehicle is connected to the grid power in plug-in mode.

Tab. 1. FIAT Grande Punto main specifications.

FIAT Punto 1.3 Multijet (Diesel) 55kW/75HP	
Original vehicle weight	1105 kg
Frontal area	2.04 m^2
Aerodynamic drag coefficient Cx	0.325
Engine power	55 kW
Rpm max	4000
Fuel	Diesel

3. HSK hardware components: installation and analysis

As mentioned above, a prototype of the HSK kit has been installed on a FIAT Grande Punto; summarizing, HSK main hardware components are:

- two 7kW in-wheel motors (replacing the original rear wheels)
- a 4 kWh lithium-ion battery pack (installed in the trunk, in the spare-wheel compartment)
- 270 W high-efficiency (18%) single-crystal silicon photovoltaic panel (installed on vehicle roof and hood)

Fig. 3. HSK installed on a FIAT Grande Punto and some wiring details.

3.1. In-wheel motors

The integration of the in-wheel motors into the original represents the most delicate process, since it involves structural analysis, drivability and safety issues. Simple but critical component were needed to properly install the wheels. Specifically, a mounting plate (Fig. 4), to fasten the wheels to the brakes and to the hub, has been designed in SolidWorks® environment, and verified through Ansys®. Based on previous studies ([8], [9], [10]) 7 kW in-wheel motors were selected (Tab. 2, Fig. 5).

Tab. 2. Kelly Controls in-wheel motors.

Motor 96V 7 kW	
Rated power	7000 W
Rated voltage	96 V
Rated rotating speed	1300 rpm
Rated efficiency (min)	83%
Brushless DC Motor	

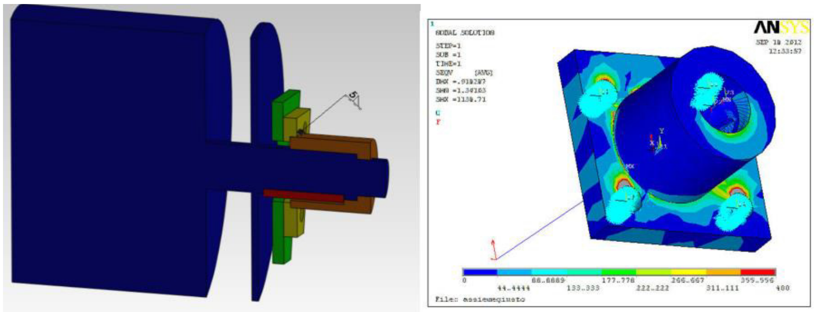

Fig. 4. (a) Mounting plate design in SolidWorks®. Blue component represents the in-wheel motor. (b) Design verification in Ansys®. Sample results (frontal strain).

Fig. 5. Kelly Controls in-wheel motor 96V 7 kW.

3.2. Lithium-ion battery pack

In accordance with recent progress on lithium-ion battery technology, increasing reliability and safety, and decreasing cost, it was chosen to employ a Li-ion battery pack for the purpose of the prototype. The system has been designed and developed *ad hoc*, optimized for the hybridization kit operations. Although the initial scope of the project was to obtain a hybrid vehicle, the battery has been purposely oversized to be eventually adapted to plug-in operations. In fact, while most existing HEVs are equipped with batteries of about 1.5-2 kWh energy storage, our prototype features a 4 kWh battery pack, more aligned towards plug-in vehicles.

The pack, installed in the trunk (in the spare-wheel compartment, Fig. 6) consists of 30 cells, operating within a voltage range of 83-117 V and maximum current of 150 A, with dimensions of 610 x 515 x 250 mm and mass of 65 kg. It is connected to a National Instruments NI 6212 bus-powered USB M series multifunction data acquisition (DAQ) module, which manages its operation and evaluates data such as voltage, current (for diagnostics and SOC estimation).

Fig. 6. Lithium-Ion battery pack installed in the FIAT Grande Punto.

It is worth noting that the battery pack has not been optimized yet, in terms of dimensions and weight, as Fig. 6 shows, and it is expected that the final design could be up to 50% smaller and lighter than the current version.

3.3. Flexible photovoltaic panels

As mentioned above, high-efficiency (18%) single-crystal silicon HF65 (ENECOM) photovoltaic panel were installed on the vehicle roof and hood, for a total of about 270W of installed power. In particular, each panel measures 1370 x 344 mm and weighs 1.2 kg.

Fig. 7. (a). ENECOM HF65 PV panel. (b). Installation on FIAT Grande Punto.

4. HSK control issues: interaction with original vehicle and energy management.

In the following sub-sections, two methodologies are proposed to address on-line energy management of the proposed hybridization kit, as well as offline investigation of maximum fuel economy, achievable via after-market installation of such a kit on existing cars. Particularly, fuzzy logic is adopted to face the complex interaction between the driver and vehicle management unit, the latter being specifically developed to optimize in-wheel motors functioning with respect to fuel economy and desired battery management (e.g. charge sustaining or plugin oriented charge depleting). Afterwards, the analyses conducted via an advanced dynamic programming optimization tool are presented, highlighting the high potential offered by the proposed hybridizing kit, on one hand, and, on the other, providing a useful fuel savings benchmark, to be targeted when finally optimizing the fuzzy rules to be implemented on-board.

4.1. Fuzzy controller

Fuzzy logic is a well-known form of many-valued logic or probabilistic logic; it deals with reasoning that is approximate rather than fixed and exact and has been extensively used in automotive applications, particularly to model Driver Behaviour [11].

The HSK prototype employs a Matlab® fuzzy model to detect Driver Intention, with the objective of deciding when it is convenient and safe to activate the rear in-wheel motors (Tab. 3). The model, integrated within the Vehicle Management Unit, would also determine the Power Split (PS) ratio between front and rear wheels. For a more detailed model description and some preliminary results, please refer to [8] and [12]. As mentioned above, the input data is obtained through OBD port, and consists of vehicle speed, engine speed and pedal position. Starting from this limited set of data, a vehicle longitudinal model ([8], [11],[12]) is used to estimate a more complete set of variables. The output is a positive, negative (braking torque) or null torque to be delivered by the in-wheel motors. More details are presented in [13]. The model has been validated in off-line mode starting from data measured by the OBD port on a FIAT Grande Punto. Since vehicle speed (km/h) was available only as integer numbers, resulting in a significant discretization error at low speed, speed data have been filtered using digital filters available in Matlab® library [14].

Typical results are shown in Fig. 8, for a driving cycle in urban conditions, up to 50 km/h. It can be observed that the decision of delivering positive, negative or null torque at rear wheels is consistent with the detected active gear and with pedal position.

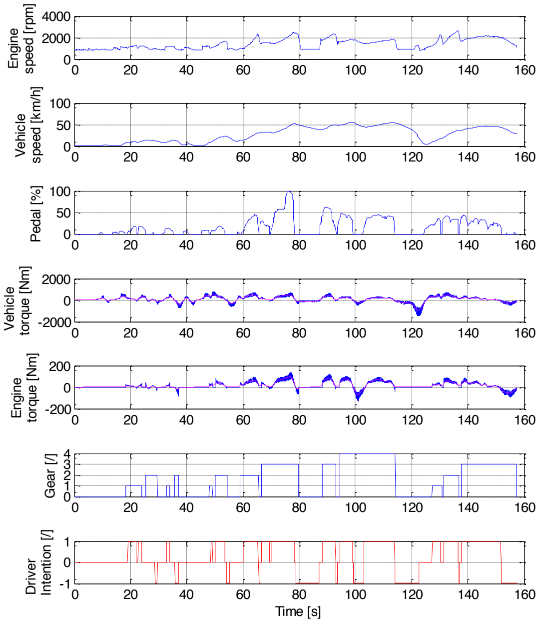

Fig. 8. Fuzzy logic – sample results.

A first release of the control system has been implemented in a LabVIEW/Matlab integrated software and tested on the road, on a FIAT Grande Punto with HSK kit. Preliminary tests, performed at limited vehicle speed (below 50 km/h), have shown a regular operation of the main control loop, and the possibility to activate regenerative braking. The vehicle was tested both in hybrid mode and in electric mode (with engine off and null gear).

Tab. 3. Fuzzy logic rules.

		OUTPUT: In-wheel motors torque					
		Braking torque (-1)				No torque (0)	Torque (1)
INPUT 1: Gear	Null gear				✓	✓	
	In gear		✓	✓			✓
INPUT 2: Pedal	OFF	✓	✓		✓		
	ON			✓		✓	✓
INPUT 3: Engine torque	Negative			✓			
	No torque						✓
	Positive						✓
INPUT 4: Vehicle torque	Negative	✓	✓				
	No torque						
	Positive				✓		
INPUT 5: Vehicle speed	Low						
	Mean	✓			✓		
	High	✓			✓		

The tests have shown that, in pure electric mode when engine is off, steering assistance is rather adequate, except that at very low speed, and that also braking is acceptable. However, some issues related to braking distribution and interactions with ABS and ESP have to be further investigated in the future, as well as the potentialities in terms of lateral stability offered by the possibility to control separately the two rear wheels [15], [16].

4.2. Dynamic Programming

A study on optimal and implementable control strategies is being completed, using a Dynamic Programming approach [[17]]. The main objective of this implementation is to define a benchmark solution, and assess the level of optimality of on-board implementable control strategies with respect to the optimal solution, achievable without constraints in terms of computational time and availability of information. The algorithm has been implemented in Matlab® and employs the optimization function realized by Olle Sundstrom and Lino Guzzella [17]. Please refer to [17] for mathematical formulation of DP algorithm and its implementation.

In the analyzed case the cost function is fuel consumption, the state variable is the state of charge SOC, and the control variable is the power split PS: this model will be integrated within the vehicle management unit, which would also determine the power ratio between front wheels (P_{RW}) and the total power demand (P_{Drive}).

$$PS = P_{RW} / P_{drive} \tag{1}$$

The main objective is to minimize fuel consumption by acting on the PS, thus determining the SOC, whose initial and final values are fixed (SOCf=SOCi for HEV operation, SOCf>SOCi for PEV operation). To validate the results a simplistic simulator has been developed, employing equations of the vehicle longitudinal dynamics, maps of efficiency of the internal combustion engine and electric motors. The simulator does not have a control module, thus PS is an input. Sample analysis were performed to assess *i)* the benefits of optimized PS(t) vs. constant PS, *ii)* the implications on fuel economy of different restrictions on PS. Sample results (driving cycle ECE-EUDC) are shown Tab. 4.

Tab. 4. DP sample results.

Scenario	Fuel economy [km/l]
ICE (Diesel) no HKS	20.41
HSK – DP	22.47
HSK - DP with constrained PS(<0.5)	21.27
HSK - Simulation with PS=0.5	40.10*
HSK - DP with SOCf=SOCf of previous case.	41.68*
HSK - DP with constrained PS(<0.3)	21.33
HSK - Simulation con PS=0.3	28.78*

*: such solutions do not respect the constraint of SOCf= SOCi. The fuel economy shown in the table should not be used in absolute values, but rather in relative terms to compare DP and Simulation results.

The results of the hybrid vehicles were compared with their respective conventional vehicles (CV), and an average fuel economy improvement of up to 10% was reported. It is worth noting that such results do not take into account the energy contribution provided by the photovoltaic panels. It has been considered possible to adapt this optimization strategy to the prototype due to the data processing time: for a driving cycle of 1200s the optimization is performed in about 50s with a pc Intel(R) Core(TM) i7 CPU 920 @2.67GHz, 8183 MB RAM.

The results listed in the above table will serve as benchmark to optimize the logic rules to be embedded in the fuzzy-controller.

5. Closure

Upgrading conventional vehicles to mild-solar-hybrid could have a relevant and short-term impact on fuel consumption and carbon dioxide 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 prototype of the hybridization kit has been developed and installed on a FIAT Grande Punto at the University of Salerno, and preliminary tests have demonstrated the feasibility of the project. The prototype, although not yet fully optimized, represents a successful proof-of-concept, having allowed to test and to verify possible critical issues related to in-wheel motors, battery, photovoltaic panels and control system.

Different methodologies have been used to address on-line energy management of the proposed hybridization kit, as well as offline investigation of maximum fuel economy: fuzzy logic is adopted to detect driver intention, facing the complex interaction between the driver and vehicle management unit, while an advanced dynamic programming optimization tool is used to evaluate the potential offered by the proposed hybridizing kit, and to providing a useful fuel savings benchmark.

Further work is in progress to: *i)* validate optimal and sub-optimal control strategies that are suitable for online implementation (i.e. real world application), *ii)* 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; *iii)* improve functionality and performance of the prototype, by optimizing their components; *iv)* finally, develop a spin-off company, aimed to the development, production and commercialization of the solar hybridization kit to install in after-market on existing cars (www.hysolarkit.com).

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