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Investigation of the Series Hybrid Electric Powertrain Architecture with Wankel Engine as a Range Extender

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Highlights

- Computational modeling of a series hybrid vehicle.
- Calculation of electric motor power rating and battery capacity.
- Performance assessment of the series hybrid powertrain architecture with WLTP driving cycle.

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Abstract

In this study, a conventional vehicle is converted into a series hybrid electric vehicle. Electric motor power, battery pack capacity, range extender operating condition is determined; a computational model of the vehicle is built and simulations are conducted using Worldwide Harmonized Light Vehicles Test Procedure (WLTP). Power rating of the electric motor is calculated as 120 kW for the same acceleration performance. Wankel engine data available in the Automotive Laboratory of Istanbul Technical University are used. Energy capacity of battery pack is determined according to the daily driving distance of the WLTP. Engine on-off control strategy is used to control range extender operation. Wankel engine is operated at a speed of 4000 rpm and load of 5.15 bar, hence it is tuned to deliver an output power of 22.3 kW. Simulation results show that the performance of Wankel engine is validated as range extender by using engine on-off control strategy. State of charge of battery pack is set as minimum (30%) at the beginning of simulation and the state of charge of the battery pack charged by the range extender is assumed to be approximately 50% at the end of the cycle. For comparison, performance of Wankel engine is compared to the range extender of a mass-produced series hybrid electric vehicle, which has a battery pack capacity of 18.8 kWh. In conclusion, it is shown that a more compact range extender unit with a battery pack of 35 kWh is advantageous from the perspective of the packaging of the battery pack.

1. INTRODUCTION

Due to the strict exhaust emission limits, limited fossil fuel reserves, environmental and air pollution issues, automotive industry has been searching for alternative propulsion systems. Thus, electric vehicles are considered as an option for the future of transportation due to their zero exhaust emission characteristics and other advantages of the electrification over conventional vehicles powered with internal combustion engines (ICE) [1]. In fact, electric motors provide close to ideal torque-speed characteristics for road vehicles, while providing excellent acceleration performance. Moreover, electric motors operate quieter than ICEs. Furthermore, electrification of the drivetrain can simplify the transmission, since the use of electric drives usually removes the necessity of using a multi-stage transmission. Though, a battery powered electric vehicle has some disadvantages as well. In the current technology level, issues related to range, charging and cost of chemical batteries still remain. Low energy density, long charging time and high costs prevent the industry to develop pure electric vehicles. Thus, the most realistic solution is to combine the electric propulsion and ICEs [2]. As it is known, there are different hybrid electric vehicle configurations such as series, parallel, series-parallel and complex hybrids. They all have different advantages and disadvantages. But the series hybrid configuration has an easier control than the other configurations, along with simple structure and capability to carry larger battery pack [3]. In series hybrid electric vehicles,

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electric motor is the only component that propels the vehicle. When the ICE is not running, vehicle operates in a pure electric mode using the energy stored in the batteries. When the state of charge (SoC) of the battery pack is reduced to the lowest permissible value, the ICE starts to operate and charges the battery pack. On the contrary, other hybrid electric vehicle configurations need a complicated control strategy. In parallel hybrid vehicles, the ICE is also connected to wheels, thus requiring a multi-stage transmission. In series hybrid vehicles, the ICE is not mechanically connected to the driven wheels, thus its operating point, i.e., speed and load, can be selected independently. In other words, the ICE can be set to operate at its most efficient running condition without disturbing the operation of the vehicle. In the literature, the most realistic and optimum solution for the electrification of vehicles is suggested as electric battery powered vehicle for daily distance driving that has an ICE as a range extender to recharge the battery pack when needed [2]. Another advantage of this configuration is that it allows the use of different types of ICEs (such as Wankel, two-stroke, etc.) that are critical for related emission standards [1]. Consequently, this study aims to investigate the performance of a series hybrid electric drive train combined with an alternative range extender unit.

1.1. Series Hybrid Electric Vehicles

Series hybrid electric vehicles, also known as the range extended electric vehicles (RE-EV), seem to be the most promising short term solution to overcome the drawbacks of Battery Electric Vehicles (BEV) such as travelling distance and battery cycle life [4]. The range extender unit consists of an ICE and a generator, commonly referred to as genset, which could provide extra electric power for charging the battery [5,6]. For series hybrid electric vehicle applications, usually an output power of 25-30 kW is suggested [7]. Furthermore; refinements from the perspective of noise, vibration and harshness (NVH) and packaging are also required as evident from several studies available in the literature that proposes the use of single cylinder ICE [7, 8]. Also, two- and four-stroke engines are compared in terms of fuel efficiency, compactness and lightweight [9].

Majority of current research focuses on fuel efficiency due to its effect on battery life, that is directly related to cost [10]. Li et al. [10] propose a multi-objective optimal control energy management strategy for RE-EVs, and conclude that the proposed strategy can help to obtain an optimal battery capacity configuration while stating a trade-off between fuel consumption and battery state of health. This favors Wankel engine as a range extender due to its compactness and reduces its disadvantage in fuel economy considering the battery state of health. Furthermore, Liu et al. [11] implements the powertrain supervisory control optimization and battery pack sizing separately. Authors combine genetic algorithm (GA) with Pontryagin’s Minimum Principle (PMP) in order to determine battery pack sizing and power split control sequence simultaneously. Zhao et al. [12] use artificial neural networks and genetic algorithm to obtain the optimum operating points of the range extenders and generators.

Besides from the optimal control strategies and optimization algorithms developed in the literature, a different approach is investigated in this study that focuses on the basic design principles of the series hybrid electric drivetrain. The capacity of the battery pack is determined from the daily driving distance requirements; the power characteristics of the electric motor is selected based on the acceleration performance of a conventional vehicle with similar dimensions; and the range extender unit is assumed to have a Wankel engine due to its compactness, light weight and good NVH behavior.

1.2. Engine on-off or Thermostat Control Strategy

The Thermostat control strategy (TCS) is known for its simplicity, robustness and achievement of good fuel economy [13]. It aims to use range extender at its optimum operating point. Thus, engine on-off control strategy is used in this study in order to investigate the performance of the range extender unit. This control strategy is illustrated in Figure 1. The operation of ICE is controlled by the SoC of the battery pack. When the SoC of the battery pack reaches its maximum level, the ICE is shut off. On the other hand, when the state of charge is at its minimum permissible level, ICE starts to operate to charge the battery pack.

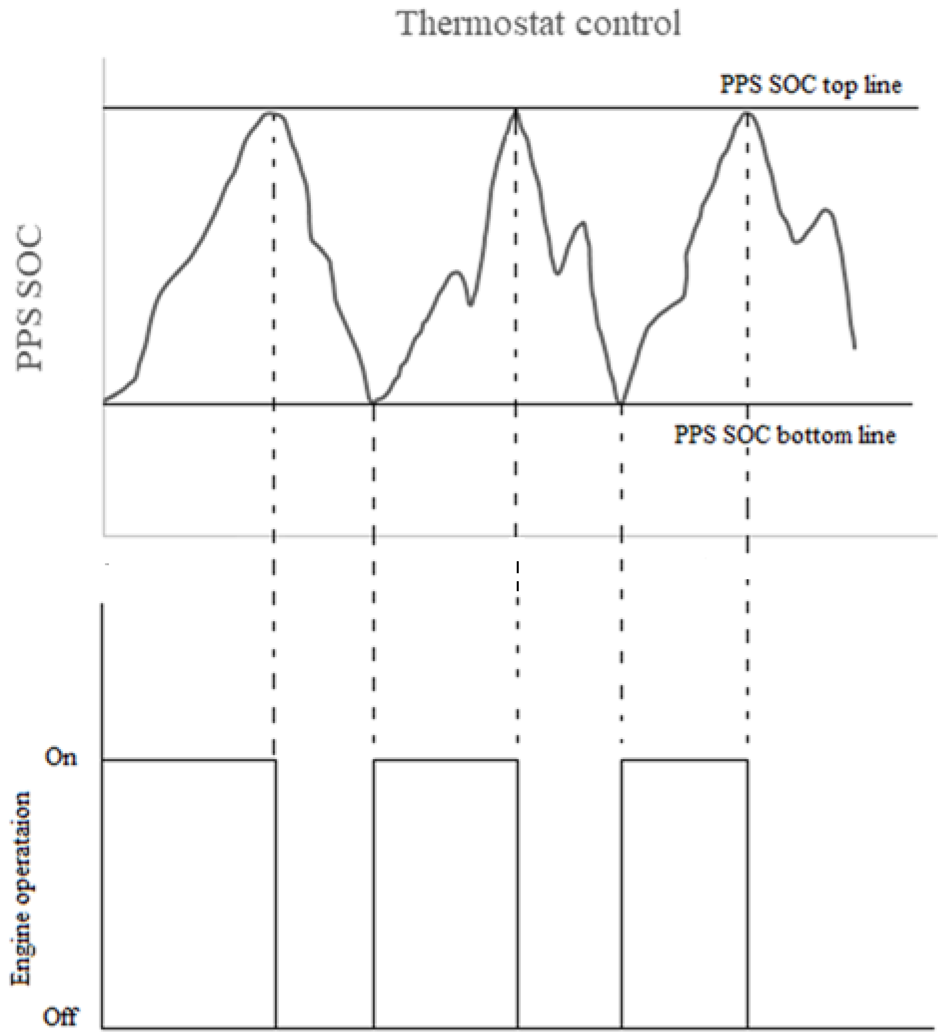

Figure 1. *Illustration of thermostat control [14]*

2. DEVELOPMENT OF THE SERIES HYBRID POWERTRAIN CONFIGURATION WITH RANGE EXTENDER UNIT

2.1. Details of the Conventional Vehicle

In this paper, a mass-produced conventional vehicle (Volkswagen Passat) is considered based on its the sales figures. Its dimensions are kept intact while converting its powertrain architecture to a series hybrid configuration. Important dimensional data of this conventional vehicle are tabulated in Table 1 [15].

Table 1. *Dimensions and mass of the conventional vehicle (VW Passat) [15]*

Length [mm]	Width [mm]	Height [mm]	Curb Weight [kg]
4767	1832	1477	1485

Furthermore, the important vehicle performance data along with engine specifications are listed in Table 2 [15].

Table 2. *Performance and engine specifications for the conventional vehicle (VW Passat) [15]*

Engine Type	Engine Size [lt]	Maximum Power [kW]	Maximum Torque [Nm]	Maximum Speed of the Vehicle [km/h]	Timer to accelerate from 0 to 100 km/h [s]
Diesel Engine	1.6	88	250	204	11

2.2. Development of the Series Hybrid Electric Powertrain Architecture

In series hybrid electric vehicles, electric motor is the only source that transmits torque to driven wheels, thus it is the only power source that propels the vehicle. Therefore, electric motor power rating must satisfy the desired acceleration performance of the vehicle. In this study, power rating of electric motor is estimated based on the acceleration performance of the conventional vehicle by the use of the Equation (1) [16].

$$P_t = \frac{\delta M}{2t_a}\left(V_f^2 + V_b^2\right) + \frac{2}{3}Mgf_rV_f + \frac{1}{5}\rho_a C_D A_f V_f^3. \tag{1}$$

The terms at the right hand side of the Equation (1) represent the acceleration, rolling and aerodynamic resistances, respectively. Furthermore, M is the total vehicle mass in kg, t_a is the expected acceleration time in s, V_b is the vehicle speed in m/s that corresponds to the base speed of the electric motor, V_f is the maximum speed of the vehicle during acceleration in m/s, g is the gravitational acceleration in m/s^2, f_r is the coefficient of rolling resistance, ρ_a is the air density in kg/m^3, A_f is the cross sectional area of the vehicle in m^2, and C_D is the aerodynamic drag coefficient.

As it is known, the base speed of an electric motor also depends on the type of the electric motor. Furthermore, the speed ratio (x) of an electric motor is defined as the ratio of electric motor's maximum speed to its base speed. Figure 2 shows the speed-torque profile of electric motors with different speed ratios.

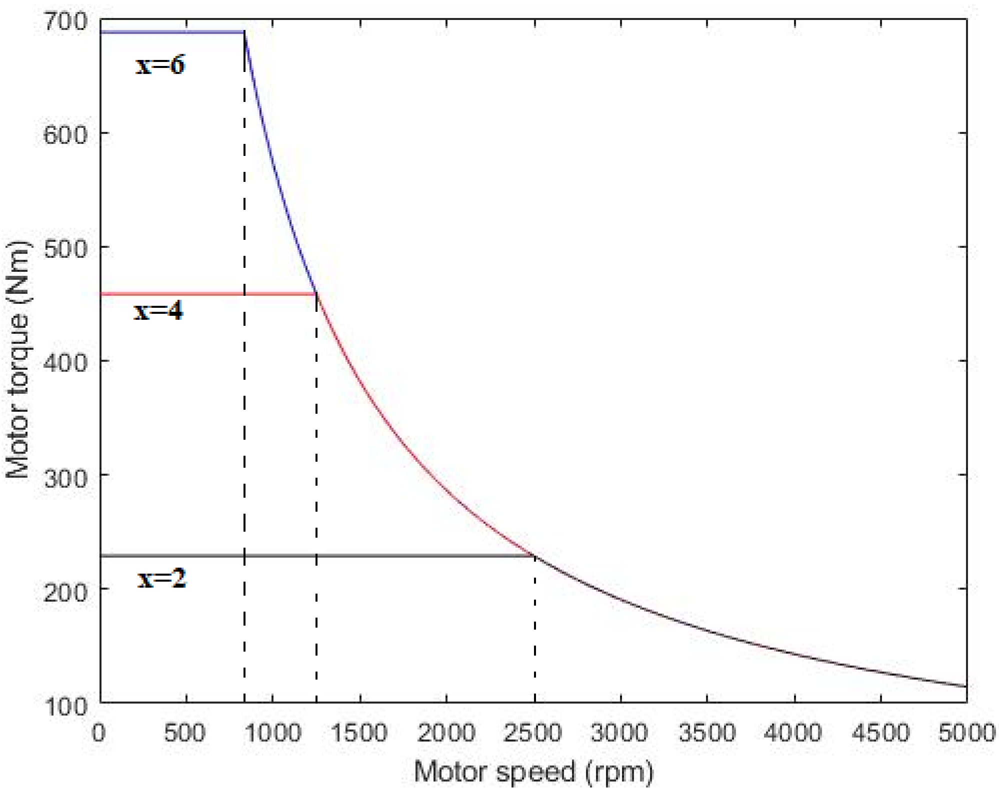

Figure 2. *Torque vs. speed profile of a 60 kW electric motor with different speed ratios [17]*

Induction and permanent magnet brushless DC motors are the two most common electric motors for hybrid electric vehicle applications with different speed ratios. Generally, induction type electric motors provide a speed ratio of four, while the speed ratio of permanent magnet brushless DC motors is usually around two. Hence, a permanent magnet brushless DC motor with $x = 2$ is selected in this study as the traction drive due to its high-power density, high speed and high operation efficiency [18]. Maximum and base speeds of the electric motor are determined as 7500 and 3750 rpm, respectively, and a single-stage transmission is coupled to the electric motor accordingly.

In order to achieve a similar acceleration performance with the conventional vehicle, the acceleration time from 0 to 100 km/h speed is set to 11 s, i.e. $t_a = 11\ s$. The mass of the series hybrid vehicle is estimated to be 200 kg heavier than the conventional vehicle due to the additional battery pack and genset. Thus, $M = 1685\ kg$. Furthermore, the maximum speed of the vehicle is assumed as $V_f = 100\ km/h$, and thus the gear ratio of the single-stage transmission is obtained to be 6. So, the speed of the vehicle at the base speed of the electric motor (3750 rpm) is calculated.

The parameter δ in Equation (1) represents the contribution of the rotational inertia and calculated as follows [19], where i_g is the transmission gear ratio and i_0 is final drive ratio

$$\delta = 1.04 + 0.0025 i_g^2 i_0^2. \tag{2}$$

The coefficient of rolling resistance f_r is calculated as follows [20], where V is the speed of the vehicle in km/h

$$f_r = 0.01\left(1 + \frac{V}{160}\right). \tag{3}$$

Finally, the aerodynamic characteristics of the vehicle are adopted from its conventional counterpart as $C_D = 0.27$ and $A_f = 2.64\ m^2$. Consequently, the power of the electric motor is calculated as 120 kW.

2.3. Energy Capacity of Lithium-Ion Batteries

In order to determine the energy capacity of the battery pack, the daily driving distance of the vehicle is considered based on the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) cycle, that covers a distance and time of 22.65 km and 30 min., respectively. Therefore, the series hybrid electric vehicle is simulated in WLTP cycle and the calculated power consumption is depicted in Figure 3. As seen in Figure 3, the maximum instantaneous power consumption for WLTP cycle is approximately 37 kW. Therefore, the energy capacity of the battery pack is calculated as:

$$E_{battery} = 37 \times 0.5 = 18.5\ kWh. \tag{4}$$

Driving the WLTP cycle twice is assumed to be sufficient as the daily driving distance, that corresponds to a range of 45.3 km. Hence, the required battery capacity is found to be 37 kWh. However, by considering the energy recovery from regenerative braking, the final capacity of the battery pack is assumed as 35 kWh.

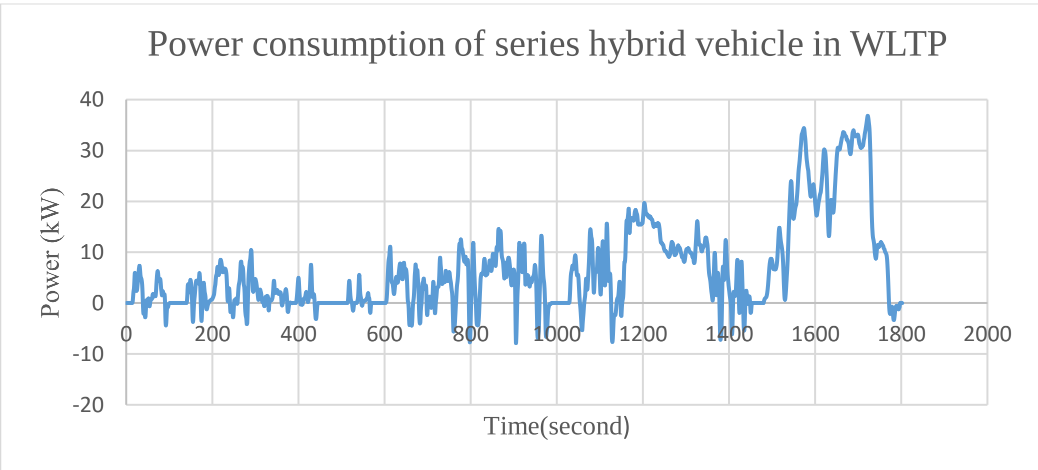

Figure 3. *Power consumption of the series hybrid vehicle in WLTP cycle*

2.4. Operational Condition of the Range Extender Unit

As the range extender, the Wankel engine is considered that has several advantages, such as compactness, few number of running parts compared to a conventional ICE, better NVH performance due to its rotational motion [1, 2, 21, 22]. Hence, torque, power and fuel consumption maps of a particular Wankel engine are experimentally obtained at the Automotive Laboratory of Istanbul Technical University and these data are then transferred to a commercial simulation software in which the performance of the series hybrid electric vehicle is investigated.

In this study, a compact range extender is used to charge relatively large battery pack. The Wankel engine has a mass of 75 kg and a volume of 0.65 l. For comparison, a commercially mass-produced vehicle (BMW i3) has a 0.65 l in-line 2-cylinder range extender with 18.8 kWh lithium-ion battery [23]. The range extender of this vehicle (BMW i3) operates at 4500 rpm and 10.7 bar for maximum power output and delivers 55 Nm torque and 25.9 kW power [23]. The Wankel engine used in this study operates at 4000 rpm speed and 5.15 bar load for maximum power output, and it delivers a torque of 53.2 Nm and a power of 22.3 kW.

2.5. Computational Modelling of the Hybrid Electric Vehicle

After determining, electric motor's power rating, range extender operating point, control strategy and battery capacity, series hybrid electric vehicle is modelled with a commercially available simulation software (AVL Cruise). As mentioned before, simulations are conducted with WLTP cycle for 30% SoC to evaluate the performance of the range extender on charging the battery pack. Charge/discharge characteristics of lithium-ion batteries, efficiency map of the electric motor and control strategy are included in the computational model along with the other parameters such as vehicle dimensions, range extender operating points, battery capacity, electric motor torque and power characteristics. The computational model constructed for performance evaluation of the series hybrid electric vehicle is shown in Figure 4.

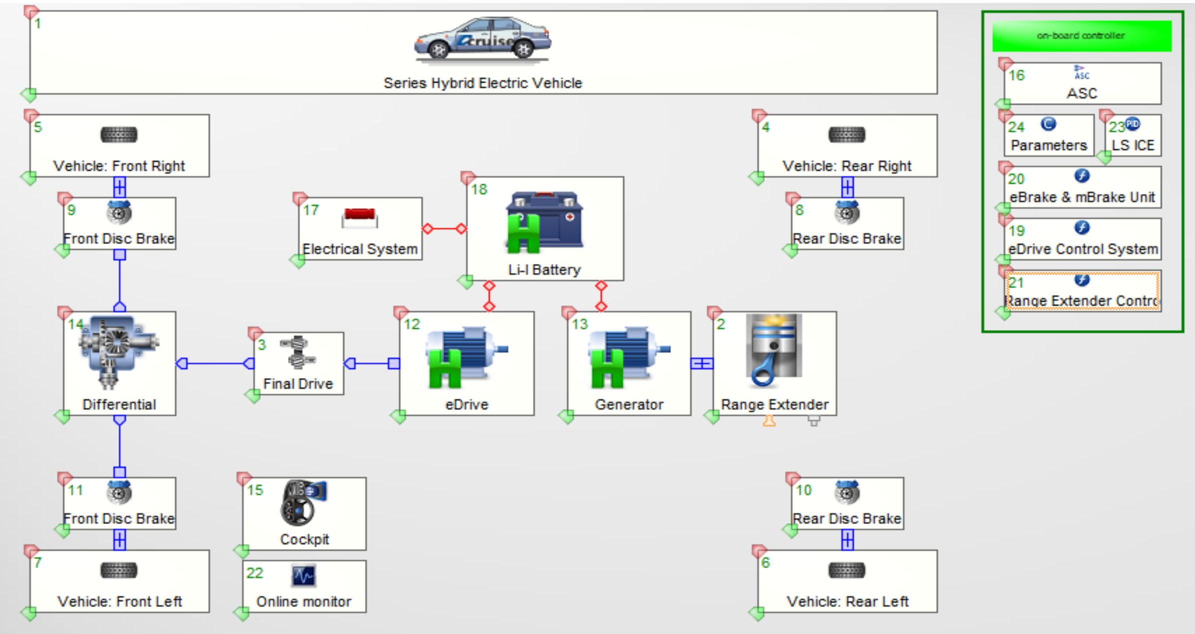

Figure 4. *Computational model developed for the series hybrid electric vehicle*

Note that the SoC of the battery pack is set to 30% at the beginning of the simulation and the simulation results in terms of time histories for several important parameters are given in figures below. Figure 5 shows the torque obtained from the electric motor during the WLTP cycle. The electrical power consumption of the electric motor is depicted in Figure 6. The electrical power of battery pack is shown in Figure 7 and the speed and mechanical power of the electric motor are given with Figure 8. Note that the Figures 6 and 8 show the conversion losses in the electric motor.

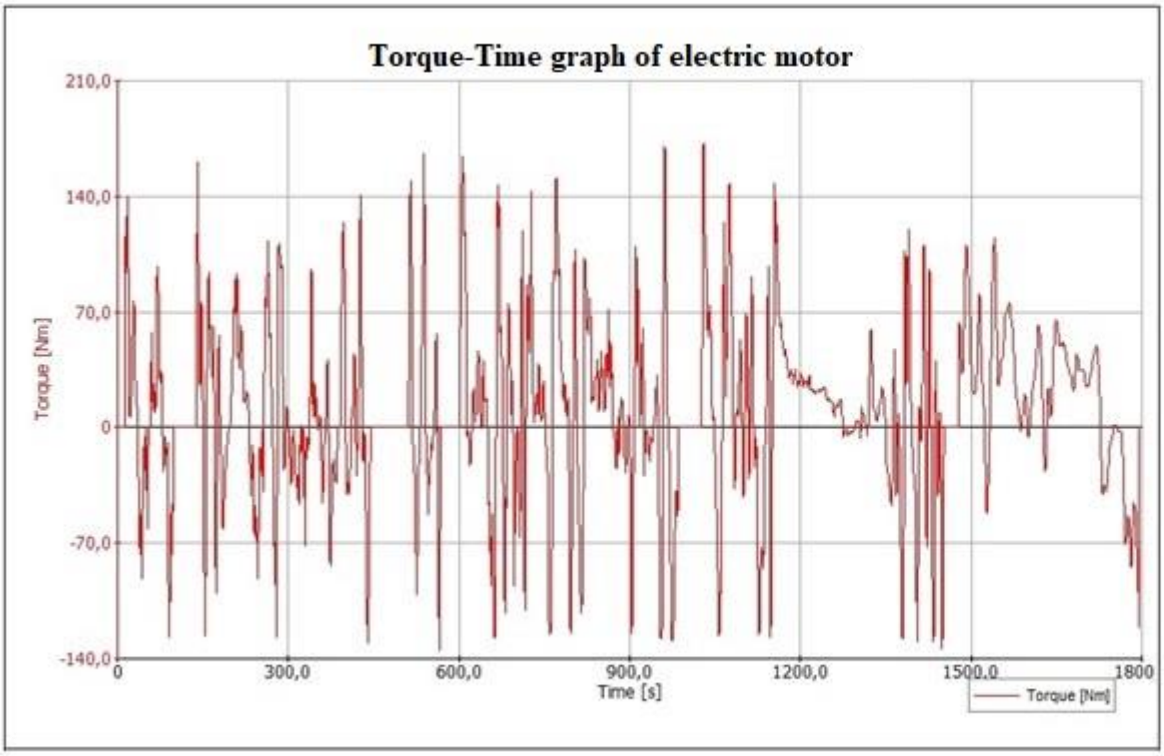

Figure 5. *Time history of the torque delivered by the electric motor*

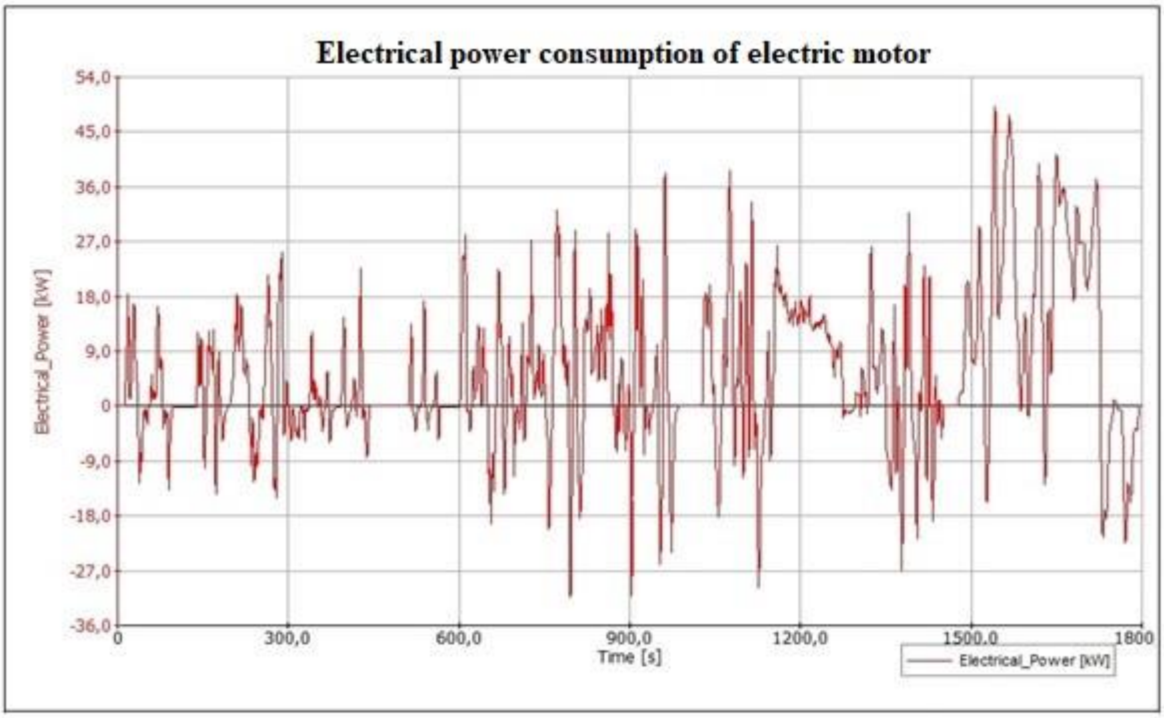

Figure 6. *Time history of the electrical power consumption*

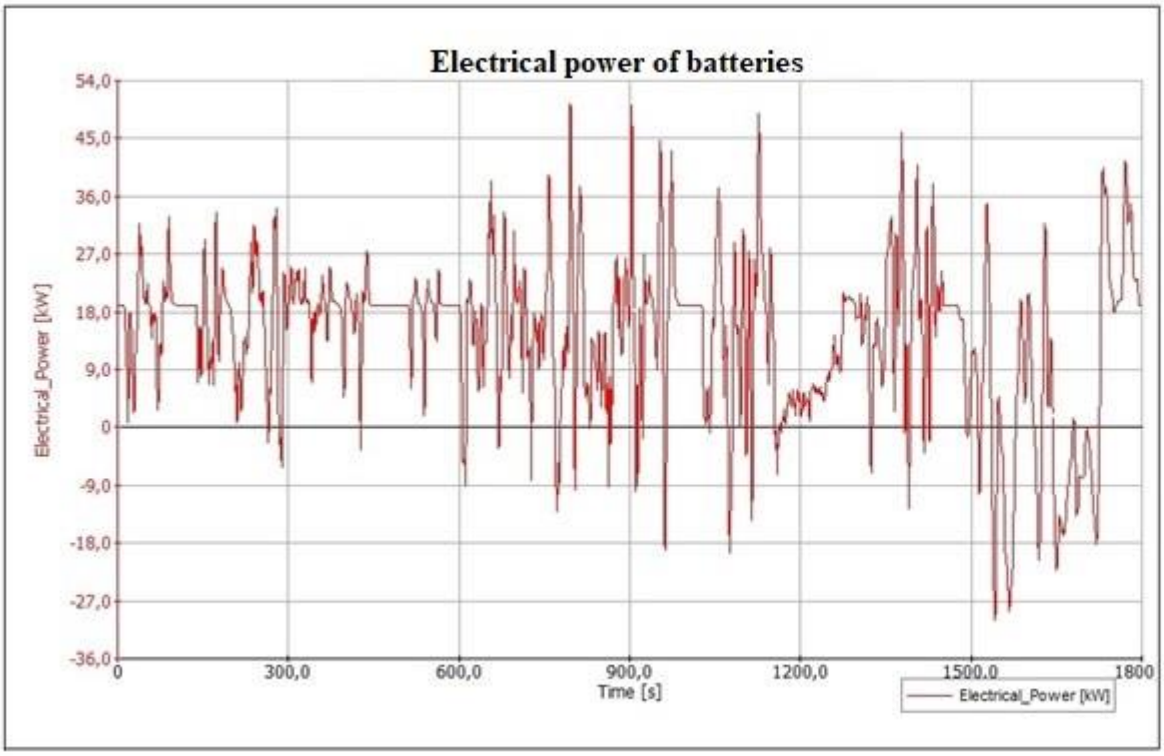

Figure 7. *Time history of the electrical power of the battery pack*

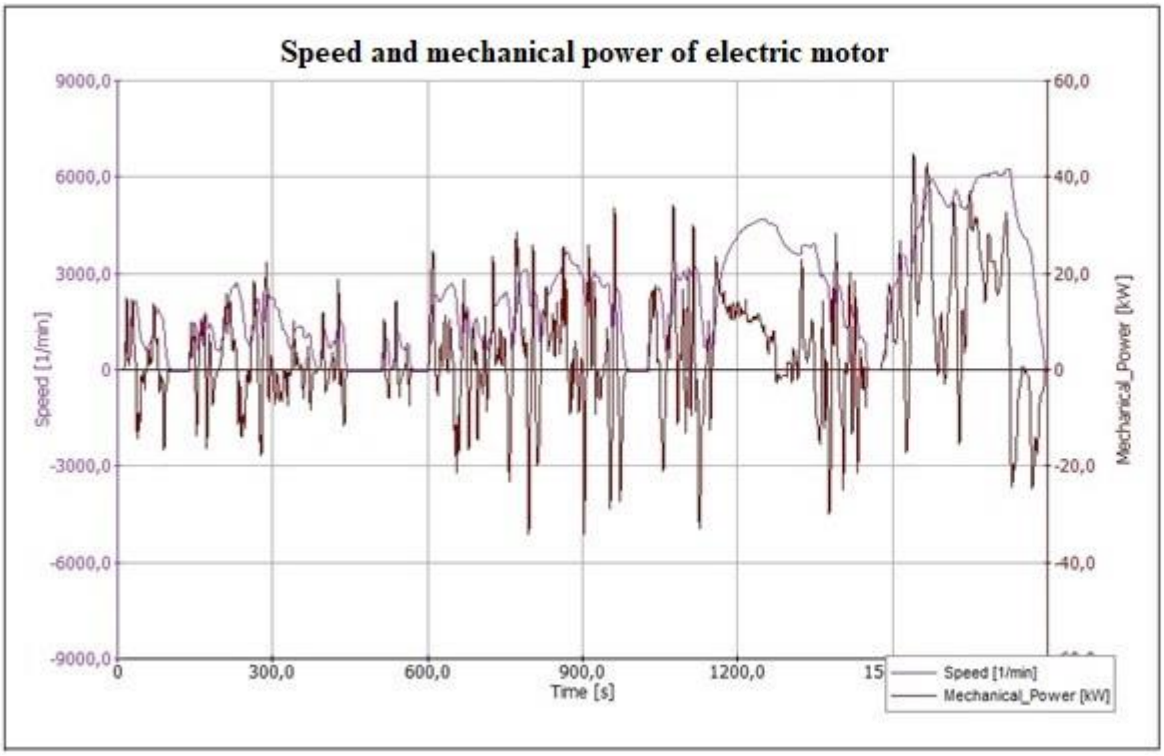

Figure 8. *Time histories for the speed and mechanical power of the electric motor*

As mentioned before, the simulations are initialized with a 30% SoC for the battery pack, which is also the minimum permissible SoC value. Thus, the range extender immediately starts to operate in order to charge the battery pack. The change of SoC during the simulation is depicted in Figure 9. As seen from the figure, the SoC of the battery pack goes up to around 50% at the end of the cycle. Furthermore, the power consumption of the vehicle during the simulation is shown in Figure 10.

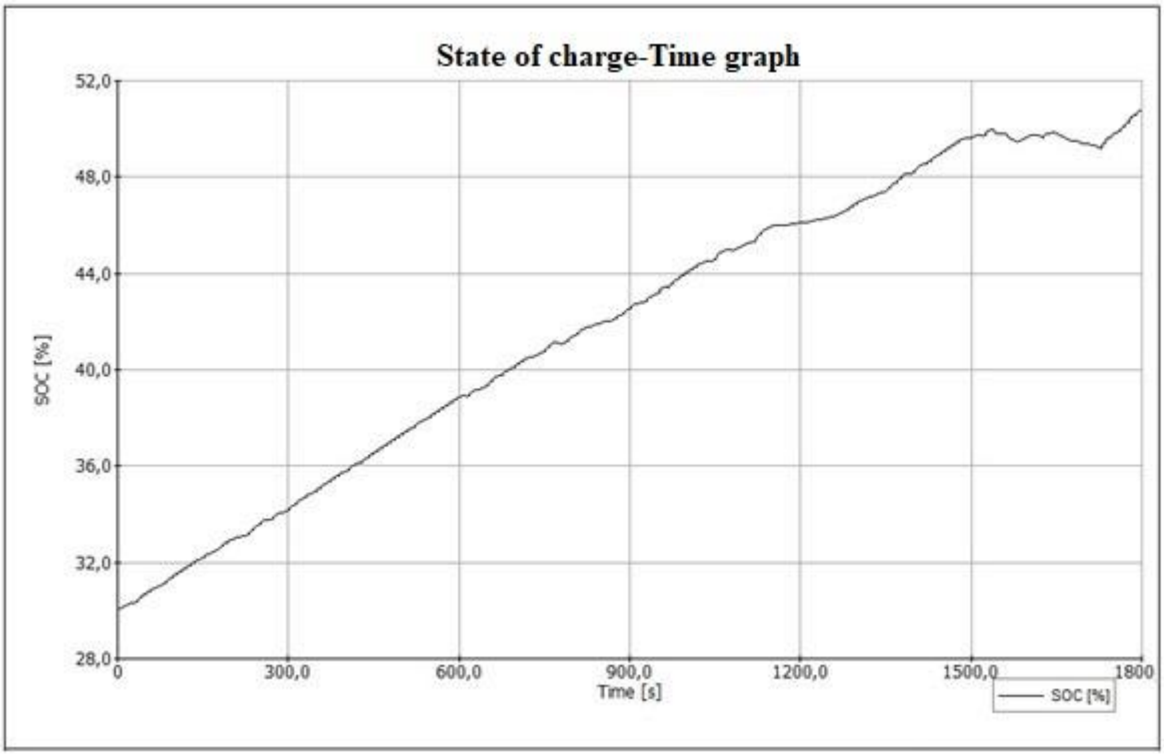

Figure 9. *Time history for the SoC of the battery pack*

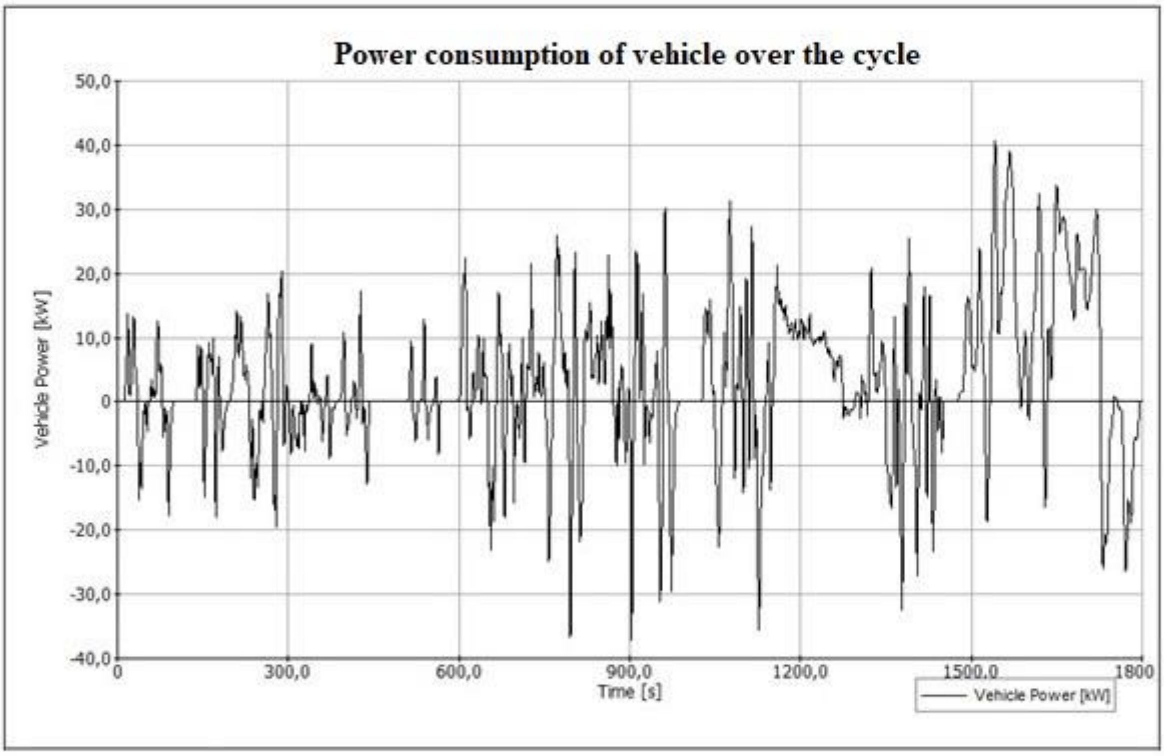

Figure 10. *Time history of the consumed power over the WLTP cycle*

4. RESULTS

In this study, basic structure of a series hybrid electric powertrain is implemented to a conventional vehicle. A simple control strategy is combined with compact, lightweight, rotary engine range extender. In order to compare conventional and series hybrid vehicles same acceleration performance is considered to determine the power rating of the traction motor. For the same dimensions, the power rating of the series hybrid vehicle is calculated as 120 kW whereas the maximum power for the conventional vehicle is 88 kW and the increased power demand for the series hybrid electric vehicle is attributed to the extra weight of 200 kg due to the additional battery pack and the genset. As a result of single-stage transmission, traction motor characteristic and increased weight of the vehicle, maximum speed of hybrid vehicle is calculated as 156 km/h whereas the maximum speed of conventional vehicle is 204 km/h. The performance of the Wankel engine, which operates as a range extender at 4000 rpm speed and 5.15 bar load, is evaluated computationally. It is observed that, the Wankel engine charged the battery pack from 30% to 50% SoC during the WLTP cycle by delivering 22.3 kW output power. Thus, the Wankel engine seems to be an eligible option as a range extender. This study aims to investigate the advantages of series hybrid electric powertrain such as simple control strategy, space for a larger battery pack and alternative range extender concepts. For comparison, the powertrain developed in this study is compared to another series hybrid electric vehicle (BMW i3) available in the market. The powertrain in the developed model has a battery pack capacity of 35 kWh whereas the battery pack capacity of the BMW i3 is 18.8 kWh. The range extender unit of BMW i3 is composed of a 2-cylinder reciprocating ICE with a volume of 0.65 l. In the model developed, a more compact and lightweight rotary engine based range extender with same volume, i.e. 0.65 l, is used to charge a larger battery pack of capacity 35 kWh. This study can be further expanded by the use of a multi-objective optimization approach based on battery pack sizing, fuel consumption and battery state of health.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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