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Design and Development of Series-Hybrid Automotive Powertrains

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ABSTRACT The new global pandemic determines people to change their ordinary habits, so personal transportation will play a very important role for a long period of time from now on. However, even though conventional vehicles offer enough range for replacing some trips that normally would be covered by planes, they have a harmful impact on the environment. By comparison, Electric Vehicles (EVs) suffer from this shortcoming (insufficient range), being more expensive, as well. Therefore, this article presents a very simple, unique and inexpensive methodology for designing the powertrain of a plug-in series-hybrid vehicle, based on measurements (regarding the engine torque requirements, but not limited to) performed on a compact passenger car, during real driving conditions, as well as based on mathematical calculations and computer-aided simulations (using MATLAB Simulink). The parameters of the proposed series-hybrid driving system which have been determined refer to the specifications of the Internal Combustion Engine (ICE) which is used to drive a generator, the rated output power of the electric generator, the required capabilities of the electric motor which is used to drive the wheels, the capacity of the high voltage battery pack (which supplies the electric motor), together with its other attributes, taking into consideration the vehicle's overall performance and characteristics. Besides this, it has been developed a very simple algorithm that manages the power generated by the engine and which can reduce the fossil fuel consumption with almost 38%, on average, compared to a conventional drivetrain.

INDEX TERMS Diesel engine, driving system, emissions, fuel economy, plug-in hybrid electric vehicle, power management control, series-hybrid powertrain.

I. INTRODUCTION

Nowadays, the global situation has a negative impact on airline companies, mostly due to the people's choice to use personal transportation (for health safety reasons), which means that automotive industry has to keep up with the new demands. Therefore, due to the increased number of vehicles, especially inside the cities, a major problem is represented by the pollution of the air, which can have dangerous effects upon pedestrians and environment, as well. On the other hand, traffic jams lead to increased fuel consumption and substantial CO_2 emissions, which accelerate the global warming process; that's why all major car manufacturers refocus their attention to less pollutant vehicles, such as Electric Vehicles (EVs) or Hybrid Electric Vehicles (HEVs). Regarding the EVs, their current major drawbacks are related to the cost of production, fairly low range, combined with long periods of time needed for recharging the batteries and the lack of infrastructure (insufficient charging stations for the current and upcoming demand) in many countries (at least in Europe), as well as the increased weight of the vehicle. Most of these issues cannot be solved very quickly, given the actual global economic situation and therefore, another viable alternative should be found.

In order to overcome the drawbacks of both conventional ICE-powered vehicles and EVs, the current solution is represented by the development of Plug-In Hybrid Electric Vehicles (PHEVs), which are very promising sustainable mobility solutions because they offer the advantage of providing enough range, combined with high energy efficiency. Apart from these two major advantages, engine downsizing translates into both weight saving and lower tax rates, which contribute to reduced overall ownership costs for the vehicle.

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With regards to the most appropriate choice when it comes to the architecture of the powertrain, it depends on multiple factors, but from the technical perspective, there are different configurations (layouts) available, such as: parallel-hybrid [1], [2], series-hybrid (as proposed in this article, as well as in [3]–[6]), series-parallel hybrid, power-split hybrid, etc.

Therefore, depending on the driving profile and the desired usage of the vehicle, one of the previously mentioned configurations should be taken into account [7]. For example, if the car is mainly used for city driving, a series-hybrid powertrain may be considered; otherwise, if the vehicle is driven most of the time on the highway, a parallel-hybrid configuration should be used.

In case of the series configuration, because the mechanical energy produced by the engine should be transformed into electrical energy and then converted back into mechanical energy to provide traction, the overall efficiency of the powertrain is lower, during constant speed driving, compared to a parallel architecture.

However, one important advantage of a series-hybrid powertrain is represented by the fact that the ICE can be operated at a constant speed, near its maximum efficiency point (regardless of the driving speed), which translates into both lower fuel consumption and emissions, compared to a conventional powertrain. On the other hand, regarding the after-treatment system which is currently used for ICEs, the Diesel Particulate Filter (DPF) or the OPF (Otto Particulate Filter) can be regenerated in optimum conditions; this eliminates the issue caused by low exhaust gas temperature or insufficient rotational speed of the engine, which are commonly encountered during city driving situations and most of the time during the cold season [3].

As Gan *et al.* propose [8], in order to identify the most energy efficient hybrid architecture, there need to be taken into consideration both the dimensions of the key components (electric motor, battery, ICE), as well as the control strategy, but unlike their approach, which refers to multi-architecture and multi-application design, this work is focused more on series-hybrid architecture design and development for passenger cars. However, by applying the proposed methodology, this study can be extended to other means of transportation, like vans, trucks or even motorcycles.

Compared to other papers, which rely on standard driving cycles when developing their energy management strategies and control [8]–[10], this article proposes a new design methodology for series-hybrid powertrains, based on mathematical calculations, MATLAB Simulink simulations and most important of all, real driving measurements. Therefore, by measuring some engine and transmission parameters (by the means of a diagnostics interface) during driving [1], [2] and [11], the power requirements for the vehicle to ride can be easily determined, thus simplifying the design process. Instead of using expensive and bulky pieces of equipment, which have several limitations with regards to their usage, a dedicated diagnostics interface is more versatile. Besides this, the proposed design methodology does not imply developing sophisticated strategies and algorithms or artificial intelligence [12]–[16], thus making it easier to be debugged, tested and implemented in series production.

In contrast with [12], which needs the future transportation information to be acquired before the departure, in order to define the variation range of the equivalent factor, by calculating a pair of boundary equivalent factors, the proposed algorithm does not need any preliminary data with regards to the trip and utilizes very low computational power for calculating the electric power requirements.

In addition to this, [13] proposes a prediction strategy based on sensor networks and communication techniques, which allow traffic data shared by vehicles on the road to be deeply utilized on this purpose, which may be considered a weak point, because the infrastructure in some countries and regions is not always fully developed. An error within the network may cause the energy management to cause inappropriate operation, which leads to increased fuel consumption and emissions, therefore the energy management proposed in this work is independent of any external preprocessed data.

This article is organized as follows: in Section II is presented an overview of the proposed series-hybrid powertrain (Section II A focuses on mathematical calculations, which have been used to determine the power requirements for a conventional vehicle, Section II B deals with some MATLAB Simulink simulations, which have the same purpose as the calculations and Section II C reveals some experimental results that were conducted during real driving conditions), Section III highlights a comparison between the results which were obtained by using different design approaches (calculations, simulations and measurements), Section IV explains the methodology used for dimensioning the proposed series-hybrid powertrain, together with the algorithm which was implemented on multiple sets of collected data, as well as some numerical results. The paper ends with the Conclusion section, which also includes some future directions of development, followed by Acknowledgement and References.

II. SERIES-HYBRID POWERTRAIN OVERVIEW

Since the main drawbacks of an ICE-powered vehicle (with regards to fuel consumption, noise and air pollution) are mostly dominant during city driving situations, this work proposes the implementation of a plug-in series-hybrid powertrain architecture that is designed to overcome them, in contrast to [1] and [2], which propose a parallel-hybrid configuration.

Therefore, Figure 1 reveals a comparison between a conventional powertrain and the proposed series-hybrid architecture, as also highlighted in [3]. Instead of a 2-litre 4-cylinder Diesel ICE that was used for propulsion in a conventional configuration, a smaller displacement (1.2 liters, in this particular case) 3-cylinder Diesel ICE drives the permanent magnet brushless Electric Generator (EG), which

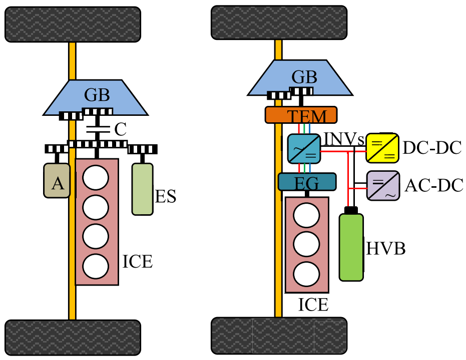

FIGURE 1. Comparison between a conventional powertrain (left) and the proposed series-hybrid architecture (right).

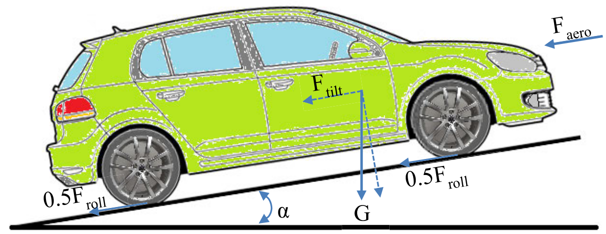

FIGURE 2. The forces acting on the vehicle during its movement.

can provide energy either for the High Voltage Battery (HVB) or for both the permanent magnet synchronous Traction Electric Motor (TEM) and the HVB. On the other hand, the role of the Alternator (A) and Electric Starter (ES) were taken by the TEM, EG, and the power inverters (INVs), which can be used either to drive the TEM, to charge the HVB pack from the EG or even to accomplish both tasks at the same time. The clutch (C) is not needed anymore in the series-hybrid configuration, since the TEM is able to provide enough torque at any rotational speed, while the conventional gearbox (GB) will be replaced by a simpler and more efficient aggregate.

Besides this, the AC-DC converter is used to charge the HVB from the power grid (being a plug-in configuration), while the DC-DC converter is utilized to charge the existing 12V lead-acid battery and to feed the conventional electrical system of the car from the HVB pack.

During the design phase of the series-hybrid powertrain, there were three major aspects that have been taken into consideration in this article, in order to achieve very accurate results when determining the correct amount of power and energy required by the vehicle to ride at various driving speeds, together with other characteristics of the whole system, as follows: mathematical calculations, computer-aided simulations and measurements performed in a real environment. Therefore, compared to [3], a series of MATLAB Simulink simulations have been performed, to strengthen the usefulness, as well as the truthfulness of the proven results.

The first two (calculations and simulations) have the main purpose of validating the accuracy of the measurements, which have been performed by using a dedicated vehicle diagnostics tool, whose features were exploited a bit differently than their original scope, in order to allow for powertrain dimensioning.

A. MATHEMATICAL CALCULATIONS

With regards to the calculations, the model utilized in this paper is very similar with the one used in [11] (being presented in Figure 2) and considers several parameters which reflect the real characteristics of the vehicle used for taking the measurements, such as: the weight of the vehicle ($G = m \cdot g$), its drag coefficient (c_W), frontal area of the car (A_F), air density (ρ), coefficient of rolling resistance for the tires (μ), gradient angle of the road (α) and vehicle's velocity (v).

The most important contributors to the total resistance to movement for a vehicle which is riding at a constant cruising speed are the rolling resistance (F_{roll}), the aerodynamic drag (F_{aero}) and the climbing resistance (F_{tilt}). According to [17], the formulas for each of them are represented by (1) – (3):

$$F_{roll} = \mu \cdot m \cdot g \tag{1}$$

$$F_{aero} = \frac{1}{2}\rho \cdot c_W \cdot A(v + v_0)^2 \tag{2}$$

$$F_{tilt} = m \cdot g \cdot \sin\alpha \tag{3}$$

Therefore, the maximum force (in Newtons) needed to move the vehicle at a certain speed (in km/h), in steady state conditions, is given by (4):

$$F_{traction} = F_{roll} + F_{aero} + F_{tilt} \tag{4}$$

By translating this traction force into power, the total running-resistance power is described by (5):

$$P_{traction} = \frac{F_{traction} \cdot v}{3600}, \tag{5}$$

where $P_{traction}$ is expressed in kW, $F_{traction}$ is expressed in N and v (which represents vehicle's velocity) is expressed in km/h.

Table 1 reveals the parameters (and their numerical values) that have been used for performing calculations with regards to the power required by the vehicle (which is a 2012 Volkswagen Golf GTD [18], [19]) for traveling at a constant speed of 100 km/h on a flat road, as well as other obtained data, such as the resulting forces.

In addition to the set of data provided by [11], Table 1 offers other important supplementary information related to the forces acting on the vehicle during driving, which helps creating a better overview of the share for each component. For example, a +0.5° incline of the road contributes with 128.41N to the total force required for riding, meaning that the climbing resistance has a big impact on the overall power requirements, regardless of the traveling speed.

The results presented in Table 1 reveal the power that should be developed by the engine, without taking into consideration the efficiency of the transmission.

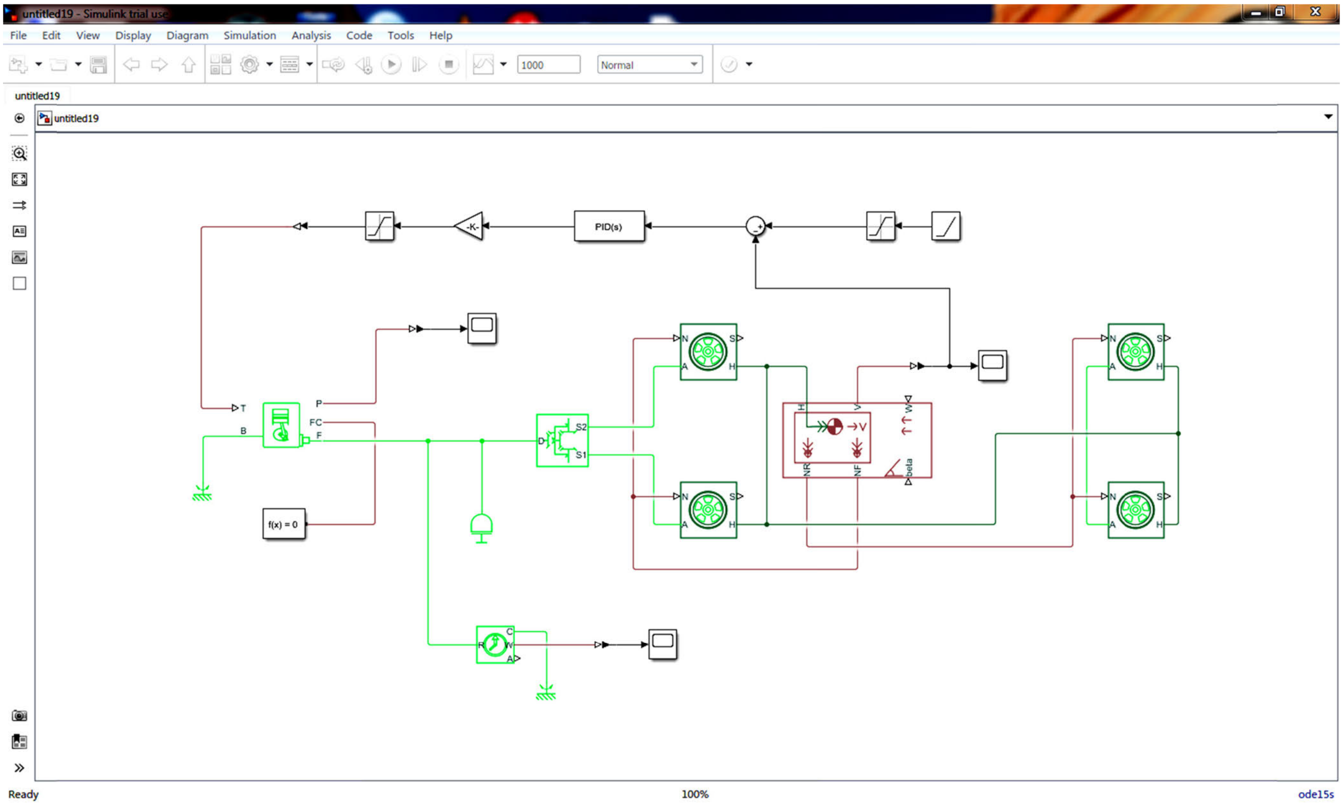

FIGURE 3. MATLAB Simulink setup used for simulating the conventional powertrain of the vehicle.

TABLE 1. The parameters used for calculating the required power by the vehicle during its driving at a constant speed of 100 km/h, together with the obtained results.

Symbol	Description	Unit	Value
μ	Coefficient of rolling resistance	–	0.015
m	Vehicle mass	kg	1500
g	Gravitational acceleration	m/s^2	9.81
G	Weight	N	14715
δ	Air density	kg/m^3	1.18
c_W	Drag coefficient	–	0.32
A	Largest cross-section of the vehicle	m^2	2.23
v	Vehicle speed	m/s	27.77
v_0	Headwind speed	m/s	0
α	Gradient angle	°	0
F_{roll}	Force of rolling resistance	N	220.72
F_{aero}	Force of aerodynamic drag	N	324.86
F_{tilt}	Force of climbing resistance	N	0
$F_{traction}$	Total force of traction	N	545.58
$P_{traction}$	Total power of traction	kW	15.15

When considering a +0.5° incline of the road, a 5 km/h headwind, as well as an 85% efficiency for the transmission (which reflect very common real world situations), the required power jumps from 15.15 kW to 23.72 kW (around 32 metric horsepower).

B. MATLAB SIMULINK SIMULATIONS

In order to validate the results obtained by the means of mathematical calculations, a series of computer-aided simulations (which were necessary for determining the amount of power required for driving a vehicle at a constant cruising speed on a flat road), have been performed, by using MATLAB Simulink tool (that includes dedicated add-ons for this kind of applications); the simulation setup is depicted in Figure 3.

The conventional powertrain which has been simulated consists of an ICE, a differential, two traction wheels at the front of the vehicle, other two wheels connected to the rear axle, a Vehicle Body and a Proportional-Integral-Derivative (PID) controller, used to control the throttle of the engine, in order to obtain the desired driving speed.

The characteristics of the ICE have been modeled such that it has a broader Revolutions Per Minute (RPM) range, which allows the vehicle to ride at both very low (30 km/h) and very high (150 km/h) speeds without stalling and without the need of adding a gearbox, which would increase the complexity of the entire simulation. This approach was chosen because the purpose of the experiment was to determine only the required power for traveling at a certain constant speed.

The characteristics of the differential, tires and Vehicle Body are presented in Table 2 and similar to the mathematical calculations, they also reflect the parameters of the vehicle

TABLE 2. Characteristics of the vehicle used for the MATLAB Simulink simulation.

Symbol	Description	Unit	Value
F_{zfl}, F_{zfr}	Rated vertical load on each of the front tires (left/right)	N	4363
F_{xfl}, F_{xfr}	Peak longitudinal force at rated load on each of the front tires (left/right)	N	5000
F_{zrl}, F_{zrr}	Rated vertical load on each of the rear tires (left/right)	N	2995
F_{xrl}, F_{xrr}	Peak longitudinal force at rated load on each of the rear tires (left/right)	N	3500
k	Wheel slip	%	10
r_w	Tire rolling radius	mm	318.6
μ	Coefficient of rolling resistance	–	0.015
n	Number of wheels on each axle	–	2
m	Vehicle mass (weight)	kg	1500
a	Horizontal distance from CG to front axle	m	1.05
b	Horizontal distance from CG to rear axle	m	1.53
h	CG height above ground	m	0.5
g	Gravitational acceleration	m/s²	9.81
A	Frontal area of the vehicle	m²	2.23
C_d	Aerodynamic drag coefficient	–	0.32
V_x	Vehicle speed	m/s	27.77
Vw	Wind speed	m/s	0
β	Incline angle	°	0
δ	Air density	kg/m³	1.18

that was used for performing all the measurements during real driving conditions.

The Vehicle Body Model uses mostly the same equations as the ones presented in the previous section, from (1) to (4), but also takes into consideration the Center of Gravity (CG) for the vehicle. A detailed description of this block, together with the tire model, is presented in [20] and [21].

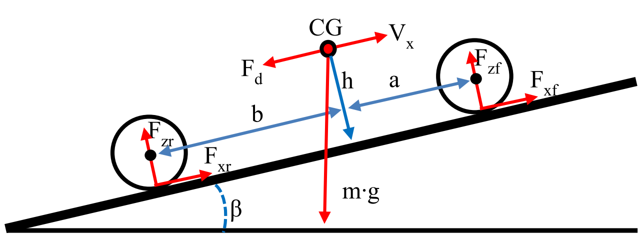

FIGURE 4. The model of the vehicle, together with the forces acting on it during driving.

Figure 4 depicts the forces acting on the vehicle's body and wheels during their movement, as well as other relevant parameters for describing the model.

The equations which describe the model presented in Figure 4 above and which correspond to the Vehicle Body Model and the Tire Model used for simulations are represented by (6) to (11), being depicted in [20] and [21], as well.

$$m \cdot \dot{V}_x = F_x - F_d - m \cdot g \cdot \sin\beta \tag{6}$$

where $\dot{V}_x$ is the derivative of the vehicle's velocity (the rate of change in velocity with respect to time), which represents the acceleration.

$$F_x = n \cdot \left(F_{xf} + F_{xr}\right) \tag{7}$$

where F_{xf} is the sum of F_{xfl} and F_{xfr}, while F_{xr} is the sum of F_{xrl} and F_{xrr}. F_{xf} and F_{xr} are the longitudinal forces acting on each wheel at the front and rear ground contact points, respectively.

$$F_d = \frac{1}{2} \cdot C_d \cdot \rho \cdot A \cdot (V_x + V_w)^2 \cdot sgn\,(V_x + V_w) \tag{8}$$

$$F_{zf} = \frac{-h \cdot \left(F_d + m \cdot g \cdot \sin\beta + m \cdot \dot{V}_x\right) + b \cdot m \cdot g \cdot \cos\beta}{n \cdot (a+b)} \tag{9}$$

$$F_{zr} = \frac{+h \cdot \left(F_d + m \cdot g \cdot \sin\beta + m \cdot \dot{V}_x\right) + a \cdot m \cdot g \cdot \cos\beta}{n \cdot (a+b)} \tag{10}$$

$$F_{zf} + F_{zr} = m \cdot g \cdot \frac{\cos\beta}{n} \tag{11}$$

where F_{zf} is the sum of F_{zfl} and F_{zfr}, while F_{zr} is the sum of F_{zrl} and F_{zrr}.

Apart from the block described before, there are also other advanced models for the whole vehicle body, which include the tires and rely on their slip ratio and stiffness [22].

TABLE 3. Characteristics of the Vehicle Dynamics System which can be used for the MATLAB Simulink simulations.

Symbol	Description	Unit	Data type
s_{FL}	Slip ratio of the front left tire	–	Input
s_{FR}	Slip ratio of the front right tire	–	Input
s_{RL}	Slip ratio of the rear left tire	–	Input
s_{RR}	Slip ratio of the rear right tire	–	Input
δ	Steering angle	rad	Input
$v_x(t)$	Longitudinal vehicle velocity	m/s	State/Output
$v_y(t)$	Lateral vehicle velocity	m/s	State
r(t)	Yaw rate of the vehicle	rad/s	State/Output
$y_a(t)$	Lateral vehicle acceleration	m/s²	Output
m	Mass of the vehicle	kg	Parameter
a	Distance from the front axle to the COG	m	Parameter
b	Distance from the rear axle to the COG	m	Parameter
C_x	Longitudinal tire stiffness	N	Parameter
C_y	Lateral tire stiffness	N/rad	Parameter
C_A	Air resistance coefficient	1/m	Parameter

Table 3 presents the characteristics of the Vehicle Dynamics System which can be utilized instead of the Vehicle Body and Tire models, in order to simulate the drivetrain of a vehicle using MATLAB Simulink.

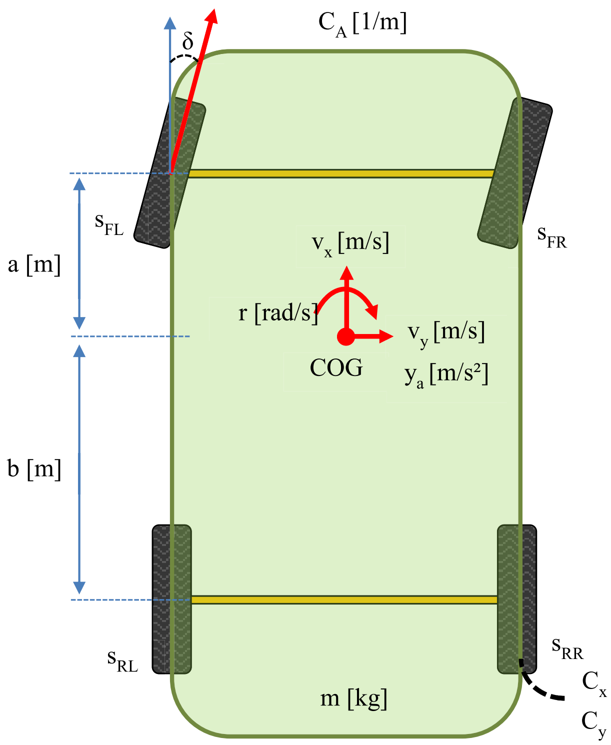

FIGURE 5. The Vehicle Dynamics System, together with the forces acting on it during driving.

Figure 5 depicts the model used for a Vehicle Dynamic System that can be used for MATLAB Simulink simulations, as well. This model utilizes a state-space model structure, described by (12)–(19) as shown at the bottom of the page, which are detailed in [22].

As in the case of the mathematical calculations, the simulations that were performed to support the results presented in this work did not take into consideration the losses associated with the transmission and return just the power required by the vehicle to travel at a constant speed, on a flat road. This kind of approach was chosen because the main purpose of the simulations is just to validate the proposed methodology, by comparing these results with the mathematical calculations, as well as with the real road measurements.

On the other hand, it is very straight forward that involving the transmission's mechanical efficiency (as a percentage) into both calculations and simulations will generate similar results, so the lack of this parameter will not impact the effectiveness of this proposed series-hybrid powertrain design technique.

Besides this, in order to obtain reliable data, the input parameters of the models used should be very accurate, as well as adequate enough for their targeted purpose; otherwise using an excessive number of variables whose values are uncertain or unknown will increase the discrepancy between different approaches, thus leading to an inappropriate outcome.

An example of a MATLAB Simulink simulation, which has been performed for a vehicle speed of 100 km/h and reveals the required output power of the ICE is shown in Figure 6.

For the simulation setup depicted in Figure 3, the parameters from Table 2 have been used in order to obtain the required accurate results. Consequently, the first scope graph (Scope1) highlights the acceleration of the car, from rest to 100 km/h, while the second scope graph (Scope2) reveals the power output of the ICE, during the same timeframe (1000 seconds).

As can be easily noticed, right after the moment when the vehicle reaches the desired traveling speed (100 km/h), the output power required to maintain steady state settles around 15 kW (on flat ground, without any incline), which is a value that matches the mathematical calculations (presented in Table 1) as expected, meaning that the simulations deliver accurate results.

$$s_F(t) = s_{FL}(t) + s_{FR}(t) \tag{12}$$

$$s_R(t) = s_{RL}(t) + s_{RR}(t) \tag{13}$$

$$\frac{dv_x(t)}{dt} = v_y(t)\cdot r(t) + \frac{1}{m\cdot\left\{C_x\cdot s_F(t)\cdot\cos(\delta t) - 2\cdot C_y\cdot\frac{\delta t-[v_y(t)+a\cdot r(t)]}{v_x(t)}\cdot\sin(\delta t) + C_x\cdot s_R(t) - C_A\cdot v_x(t)^2\right\}} \tag{14}$$

$$\frac{dv_y(t)}{dt} = -v_x(t)\cdot r(t) + \frac{1}{m\cdot\left\{C_x\cdot s_F(t)\cdot\sin(\delta t) + 2\cdot C_y\cdot\frac{\delta t-[v_y(t)+a\cdot r(t)]}{v_x(t)}\cdot\cos(\delta t) + 2\cdot C_y\cdot\frac{b\cdot r(t)-v_y(t)}{v_x(t)}\right\}} \tag{15}$$

$$\frac{dr(t)}{dt} = \frac{1}{\left(\frac{a+b}{2}\right)^2\cdot m\cdot\left\{a\cdot\left[C_x\cdot(s_{FL}(t)+s_{FR}(t)\cdot\sin(\delta t)) + 2\cdot C_y\cdot\left(\delta t - \frac{v_y(t)+a\cdot r(t)}{v_x(t)}\right)\cdot\cos(\delta t)\right] - 2\cdot b\cdot C_y\cdot\frac{b\cdot r(t)-v_y(t)}{v_x(t)}\right\}} \tag{16}$$

$$y_v(t) = v_x(t) \tag{17}$$

$$y_a(t) = \frac{1}{m\cdot\left\{C_x\cdot s_F(t)\cdot\sin(\delta t) + 2\cdot C_y\cdot\frac{\delta t-[v_y(t)+a\cdot r(t)]}{v_x(t)}\cdot\cos(\delta t) + 2\cdot C_y\cdot\frac{b\cdot r(t)-v_y(t)}{v_x(t)}\right\}} \tag{18}$$

$$y_r(t) = r(t) \tag{19}$$

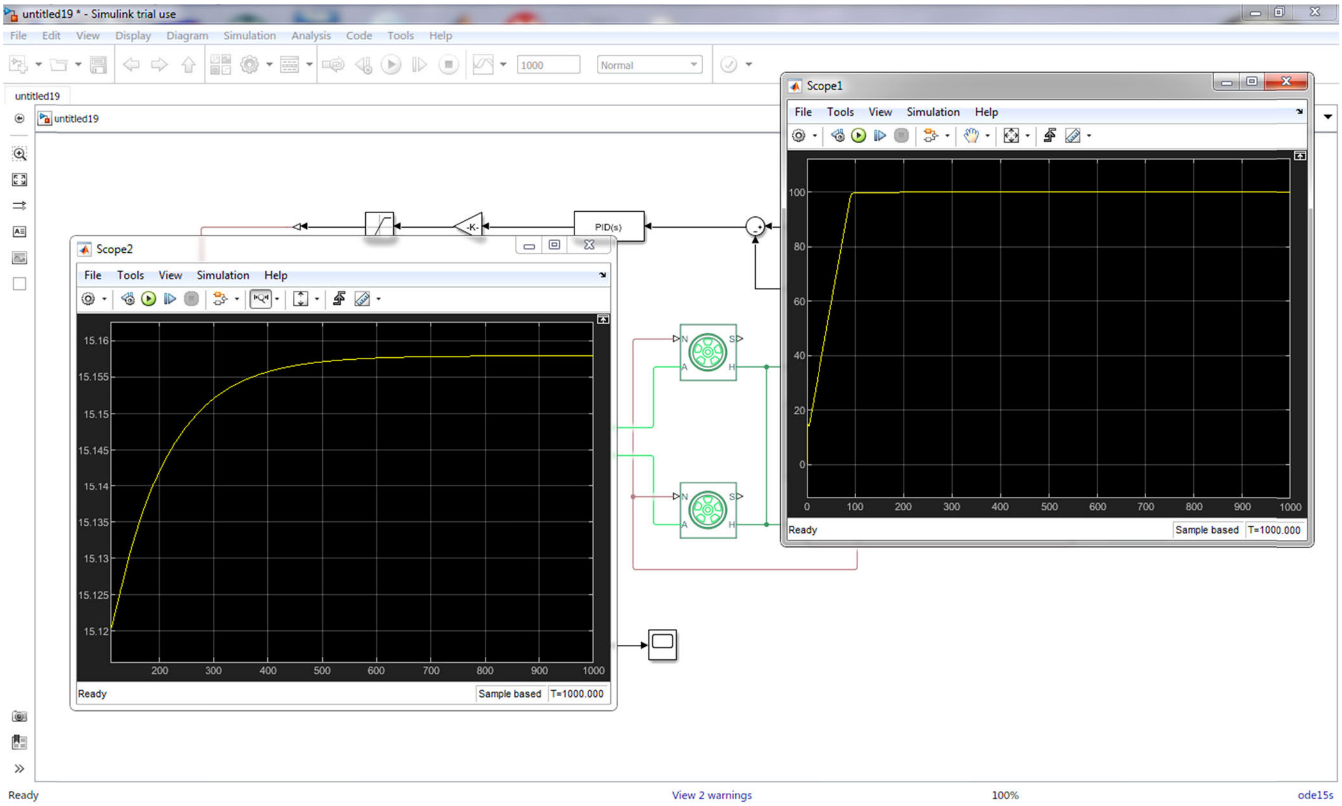

FIGURE 6. Results of the simulations, with regards to the output power developed by the ICE versus driving time, in order to ensure a constant traveling speed for the vehicle of 100 km/h.

Depending on the theoretical model used, the complexity of the simulation can be further increased, by adding road profiles, multi-gear transmissions, additional inertias and loads, but in this case, the calculations would become more complex and might require high computational power in order to be solved.

Apart from the previously mentioned example, multiple other simulations have been run, at various driving speeds, and some of the results were summarized in Section III of this article.

C. EXPERIMENTAL RESULTS

With regards to the real measurements, they have been collected during road driving conditions, in a similar manner with what was also described in [1], [2] and [11], their main purposes being to check the accuracy of the diagnostics tool, as well as to create a database which has been used for designing the proposed series-hybrid powertrain.

Therefore, instead of relying on standard driving cycles or performing tests on the dynamometer (inside a laboratory), the diagnostics interface allowed for a high degree of customization with regards to the length of the trips, their duration, the driving speed profile, weather conditions, ambient temperature, and so on.

To collect all the necessary parameters from the vehicle's powertrain, the VCDS software has been used, as also proposed in [11]. This tool is a Windows compatible application that was developed to emulate the functionality of the original diagnostics equipment of the Volkswagen Group, such as VAS or ODIS [23].

Apart from the GUI (Graphical User Interface), in order to be able to connect the computer with the car, a special hardware interface should be utilized, which communicates through the OBD-II (On Board Diagnostics) port, as depicted in Figure 7.

FIGURE 7. The setup connection between the car, OBD-II interface and VCDS GUI.

From the main menu of the VCDS GUI, several functions can be selected, such as automatic scanning of each electronic controller (for diagnostics purposes), accessing any of the installed electronics modules, resetting Service Reminder Intervals, checking for the connection with the vehicle, etc.

Each of the aforementioned menus has several other submenus; for example, the "Select" menu includes all the electronic modules that are installed on the car and which can be accessed and examined (for example, the Engine Control Unit or the Transmission Control Unit, for the vehicles equipped with automatic transmission), as presented in Figure 8.

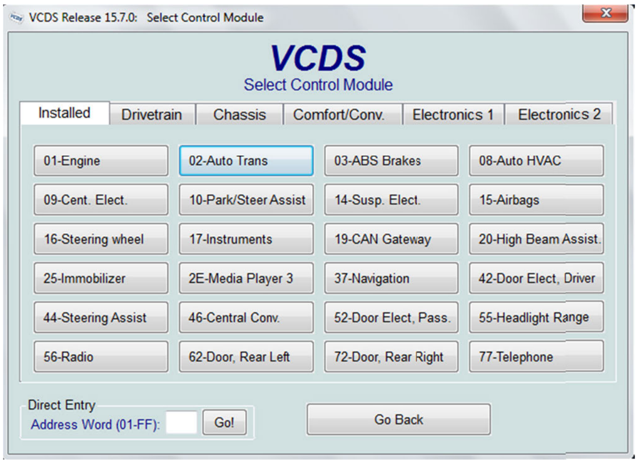

FIGURE 8. The "Select" submenu of the VCDS GUI.

Moreover, by selecting each submenu, a pop-up a window will allow for fault codes reading, performing different adaptations of the components and, very important for this paper, measuring various parameters in real time.

For instance, selecting the "01-Engine" or "02-Auto Trans" buttons will provide access to the desired parameters, such as the engine torque, its rotational speed, vehicle speed, coolant temperature, boost pressure, battery voltage, vehicle acceleration, etc., through the "Adv. Meas. Values" submenu, which is revealed in Figure 9.

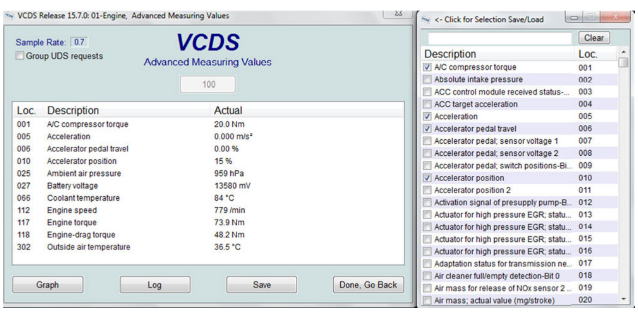

FIGURE 9. "Advanced Measuring Values" submenu of the VCDS GUI.

In a similar manner, for all the other installed modules there is the option to perform real time measurements, which can be saved on and exported to a computer as .CSV (Comma Separated Values) files, allowing for later interpretation, further processing (using the "Log" button) or even displayed as a graph (using the "Graph" button).

Therefore, by using the previously mentioned functionality of the diagnostics tool, a series of real time measurements have been performed, allowing for real time engine power output computation.

Besides the real time parameters that have been measured during road driving conditions and compared to [11], this work reveals the characteristics of the car used for performing these tests, which are being covered in Table 4.

TABLE 4. The parameters of the vehicle used for measuring the output power requirements during driving.

Symbol	Description	Unit	Value
P_{max}	Maximum output power/Engine speed	kW/RPM	125/4200
T_{max}	Maximum output torque/Engine speed	N·m/RPM	350/1750 – 2500
WD	Weight distribution F/R	%	59.3/40.7
μ	Coefficient of rolling resistance for tires (approximation)	–	0.015
r	Tire rolling radius	mm	318.6
G	Weight (approximation)	N	14715
m	Vehicle mass (approximation)	kg	1500
C_d	Drag coefficient	–	0.32
A	Largest cross-section of the vehicle	m^2	2.23

In order to validate the veracity of the measurements, a series of tests have been conducted. The methodology of gathering all the necessary information with regards to the parameters of the ICE during driving (rotational speed, output torque, fuel consumption, coolant temperature, etc.) was presented a few paragraphs before, as well as in [1], [2] and [11].

A relevant example of real driving speed profile versus time, which was measured for a 40 minutes (approximately) trip, is presented in Figure 10.

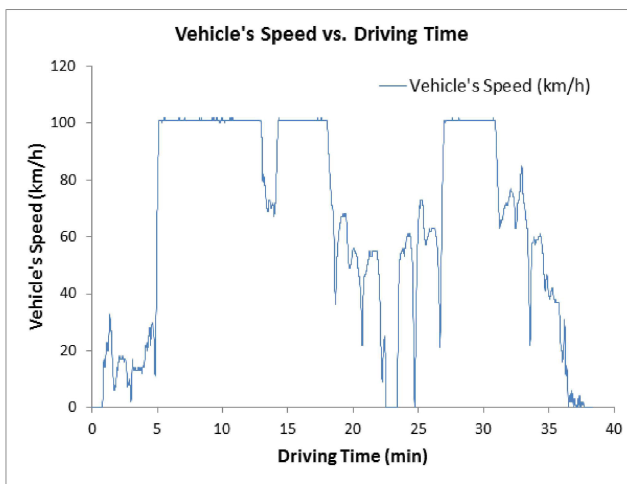

FIGURE 10. Vehicle's speed versus driving time, for a 40 minutes (approximately) trip.

This profile has been used mostly to calculate and highlight the power requirements for two different situations: driving slightly downhill, from minute 14 to minute 18 and driving slightly uphill, from minute 27 to minute 31, respectively, on the same portion of the road and at the same cruising speed.

The corresponding output power delivered by the ICE (which was calculated based on the measured torque and rotational speed values) for the same trip (approximately 40 minutes) is shown in Figure 11.

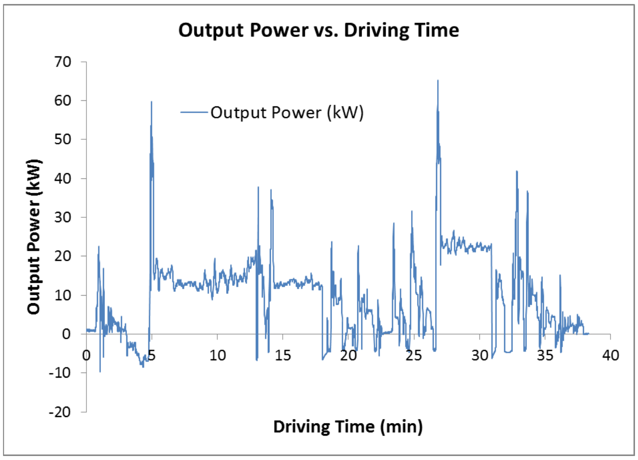

FIGURE 11. The output power delivered by the ICE versus driving time, corresponding to a 40 minutes (approximately) trip.

From the previously mentioned graph, it can be easily noticed that the ICE delivers around 14 kW of power during downhill driving (approximately -0.5° inclination of the road) and around 23 kW during uphill (approximately +0.5° inclination of the road), at a constant vehicle speed of 101 km/h, highlighting that the aforementioned result matches the calculations revealed at the end of Section II A, thus strengthening the effectiveness of the methodology proposed in this paper.

Compared to [11], which only summarizes the results, this paper provides an example of distribution of probability for the power requirements at a constant vehicle speed of 101 km/h and 102 km/h, respectively, on a slightly inclined road (which is the case for most of the real situations), that is presented in Figure 12.

Therefore, by looking at the numbers presented in Figure 12, it can be clearly noticed that the mean value of the power required by the vehicle to travel at a constant speed of around 100 km/h during a slight downhill is around 14 kW, while the mean value of the required power during uphill riding settles around 23 kW, taking into consideration all the auxiliary equipment of the car (exterior lighting, air conditioning system, infotainment system, power-assisted steering, power windows, etc.), including the mechanical efficiency of the six-speed transmission.

Regarding the variance of the probability distribution presented in Figure 12, for this particular case, it varies from 1.76 (for 101 km/h, during downhill) to 3.68 (for 102 km/h, during downhill) and it can be determined for each vehicle

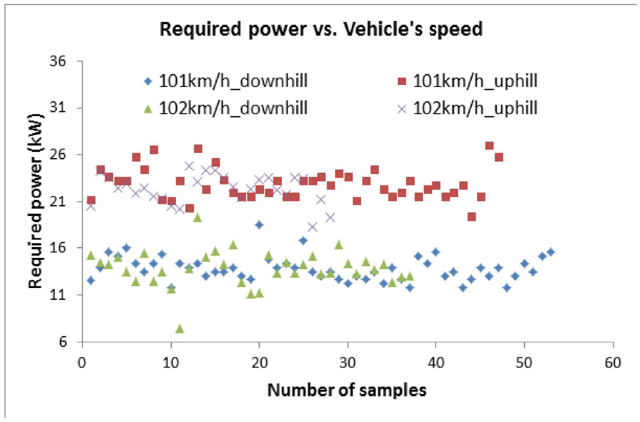

FIGURE 12. The distribution of probability for the power required to maintain a constant traveling speed for the vehicle of about 100 km/h.

speed, by using (20).

$$\sigma^2 = \frac{1}{N-1} \cdot \sum_{i=1}^{N} (x_i - \overline{x})^2, \tag{20}$$

where N is the number of samples, x_i are the observed values and $\overline{x}$ is the arithmetic mean of these observed values.

On the other hand, the standard deviation (which is the square root of the variance) for the same distribution (Figure 12) varies from 1.32 (for 101 km/h, during downhill riding) to 1.92 (for 102 km/h, during downhill riding) and it can be calculated for any other particular case (vehicle speed), by using (21).

$$\sigma = \sqrt{\frac{1}{N-1} \cdot \sum_{i=1}^{N} (x_i - \overline{x})^2}, \tag{21}$$

The foregoing results show that the dispersion of the collected data is very small, therefore strengthening the validity of the measured parameters that have been collected during real driving conditions, meaning that they can be reliably reproduced.

III. COMPARATIVE ANALYSIS BETWEEN DIFFERENT TYPES OF DESIGN APPROACHES

After collecting a series of over a hundred measurements while driving on various roads, in different conditions, the results have been summarized in a comparison between mathematical calculations, computer-aided simulations and measurements, as shown in Table 5. They offer a more complex overview compared to the results proposed in [11], providing also data for a broad range of driving speeds (including both city and highway riding), as well as considering different scenarios, including the efficiency of the transmission and the road incline.

With regards to the measurements that have been performed during real driving conditions, it should be taken into consideration the fact that the efficiency of the 6-speed Direct Shift Gearbox (DSG) transmission is approximately 85% in fifth gear [24]; therefore, a part of the mathematical

TABLE 5. Comparison between mathematical calculations, simulations and real measurements, with regards to the power required by the vehicle, in order to travel at a constant speed.

Results type	Engine's required output power (kW						
	Vehicle's speed (km/h)						
	30	50	70	80	90	100	130
Calculations / 0° inclination (100% transmission efficiency)	2.08	4.19	7.38	9.52	12.09	15.15	27.79
Simulations / 0° inclination (100% transmission efficiency)	2.08	4.19	7.38	9.52	12.09	15.15	27.8
Calculations / 0° inclination (85% transmission efficiency)	2.39	4.82	8.49	10.95	13.91	17.42	31.96
Calculations / +0.5° inclination (85% transmission efficiency, without ICE accessories)	3.62	6.87	11.36	14.23	17.6	21.95 @ 101 km/h	37.29
Measurements / +x° inclination (85% transmission efficiency, with ICE accessories)	3.65	7.06	10.49	13.68	18	22.90 @ 101 km/h	43.42
Calculations / -0.5° inclination (85% transmission efficiency, without ICE accessories)	1.16	2.77	5.62	7.67	10.21	13.67 @ 101 km/h	26.63
Measurements / -x° inclination (85% transmission efficiency, with ICE accessories)	1.23	2.44	6.40	8.61	11.78	13.83 @ 101 km/h	30.28

calculations and simulations were scaled based on this information, in order to match the results. On the other hand, it can be noticed that the measurements reveal higher values at higher cruising speeds, compared to the calculations, mainly because the efficiency of the vehicle's transmission drops below 85%.

IV. SERIES-HYBRID POWERTRAIN DIMENSIONING

The main purpose of this paper is to provide guidance regarding several design considerations for series-hybrid vehicle powertrains, which are mainly based on real measurements and mathematical calculations (which have been used for dimensioning the driving system).

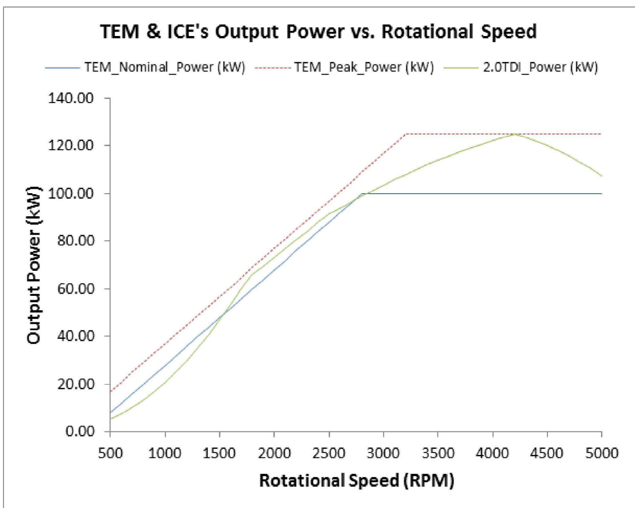

FIGURE 13. TEM's and ICE's output power versus rotational speed.

A very important goal of this work was to develop a powertrain that is able to offer the same performance as a conventional vehicle, hence Figure 13 presents a comparison between the power output of a 2-liter 4-cylinder Diesel engine (which has been used for measurements) [25] and the power output capabilities of the proposed TEM, which should be quite similar, as also proposed in [3].

To achieve the same dynamic performance, similar to what is provided by the ICE, the TEM should be able to develop a continuous output power of 100 kW, and a peak power of 125 kW, available for at least 30 seconds, because most of the overtakes do not need a massive amount of power and will not last very long.

Apart from this, because the proposed plug-in hybrid powertrain should be able to recover energy while decelerating from any vehicle speed (even during city driving situations), as well as reaching high cruising speeds (150 km/h), a gearbox featuring at least two ratios should be taken into consideration [26].

In comparison with other articles, which depend upon using standard driving cycles [10], [12], such as the New European Driving Cycle (NEDC) and/or the Worldwide harmonized Light vehicles Test Procedure (WLTP), as presented in Figure 14 and Figure 15, this paper proposes a series-hybrid architecture which is dimensioned based on real road driving measurements, which have been performed during different weather conditions, different ambient temperature ranges, various altitudes, while using different types of tires (summer/winter tires).

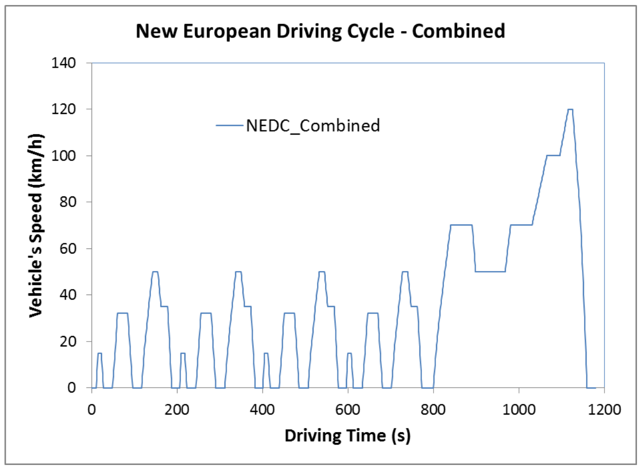

FIGURE 14. New European Driving Cycle (NEDC) Combined – vehicle's speed profile versus driving time.

For example, the ambient temperature change affects the efficiency of the powertrain, because in cold weather the engine and transmission losses increase due to cold oil and fluids, which have lower viscosity; it takes a longer time for the engine to reach its optimum fuel-efficient temperature, heated seats and windows defrosters use additional power, warming up the vehicle before start uses fuel as well (without producing useful traction), colder air is denser, which means that the aerodynamic drag increases, tire pressure drops in cold weather, thus increasing the rolling resistance and battery performance decreases in cold weather, causing the alternator to pump more energy into it.

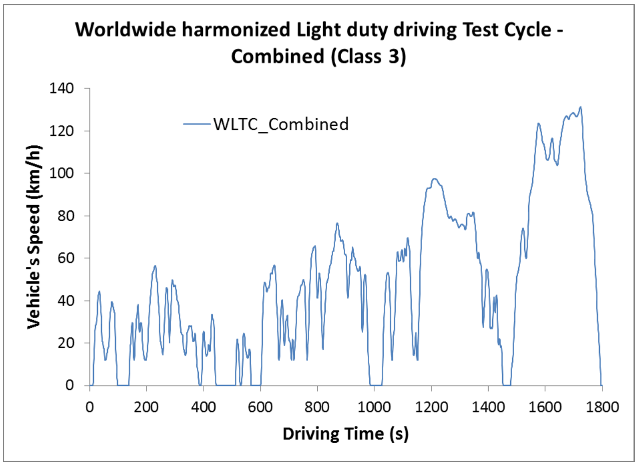

FIGURE 15. Worldwide harmonized Light duty driving Test Cycle - Combined (Class 3) – vehicle's speed profile versus driving time.

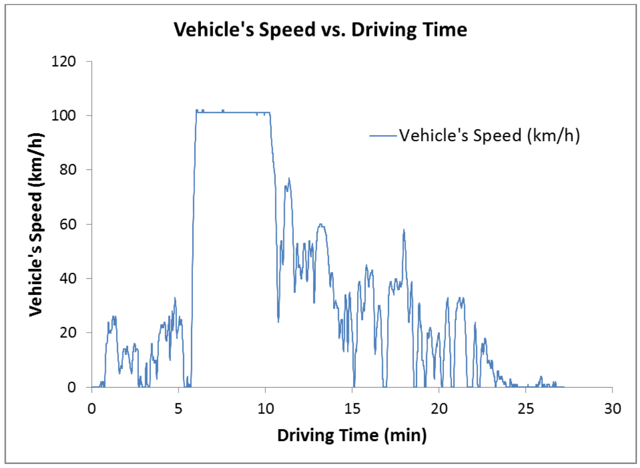

FIGURE 16. Example of vehicle's speed versus driving time, for a 30 minutes (approximately) trip.

On the other hand, hot weather implies using the air-conditioning system of the car, which adds around 0.5l/100 km to the average fuel consumption for a compact passenger car, as the one used in this paper.

Therefore, after analyzing the collected data, the best fuel efficiency with regards to the ambient temperature was obtained during driving in dry weather conditions, at around 20°C.

As an example, the NEDC consists of an urban cycle, which is composed by four elementary cycles of 195 seconds each, lasting for 780 seconds (in total) and an extra-urban cycle of 400 seconds, while the total combined cycle lasts for 1180 seconds [27], as shown in Figure 14.

Because the NEDC has become outdated and does not reflect the current real driving conditions and situations, starting from the 1st of September 2019, it was replaced (at least in Europe) with the WLTP, which relies on the new WLTCs (Worldwide harmonized Light duty driving Test Cycles).

There are three different cycles that can be applied, depending on the vehicle class, but WLTC Class 3 is used for most of the modern passenger cars, which have a ratio of rated power (in Watts) per curb weight (in kilograms) higher than 34 (this also applies for the vehicle utilized in this article for performing the real driving tests) and consists of 4 phases: low (which lasts for 589 seconds), middle (433 seconds), high (455 seconds) and extra-high (323 seconds), all the cycle combined lasting for 1800 seconds [28], as described in Figure 15.

As a comparison to the standard cycles that were presented in the previous paragraphs, a relevant example of vehicle speed versus driving time, which was measured during a 30 minutes (approximately) trip and which has been used in this article (among others) for developing both the proposed series-hybrid powertrain, as well as the algorithm that manages the output power delivered by the ICE, is presented in Figure 16.

The average traveling speed of the vehicle for the trip depicted in Figure 16, was 33.58 km/h, a value which is very close to the average speed of the NEDC (33.35 km/h), therefore confirming the validity, as well as the usefulness of the tests which were performed during real road driving conditions.

The corresponding output power profile provided by the ICE (for the same trip), including all the auxiliary loads (air conditioning and ventilation system, exterior and interior lighting, power-assisted steering, infotainment, electronically controlled dampers, electric windows, etc.) is represented in Figure 17.

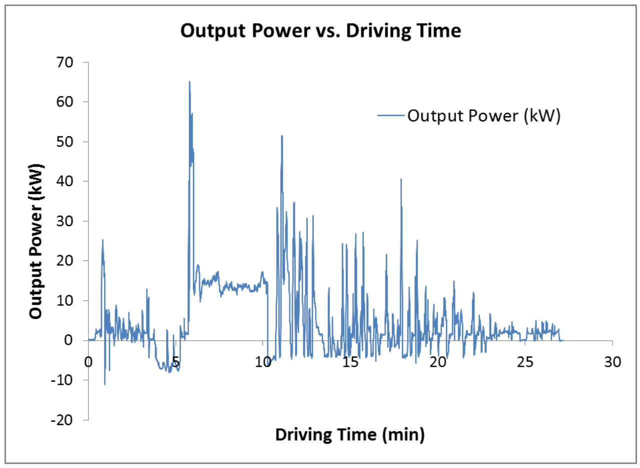

FIGURE 17. The output power developed by the ICE versus driving time, corresponding to a 30 minutes (approximately) trip.

In the previous example, it can be noticed the fact that the mean output power needed by the vehicle does not exceed 20 kW. Moreover, given that a compact size passenger car (as the one used in this article for performing real measurements on it) requires an average power of almost 18 kW (taking into account an 85% efficiency of the transmission) for traveling at a cruising speed of 100 km/h (on a flat ground) and 32 kW (considering an 85% efficiency of the transmission, as well) for traveling at 130 km/h (which is the maximum allowed driving speed in most countries), the nominal output power of the electric generator (which is part of the proposed series-hybrid powertrain) was chosen to be around 50 kW, in order to allow constant driving at high speed, with a slightly incline of the road of $+1.5°$, without drawing energy from the HVB.

For this reason, the engine that drives the electric generator should be able to develop more than 50 kW of power in order to fulfil the requirements of the powertrain.

Consequently, in this particular situation of the proposed plug-in series-hybrid architecture (which is being described in this paper, as well as in [3]), a 1.2-litre turbocharged Diesel engine has been chosen; the main reason is that the 1.2TDI compression-ignition engine is capable of producing a maximum output power of 55 kW at 4200 RPM, while delivering a peak output torque of 180 N·m at 2000 RPM [29], as shown in Figure 18.

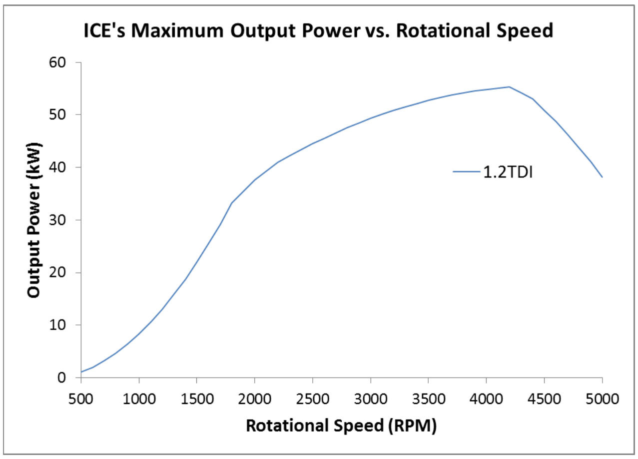

FIGURE 18. **The maximum output power developed by the 1.2TDI engine versus its rotational speed.**

In any case, depending on the application, the ICE which drives the EG may have either smaller or bigger displacement, based on the power requirements of the vehicle or can feature other constructive characteristics, like spark ignition (for Otto engines), Homogenous Charge Compression Ignition (HCCI), Stratified Charge Compression Ignition (SCCI), Reactivity Controlled Compression Ignition (RCCI) [30] or it can even employ rotary design (which has a high power to weight ratio, making it suitable for this kind of applications), such as the Wankel engine or a gas turbine, as proposed in [31].

However, one other important advantage of a Diesel engine besides its high thermal efficiency is the capacity to run on vegetable oil (as presented in [6]) or on other types of bio-fuels (with some adaptations). Moreover, the addition of steam and oxyhydrogen into the intake of the engine reduces both the emission of CO_2 and NOx gasses, as well as the fuel consumption [32].

Based on these data, in this article, a very simple (rule-based) algorithm that manages the power generated by the ICE has been developed, in order to allow achieving a high efficiency series-hybrid powertrain, while maintaining the overall performance of a 2-liter Diesel ICE-powered car, capable of producing 125 kW of maximum output power.

Compared to [3], in addition to the equations, this work also presents the flowchart which describes the algorithm of managing the generated power (based on vehicle's driving system demand) for the proposed plug-in series-hybrid powertrain; it is depicted in Figure 19 and the functionality will be further explained into the following paragraphs.

After turning on the ignition, the ICE will run for about 2 minutes at idle (with no load applied), to warm up and to check its functionality.

Following the first 2 minutes, it will start to drive the generator for another 2 minutes, delivering an output power of 20 kW, which will recharge the HVB. This behavior is described by (22).

$$P_{ICE}(t) = \begin{cases} 0, & when\ et < 2 \\ 20, & when\ 2 \leq et < 4, \end{cases} \tag{22}$$

where et represents the elapsed time (expressed in minutes) since the ignition of the vehicle has been turned on by the driver and t is the moment in time when the sampling takes place.

Once the first 4 minutes have passed, the ICE will be shut off for 2 minutes every 4 minutes. When running, it will deliver an output power (in kilowatts) proportional to the average power needed in the moments prior to its restart. In addition to this situation, in case the driver pushes the throttle pedal harder or the power requirements exceed 50 kW (while the ICE is shut off), the engine may be restarted for a while, in order to provide a fraction of that needed power, thus protecting the HVB from high discharge current rates. Therefore, (23) – (25) reveal the previously mentioned operation:

$$P_{ICE}(t) = \begin{cases} 0, & when\ et\ MOD4 < 2 \\ P_{avg}(t), & when\ et\ MOD3 < 2 \\ 50, & when\ P_{req}(t) > 50 \end{cases} \tag{23}$$

$$P_{avg}(t) = \frac{P_{gen}(t-1) + P_{gen}(t)}{2} \tag{24}$$

$$P_{gen}(t) = \left[P_{req}(t) - P_{recov}(t)\right] \cdot \left[1 + 0.02 \cdot V_{av\_spd}(t)\right] \tag{25}$$

where P_{avg} is the average power needed by the vehicle (expressed in kilowatts), while MOD represents the "modulo" operator; P_{gen} is the power generated (expressed in kilowatts) by the EG, P_{req} is the power (expressed in kilowatts) delivered by the electric motor, P_{recov} is the power (expressed in kilowatts) recovered during the vehicle's decelerations and V_{av_spd} represents the average speed (in km/h) of the car.

Moreover, this algorithm can be adapted based on weather conditions (the ICE can be let running for longer periods of time, which helps for both faster warming up, as well

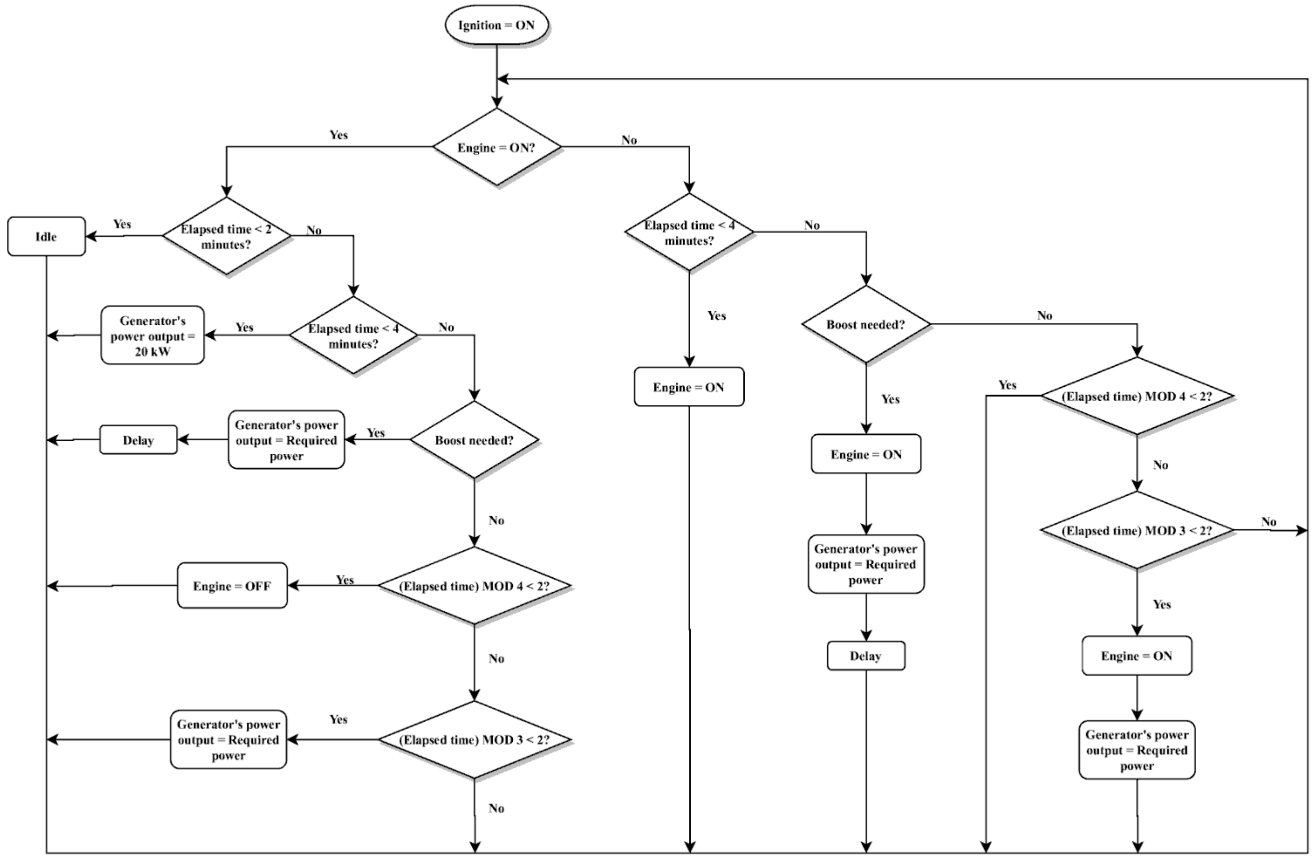

FIGURE 19. **The algorithm used for managing the proposed series-hybrid powertrain.**

as for cooling or warming up the cabin), or based on ICE's characteristics (including its cooling system size). In addition to this, it can be customized based on the HVB's capacity or even on the driver's wish, in order to improve efficiency [33]; this is due to the fact that humans have the ability to predict some events (e.g. traffic jams), depending on the route that will be chosen.

After taking over a hundred measurements (most of them being similar to what was presented in Figures 16 and 17, above) and after applying the proposed algorithm (without taking into consideration the short periods of time when the ICE is restarted under heavy load conditions, as well as the time needed for the regeneration of the DPF), the conclusion is that the average fuel consumption was around 3.21 liters/100 km, while using a 20 kWh HVB at a 50% Depth Of Discharge (DOD) rate. In order to protect the Lithium battery pack, it should never be discharged below 30% of its capacity and it should not be charged over 80% [1], [2]. However, in some particular cases, while recuperating kinetic energy during deceleration or during the open loop phase (2 minutes), when the ICE provides 20 kW to the EG, regardless of the required driving power for the vehicle, charging the HVB over 80% of its capacity is permitted.

With regards to the thermal efficiency of the Diesel engine which drives the EG, it was assumed (based on real measurements) that the fuel consumption at idle is 0.5 l/h (during the first 2 minutes), and it has an efficiency of 37.3% (0.25 l/h for every 1 kWh produced, at an energy density for the Diesel fuel of 10.72 kWh/l) under load, when the EG produces energy.

On the other hand, the average electric energy consumption (from the HVB pack) was around 9.33 kWh/100 km. This indicates the fact that the mean range in hybrid mode is around 120.73 km, considering a 90% efficiency for the TEM and an 80% efficiency for the EG. When taking into account the efficiency of the inverters, the overall efficiency of the TEM drops to around 80%, while the efficiency of the EG drops to around 70%, which is quite a pessimistic assumption for the current technology available. Even so, this translates into a very good combined fuel consumption of 3.53 l/100 km for the engine and an average electric power consumption of 11.38 kWh (from the HVB), which decreases the hybrid range of the vehicle to around 97.29 km per 10 kWh of useful energy.

By comparison, the average fuel consumption of the conventional ICE-powered vehicle (which has been measured using the VCDS diagnostics tool in the exact same conditions) was 5.62 l/100 km. This means that the proposed series-hybrid configuration uses 2.09 liters less fossil fuel for 100 kilometers, being almost 38% more efficient, from this standpoint.

The average traveling speed for all combined tests that have been performed during real driving conditions was 42.69 km/h, which is slightly lower than the average speed of the WLTP cycle (46.5 km/h), therefore strengthening the validity of the measurements, as well as the usefulness of the proposed algorithm.

The mean energy consumption of the proposed plug-in series-hybrid system, aside from the energy recovered during braking (and excepting the energy provided by the generator, as well) was around 22.35 kWh/100 km.

After processing and analyzing all the collected data, it was concluded that the major benefits of this series-hybrid configuration, complemented by the proposed power management algorithm seem to be prominent for trips which take longer than 10-15 minutes, while the average cruising speed is lower than 70 km/h, and the trip duration does not exceed 2 hours, which is the case for most of the daily travels.

To overcome the first issue, a fully-electric mode should be implemented; in this case the vehicle will use just electric energy for traveling, which can be also harvested from different renewable sources [33] or replenished from the mains. For addressing the second drawback, a higher DOD rate can be set or a bigger HVB pack (with a larger capacity) should be considered; otherwise, if most of the trips will be performed at high speeds, on highways, either a plug-in parallel-hybrid powertrain [1], [2] or a conventional ICE-powered vehicle should be considered. Moreover, in order to protect the HVB from getting damaged and to extract as much energy as possible from it (in a very efficient way), active balancing circuitry may represent a viable solution [34].

To further highlight the benefits of the proposed algorithm, an example of a 50 minutes trip (mostly dominated by traffic jam) was considered and the measured traveling speed of the vehicle versus driving time is presented in Figure 20.

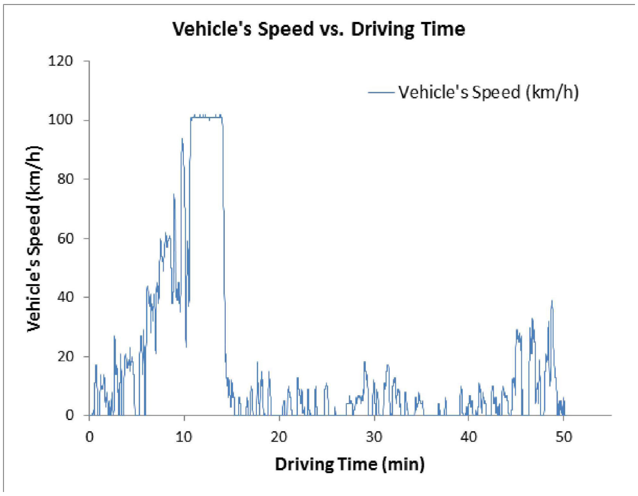

FIGURE 20. **Measured vehicle speed versus driving time, for a 50 minutes (approximately) trip, mostly spent in a traffic jam.**

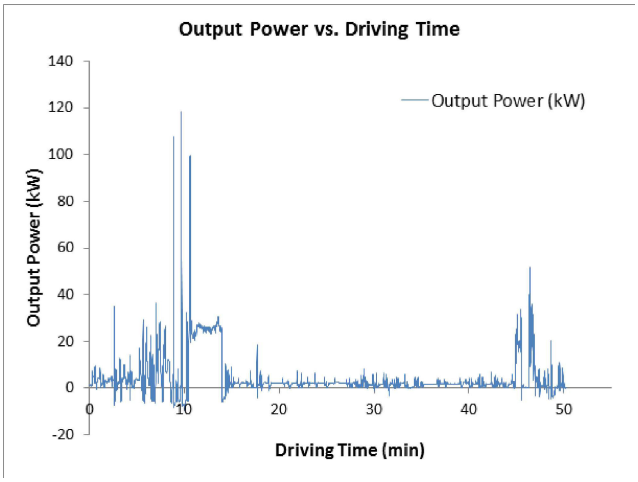

FIGURE 21. **ICE's output power versus driving time, corresponding to a 50 minutes (approximately) trip, mostly spent in a traffic jam.**

Looking at the driving speed profile depicted in Figure 20, most of the time the vehicle stands still and when it moves, it barely exceeds 20 km/h; this means that in case of a conventional powertrain, the engine runs mostly at idle, burning fuel without producing useful energy, which is opposite to the proposed series-hybrid configuration.

The power requirements (which have been determined based on measuring both the rotational speed and the output torque developed by the ICE) corresponding to the 50 minutes trip mentioned before, are shown in Figure 21.

By applying the proposed algorithm on this set of data, the resulting fuel consumption of the engine was 5.14 l/100 km, while the available range of the vehicle in hybrid mode was around 46.05 km, which translates into 2.85 hours (approximately 171 minutes) of driving, given that the average traveling speed was only 16.11 km/h.

In addition to the previously mentioned examples, the data provided by [3] have been complemented by other results and the characteristics of the proposed plug-in series-hybrid powertrain were summarized in Table 6.

With regards to the total weight of the vehicle which will be equipped with the proposed series-hybrid powertrain, the Dual-Clutch Transmission (DCT) which weighs around 93 kg [24] should be replaced by a 74 kg electric motor, combined with a two-ratio gearbox [26]; this configuration also allows the driving system to achieve high torque for the reverse movement of the vehicle when using the first ratio, which translates into a simpler motor control at low driving speeds and RPMs. On the other hand, the weight difference between the 3-cylinder 1.2-liter Diesel engine (which drives the EG) and the 4-cylinder 2-liter TDI engine with all its accessories (electric starter, alternator, bigger 12V Lead-acid battery) may equate the weight of the HVB (assuming that the 20 kW battery pack weighs around 140 kg), together with the power electronics (AC-DC converter, DC-DC converter and the two power inverters) and the electric generator.

TABLE 6. Characteristics of the proposed series-hybrid driving / propulsion system.

Parameter	Unit	Value
ICE displacement	cm^3	1199
ICE peak power / Engine speed	kW/RPM	55/4200
ICE peak torque / Engine speed	N·m/RPM	180/2000
EG nominal power / Generator speed	kW/RPM	50/4000
TEM nominal power / Motor speed	kW	100/5000
TEM peak power / Motor speed	kW	125/5000
HVB capacity	kWh	20
HVB capacity	Ah	54
HVB nominal voltage	V	370
HVB nominal discharge rate	C (capacity in Ah)	3
HVB peak discharge rate (maximum 30s)	C (capacity in Ah)	7

V. CONCLUSION

Given the actual global situation, personal transportation plays a very important role in slowing down the spread of the pandemic and also increases the feeling of safety for car owners; however, current conventional vehicles are inefficient and produce harmful emissions for the environment, while the electric counterparts are too expensive and offer insufficient range for people's emerging mobility needs.

This article provides a new and simple design methodology for plug-in series-hybrid powertrains, being mainly based on real road driving measurements that have been complemented by mathematical calculations and computer-aided simulations, in comparison with other papers that propose more sophisticated algorithms based on artificial intelligence, which require high computing power.

Even if, at first glance, the efficiency of using a series-hybrid propulsion system seems rather low because of the necessity for converting mechanical energy (produced by the ICE) into electricity (via the electric generator), which should be then converted again into mechanical energy (via the traction electric motor, which drives the wheels), the results showed that by applying the appropriate algorithm for a plug-in series-hybrid propulsion system which includes a high-voltage battery pack (with a predefined capacity), its efficiency is higher (under certain conditions), compared to a conventional drivetrain (which is powered by an ICE alone).

Therefore, by combining a small displacement compression ignition engine of 1.2 liters (capable of producing a maximum output power of 55 kW), which is used to drive an electric generator of 50 kW (nominal power), along with a high-voltage lithium-based battery pack that has a capacity of 20 kWh (allowing for a 50% DOD rate) coupled to an 125 kW (peak power) permanent magnet traction electric motor, the average fuel consumption of the engine was around 3.53 liters/100 km, meaning that it uses almost 38% less fossil fuel, compared to a conventional drivetrain (which consumes around 5.62 liters/100 km, on average).

The resulting fuel efficiency corresponds to a vehicle range of approximately 97 km in hybrid mode, at an average speed of 42.69 km/h (being very close, but lower than the combined speed of the WLTP cycle), meaning that the average driving time in hybrid mode is 2.29 hours, which translates into about 137 minutes.

For future directions of development, the algorithm can be customized based on the specific requirements of the application (public transportation, passenger cars, vans, etc.), on the characteristics of the powertrain (ICE's maximum output power, displacement, cooling system's capabilities, HVB's capacity, etc.), on weather conditions or even based on the driver's preferences, in order to improve the overall efficiency of the plug-in series-hybrid powertrain. Therefore, by applying the proposed methodology, this study can be easily extended to any other type of hybrid or electric vehicle, meaning that the powertrain components, as well as the algorithm should be scaled according to the power requirements and energy consumption.

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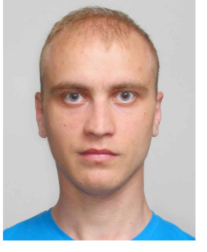

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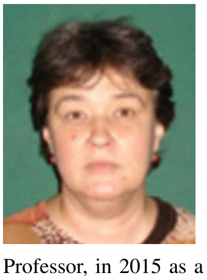

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