

A Model to Assess the Benefits of an After-Market Hybridization Kit based on Realistic Driving Habits and Charging Infrastructure

Vincenzo Marano, Hebert Medina, Marco Sorrentino, and Gianfranco Rizzo
Universita Degli Studi Di Salerno

ABSTRACT

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, it is unlikely that, in next few years, the scenario will drastically change, since relevant investments on production plants would be needed and the market does not seem to provide the expected growth for such technologies. Therefore, the possibility of upgrading conventional vehicles to hybrid electric vehicles is gaining interest. Among the diverse options for hybridization, researchers are focusing on electrification of rear wheels in front-driven vehicles, by adopting in-wheel motors and adding a lithium-ion battery. Thus, the vehicle is transformed in a Through-The-Road parallel hybrid electric vehicle.

This paper presents an energy-based model, developed in Matlab/Simulink environment, of a conventional vehicle hybridized by means of such conversion kit. The model has a modular approach, where different powertrain configurations are considered, specifically with different battery sizes, different in-wheel motors power, with/without plug-in capabilities. An additional level of complexity comes from the opportunity to integrate flexible PV panels into the hybridization kit.

In order to assess the benefits of the proposed kit with respect to the conventional vehicle, the analysis was performed over a variety of realistic driving cycles to reflect common driving habits. Results show that driver habits (in terms of driving style and distance driven), and the availability of charging infrastructure play an important role in fuel economy of the vehicle, thus making one configuration more convenient than others.

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INTRODUCTION

Today, the majority of the personal transportation energy comes from petroleum, which is used either in form of gasoline or diesel in conventional vehicles powered by internal combustion engines. Displacing petroleum without penalizing personal and commercial mobility has therefore become a major objective for the automotive industry and for government agencies worldwide. Today, the most viable options include fuel economy improvements in conventional vehicles, vehicle hybridization/electrification, and the recourse to alternative fuels (natural gas, LPG, bio-diesel, etc) [1, 2].

Passenger cars are required by law to become more efficient and environment-friendly. In US, the National Highway Traffic Safety Administration (NHTSA) has

recently set standards to increase Corporate Average Fuel Economy (CAFE) levels rapidly over the next several years, while in other countries fuel efficiency standards are regulated by way of CO₂ emissions mandates, and are well above those of the United States, as shown in [Figure 1](#) and [Figure 2](#).

In spite of technology improvements and legislative requirements, consumers will be the key drivers in the development of alternative vehicles. Higher cost, limited range and long recharging time represent serious drawbacks that limit market penetration of virtually all alternative-fuel vehicles in the personal transportation sector [4]. The choice of an option with respect to others is complex, and involves a variety of subjective factors regarding income, attitude towards cleaner technologies, practical needs, and others.

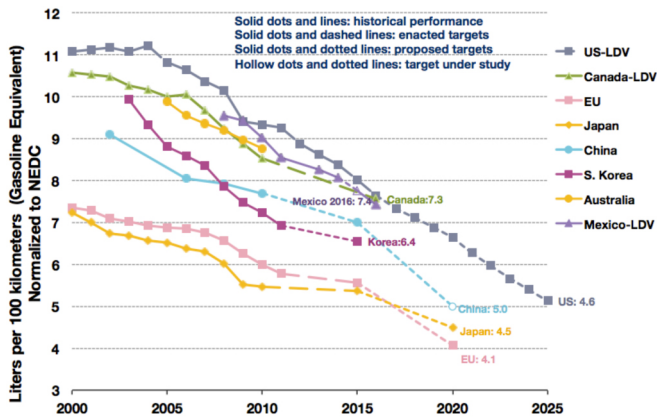


Figure 1. Efficiency Standards: Fuel Economy (l/100km) normalized to New European Driving Cycle [3].

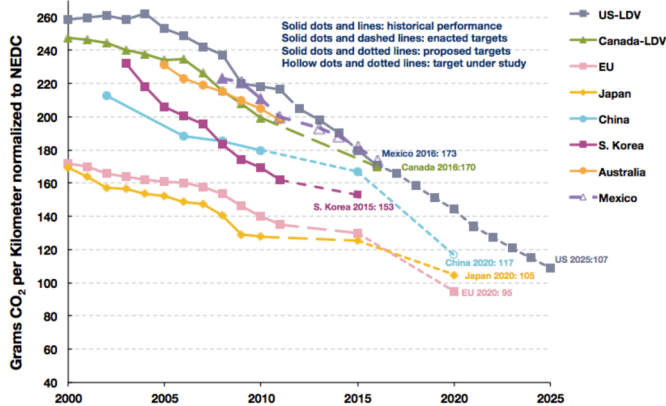


Figure 2. Efficiency Standards: CO₂ g/km normalized to New European Driving Cycle [3].

As discussed in [5, 6], the automotive industry is focusing on alternative fuels, various technologies including engine downsizing and boosting, direct injection and variable valve actuation, weight reduction, and mild hybridization (including engine start-stop technologies) to achieve greater fuel economy in conventional vehicles.

This paper is focused on the opportunities of after-market hybridization for conventional vehicles, and the possible integration of renewable energy.

Vehicle Electrification

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%. In the framework of vehicle electrification, Plug-in Hybrid Electric Vehicles (PHEVs) seem the most promising solutions. A PHEV is a hybrid vehicle, where both

an internal combustion engine and an electric motor connected to a battery are present on-board. The battery is discharged while driving and then it is recharged when the vehicle is connected to the electric grid (plugged-in). The ability of recharging allows for the vehicle to be run in *pure electric mode* (for 15- 100 kilometers depending on the battery size). PHEVs represent the middle point between hybrid and electric cars, thus combining benefits of the two architectures. They can achieve much higher fuel economy while preserving full functionality of conventional vehicles - long driving range, easy refueling (gasoline or electricity), etc.

It is worth pointing out that PEVs could impact the electric grid, especially regarding grid-stability and peak-load management. Moreover, the distribution network, in particular residential transformers, will need significant investments to accommodate a high concentration of PEVs (market penetration has been shown to be extremely geographically-dependent, thus high concentration of PEVs in certain residential areas is expected) [7,8].

Photovoltaic Power in Automotive Applications

The use of photovoltaic in cars has some unique features that makes it different from every other alternative. In fact, in all the other cases (fossil fuels, biofuels, electricity, and hydrogen) an energy carrier is needed to store the energy in the vehicle (with related conversion and transportation/distribution issues). This generates energy losses and emissions. The direct use of photovoltaic on the car is then the only way to realize a short circuit from primary renewable energy directly to the wheels, by cutting emissions, transportation and distribution losses.

Since 1970's, various prototypes of cars powered only by solar energy have been proposed, mainly for racing and demonstrative purposes and some solar vehicles reached very interesting results in terms of performance, maximum speed, and panel efficiency. However, these solutions do not represent a practical alternative to conventional vehicles, due to limited power and performance, limited range, discontinuous energy availability and, finally, high cost [9].

A practical and promising opportunity is the integration of solar PV on hybrid or conventional vehicles, in order to increase energy saving and face 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 [9, 10].

When dealing with alternative propulsion technologies one might tend to primarily analyze power performance and related issues. In this regard, a first evaluation of the usage of photovoltaic energy in the automotive sector could be discouraging: the power of a solar panel (that could be fitted on a conventional vehicle) is about two orders of magnitude lower than the power of the engine of a small or medium car. Nevertheless, this simple consideration is misleading. In fact, a small/medium vehicle in urban driving conditions has an

average road load of about 8 kW - considering regenerative braking. Therefore, this average power is one order of magnitude less than the car maximum power. Furthermore, a photovoltaic panel exposed to light can work at an average power of about two thirds of its maximum power for about 10 hours a day. It emerges that solar panels can provide up to 25% of the energy required for traction, if the vehicle is used in typical urban driving [11].

Hybridization of Conventional Vehicles

As discussed above, the premium for electric and hybrid vehicles, the limited market readiness, and incomplete customer technology awareness, make such vehicles still inadequate to displace conventional gasoline-power automobiles. Their market penetration is not (and will not, in the near future) enough to provide significant impact on energy and emissions savings.

Therefore, the possibility of upgrading conventional vehicles to hybrid vehicles is gaining interest. Hybridization can be achieved in different ways. In this paper, the analysis is focused on hybridization by means of electrification of rear wheels in front driven vehicles, often by adopting in-wheel motors. In such a way, the vehicle is transformed in a Through-The-Road (TTR) parallel hybrid electric vehicle. To enhance energy savings and emissions reduction, the hybridization configuration presented in this study also includes photovoltaic panels mounted on the vehicle roof and hood [12].

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 effects. On the other hand, the addition of electric propulsion may offer further advantages, such as *i*) the enhancement of vehicle power and performance (in particular acceleration); *ii*) increase in vehicle reliability, due to presence of two propulsion devices; *iii*) better driveability, due to the possibility of exploiting advanced vehicle control schemes.

In order to measure the real benefits of installing a hybridization kit on a conventional vehicle, a parametric analysis has been carried out considering a variety of configurations, for different battery size, in-wheel motors installed power and PV panels efficiency. The analysis has been performed over real driving cycles (data acquired during field testing), properly combined to reflect common driving usage patterns for European customers. Furthermore, different charging scenarios have been considered, as discussed in the following sections.

LONGITUDINAL VEHICLE MODEL

The parametric analyses presented in the next sections were accomplished by means of a longitudinal vehicle model developed under the following hypotheses:

- *i*) the drag force is considered acting on vehicle center of gravity;

- *ii*) vehicle inertia accounts for both vehicle mass (MHSV) and rotational inertia of ICE, EM/EG and wheels, through the term M_{eff} ;

- *iii*) 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:

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

where a and v are the road grade and vehicle speed, respectively. In case of non-negative power demand, the mechanical power is supplied by the ICE (P_{ICE}) and/or the in-wheel motors (P_{IWM}), depending on the control variable PS (Power Split) defined as:

$$PS = \frac{P_{IWM}}{P_w} \quad \text{if} \quad P_w \geq 0 \quad (2)$$

The control variable PS may range from negative values, in case ICE provides an extra power to be stored 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:

$$P_w = P_{ICE} + P_{IWM} \quad (3)$$

In case of vehicle braking or deceleration, the regenerative braking mode is active and the power is recovered into 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 (PB) requested or supplied to the battery is given by the following relationships:

$$P_b = \frac{P_w}{\eta_{IWM}}, \quad \text{if} \quad P_w \geq 0 \quad (4)$$

$$P_b = P_w \cdot \eta_{IWM}, \quad \text{if} \quad P_w < 0 \quad (5)$$

where η_{IWM} is the in-wheel motor efficiency. Figure 3 shows the normalized map here adopted to estimate in-wheel motor efficiency as a function of torque and angular speed. It is also worth mentioning here that ICE fuel consumption is computed through another normalized map, as shown on Figure 4.

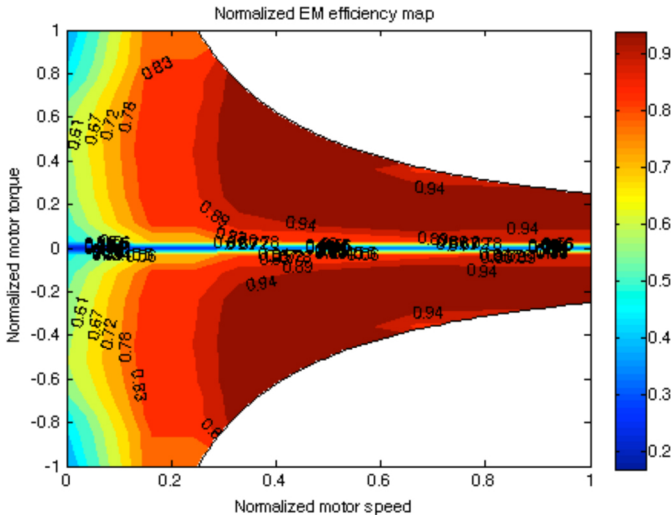


Figure 3. Normalized In-wheel motor efficiency map.
Maximum efficiency is lower than 0.9 and higher than 0.85.

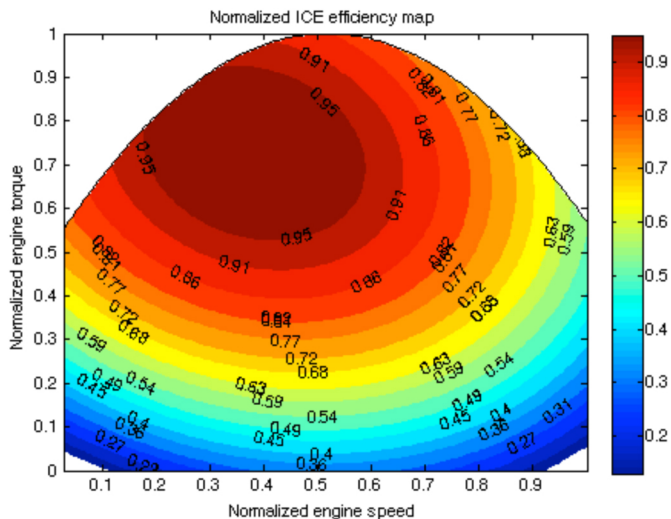


Figure 4. Normalized ICE map. Maximum efficiency is lower than 0.35 and higher than 0.3.

Energy management of hybrid components was performed as detailed in Eqs. (6) and (7):

$$P_b(t) = -P_{PV} + \min \left\{ P_w \cdot \eta_{IWM} \cdot \eta_c, P_{\max, IWM}(\omega_w) \cdot \eta_{IWM} \cdot \eta_c \right\}, \quad P_w(t) < 0 \quad (6)$$

$$P_b = \begin{cases} -P_{PV} + \min \left\{ \frac{PS \cdot P_w}{\eta_{IWM} \cdot \eta_c}, \frac{P_{\max, IWM}(\omega_w)}{\eta_{IWM} \cdot \eta_c} \right\}, & P_w(t) \geq 0 \text{ \& } SOC(t) > SOC_{\min} \\ -P_{PV}, & P_w(t) \geq 0 \text{ \& } SOC(t) \leq SOC_{\min} \end{cases} \quad (7)$$

where the footers w, IWM, b, PV and c stand for, respectively: wheel, in-wheel motor, battery, Photovoltaic

panel and converter. The term associated to photovoltaic panel power contribution, which is actually minor during drive phases, already accounts for PV converter losses. In the analyses conducted below, the value of the power splitting factor PS (see Eq. 2) was constantly set to 0.5. It is also worth mentioning that when $P_w(t) \geq 0$, the remaining power demand is always met by the ICE. The parameter $SOC_{\min}$ in Eq. (7), which defines the threshold below which no current can be drawn from the battery, has been found as a function of the following variables: in-wheel motors power, size of battery pack and presence of the PV roof (i.e. different final SOC (SOC_f) to be reached at the end of the driving path to ensure charge sustaining operation is guaranteed over the entire day).

HYBRIDIZATION KIT AND CONFIGURATIONS

The hybridizing equipment - installed on a conventional car (two front wheels drive), in which the front wheels are propelled by the Internal Combustion Engine (ICE) - consists of (Figure 5):

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

Thus, a mild parallel hybrid structure is obtained by substituting/integrating the rear wheels with in-wheel motors.

The vehicle can operate in pure electric mode (when ICE is switched off or disconnected from 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 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.

Kit Configurations

The vehicle model provides an estimation of energy consumption as function of vehicle parameters and driving patterns. In order to assess the benefits of the analyzed hybridization kit for different configurations, several simulations have been carried out, with main specifications summarized in Table 1, Table 2, Table 3 and Table 4.