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Retrofit Electrification of Road Vehicles

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Abstract: **electrification of road vehicles is a fundamental step for decarbonization. A rapid transition is urgent and probably is the most rational solution however the sudden obsolescence of tenth of millions of vehicles around the world pose a serious trouble also in terms of environmental impact . For this reason, a second life reuse of existing vehicles represents an important mitigation factor and an instrument for a sustainable and inclusive diffusion around the world of electric mobility also for emerging economies of countries which represents a large part of present and future Humanity. In this study authors introduce some design and application examples that should be easily managed with affordable and ready to market technologies.**

Keywords— Vehicle Electrification, Second Life of Vehicle, Retrofit Kit, energy efficiency of vehicles

I. INTRODUCTION

Electrification of road vehicles plays a key role in the decarbonization of modern industrial society [1]. A rapid transition from conventional to electric mobility is a mature and widely accepted step[2]. However, this rapid change is associated with a relevant environmental impact associated to the disposal of millions of conventional vehicles.

Also not secondary aspects are related to consumption of rare natural resources [3,4], such as metals that are involved in the construction of electric storages (Lithium, Cobalt, etc), Motors (precious metals, conductors , rare-earth elements) or power electronics.

The reuse of second life components such as batteries [5,6] or the recovery of precious material such as rare earths[7] are mitigative actions that are often proposed in literature.

In this sense electrification of conventional vehicles through a properly designed retrofit should be considered as a second life application aiming to increase the life of pre-existing vehicles, avoiding their premature disposal reducing the quantity of resources needed to provide efficient systems electrical mobility systems.

Profitability of a retrofit electrifications clearly depends on different factors such as energy costs, cost of manpower, availability of investments, industrial plants efficient and other logistic aspects. Results of this kind of analysis give variegate indications: as example retrofit of light tricycle truck [8] is a potentially good solutions not only for emerging industrial powers such as India where this kind of vehicles are widely used but also to some European countries such as Italy, where cost of energy, a favorable legislation [9] and taxation policy and the overall organization of service and transportation in urban areas are substantially favorable to a wide application of this kind of solutions. Finally retrofitting represents an affordable solution for a wider diffusion of developing countries since the retrofitting process is also more compatible with a low cost, decentralized model of production, diffusion and management of electrified vehicles which is more suitable for a less structured industrial and logistic chain[10].

For all these reasons there is a wide interest in recent literature[11][12] for the development of retrofit kits for the electrification of pre-existing conventional vehicles.

In this work author propose the retrofitting of small light vehicles corresponding for passengers' cars to EU segments from quadricycle to A segments minicars (roughly corresponding to US-EPA Minicompact). For what concern transportation of goods similar considerations should lead to the choice of light tricycle and quadricycle trucks.

It is considered as benchmark test case the retrofit of a Smart Fortwo (as example of minicar), and a Panda Van (as an example of mixed car, minivan for work applications)in which the original combustion engine is removed in favor of a compact and relatively cheap retrofit electrification.

In this work authors discuss proposed application and relatively simple methods used for fast identification, modelling, and optimization of the proposed system.

II. PROPOSED RETROFIT

A. Classification of different Retrofitting solutions for Electric and Hybrid Vehicles

Most of the research works cited in the introduction, perform a distinction respect to the kind of retrofit procedure that is implemented according to the typical powertrain scheme visible in Fig. 1 and 2:

- PS (Power Split): ICE(internal combustion engine) are continuously combined with one, two or more electrical motors to manage a continuous power split through a variable rate MDOF (Multi Degree of Freedom) transmission systems like the planetary solutions adopted on Toyota hybrid synergy drive[13] (visible in Fig.1) or in Chevrolet Volt[14]. Typically, these solutions are relatively complex and quite expensive representing the best solution for a large-scale production of new hybrid vehicles, but it's a quite impracticable solution for the construction of a cheap retrofit kit.
- P0: as visible in Fig.2, the electric motor is connected to the motor through a belt transmission system or other

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similar solutions that are normally adopted for auxiliaries. Clearly this solution should be feasible for a hybridization but not for a complete electrification of the vehicle

- P1: the electric motor is connected to the crankshaft before the clutch or other shape of sliding joint before the gearbox.
- P2: the electric motor is applied after the clutch directly or indirectly connected to the input shaft of the gearbox
- P3: the electric motor is connected to outputs shaft of the gearbox
- P4: the motor is directly connected to wheels or to differential gearbox.

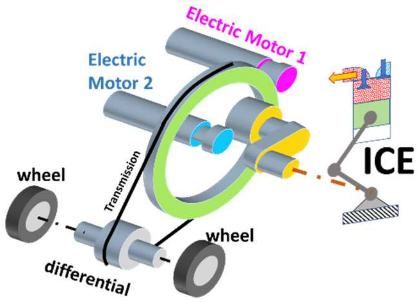

Fig. 1. Example of PS (Power Split) Hybrid Powertrain (Toyota Hybrid Sinergy drive)

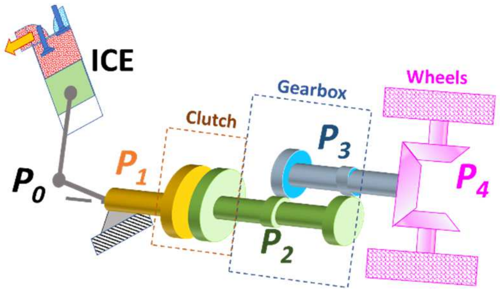

Fig. 2. Classification of P0-P4 Powertrain considering different location of electric motors

Respect to solutions described in Fig.1 and 2, authors focused their attention to the study of a P1 solution to study a retrofit kit in which the ICE(internal combustion engine) is substituted by an electric motor. A P1 layout was preferred to other possible solutions since proposed system as the following specifications:

- Use of a cheap, robust, and simple drive & motor which minimize usage of precious materials such as rare earths of PM machine. In this sense more robust and cheap machines are probably represented by induction motors; however, authors are strongly interested also to switched reluctance solutions[15][16].
- Reuse of the gearbox of the vehicle allows to chose relatively small electric machine and drive which can be easily optimized to work in near to optimal conditions exploiting multiple transmission ratio that are available on a standard gearbox.
- Minimum impact on pre-existing vehicle layout and management not only for a mere cost reduction but for an overall reduction of troubles related to overall harmonization on pre-existing systems of the wide variety of vehicles that can be revamped.

B. Smart Fortwo and Panda Van: main features of the Proposed Benchmark Test Vehicles

Main features of proposed benchmark vehicles are shown in Table I also in Fig.3, a picture of Smart for two is also shown : listed data are substantially enough to build up a simplified 1 DOF longitudinal vehicle according simplifications that are commonly assured as valid in literature[17,18]. For what concern the calculation of friction rolling resistances an equivalent force Frot is calculated according (1):

$$F_{rot} = \left(mg\cos\alpha - \frac{1}{2}\rho S C_L \dot{x}^2 \right)\left(f_0 + k\dot{x}^2 \right) \quad (1)$$

In (1) the following symbols are adopted:

- α =slope of the street.
- ρ,S and C_L are respectively air density, equivalent surface and lift coefficient of the car to calculate behavior of lift forces respect to vehicle speed.
- Coefficients f_0 and k are used to introduce a equivalent rolling friction of the car.

TABLE I. MAIN DATA OF BENCHMARK VEHICLES FOR PROPOSED RETROFIT KIT

	Smart W450 (1998-2007)	**Panda (2nd series 2003-2012)**
Mass	800 [Kg]	935[Kg]
Length	1,515 [m]	3,538[m]
Width	2,5 [m]	1,589 [m]
Height	1,53 [m]	1,578 [m]
Eq. Frontal Area	2[m^2]	1.7[m^2]
Aer. Drag Coeff.	0.35	0.35
ICE	Gasoline	Diesel
Max Power (ICE)	40 [kW]	55 [kW]
ICE displ.	599[cm^3]	1248[cm^3]
ICE, shaft speed	5250 [rpm]	1500 [rrpm]
Max Torque (ICE)	88 [Nm]	145 [Nm]
Max Speed	135[kmh]	160[kmh]
CO2 emissions (ICE)	118 g/km	109 g/Km
Emission Std	EURO 3	Euro 4
Gearbox gears	6	5
Gearbox ratios	3.308 (1^{st}),2.45(2^{nd}), 1,76(3^{rd}),1,25(4^{th}), 0.9(5^{th}),0.65(6^{th})	3.909 (1^{st}),2.056(2^{nd}), 1,273(3^{rd}),0.978(4^{th}), 0.73(5^{th})
Fixed ratio at differential	4.529	4.455
Traction	rear-wheel Drive	front-wheel drive
Wheel radius (motorized axle)	0,285[m]	0,35[m]
Rolling Friction losses:*	f_0=0.01 k=0,000065s^2m^{-2}	f_0=0.01 k=0,000065s^2m^{-2}

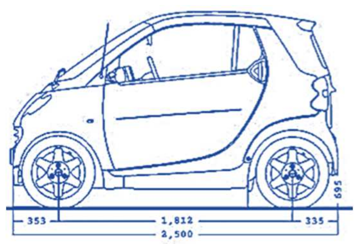

Fig. 3. Smart Fortwo W450 one of the proposed benchmark vehicles

C. Sizing of Electrification Kit

Affordability, low consumptions, reduced weight, and encumbrances are key factors for the success of a retrofitted vehicles respect to a new one. A key factor in term of costs, weight and encumbrances is represented by batteries[19][20].

It should be also notice that an oversizing of the storage systems should not be justified for a vehicle retrofit considering the reduced operational life respect to a new one and the need for a competitive pricing.

For all these reasons authors focused the optimization of the system respect to a typical urban mission profile as described by different publications that are both referred to Western Europe [21] and Emerging Countries[22] which substantially indicate a required daily autonomy of no more than 80-100km with a mean traveling speed between 20 and 40kmh. This speed reduction is also in favor of further safety and life extension of a second life vehicle which was originally designed for much higher operational speed. For the Panda Van for which is expected a much more severe service is possible to install an additional battery pack to substantially double the foreseen autonomy without

Starting from these evaluations, authors chose a battery pack of about 13-14kWh that is described in Table II: chosen $LiFePO_4$ cells were preferred for their safety and thermal stability.

TABLE II. MAIN DATA OF THE CHOSEN BATTERY PACK

Manufacturer	Zijin
Cell Tech.	$LiFePO_4$
Nom. Energy	13.9[kWh]@0.2C
Nom.Voltage	51.2 [V] (16Series Connnected)
Charge Current	Stanndard 0.5C Fast 1.0C
Discharge	1.0C (continuous),2.0C (60s Peak)
Op. Temp. Range	-35+65C° (Discharge)
Case dim.	680x410x230[mm]
Weight	94[kg]

Considering the installed battery pack and the necessity of maintaining comparable performances on a speed range which is substantially a quarter, a fifth respect to the original one.

The chosen motor-drive system is described in Table III: proposed motor is a robust squirrel cage induction machine able to exert almost the same torque of the ICE originally installed on the Smart Car. It’s interesting to notice that the total weight of installed electric devices (batteries, motor and drive) is lower respect to to the original layout considering both weights of ICE and of the transported Fuel. A lower weight also implies lower inertia and motion resistances.

A not negligible advantage of the proposed solution is also represented by the favorable mass distribution of the proposed solution: as visible in Fig.4, which is referred to the retrofitted Panda prototype the weight of the electric motor is placed on a relatively low position in the front of the vehicle that is quite useful both for stability and safety of the vehicle.

Both Motor encumbrances and the shape of the battery pack, a flat parallelepiped are exploited to optimize weight distribution of the vehicle, as visible in Fig.5 and 6 allowing a placement under the body chassis/frame.

Also, encumbrances of adopted power electronics, as visible in Fig,7 and 8 are fully compatible with a vehicle installation both considering the installation in a dedicated space (Fig. 7, Smart Prototype) or integrated with the motor (Fig.8 Panda Prototype). For the recharge, each vehicle is equipped with Mennekes connector [23] and an AC-DC converter allowing a 6kW recharge at public stations as visible in Fig.9. 6kW size of the recharge system assure a two-hour complete recharge with a 0.5C rate that is indicated by the cell manufacturer as the optimal one in terms of battery life.

TABLE III. MAIN DATA OF THE CHOSEN ELECTRIC MOTOR AND DRIVE

Manufacturer	Best Motor
Elec. Machine	Squirrel Cage Induction Motor
Power	10[kW]
Voltage	48 [V]
Nominal Current	235[A]
Max Torque	89 [Nm]
Ang. Speed	4500[rrpm]
Axial Encumbrance	299[mm]
Diameter	180[mm]
Weight	55[kg] (including drive and power electronics)

Fig. 4. Installatio of the electric motor in the Panda Prototype

Fig. 5. Motor Installation on the rear of the Smart Prototype

Fig. 6. Installatio of the Battery under the Smart Prototype

Fig. 7. Installatio of powe electroncs on the Smart Prototype (motor controller and battery AC/DC rectifier)

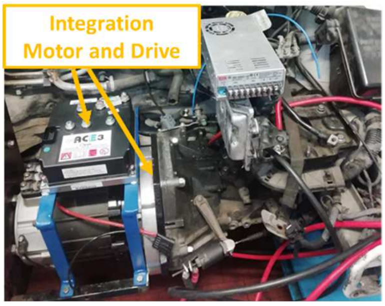

Fig. 8. Integration of Motor and Drive on retrofitted Panda

Fig. 9. Smart of the Prototype at recharge station

D. *Modelling and Preliminary Performance Evaluation*

Vehicle behavior, at least in terms of longitudinal performances can be evaluated using a model of vehicle longitudinal dynamics that is described in [24].

Vehicle acceleration and consequently vehicle dynamic is calculated imposing longitudinal equilibrium (2) respect to different forces acting on the vehicle:

$$\ddot{x} = \frac{T_e / \tau_i - F_a - F_{rot} - F_i}{\left(m + \sum_{i=1}^{n} I_\omega / \tau_i^2 \right)} \quad (2)$$

In (2), following symbols are adopted:

- T_e is the electric torque provided by the motor which is multiplied by a variable transmission ratio τ_i which depend from the inserted gear of the gearbox.
- F_a is the aerodynamic drag calculated according (3) from known values of drag coefficient C_D, air density ρ and frontal area A.

$$F_a = \frac{1}{2} \rho A C_D \dot{x}^2 \quad (3)$$

- F_{rot} is the equivalent rolling resistance of the vehicle calculated according (1).
- F_i is the resistance due to road slope defined according (4)

$$F_i = \left(mg \cos\alpha - \frac{1}{2} \rho S C_L \dot{x}^2 \right) \sin\alpha \quad (4)$$

Exploiting the over described model is possible to define a performance index the so-called residual acceleration a_r: maximum exerted torque of the motor $T_{emax}(\omega)$ is a function of the rotating speed of the motor and consequently of vehicle speed also considering the chosen gear of the gearbox. Assuming a flat road, the contribution of F_i is null and it is possible to calculate the maximum acceleration a_r that the vehicle can reach according (5):

$$a_r(\dot{x}) = \frac{T_{emax}(\dot{x}) / \tau_i(\dot{x}) - F_a - F_{rot}}{\left(m + \sum_{i=1}^{n} I_\omega / \tau_i^2(\dot{x}) \right)} \quad (5)$$

In (5) also the chosen gear is a function of vehicle speed: since the object of this calculation is the vehicle performance the chosen gear is the one that assure the maximum acceleration of the vehicle.

In Fig. 10 and 11 calculated a_r for both vehicles are shown: as previously introduced the motor-drive system is deliberately undersized in terms of installed power respect to the original vehicle but not in term of exerted torque; so, the resulting performance of the vehicle corresponds to quite good accelerations for the speed range corresponding to the optimized mission profiles. Higher speed should be reached but maximum speed is limited by altimetric profile of the road: considering the typical design criteria of an Italian highway[25] which involve a max slope of about 5% the max speed of the vehicle is substantially reduced to about 60-70kmh for both retrofitted vehicles. So it should be concluded that probably for both vehicles the last gear should be used only in limited occasions or should be more useful for retrofit kit involving the exploitation of a bit higher installed power (15-20kW).

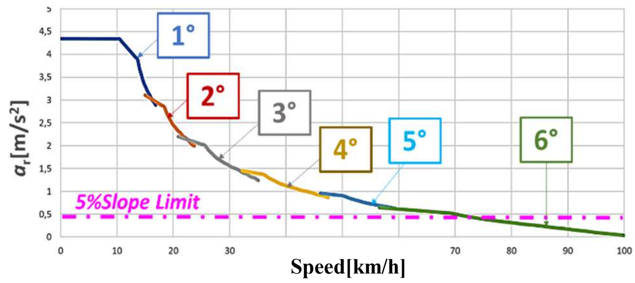

Fig. 10. Residual Acceleration of Retrofitted Smart Prototype

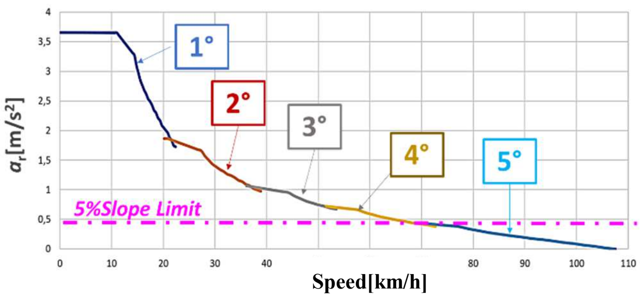

Fig. 11. Residual Acceleration of Retrofitted Panda Prototype

E. *Application of Regenerative Braking*

Application of regenerative Braking play a key role in increasing vehicle autonomy and efficiency, however electric braking as an overall influence on vehicle lateral stability since an excessive allocation of both electric and mechanical brake torques on wheels should saturate available adhesion in wheel-road interface[8]. More generally the application of strong electric braking forces should involve a better integration of the electric retrofit with an on-board brake blending algorithm[26] able to properly manage also the interaction with installed safety related systems like ABS and ESP. This is not clearly a good solution for a retrofit kit in terms of cost and time needed for a proper integration. For these reasons, authors preferred to operate alternatively with different mitigation policies:

- Disposition of added weights and inertia due to retrofit kit, privilege a mass distribution over motorized wheel
- Maximum Electrical braking is limited to avoid excessive braking loads on wheels and an emulated motor brake[26] function is implemented: as the driver leave the accelerator pedal a smooth regenerative braking torque is applied (10-20% this function can be customized to allow different drive style). A smoother, anticipated regenerative braking substantially allow a more efficient energy and thermal management, reproducing the typical brake motor effect of the ICE and consequently improving the controllability and the safety of the vehicle.

F. Experimental Evaluation of Motor Efficiency

To evaluate motor efficiency some preliminary traction tests have been performed according to the scheme of Fig. 12: a very simple testing procedure is managed by imposing a known speed reference to the motor drive, then a variable braking torque is imposed to the motor. Since the adopted driver perform an indirect field-oriented control[27] of the motor, the same drive is able to provide all the desired output to verify the input-output power balance of the system measuring inputs from its DC bus input and estimating with its on line filters the full state of the motor starting from an internal set of measurements that are functional respect to implemented control logic (current measurement, inverter conduction state, measured motor speed).

In this way authors were able to evaluate with a reduced set of experimental data a rough mapping of motor efficiency with a procedure that can be applied with limited or null cost also by a wide network of potential user and installers since the only needed equipment is a galvanically insulated USB to CAN converter connected to a PC. Also the braking load represented in Fig.13 can be represented by the same vehicle or it can be easily assembled using quite common components that are commonly diffused on a automotive maintenance shop. This is clearly an advantage for a massive diffusion of proposed kit among a wide network of installers even in contexts with low infrastructures corresponding as example to the distribution on developing countries. An example of obtained results in terms of Speed, Slip, Efficiency surface is shown in Fig.13. Some distortion on interpolated data due to the limited number of measured values are noticeable, but at the end a near to realistic evaluation of system efficiency can be easily performed. From Fig.10 and 11, it's clear that from 10kmh to the max one, performances are limited by performances of the motor working in the iso-power region from 1500 to 3000rpm. As visible in Fig.13 also the region in which maximum efficiency of the motor is reached is located within the typical speed range of 1500-3000 rpm which is exploited by each gear. So, it should be concluded that thank to the gearbox, the motor is mainly exploited in which its efficiency is near to optimal.

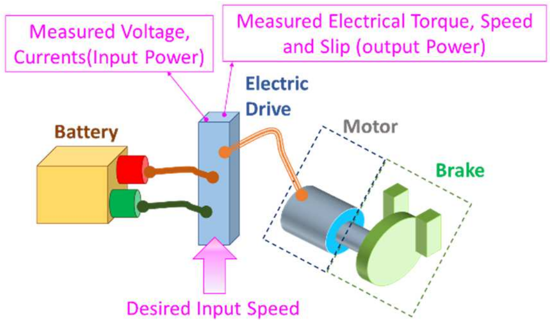

Fig. 12. Simplified Testing Procedure

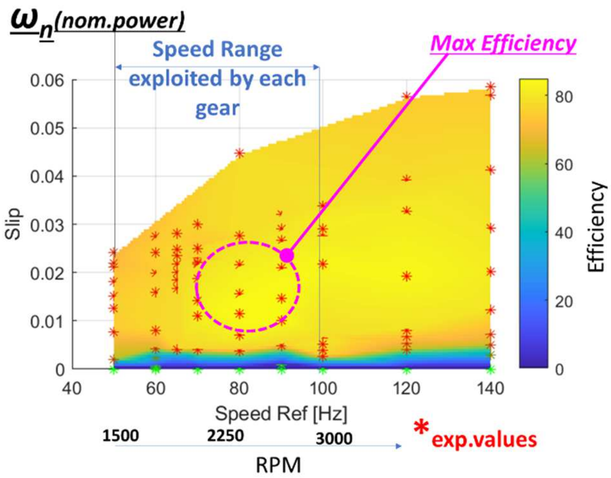

Fig. 13. Ref Speed, Slip and Efficiency surface of the motor-drive system.

III. Conclusions and Future Developments

In this work authors have presented the design and the construction of two prototypes of electrically retrofitted vehicles. Obtained results are substantially encouraging. Since both prototypes are currently working properly, next step of the work should be focused on two different complementary aspects:

- An extended experimental campaign will be performed to monitor performances and reliability of the proposed system.
- Exploiting data from experimental campaign a complete model/digital twin of the system should be calibrated. This model should be a fundamental tool for further optimization and design of the system.
- For what concern the storage a possible upgrade is represented by the adoption of next gen hybrid lithium batteries [29-31].

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