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## Extended Range Electric Vehicles components preliminary sizing based on real mission profiles

Filippo Colzi<sup>1</sup>, Michele de Nigris<sup>1</sup>, Andrea Corti<sup>2</sup>, Sergio Maria Savaresi<sup>2</sup>

<sup>1</sup>Ricerca sul Sistema Energetico-RSE SpA, via R. Rubattino 54, 20134 Milan

[Filippo.Colzi@rse-web.it](mailto:Filippo.Colzi@rse-web.it), [Michele.DeNigris@rse-web.it](mailto:Michele.DeNigris@rse-web.it)

<sup>2</sup>Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Via Ponzio 34/5, 20133 Milan

[Corti@elet.polimi.it](mailto:Corti@elet.polimi.it), [Savaresi@elet.polimi.it](mailto:Savaresi@elet.polimi.it)

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### Abstract

Considering the increasing attention paid by many actors in the automotive field on the hybrid-series/range extender technology, the article proposes a preliminary sizing for the battery pack and the thermal engine in an Extended Range Electric Vehicle. Aiming at carrying out a procedure the most possible “close” to final users’ real life, real world driving data have been used, avoiding standard cycles. The data, collected during a 5 month acquisition campaign on 4 vehicles, have then been used as input to a longitudinal dynamic model of the vehicle. The preliminary sizing procedure has been performed by imposing three main requirements, related to the mean daily travelled distance, the “total-life” battery range and the satisfaction of the worst-case in the acquisition campaign. This last point implied the execution of a cost analysis on different vehicle configurations, going from a pure-electric solution to a “pure fuel” one. The procedure has shown that the battery pack sizing is strictly related to the chosen daily and “total-life” range, while the range extender nominal power is much more related to the worst-case required energy. At last, a simple comparison between the dimensioned vehicle and a gasoline one has been carried out, showing high advantages in terms of CO<sub>2</sub> emissions but low benefits in terms of costs.

*Keywords: battery, EREV (Extended Range Electric Vehicle), powertrain.*

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## 1 Introduction

Although their impressive developments in the last few years and the opportunities for continuous and tangible improvements in the very next period, electric vehicles are still nowadays suffering problems in guaranteeing a “mass-market acceptable” costs/range ratio. As well known, one of the most interesting solutions to immediately alleviate this problem is to adopt hybrid systems, which can integrate the benefits of the electric traction with the most

valuable features of the internal combustion engines. In particular, during the last years, the attention of the main OEMs in the automotive field is increasingly focusing also on the “hybrid-series” vehicle architecture. In this particular configuration, the vehicle is equipped with an electric motor and a battery pack, such as a pure electric vehicle, but also with a fossil fuel tank and an internal combustion engine, used as a “range-extender” (RE) (and is therefore defined as Extended Range Electric Vehicle – EREV). Several vehicles adopting this powertrain architecture have already been proposed, for

example by GM, Audi, Volvo, BMW, Suzuki and Fisker.

Bearing in mind this new trend, it has been considered useful to investigate this kind of structures and in particular to try to understand the most interesting configurations of the powertrain, by performing a preliminary sizing of its main components, i.e. the battery pack (BP) and the thermal engine. To carry out a sizing procedure the most possible “close” to final users needs, real world driving cycles data have been collected and analysed, thanks to a dedicated acquisition campaign and a vehicle longitudinal dynamic model.

More in particular, it has been chosen to estimate the vehicle required energy through the measurement of its instantaneous speed and acceleration, as proposed in Ahn and Van Aerde [1], Manzoni et al. [2][3], Savaresi et al. [4] and Corti et al [5].

In the remainder of the article, the data acquisition campaign and the vehicle model will be described respectively in sections 2 and 3, while sections 4 and 5 will be devoted to the preliminary sizing procedure and the conclusions of the work.

## 2 Real world data acquisition campaign

A literature analysis has underlined that, despite of the high number of projects and works in the field of mobility, there is a lack of availability of reliable and exploitable vehicle missions data. Due to that, in many cases the standard driving cycles as the New European Driving Cycle or the Environmental Protection Agency Test Cycles (or parts of them) are used as a basis to carry on studies and analyses. In the authors’ opinion, standard driving cycles very seldom provide a good representation of real vehicle usage and it has so been decided to collect data from real missions, performed by common drivers.

A stand-alone system for sampling and logging absolute position, longitudinal speed, and longitudinal acceleration has been installed on four Internal Combustion Engine (ICE) vehicles of RSE fleet. The system used in the acquisition campaign is represented in Fig. 1 and is composed by:

- An inertial platform with a 3 axis accelerometer and one gyrometer;

- A microcontroller used for processing and data logging with a micro-SD card;
- A remote GPS receiver;
- A power supply system connected to the 12 V socket;
- A 9V battery to ensure closing and saving of data files.



Figure 1 Acquisition system

The instrumentation setting is very simple because the chosen architecture does not require any connection with the vehicle buses. This makes it a completely “vehicle-independent” system. With a 10 Hz sampling frequency, the significant physical characteristics (speed and acceleration) are recorded, and will then be input of a Matlab code for their processing and for the inclusion in the dynamic vehicle model.

The acquisition campaign has been carried out in the Milan area from July 2011 to March 2012 on four Lancia Delta cars (1.6 JTD 88kW engine). In total, approximately 5 months of data are available for each vehicle.

## 3 Longitudinal Dynamic Model

In order to obtain a simple but reliable description of the vehicle motion, a modified version of the approach firstly proposed in [3], [5] and [6] has been adopted. The mechanical energy spent at the wheel by the vehicle is reconstructed through its speed and acceleration, considering the following forces:

$$\text{InertialForce} \rightarrow F_{in} = Ma \quad (1)$$

$$\text{GravityForce} \rightarrow F_g = Mg \quad (2)$$

$$\text{Aerodynamic Force} \rightarrow F_{aero} = \frac{1}{2} \rho C_v A_{aero} v^2 \quad (3)$$

$$\text{RollingForce} \rightarrow F_{roll} = C_{roll} F_g \quad (4)$$

$$\text{ViscousFrictionForce} \rightarrow F_{visc} = K_{visc} v \quad (5)$$

The braking force and the forces due to the slope, as defined in [6] have not been considered in this case, and the traction force at the wheel  $F_{wheel}$  can be so determined as:

$$F_{wheel} = Ma + \frac{1}{2} \rho C_v A_{aero} v^2 + \underbrace{C_{roll} F_g + K_{visc} v}_{F_{res}} \quad (6)$$

The power at the wheel in each instant of the vehicle mission is therefore defined as:

$$P(t)_{wheel} = Ma(t)v(t) + F_{res}(t)v(t) \quad (7)$$

while the energy spent can be simply determined as:

$$E_{wheel} = \int_{t_0}^{t_f} P(t)_{wheel} dt \quad (8)$$

To obtain a good estimation of the resistance force, coasting-down trials have been carried out, following the procedure described in [5]. The results of the trials have let the identification of the vehicle resistance parameters:

$$C_v = 0,2879 \quad (9)$$

$$K_{visc} = 4,5124 \quad (10)$$

$$C_{roll} = 0,0178 \quad (11)$$

## 4 Preliminary Optimal Sizing

The goal was to find the most rational sizing in terms of functionality and costs for the main components of the vehicle powertrain, hypothesizing that the ICE monitored vehicles could be substituted by “hybrid-series/range-extender” vehicles.

### 4.1 Main results of the acquisition campaign

The five-month acquisition campaign let to identify a lot of different parameters to characterize the vehicle usage and its physical behaviour. Here, the most valuable results for the sizing purpose are reported. At first, as represented in Fig. 2, it has been possible to evaluate the mean daily distance covered by each monitored vehicle. It can be seen that the mean driven distance is quite high, coherently with a “medium commuter” usage in the surrounding of Milan. The mean value for the four vehicles is approximately 63 km/day.

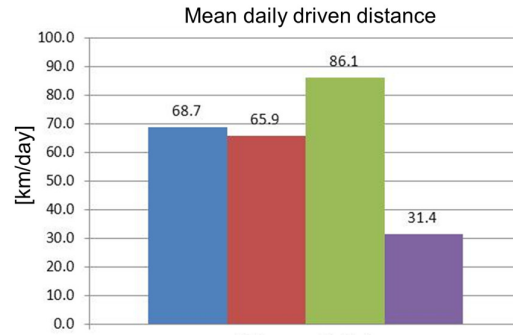


Figure 2 Mean daily driven distance of the 4 monitored vehicle (one for each bar)

In order to identify a solution that could fully substitute the ICE monitored vehicles, it is also useful to analyse the maximum distance travelled during the considered period. As depicted in Fig. 3, two of the four cars have travelled for more than 500 km.

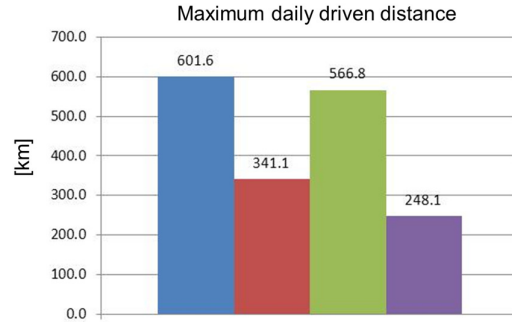


Figure 3 Maximum daily driven distance of the 4 monitored vehicle (one for each bar)

The use of the dynamic model let also to evaluate the mean specific energy at the wheel required for the vehicle motion (Fig. 4). This value is different among the four cars depending mainly on the kind of route and on the driver driving-style. The mean value for all the vehicles is 0,165 kWh/km.

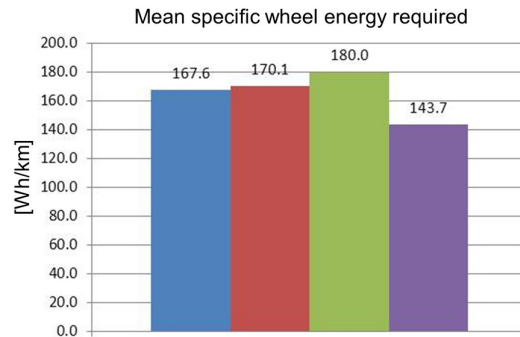


Figure 4 Mean specific wheel energy required by the 4 monitored vehicle (one for each bar)

## 4.2 Sizing objective

The objective of this preliminary sizing procedure is to identify the most suitable dimensions of the Battery Pack and of the Range Extender thermal engine in order to comply with the following three specifications.

- Pure electric daily use: according to the EREV approach (different from other hybrids ones), the vehicle should be normally used as a pure electric car, and only in particular cases switch on the Range Extender.
- Battery Pack capacity coherent with the vehicle normal lifespan: the range allowed with a single charge and the total number of charging cycles should let the use of the battery pack during the whole life of the vehicle.
- Possibility to fully substitute the monitored vehicles: the chance to have a vehicle that will not imply negative changes in the user behaviour seems to be a key point to guarantee the introduction of new technologies in the car market.

## 4.3 Powertrain architecture and management

To perform the sizing procedure, the EREV has been considered as a set of five main components:

- Electric grid (including charger);
- Battery Pack;
- Electric Motor (including inverter);
- Internal Combustion Engine;
- Electric Generator (including power electronics).

For each component a conversion efficiency has been fixed, as shown in Fig.5.

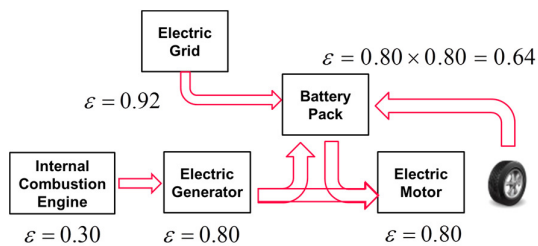


Figure 5 Powertrain components and efficiencies

In terms of system management, three main hypotheses have been defined:

- The Range Extender is always on when the car is on;
- The vehicle starts the mission with 100% State of Charge (SOC) and ends it with 0% State of Charge;
- There is no intermediate charging.

Note that the just mentioned hypotheses are valid only to perform a sizing procedure based on a total a-priori knowledge of the mission profile. They are thought to minimize the required size of the Range Extender completely exploiting the energy stored in the battery (from 100% to 0% SOC). It has not to be confused with a real control algorithm.

## 4.4 Minimum sizing for mean usage

As detailed in section 4.2, the first aim of the sizing procedure is to allow a pure electric drive at least on the mean daily mission. The data obtained from the acquisition campaign and the previously described hypotheses let to calculate:

$$BP_{\min} = \frac{0,165 \left[ \frac{kWh}{km} \right]}{0,8} * 63[km] = 13,0[kWh] \quad (12)$$

At the same time, the second specification described in 4.2 imposes that:

$$BP_{\min} = \frac{150.000[km] \cdot 0,165 \left[ \frac{kWh}{km} \right]}{2.000[\#cycles] \cdot 0,8} = 15,47[kWh] \quad (13)$$

where 150.000 km has been considered as a reference “total lifespan” range for a standard vehicle and 2.000 is the typical number of cycles declared by many battery producers.

Between the two minima, the highest has to be chosen. A battery pack with a 15,47 kWh energy capacity will so theoretically allow to use the car as pure electric for the whole lifespan, and will let a daily pure electric travel of 75 km (satisfying also the minimum requirement of 63 km/day).

## 4.5 Sizing for the Worst Case

The third specification described in section 4.2 states that the new vehicle needs to allow exactly the same performances of the traditional monitored ones. That means being sized to perform the worst-case mission in the data acquisition period, i.e. a mission covering 601 km with a total wheel energy consumption of 178 kWh.

Starting from the minimal “pure-electric” configuration identified in section 4.4, the satisfaction of the worst-case can be obtained operating on two parameters:

- BP capacity;
- Range Extender nominal power.

It is easy to understand that increasing the BP capacity, the energy stored on board increases and therefore decreases the need for a big range extender (and the opposite). To identify the best solution, it has been chosen to study the specific costs [€/km] of the worst-case mission for many different vehicle configurations.

In particular the analysis started from a pure electric vehicle (0 kW range extender and huge battery) and arrived to a “pure fuel” vehicle (60 kW range extender and negligible battery).

In Fig.6, the cases of 0, 8, 20 and 32 kW range extenders are depicted, corresponding to 178, 138, 83 and 28 kWh Battery Packs. In particular, in the first graph the energy level in the Battery Pack is represented. It can be seen that during the night the batteries are fully recharged, reaching their maximum storage level in early morning. At the end of the mission, around 7.30 PM, the BP is instead completely empty, according to the management choices expressed in section 4.3. The profile of power spent during the mission is represented in the second graph. The car has been used for a quite long trip during the

morning and for the comeback in the evening, with two additional short trips before and after noon. It can be noticed how the discharge curves in the first graph correctly follows the power requirements. In the third graph, the cumulative curve indicates the energy provided by the range extender. When the curve is horizontal, the vehicle is shut-off and the range extender too. It can be noticed how at the end of the day the sum between the energy stored in the battery in the morning and the total energy provided by the range extender gives exactly the total amount of energy required for the whole mission (178 kWh).

The identification of the best option for the worst-case has been carried on considering the following cost components for the mission:

- Electric energy cost: 0.15 €/kWh;
- Fuel cost: 1.8 €/l;
- Battery pack purchase cost: 600 €/kWh.
- Range-extender purchase cost: from 1500 € (4 kW) to 2500 € (60 kW).

The fixed costs due to the BP and RE purchase have been “amortized” on the whole vehicle life (150.000 km), while the variable costs of energy and fuel have been directly applied. The results of the analysis is shown in Fig. 7. Each bar represents a vehicle configuration and the related specific cost.

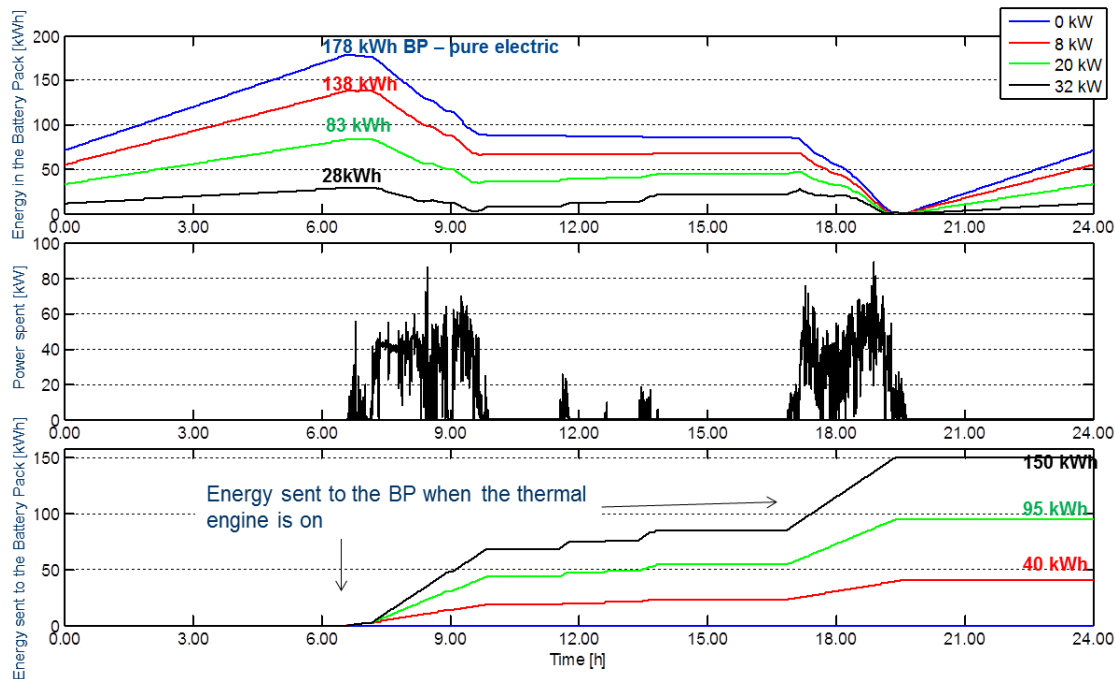


Figure 6 Worst-case modelling data: energy in the BP, spent power and energy provided by the RE

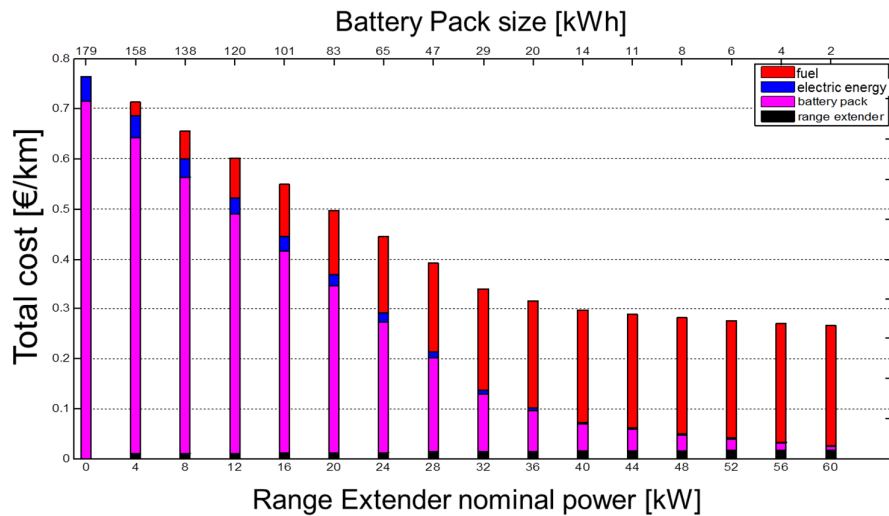


Figure 7 EREV specific costs [€/km] for the worst-case, varying BP and RE sizing

It can be seen that the “all-electric” configuration, with a 178 kWh BP is the most expensive solution and that the bars follow a monotone decreasing curve. It is clear that the high purchasing cost of the BP is the dominant aspect, and that the cost saving due to the smaller amount of fuel consumption is not able to balance it.

The most convenient solution is therefore the one characterized by the smallest BP and the biggest RE (60 KW). In order to respect this result but also to comply with the minimum BP size defined in section 4.4, it can be said that the best solution with the chosen constraints is:

- BP capacity = 15.47 kWh;
- RE nominal power = 38,95 kW.

## 4.6 Sizing comments and further analyses

### 4.6.1 Whole-period analysis

In theory, to obtain a more reliable definition of the optimal solution in terms of usage costs, the procedure carried on for the worst-case should be repeated for every day of the acquisition campaign, progressively adding the daily results and then obtaining a total cost value for each configuration in the whole period. In practice, due to the monotone trend of the curve and the strong influence of the BP costs it can be expected that in each monitored day the most convenient solution would be the one with the

smallest battery pack, so converging on the already chosen size.

Moreover, it has to be said that, accordingly to the chosen requirements, the vehicle missions during the acquisition campaign would be for approximately the 85% covered only with the electric energy stored in the battery. Only in the 15% of the cases the vehicle will need to use the range extender. This is clearly shown in Fig. 8, where the black bars show the amount of energy provided by fuel in the range extender.

### 4.6.2 Introduction of speed limitations

The presented sizing is to the truth strongly influenced by the peculiarity of the chosen worst-case mission, which is remarkably challenging for the vehicle components (mean speed of 100 km/h and maximum speed over 150 km/h). To alleviate this problem, it has been considered interesting to evaluate other two sizings, defined virtually imposing performance limitations to the vehicle:

- Maximum speed limitation: 120 km/h;
- Maximum speed limitation: 90 km/h.

In these cases, the battery capacity remains constant, due to the “minimum size” imposed constraints, but the range extender nominal power significantly decreases, respectively to 31,65 kW and 17,92 kW.

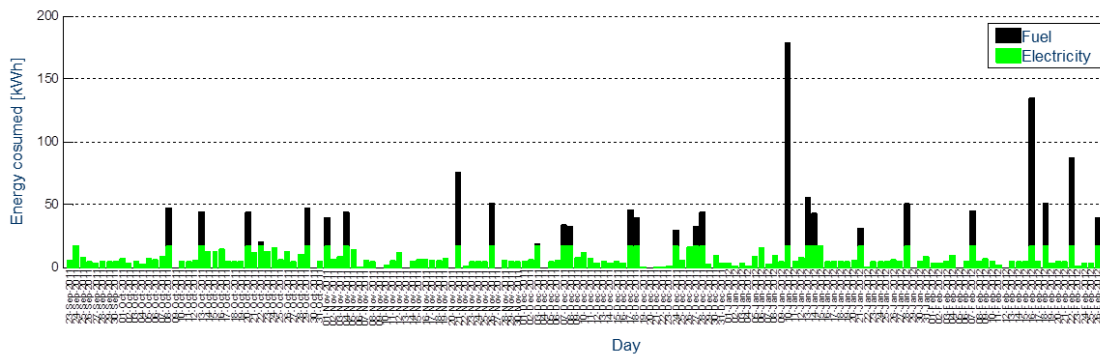


Figure 8 Energy spent in each monitored day, hypothesizing the "worst-case dimensioned" vehicle

#### 4.6.3 Comparison with a fuel vehicle

The real mission profiles of one vehicle among the four monitored have been used also to carry on a simplified comparison between a traditional fuel vehicle and the EREV in terms of CO<sub>2</sub> emissions and global costs in the analysed period.

The results show that the adoption of the above-dimensioned EREV would allow a CO<sub>2</sub> emission saving of 31,4% with respect to a gasoline vehicle. In terms of costs, the results show that the "worst-case dimensioned" vehicle is not convenient in comparison with the gasoline one, due to the high cost of the battery pack. The introduction of 120 km/h and 90 km/h maximum speed limitations, instead, let the range extended vehicle gain advantages with respect to the gasoline one, with a money saving of 1,6% and 13% respectively.

## 5 Conclusions

Considering the growing attention of the automotive actors on the Extended Range Electric Vehicles, an already proposed vehicle model has been properly modified and adapted to this new kind of powertrain architecture. Noticing in parallel that there is a lack of availability of reliable mission profiles data to simulate the vehicle behaviour, a five months acquisition campaign has been carried out on four real cars of the RSE fleet. The integration of the new model with the new data, has let to perform a preliminary sizing of the EREV powertrain, imposing the respect of three main requirements:

- Pure electric daily use;
- Battery Pack capacity coherent with the vehicle normal lifespan;

- Possibility to fully substitute the monitored vehicles (worst-case satisfaction).

The first two conditions, crossed with the real world mission data, immediately gave indications on a minimum size of the BP. To understand the better solution to satisfy the worst-case, instead, a cost comparison among different vehicle configurations has been executed. The results have shown a strong dependence of the worst-case sizing on the high costs of the battery pack purchase.

More in general, the sizing procedure has shown that the BP sizing is strictly related to the chosen daily and "total-life" range, while the RE nominal power is much more related to the worst-case required energy. The virtual introduction of speed limitations on the worst case mission has indeed let a substantial decrease in the RE size.

In comparison with a gasoline vehicle, no relevant benefits have been detected in terms of costs, while in terms of CO<sub>2</sub> emission more than a 30% of reduction would be obtained.

The study is composed by many parts (model, data acquisition, sizing, global analyses, etc) and each one could be substantially improved in the next steps of the work. One topic that is considered to be particularly interesting to further investigate and to include in the model is a more refined EREV components management, including control algorithms and battery aging aspects.

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## Authors



Filippo Colzi was born in Florence on 1985. He received his B. Sc. in Mechanical Engineer from University of Florence (2007) and a double M.Sc. in Energy Engineer in Politecnico di Milano and Politecnico di Torino (2010) within the Alta Scuola Politecnica education program. After a first working period in the field of renewable energies, he works in RSE since 2011, focusing on electric and sustainable mobility



Michele de Nigris is the director of the T&D Technologies Department in RSE since 2006. Graduated in electrical engineering, he started his professional life in CESI in 1984 working on electric components for the distribution and transmission grid. He participated to the Major Economies Forum and he is the president and one of the founders of ISGAN (international Smart Grids Action Network).



Andrea Corti was born in Como, Italy, on 1984. He received his B.Sc. and M.Sc. in Computer Engineering from Politecnico di Milano (Italy) in 2006 and 2009, respectively. He earned the Ph.D. in Information Engineering in 2013 and he was visiting student at MIT SENSEable city Lab, US. His main research interests are the analysis and development of Intelligent Transportation Systems for enhancing the vehicle efficiency by exploiting a real-time interaction with the driver.



Sergio M. Savaresi was born in Manerbio, Italy, on 1968. He received the M.Sc. in Electrical Engineering (Politecnico di Milano, 1992), the Ph.D. in Systems and Control Engineering (Politecnico di Milano, 1996), and the M.Sc. in Applied Mathematics (Catholic University, Brescia, 2000). He is Full Professor in Automatic Control at Politecnico di Milano since 2006, head of the “mOve” research team, and Chair of the Systems&Control Section of Department of Electronics and Computer Sciences, Politecnico di Milano.