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Application and Efficiency of a Series-Hybrid Drive for Agricultural Use Based on a Modified Version of the World Harmonized Transient Cycle

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Abstract: Off-road vehicles and transportation are vital for agricultural economics, yet the transition to green energies is challenging. To make this transition easier, a tool that enables the testing of heavy-duty off-road vehicles in various scenarios was created. Based on the methods of the World Harmonized Transient Cycle (WHTC), a new Hybrid Operational Cycle (HOC) that reflects the features of agricultural work was created and applied in a graphical model simulation. This was a newly developed methodology. The cycle and the model were based on gathered research data. A numerical model of a medium-power tractor with an internal combustion engine and a series-hybrid setup was created, and simulations were performed in Matlab and AVL Cruise. Both diesel and hybrid vehicles were compared in terms of their power production, fuel consumption, and efficiency in fieldwork and transportation scenarios. The results showed that a series-hybrid transmission can achieve an efficiency similar to that of a tractor with a continuously variable transmission (CVT), but because it uses an electric powertrain, it still provides the opportunity to exploit energy regeneration during transportation and under low-load conditions. The designed model may also be used to develop control algorithms for hybrid drives and improve their efficiency.

Keywords: series-hybrid; off-road; heavy-duty; WHTC; HOC; hybrid; tractor; hybrid drive cycle; AVL Cruise

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1. Introduction

The Green Course and emission requirements for vehicles are becoming tighter and tighter, and this applies not only to road vehicles. In recent years, this trend toward more sustainable living has led to increased interest in agricultural vehicles as a research field within transport development [1–3]. Electrification is recognized as the most promising means to make tractors work more efficiently because electric motors—especially those for propulsion systems—have grown in power and become smaller in size since they were first developed [4–8].

Few applications of electrification are being tested. In the early development of heavy-duty vehicles, series-hybrid systems were used to match the high power demands. Kim et al. [9,10] proposed a series-hybrid electric vehicle with an engine and alternator couple, four inverters, and a battery, as well as an energy management strategy that allowed the vehicle to be used in three modes: with the internal combustion engine (ICE) as a primary energy source; as an electric vehicle powered by the battery; and as a hybrid that could be powered both by the ICE and by stored energy. This application showed promising fuel savings, but despite its high power, the vehicle was of a medium weight, and it was tested under road conditions, not on rough terrain. A quite different approach was taken by Feng [11,12], who developed a hybrid electric mining truck. Special work conditions—even when comparing agricultural vehicles—require special energy management strategies. However, Feng's research, as well as the work of others who have

have considered heavy-duty transport, indicates that a series-hybrid system is suitable for off-road vehicles [13–17].

There are two main criteria for efficient hybrid vehicles. The energy management strategy (EMS) is crucial, especially when moving from general road cars to special forms of transport [18–21]. The greater the complexity of the vehicle setup, the more complex the strategy for controlling efficient energy usage [22–25]. Xu et al. explained that the large load fluctuations that occur in fieldwork with an agricultural vehicle make the selection of an effective EMS necessary [26]. Efficient transmission is another criterion. To achieve this, several methods have been established. Dou et al. suggested an application in which an EMS was used to partly replace a complicated though commonly used transmission [27]. Dual-powered hybrid vehicles have also been widely proposed, but the approaches often differ. Zhu et al. [28] applied a dual power source by using a parallel-hybrid system and an EMS with five modes. The performance of the vehicle was assured by the same hydromechanical continuously variable transmission (CVT). Goswami et al. [29] compared a series-hybrid system and a series–parallel-hybrid system, keeping the vehicles' original transmissions. However, neither of these studies provide comparable data for evaluating the overall efficiency of hybrid tractors in comparison with conventional ones.

Another dual-power method is provided by Mocera [30–33], in whose research an ICE and a motor couple were used in combination with an additional motor, which enabled the use of a hybrid e-CVT. This hybrid performed well under high power demand conditions and achieved an overall decrease in fuel consumption compared with that of conventional vehicles. Dual-power applications are also seen in fully electrical heavy-duty vehicles, but these models can be used more successfully for on-road transportation [34–37].

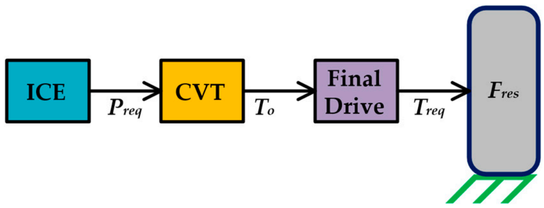
As has been described in different studies, the use of a power split allows one to downsize an ICE unit and to increase the fuel efficiency for this reason alone. Additionally, by altering the transmission of an off-road heavy-duty vehicle, its efficiency can be increased. It is hypothesized that a CVT can be replaced by highly effective electric motors [17,38–47], thus achieving similar transmission effectiveness while reducing the number of parts that cause mechanical losses. In this study, a power-splitting method for a series-hybrid system is investigated.

The main objective of this study is to compare a tractor with a series-hybrid drive and a tractor with a conventional CVT with the aim of determining and comparing their efficiency and the feasibility of using this type of drive in agriculture. Since there is no unified methodology for assessing the efficiency of tractors, the authors modified and adapted (recalculated using possible tractor acceleration) the WHTC, making it suitable for the low-speed agricultural machinery used in the study by taking into account the workings and movement velocities specific to these machines.

2. Methods

2.1. Vehicle Models

An off-road heavy-duty vehicle is a machine that weights more than 10 tons and is used for high-tow-demand and high-torque tasks, such as agricultural work, forestry, and the transportation of harvested raw materials. To compare the execution of these tasks by a vehicle that has a series-hybrid drive installed (Figure 1a) and a common CVT version of that vehicle (Figure 1b), a simplified graphical model was created for both vehicle options. Both 14-ton vehicles were powered by the same 254 kW diesel engine. The final drive ratio for both vehicles was 28. The hybrid vehicle was equipped with an ICE-matching alternator, two 100 kW electric motors (one for each driving axle), and a 46 Ah battery to store excess energy. The CVT used for the non-hybrid vehicle was a ZF ECCOM 3.5. Table 1 shows the technical parameters of the vehicles.



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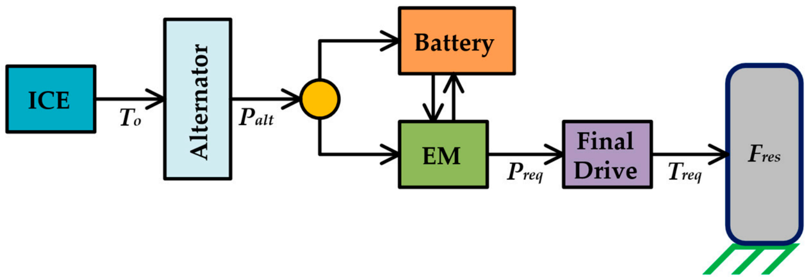


(**b**)

Figure 1. Schematic representation of vehicle models: (**a**) the series-hybrid model; (**b**) the CVT model (P_{alt}: alternator power output; P_{em}: motor power output; P_{req}: power demand; T_o: optimal torque; T_{req}: torque demand).

Table 1. Technical parameters of the vehicles.

Parameter	Value	Unit
Maximum Engine Power	254	kW
Continuous Alternator Power	177	kW
Peak Motor Torque	1900	Nm
Battery Capacity	46	Ah
Vehicle Mass	12,600	kg
Wheel Load	3500	kg
Vehicle Frontal Area	7.75	m^2
Wheelbase	3.3	m
Final Drive Ratio	28	-
Tire	900/60 R38	-

The start and the end of these schemes were similar, but the hybrid had more components that could cause higher transmission losses. On the other hand, while the CVT vehicle might appear simple, the main transmission (CVT) part was quite complex and could also cause considerable losses, as well as high efficiency.

There was also a difference in how the power demand was distributed in these two models. Despite the length of the drivetrain of the hybrid vehicle, the required power P_{req} for overcoming the resistance force F_{res} was supplied at the end of the chain. The path of the P_{req} in the CVT vehicle was slightly longer, and this could cause higher energy losses and thereby consume more power than in the hybrid vehicle when overcoming the resistance force.

Another difference between the hybrid and CVT vehicles was point in the drivetrain chain at which the optimal torque T_o could be applied. The optimal torque is a load point at which the highest efficiency available is reached. In the hybrid vehicle, the T_o was reached by using an ICE, allowing a reduction in fuel consumption. The CVT vehicle was designed with a greater focus on different speed-to-torque ratios than on achieving lower fuel consumption related to power output; here, the T_o could indicate higher transmission efficiency, but not in direct relation to the ICE. To determine which drivetrain was more efficient overall, the following method of evaluation was established.

To ensure the application of the optimal torque in the ICE of the hybrid vehicle, a control algorithm (Figure 2) was used.

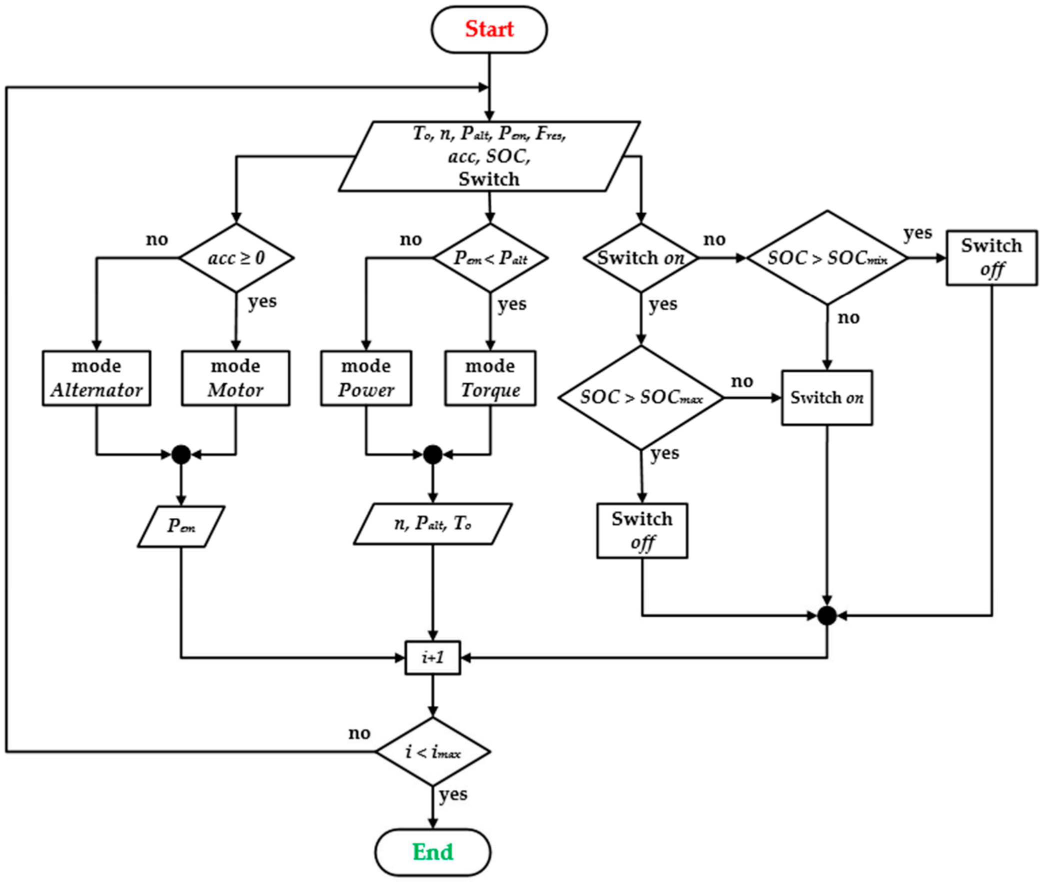


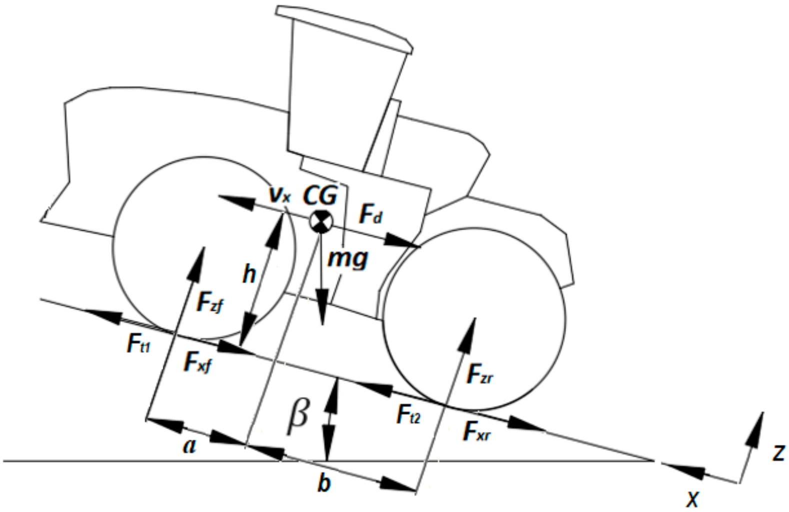
Figure 2. Control algorithm for the series-hybrid vehicle (*n*: engine speed; *acc*: acceleration; *i*: adaptive variable step).

The algorithm can be divided into the following main parts: a loop for the ICE mode, another loop for charging/discharging, and a third loop for regeneration. An ICE has two main operational modes: the power mode, which is used when the required power P_{req} for the electric motors P_{em} exceeds the power generated by the supply couple of the ICE and the alternator, and the torque mode, which is used when the power generated exceeds the power demand, at which point the excess energy can be stored. In this mode, the T_o is reached.

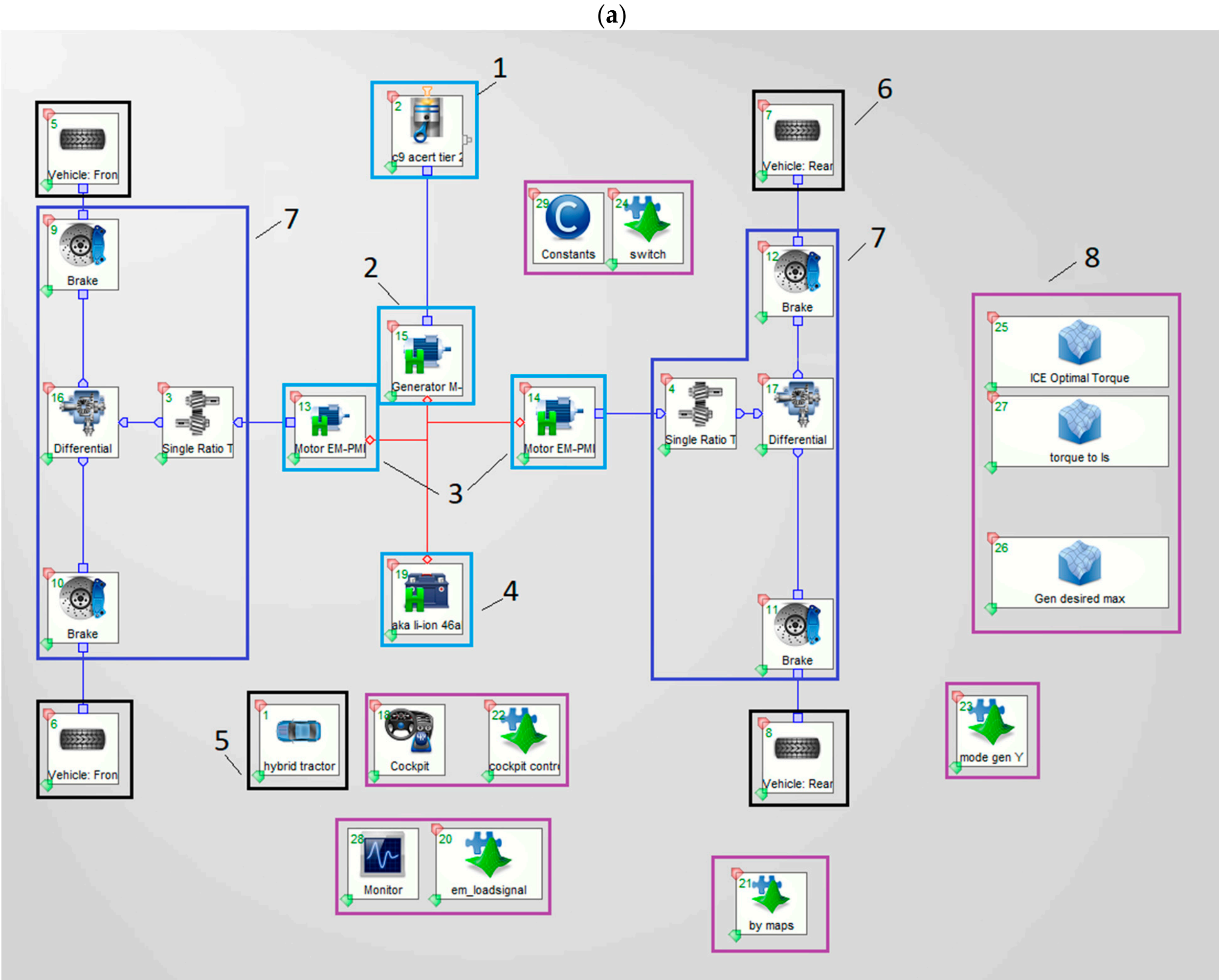
To keep it at its optimal point, the hybrid powertrain was managed according to the efficiency of the internal combustion engine. The supply couple was controlled by the state of charge (SOC) of the battery. After reaching 100% charge, the switch of the ICE was turned off, and it was turned back on when the SOC dropped below 30%.

Electric motors, as well as ICEs, have two modes: the motor mode and the alternator mode. Normally, the motor works as a drive until the braking phase, at which point it starts collecting brake energy. The charging mode can be used both with a working main alternator or separately as a means of extending the operation of the vehicle with electric energy.

A numerical model of a hybrid and a conventional tractor was built using the AVL Cruise 2016 software package, and MATLAB 2021b was used for the management algorithms (Figure 3).



(a)



(b)

Figure 3. Control algorithm for the series-hybrid vehicle: (**a**) longitudinal model of the tractor; (**b**) AVL Cruise tractor architecture model (1: ICE; 2: alternator; 3: motors; 4: battery; 5: vehicle; 6: wheel; 7: axle; 8: controls).

The tractor dynamic was described using the longitudinal dynamic model shown in Figure 3a and given by the following equations [48,49]:

$$m\dot{v}_x = F_t - 2\left(F_{xf} + F_{xr}\right) - F_d - mg\cdot \sin\beta \quad (1)$$

$$F_t = \frac{P_{em} i \eta_t}{r_d} \quad (2)$$

$$F_{t1} = F_t/2,\ F_{t2} = F_t/2 \quad (3)$$

$$F_{zf} = \frac{-h\left(F_d + mg\cdot\sin\beta + m\dot{v}_x\right) + b\cdot mg\cdot\cos\beta}{2(a+b)} \quad (4)$$

$$F_{zr} = \frac{h\left(F_d + mg\cdot\sin\beta + m\dot{v}_x\right) + a\cdot mg\cdot\cos\beta}{2(a+b)} \quad (5)$$

$$F_{xf} = F_{zf}\mu,\ F_{xr} = F_{zr}\mu \quad (6)$$

$$F_d = 0.5\rho C_d A v_x^2 \quad (7)$$

where a, b, and h represent the relative position of the center of gravity (CG) of the vehicle with respect to the front and rear axles, m is the tractor mass, g is the acceleration of gravity, β is the road slope angle, v_x is the vehicle longitudinal speed, F_d is the aerodynamic drag force, ρ is the air density, C_d is the drag coefficient, A is the frontal cross-sectional area of the vehicle, F_{xf} and F_{xr} are the contact forces between the wheels and the ground in the longitudinal direction (front and rear axle), F_{zf} and F_{zr} are the normal contact forces between the wheels and the ground (front and rear axle), F_t is the resultant force of the tractor force in the x direction, i is final drive ratio, μ is the rolling resistance coefficient, η_t is the mechanical transmission efficiency, r_d is the driving wheel radius, F_{t1} is the front wheel traction force, and F_{t2} is the rear wheel traction force.

As is shown in Figure 3b, component (5) of the vehicle describes its main physical parameters, such as its weight and center of gravity (which can change depending on the load of the vehicle), as well as the data required for aerodynamic drag. Total vehicle resistance is calculated using the course data (velocity and road characteristics) and wheel data (6), which include speed, load, and pressure-sensitive rolling resistance. The main power components are the ICE (1), the alternator (2), the motors (3), and the battery (4). All of the models are made using curves and maps of the working characteristics, namely, energy gain, conversion, and energy transfer. To control these processes as needed, additional maps and curves, as well as signals, are created. To manage this, general map components and Matlab DLL interfaces are used (8).

A representative numerical model of an agricultural tractor must be able to describe subsystems from several physical domains. As is shown in Figure 3b, a physical network (PN) modeling approach was chosen to model the architecture of both the traditional and the hybrid electric power unit of the tractor considered in this study. The mechanical and electrical parts of the vehicle model are connected using a controller area network (CAN) bus that includes signal control, which uses a component map, as well as component behaviour programming. The PN is based on a modular modeling approach according to which each element is considered a physical entity capable of exchanging energy with all the other subsystems to which it is connected. The solutions of the systems must satisfy the power balance equations for each component at each time step.

Depending on the calculation task and the desired accuracy of the results, the complexity (modelling depth) of the vehicle models can be continuously increased. The blocks marked "8" (the violet-coloured blocks) are subsystem blocks. The AVL software connects them programmatically to the corresponding circuit elements (motor, generator, etc.), though the connection is now shown visually. These sub-blocks contain the control, motor, and generator efficiency maps, values, outputs, etc. Furthermore, data, such as the dimensions of the parts, transmission ratios, and losses in the different parts, can be defined in sub-blocks. For the engine, different characteristics are needed, e.g., full load characteristics, motoring curves, and consumption maps. It is possible to use different model depths for individual components.

2.2. Hybrid Operational Cycle

The WHTC was created to evaluate the emissions of heavy-duty engines, regardless of their intended application. However, to use it correctly, the cycle requires a transmission model [50]. This makes it less likely that the WHTC will be used in the early stages of vehicle development, especially for small batches or unit production. The WHTC is based on engine load, which differs between trucks that are used as a means of road transportation and agricultural vehicles, as these have relatively defined fields of application. A cycle based on time-dependent velocity would make comparisons of agricultural vehicles easier.

Existing energy efficiency and emissions evaluation cycles (e.g., the WHTC and the Worldwide Transient Vehicle Cycle (WTVC)) are currently designed to evaluate the performance of road vehicles, such as trucks and buses. To evaluate the efficiency of agricultural machines such as tractors, each researcher currently uses his own non-standardized methodology [45,49]. Due to this fact, it is practically impossible to compare such machines with each other. For this reason, the authors have created a new Hybrid Operational Cycle (HOC) (Figure 4) based on the existing methodology for trucks (the WHTC), and taking into account the velocities and the resistances to motion that are typical in agricultural work.

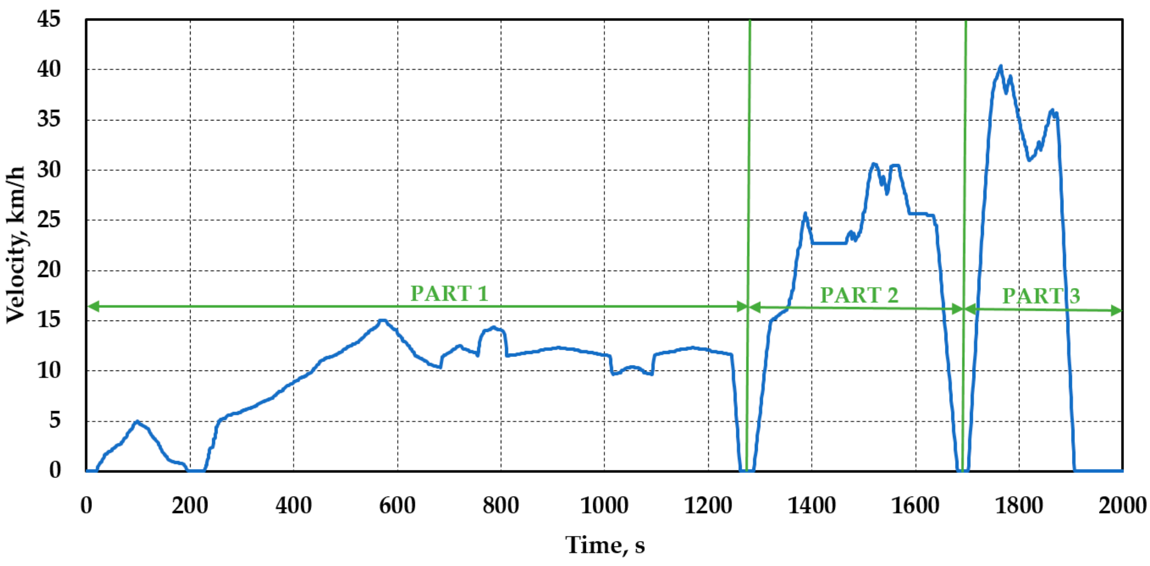


Figure 4. Hybrid Operational Cycle.

The term "HOC" reflects the fact that the cycle combines off-road and road movement. This cycle can be used to evaluate and compare the performances of conventional and hybrid heavy agricultural vehicles (powered by internal combustion). The WHTC was modified by replacing the normal urban cycle with a tillage part (i.e., the WHTC was recalculated using possible tractor acceleration) characterized by low speeds of around 8–11 km/h and a stop at the headland, and the rural part was replaced with a transport part characterized by speeds typical for tractors, with accelerations also chosen in accordance with those typical for agricultural tractors. In addition, the load in each part of the cycle is expressed through the rolling resistance and the tyre friction coefficients obtained in the simulation.

The HOC describes the typical operations of an agricultural vehicle by using time-dependent velocity and keeping the proportions of different types of work, such as field-work, steady-state work, and local and transitional transportation. To improve the accuracy of simulations and better evaluate the influence of the traction battery, the ability of the hybrid system to use the battery for operation and charging can be proportionally extended; we call this the Extended Hybrid Operational Cycle (EHOC). The EHOC consists of the HOC repeated three times. The purpose of this repeatability is to better evaluate the influence of the traction battery, i.e., the ability of the hybrid system to use the battery for operation and charging.

The HOC is composed of three parts. The first part (0–1250 s) (part 1) is the longest and shows different work cycles. It was formed using data collected from different types of field and forestry work of various durations and speeds at different time intervals. Overall, work accounted for nearly 70% of all agricultural vehicle operations, with some machines almost never leaving the field while others mainly performed transportation work.

Another advantage of this cycle is its use in agricultural vehicle evaluation. Because it can focus on one vehicle performing a specific task, a specific part of the cycle can be used for evaluation. The remaining 30% of the cycle time represented transportation. Part 2 (1250–1700 s) and part 3 (1700–2000 s) are separate and describe different types of transportation. Part 2 features a slower speed because it marks local transportation, i.e., moving from field to field, collecting raw materials, and towing loaded trailers to storage. Part 3 of the HOC represents high-speed transportation, i.e., delivering goods and driving in traffic. Part 1 represents off-road work conditions, so it had to be designed from scratch. Parts 2 and 3 represent movement on a road, so the WHTC was adopted. The transportation parts of the cycle were generated by taking the engine load value from the WHTC and converting it into a load that matched the maximum speed of an agricultural vehicle. It was assumed that the vehicle could typically reach a maximum speed of 40 km/h, with the understanding that some cannot reach this speed while others can go faster. Road conditions were also included in this cycle. Without evaluating changing road conditions, fewer vehicles can be compared, although better overall results might be obtained. To obtain the most accurate results possible, road properties must be taken into account. The road properties applied in this research are presented in Table 2.

Table 2. Road properties that were defined.

Cycle pt.	Rolling Resistance	Tire Friction
Part 1	0.09	0.6
Part 2	0.02	0.6
Part 3	0.02	0.75

In Table 2, the rolling resistance is expressed as a coefficient. The tire friction is also expressed as a coefficient, and it has a specific value for each tire/road match. In Part 1, the working ground can differ widely; because of this, a medium resistance was chosen. This can be thought of as a slightly moist soil that is relatively smooth and can be easily displaced. The rolling resistance for transportation is similar, but part 2 of the cycle involves moving on a gravel road, while Part 3 involves an asphalt road. This difference is indicated by the different friction coefficients.

3. Results and Discussion

Both the hybrid and non-hybrid vehicle work cycles are shown in this section. The EHOC was used to provide an evaluation of the vehicle's performance in realistic conditions. It was used to determine the advantages and disadvantages of hybrid drive usage in vehicles intended for both off-road work road transportation.

A hybrid drive in a heavy-duty off-road vehicle enables one to adjust the required engine power according to its efficiency, as does the CVT. However, the means of doing so are quite different in each case. The hybrid vehicle had an ICE accompanied by an alternator and a battery; this allowed the ICE to work in bursts during the cycle, though not necessarily in response to the current power demand. The CVT could adjust to the power demand and keep a relatively optimal ICE efficiency, although it had to work continuously throughout the whole cycle. The power bursts of the hybrid drive and the continuous power of the CVT vehicle are shown in Figure 5.

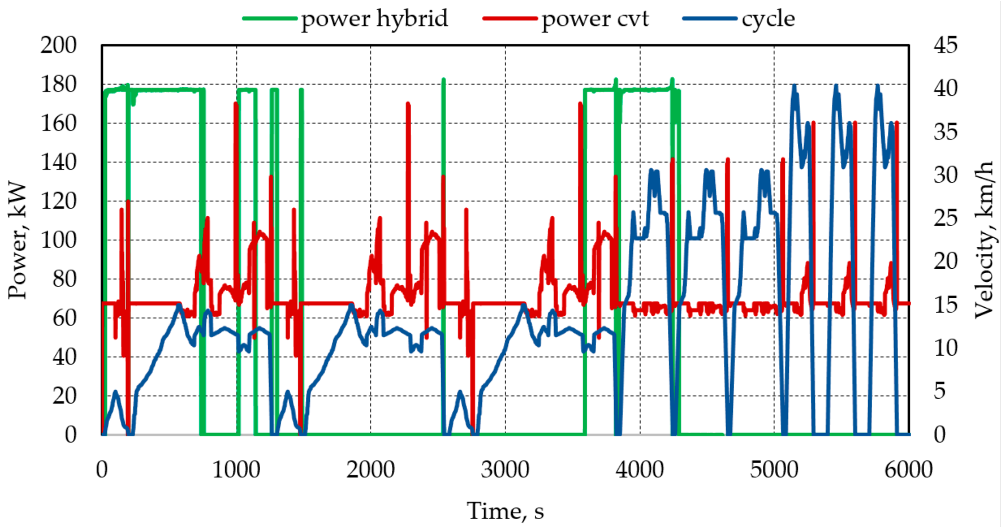


Figure 5. Power generated by the ICE during the EHOC.

The ICE of the hybrid vehicle kept working at optimal efficiency during the whole time of operation, unlike that of the CVT vehicle, which produced a roughly even amount of power during the cycle, with few power outbursts at acceleration points in part 1 of the cycle. At the beginning of part 1 of the EHOC, the hybrid vehicle produced around 2.5 times the power that was produced by the CVT vehicle. However, the greater power produced in the short term led to an operation time that was 3.5 times shorter. Moreover, this highly intensive energy production resulted in a better fuel-to-power ratio, as is depicted in Figure 6.

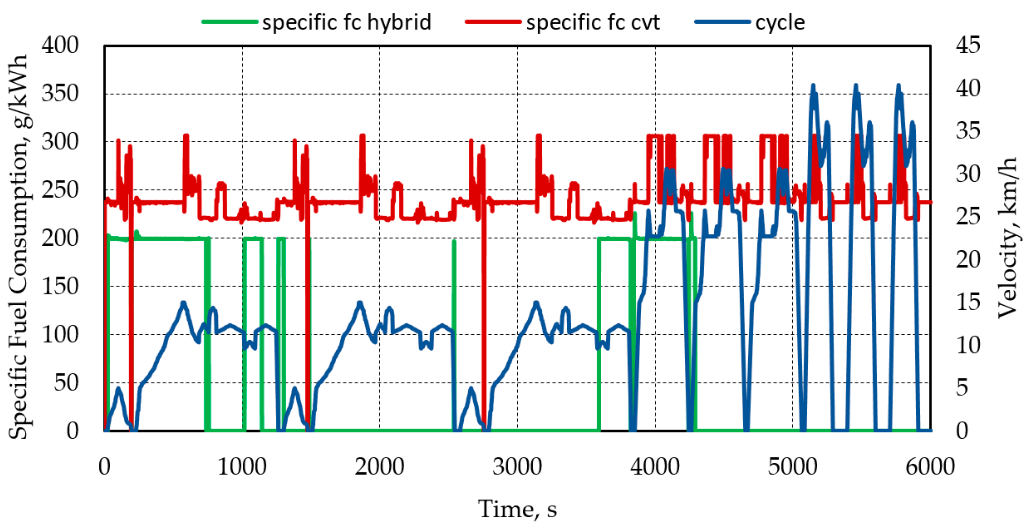


Figure 6. Specific fuel consumption during the EHOC.

During the investigated cycle, both vehicles indicated narrow overall specific fuel consumption distributions (Figure 6), and these corresponded to their power production (i.e., bursts of higher consumption for the CVT vehicle and power breaks for the hybrid vehicle) (Figure 7).

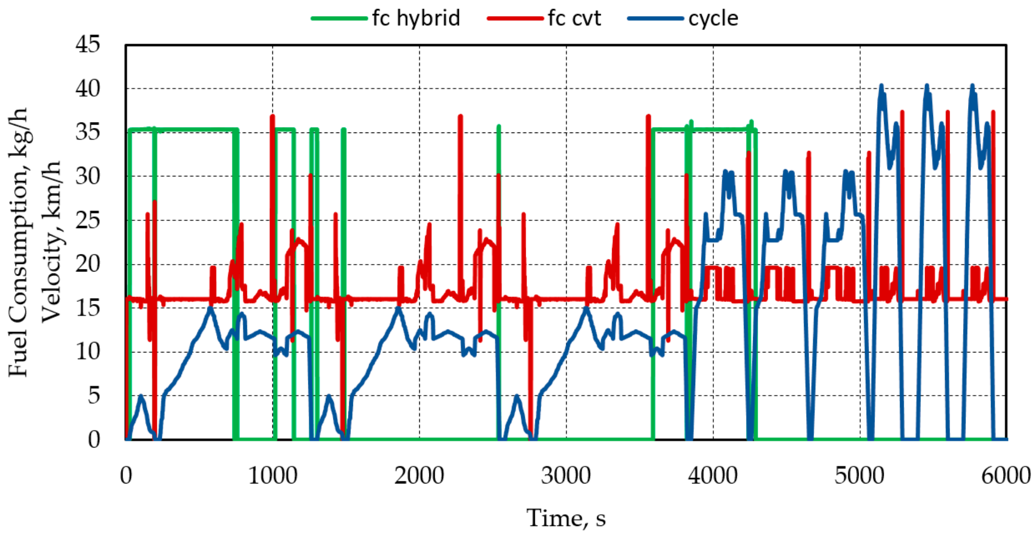


Figure 7. Fuel consumption by mass during the EHOC.

Due to the high power production of the hybrid vehicle, its fuel consumption by mass was also significantly higher (approximately 2.2 times) than that of the vehicle using the CVT. The ICE and CVT coupling exhibited the adaptability needed for major speed changes (e.g., when starting from the steady state and reaching the determined vehicle velocity). However, it did not adapt as well to lower speeds in relation to time changes. This property led to the overall higher fuel consumption of the CVT vehicle (Figure 8).

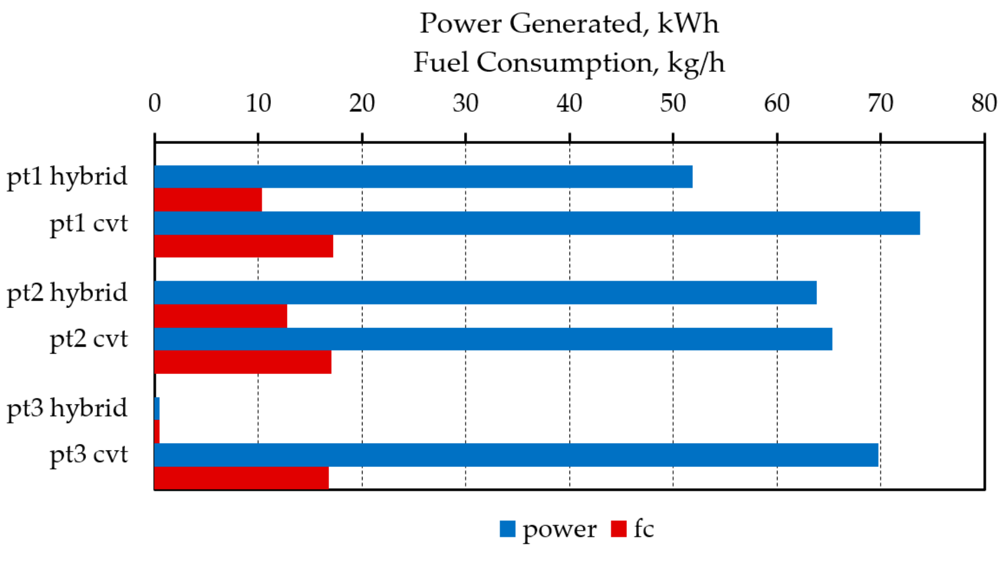


Figure 8. Power generation and fuel consumption throughout the EHOC.

Despite the fact that the hybrid vehicle used significantly more fuel in its generation mode, the efficiency of the working point of its ICE resulted in better overall fuel consumption than that obtained when using the CVT vehicle in the same operational cycle. In part 1 of the EHOC, the hybrid vehicle generated less power under the same work conditions, and this resulted in a higher overall vehicle efficiency than that obtained when using the CVT vehicle. The hybrid vehicle produced around 30% less power and used around 40% less fuel while performing the same task as no hybrid regeneration was available (Figure 9).

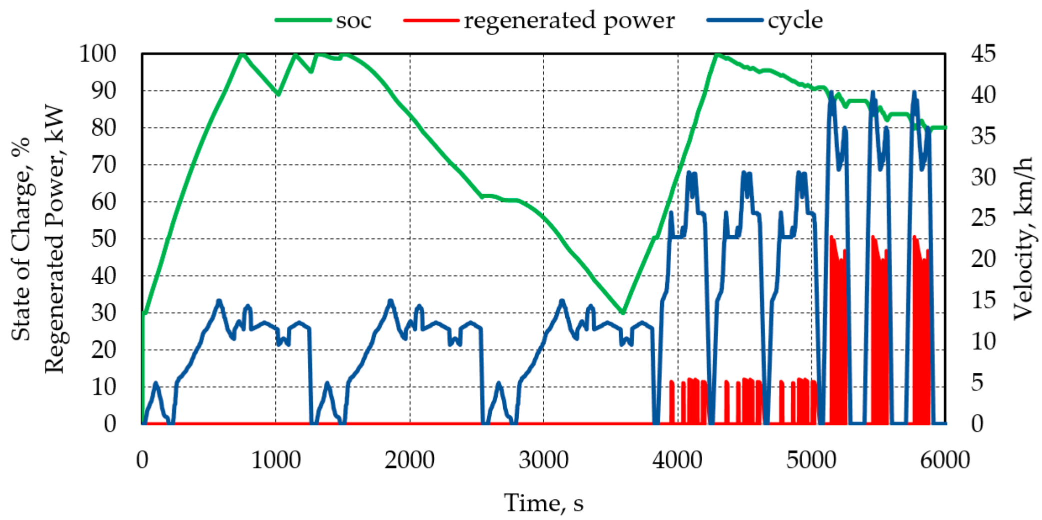


Figure 9. Hybrid vehicle's state of charge and regeneration.

In part 2 of the EHOC, which represented local transportation, there were no such differences between the power generation of the hybrid vehicle and that of the CVT vehicle (Figure 8). Nevertheless, the hybrid vehicle used less fuel; in this case, its regeneration ability contributed. Another point that is essential to note is that in part 3, which described transportation in traffic, the hybrid vehicle used the same amount of energy as it generated in part 2, thus significantly reducing the overall demand for power production.

Although the amount of power generated by the ICE in the hybrid vehicle was slightly smaller than that generated by the CVT vehicle, not all of it was used to complete the cycle (Figure 8). A part of that generated power was stored in a battery and used after it was fully charged. The use of the battery formed two generation phases: one in the beginning of the cycle, which was prolonged due to the high power consumption required for performing the task, and another that took place at the end of part 1 and extended into part 2 of the EHOC. The second charging phase was shorter than the first since the vehicle required less power in part 2 of the cycle. As a result, the use of the hybrid drive enabled the vehicle to finish the cycle and still maintain an energy reserve.

Figure 9 shows the power regeneration of the hybrid vehicle. In part 1 of the cycle, the regeneration was minor. In parts 2 and 3, the regeneration was more significant. The transportation velocities in the parts 2 and 3 (local transportation and transportation while driving in traffic) differed by about 10 km/h, yet the amount of regenerated power was more noticeable in the latter (Figure 10).

In part 2 of the cycle, only around 9% of the charged kilowatt-hours were gained from regeneration; the vast majority of the power was derived from the surplus power produced by the ICE and the alternator. However, since the battery was fully charged at the beginning of part 2 of the cycle, the ICE was not used any further in part 3. Therefore, all the energy that was charged was acquired from the regeneration of the electric motors. The difference between the energy recovered in part 2 and that recovered in part 3 was determined not only by the velocity differences during transportation, but also by the road characteristics; these allowed the vehicle to move more easily in part 3, giving much more inertia to this heavy machinery.

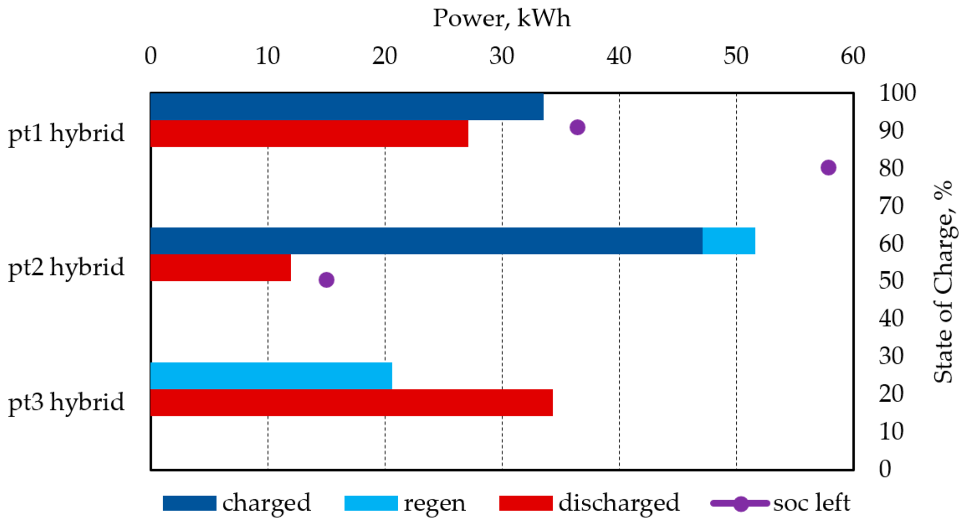


Figure 10. Battery power distribution over the EHOC.

The most efficient charging occurred during part 2 of the EHOC, when a relatively large amount of charge was gained in a relatively short time. In comparison, long charging periods took place in part 1 (Figure 9), but these periods were prolonged because the majority of the power generated during this part of the cycle was consumed in order to perform the cycle task (Figure 11). It is necessary to point out that the amount of discharged energy shown in Figure 6 is not the same as that shown in Figure 11. In Figure 10, the discharge refers to energy that was initially stored in the battery and later used when the ICE of the hybrid vehicle was not operating. In Figure 11, the overall energy consumed by the electric motors is noted, regardless of its origin. The power consumed by the vehicles was not proportional to the power generated. As is shown in Figure 8, during every part of the cycle, the power production of the CVT vehicle was higher than that of the hybrid vehicle, regardless of the different amounts. The hybrid vehicle generated less power but consumed more. However, it did this while maintaining lower fuel consumption (Figure 11).

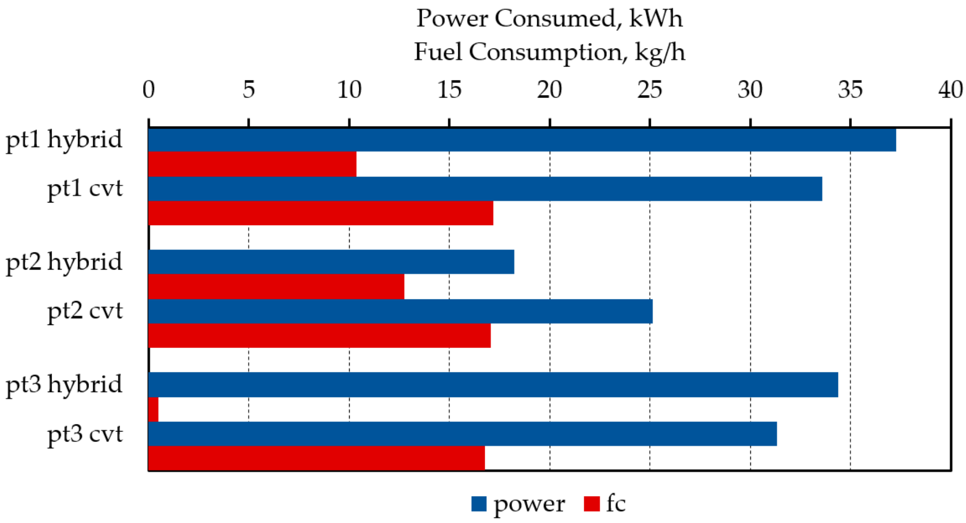


Figure 11. Power consumption and fuel consumption throughout the EHOC.

It can be stated that, compared with the vehicle using the CVT (which had a better transmission efficiency, though its ICE worked less efficiently), the losses of the hybrid vehicle were greater when it used only its electric motors as a transmission. In general, using less initial power led to an overall higher vehicle efficiency, and, at the end of the cycle, the hybrid vehicle had the advantage of stored excess power (Figures 9 and 10). At the end of the EHOC, the hybrid vehicle had a battery charge of around 80%, enough for another full EHOC.

Figure 12 shows the power consumed during each part of the extended cycle and the amount of battery charge required to cover that power demand. As Figures 9 and 12 illustrate, in part 1 of the EHOC, the battery was incapable of supplying enough energy for the entire work duration. It surpassed 100% of its capacity, even when taking the 30% reserve power into account. However, in parts 2 and 3, it took only a fraction of the battery capacity to run the vehicle for the entire duration if it started with a full charge.

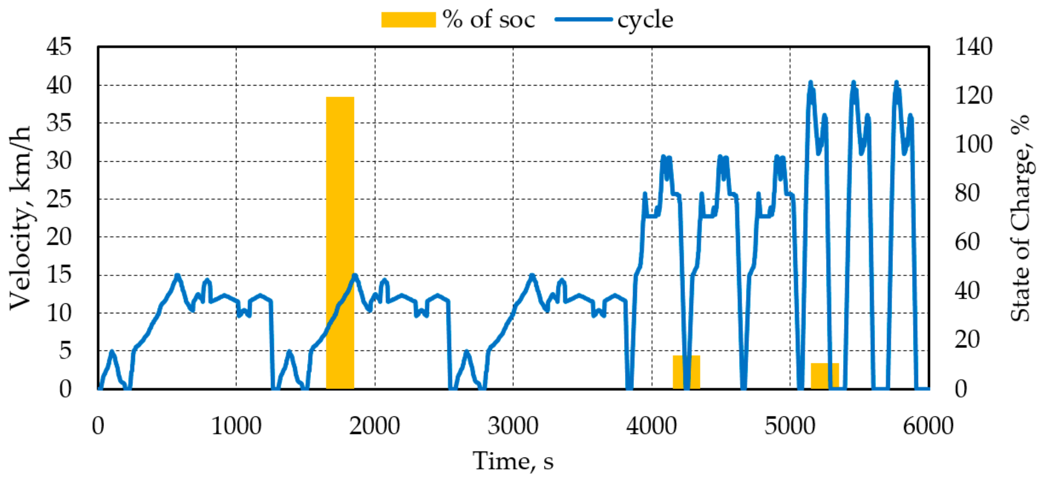


Figure 12. Power consumption and state of charge.

4. Conclusions

Introducing the HOC enabled a comparison of the benefits of a hybrid vehicle with those of a conventional one. The results showed that, when completing the same task, having a steady work point for an ICE in a hybrid vehicle uses up to 45% less power overall than that required by a conventional CVT vehicle, which can also work in relatively steady cycles, but does not have the ability to store and use surplus energy. Using the stored energy and enabling the ICE of a hybrid to work in intervals saved up to 55% of the fuel under the tested cycle conditions.

The direct power-to-fuel efficiency ratio of the hybrid drive was 18% higher than that of the CVT vehicle. Despite this, at the end of the cycle, the battery charge of the hybrid vehicle was 80%, enough to provide 23 kWh of additional power, thus raising the fuel efficiency to nearly 32% for these cycle conditions. However, a different workload and more demanding soil conditions might affect the overall efficiency of hybrid heavy-duty off-road vehicles by forcing the ICE to provide more power, leading to lower fuel consumption rates if the battery charge is sufficient to meet the power demand. However, as previous research by the authors has shown, a hybrid drive can be both less and more efficient on rough terrain, and with an initial plug-in charge of 100% and a power split in use, possible drops in the efficiency of the ICE can be avoided. Additionally, a hybrid drive would still be the best option for use in transportation.

The results of this research are yet to be confirmed with experimental data; additional tests of the series-hybrid drive's efficiency under rougher work conditions and with a significant workload are planned. To date, there have been several confirmations of the beneficial use of power-split hybrid drives in agricultural and forestry vehicles. The hybrid drive concept proposed in this study can be easily used to modify vehicles that are currently in use. With its reasonable method for evaluating high-demand hybrid vehicles, this work confirms the possibility of achieving greener agriculture using electrification.

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