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Electrification of agricultural tractors

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Summary

Electric powertrains have been successfully used in passenger and heavy vehicles as well as in machinery applications. Mechanical and hydraulic power systems have been widely used in agricultural vehicles and machines despite the fact that the electric systems can increase energy efficiency, improve controllability, and reduce emissions. Therefore, more research needs to be done for better understanding the opportunities and limitations of using electric power in agricultural tractors and implements. This research focuses on analysing the benefits of using electrified powertrains in agricultural tractors. The paper presents a comparison analysis between conventional, hybrid and electric powertrain technologies. Agricultural tractor simulation models were developed for the different powertrain technologies. Simulations were carried out in dedicated test cycles including tillage operation and road driving cycle. According to the simulation results, powertrain hybridization could reduce energy consumption up to 20% whereas a battery powered electric tractor could save energy more than 60%.

Keywords: Electrification; agricultural tractor; hybrid powertrain, modelling; simulation

1 Introduction

The demand for higher productivity in agriculture and increasing consumption of food products has created the need for new technological solutions for agricultural machinery employed in different sections of agricultural production. Electrification of vehicles and non-road mobile machinery (NRMM) has been steadily increasing during the past two decades [1]. The recent developments of energy efficient and powerful lithium-ion battery technology and power electronics have finally enabled large-scale breakthrough of hybrid and electric powertrains [2]. The passenger car industry has been the forerunner in powertrain hybridization and electrification mostly due to the large volume production, which enables to reduce the costs of expensive electronic and electric components as well as the costs of the alternative powertrain designs.

Among heavy vehicles, a lot of research and development has been done for hybridization and electrification of city buses [3]. Electric and hybrid powertrains are well suitable for city bus driving because it usually contains many acceleration and deceleration phases. By using electricity as the power carrier in the powertrain of city buses, the powertrain efficiency can be improved and the braking energy recovered into electrical energy storage [4]. Agricultural vehicles are often specialized applications and their production volumes are much lower in comparison to on-road vehicles [5]. This is also the case for heavy mobile machines such as construction, forest and mining machines [1].

Most of the vehicles and machines have an internal combustion engine as primary power and energy source. Diesel engines are the most popular among heavy vehicles, NRMM and agricultural tractors. Over the years, emission regulations have been tightening and fossil fuels are getting more expensive. This have generated the need to develop more energy efficient and less pollutant technologies for vehicles, machinery, and agricultural vehicles [1]. However, it seems that even higher energy efficiency is not strong enough benefit for the electrification but there needs to be additional advantages for successful electrification among agricultural vehicles and machines. There are many advantages of using electricity as the power carrier in traction powertrains and power delivery for implements [6]. For example, by replacing mechanical transmissions with electric motors, the number of mechanical gears and hydraulic motors can be reduced in continuously variable transmission (CVT) [7]. The usage of electric powertrains can offer significant advantages compared to the traditional systems due to their superior efficiency and excellent controllability. Electric powertrains are already widely used solutions in some NRMM applications such as construction machinery [8] and large mining machinery [9] [10]. The electrification of agricultural tractors has not been widely investigated, only a few scientific research studies have been published e.g. [11] [12], therefore it is important to research the potential of electric powertrains in agricultural vehicles and machines.

2 Agricultural tractors and electrification

2.1 Description of agricultural tractors

An agricultural tractor is a versatile mobile machine in modern farming and tillage operations. Figure 1 presents typical modern, agricultural tractors. Most of the tillage operations are carried out by tractors with implements or self-propelled agricultural machines such as forage harvesters and combine harvesters. In agricultural tractors, the driving power is transferred through a specific transmission to the tires and the working power is delivered via the power take-off (PTO) to the implements. Because of the limited speed range of the diesel engines, the tractor transmission needs to have multiple gear reductions from engine to the wheels in order to generate adequately high torque and power at low driving speeds. Historically, most of the transmissions operated mechanically but nowadays CVTs are more often used for better speed control especially in heavy field operations [13]. There are many different types of CVTs developed for agricultural tractors and most of them rely on hydraulic power transfer [14]. It is a practical way for step-less gearbox but inherently increases the power losses and requires a substantial amount of design development work. CVTs tend to be quite expensive components especially for the higher power class agricultural tractors [13]. Powertrain electrification offers much simpler powertrain structure and less gear reductions due to the wide speed range and torque characteristics of electric motors [15].

Figure 1: Modern agricultural tractors.

2.2 Powertrain electrification

The last 70 years, the most common power source for agricultural tractors has been a diesel engine and the basic principles of tractor technology have not changed significantly. Major technological developments have been done for transmissions and control systems with electronics. Many of the modern CVTs are based on a power split by mechanical and hydraulic power paths. The hydraulic part could be replaced by electrical power path representing a hybrid electric powertrain, which is becoming more and more common in passenger vehicles [16]. There are many benefits related to energy savings in powertrain hybridization for on-road vehicles but probably less for off-road and agricultural vehicles. For agricultural vehicles, a hybrid electric powertrain would not reduce significantly energy consumption even if electrical components have typically high efficiency. However, a hybrid electric powertrain would enable pure electric driving, better driving control, less complex transmission, electric PTO, and more freedom for powertrain layout depending on the powertrain configuration. Full electric powertrains powered by a battery have a significant potential to reduce energy consumption also in tractors but the limited battery capacity limits the operation time. Electric motors that are suitable for vehicular applications have a wide speed range that simplifies the transmission, can reduce weight and, provide cost savings. Electric power transfer allows exceptional freedoms for power delivery, for example, the driving power for front axle can be produced by a separate electric motor when no mechanical link would be needed from transmission. The transmission is one of the most expensive components of the modern agricultural tractor. Depending on the transmission technology, it may account from 20% up to 30% of the tractor production costs [17]. A relatively large amount of resources are being used for the product development and manufacturing of transmissions.

Various types of electric powertrain architectures can be utilized in mobile machinery but the basic principles and components of all architectures are somewhat the same. The key components are the energy storage, power converters, and electric machines [17]. Diesel-electric powertrains does not have an energy storage but the powertrain is electric. Hybrid electric powertrains have always one or multiple energy storages. Most common energy storage is an electro-chemical battery and nowadays lithium-based batteries are the most typical solution [18]. Ultracapacitors are also suitable as an energy storage for example in machines that have high power peaks in their operation and do not need large energy buffer [8]. The most common types of electric motors are induction and permanent magnet motors. In an induction motor, a magnetic field is generated in the rotor, induced by the rotating magnetic field of the stator. The design of the induction motor is simple and the motor control is relatively easy. One inverter can control simultaneously multiple motors [16]. In permanent magnet electric motors, the rotor produces a magnetic field and alternating current causes a rotating magnetic field in the stator. As the stator magnet field must rotate at the same pace with the rotor, the motor control can be demanding. Permanent magnet motors have high efficiency and a relatively high torque density. However, these motors are expensive whereas induction motors are inexpensive and well available [17]. For the time being, the limited battery energy capacity and their high costs are obstacles to the wider implementation of electric powertrain technologies. Figure 2 shows an illustration about the traction battery assembly from the cell to the system level. Often in vehicular applications, the energy density of the battery system is much lower than in the cell level due to the packing material and auxiliary systems such as thermal management.

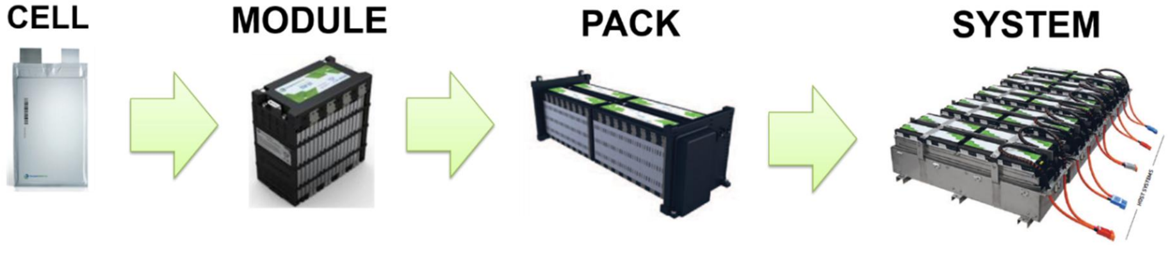

Figure 2: A system integration for a traction battery.

2.3 Electrical systems

The electrical systems in agricultural tractors have been based almost exclusively on the 12 Volt system. Therefore, electricity is used only on relatively low power functions such as lighting, controls, and engine starter motor [11]. The increase in using electrical power in variety of devices has generated interest to move to higher voltages. So far, higher voltages, such as 24 V or 48 V, have been used only on single tractor models. In these cases, the continuous power of the electrical system is limited to about one kilowatt for 24 V system and less than 10 kW for 48 V system. For powertrains, much higher voltage level is required to transfer the required power to the wheels and PTO. The developed research tractors and prototypes have typically DC voltage level from 450 V to 850 V [13].

In modern tractors, the auxiliary devices such as engine cooling fan, power steering, and cabin air conditioning may require more than 10 kilowatts of power. The auxiliary devices are traditionally powered by belt from engine so that their operating speed depends on the speed of the engine. With electrification, the power of the auxiliary devices can be freely adjusted allowing for considerable fuel savings especially when tractor operation includes idling and low power operation. The electrification of auxiliaries is a natural, and sometimes necessary, part of the tractor electrification.

2.4 Electrification of implements

The power transfer from the tractor to the implements has traditionally been done via a mechanical PTO shaft or hydraulic connections. A mechanical power transfer is often energy efficient way of operate implement but is limited by the operating speed of PTO shaft and it does not offer any practical power control. Hydraulic power is more often used in implements due to multiple available power outlets and better controllability than mechanical systems. Electrical power is comparable in its benefits to hydraulic power but even better because it would need fewer connections, better controllability of the implement, and higher efficiency. Furthermore, better operating comfort, for example in the form of easier connectivity and avoidance of hydraulic oil leaks, is considered an essential advantage. The electrification of implements is more or less dictated by the electric system of the tractor. Because agricultural tractors are used in wide variety of field operations with implements, a flexible and safe electrical power connection is required for the tractor. Depending on the electrical architecture (commonly called as AC or DC architectures), the electricity is transferred to the implement by either using AC or DC current as presented in Figure 3. In the DC architecture, the implement is connected in a simple way to directly on the tractor DC-link and the control inverters of electric drives are placed on the implement.

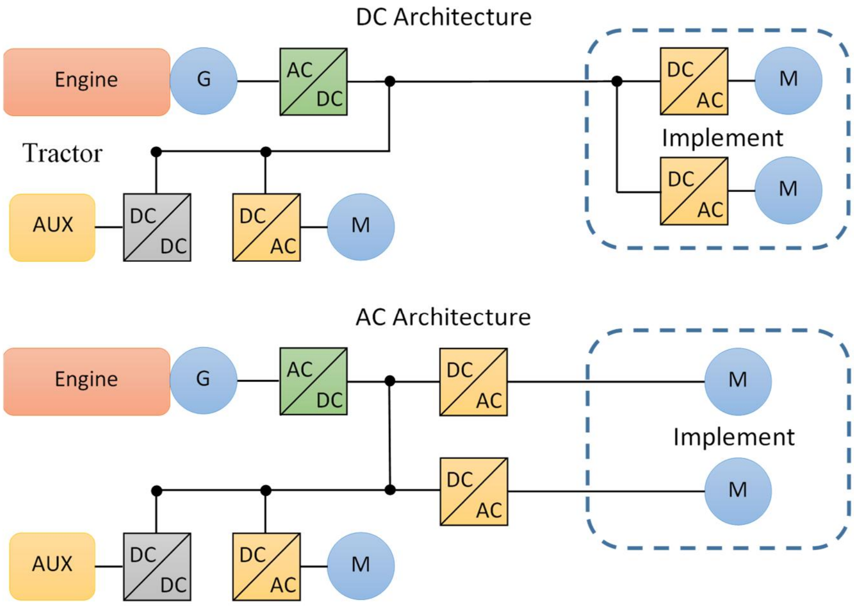

Figure 3: DC and AC electric system architectures for agricultural tractors.

The standardized ISOBUS communication protocol (currently used in DC architecture) is sufficient for data transfer between the implement and the tractor. A wide variety of electric motors can be used in the implements and the compatibility between the inverter and the motor can be optimized. In AC architecture, the control inverters for the electric motors in the implement are installed in the tractor. The inverters often need the rotor position information in real-time and ISOBUS is too slow to transmit the information needed therefore a faster data bus is required between the tractor and the implement. The advantage of AC architecture is the easier cooling of power electronics as the components are placed on the tractor. In the DC architecture, the division of responsibilities between the tractor and implement manufacturer is clear.

3 Powertrain modelling

In this research, simulation models of agricultural tractors were developed in the Autonomie software. Different types of powertrains were modelled including conventional, parallel hybrid electric, and battery electric. The conventional tractor model represent a typical diesel powered tractor with a dual-clutch transmission. In the parallel hybrid tractor, the transmission has mechanical and electric power paths and it uses an electrical energy storage to power the electric motor. In this case, a lithium-ion battery model will be used as the energy storage. The battery electric tractor has a full electric powertrain with a three-speed gearbox. The primary use of the models is to predict the tractor and transmission performance in different tillage and driving operations. The conventional and hybrid powertrain topologies were presented and described in the previous research paper of the author [19]. Figure 4 presents the powertrain structures in the Autonomie software [20].

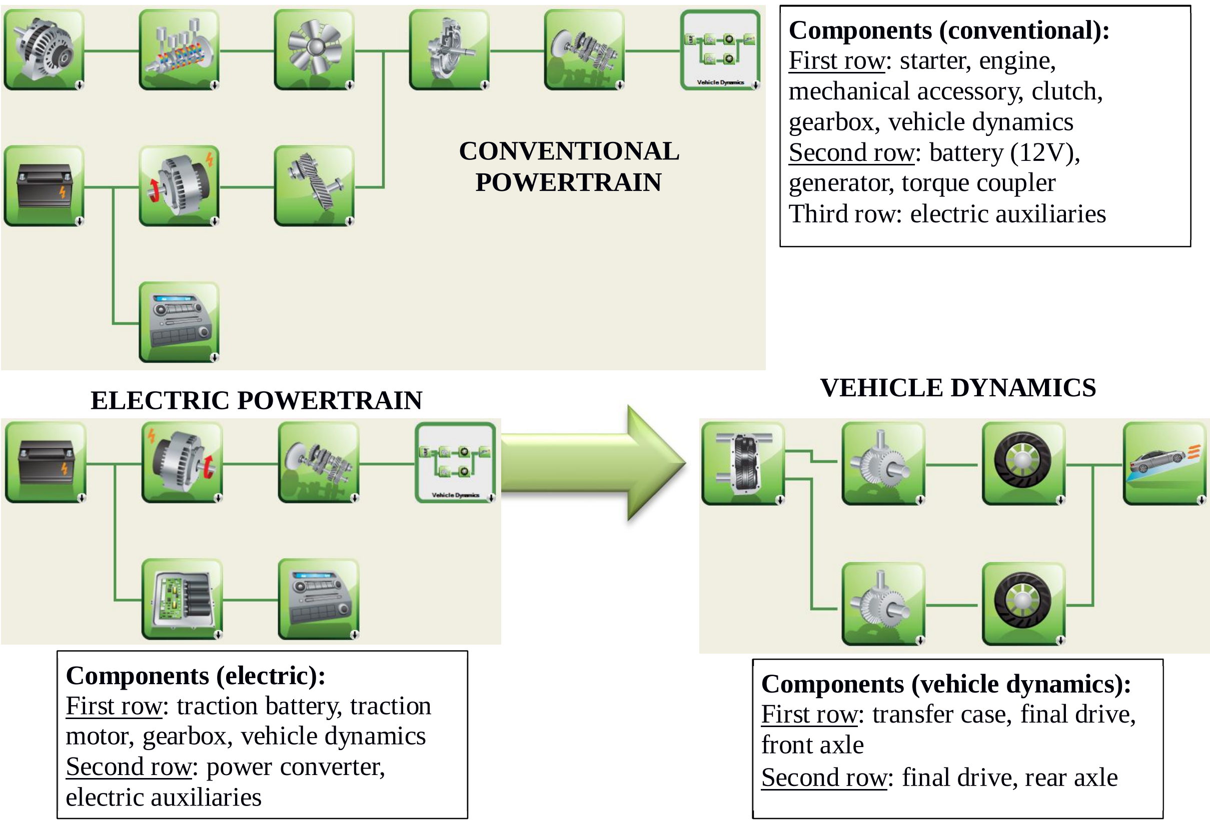

Figure 4: Powertrain layouts of the conventional and battery electric tractors in the Autonomie.

The simulation models correspond to typical agricultural tractors of power range around 200 kW. The models were parameterized by using the Autonomie libraries that provide component initialization data for a wide range of components used in light and heavy-duty vehicles. Table 1 presents the general technical specifications of the tractor models and Table 2 the specifications of the hybrid and electric powertrains.

Table 1. General technical specifications of tractor models.

Component	Description
Diesel engine	maximum power 225 kW, maximum torque 924 Nm
Transmission	8-speed dual clutch transmission (DCT) with 3 ranges
Rear axle	bevel set ratio of 3.28:1 and planetary gear ratio of 6:1
Front axle	bevel set ratio of 2.48:1 and planetary gear ratio of 6:1
Tires	front: 540/65R30, rear: 650/65R42
Weights	kerb weight: 8600 kg, payload: 3900 kg

Table 2. Specifications of the hybrid and electric transmissions.

Component	Parallel hybrid	Electric
Diesel engine	maximum power 175 kW, maximum torque 719 Nm	---
Transmission	8-speed (DCT) with 2 ranges	3-speed gearbox
Battery configuration	Saft 6 Ah cell, 2 packs in parallel, 180 cells in series in a pack, 648 V, 7.8 kWh	33 Ah cell, four packs in parallel, 192 cells in series in a pack, 720 V, 95 kWh
Electric motor	max power 100 kW, max torque 542 Nm, max speed 4400 rpm	max power 225 kW, max torque 611 Nm, max speed 8000 rpm

The developed tractor models were simulated in dedicated test cycles that correspond a tillage operation and road cycle driving. The tillage cycle consists of 12 consecutive phases of work and stops. The workload is 25 kN on average and target speed is 8 km/h. The road cycle represent a speed profile on a road route with elevation. The road cycle was simulated with a trailer having a load of 15000 kg.

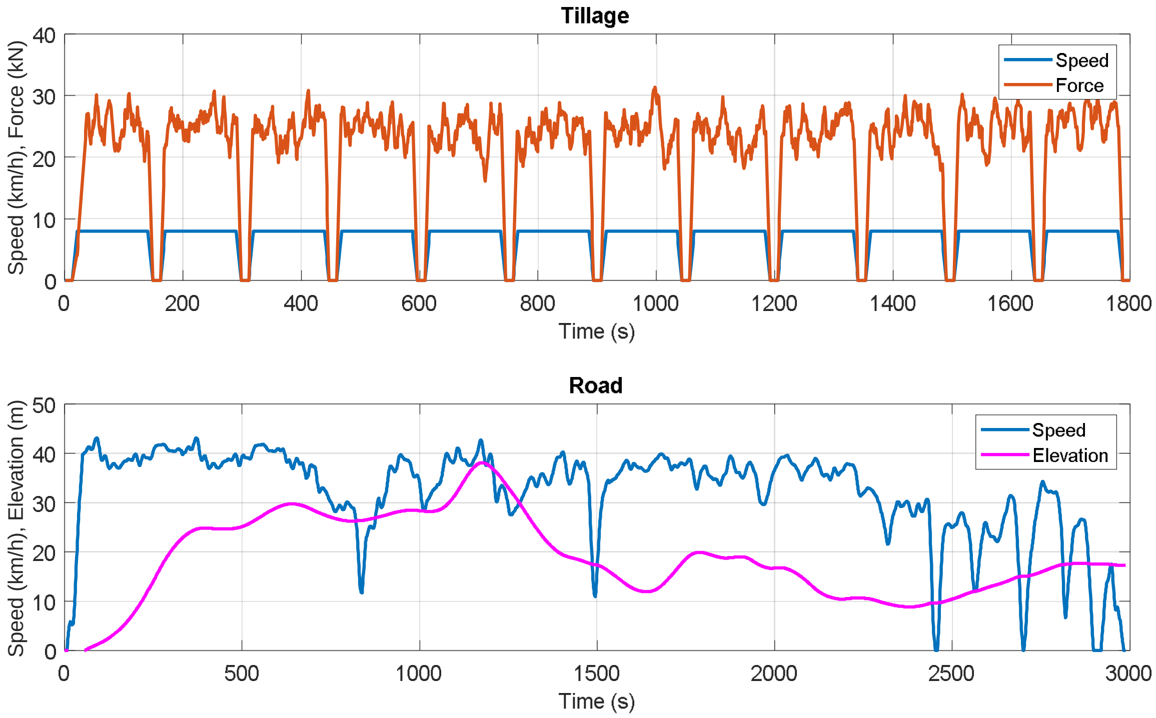

Figure 5: Tillage and road test cycles.

4 Simulation results and analysis

4.1 Tillage operation

The simulation results of the tractor models were analysed thoroughly in order to verify correct operation of the models. Figure 6 shows the speed profiles and gear number of the transmission in the tillage cycle. All the tractors have the same driver model but it can be seen from the results that the full electric powertrain can response faster to load changes. The electric motor in the parallel hybrid powertrain can rapidly provide additional torque for driving which improves the speed control. Overall, the dual-clutch transmission in the conventional and hybrid tractors works smoothly and provides a good speed control for tillage operations.

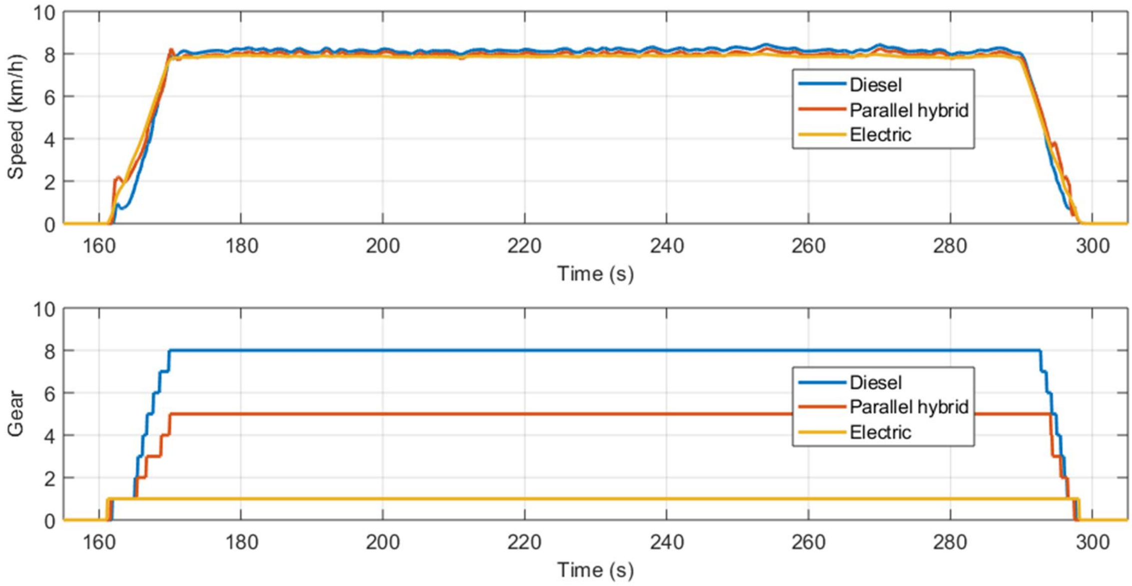

Figure 6: Speed and gear number on the tillage cycle.

The engine operating points in the tillage cycle are presented for the conventional and parallel hybrid tractors in Figure 7. In the same figure, the operating points of the traction motor are shown for the electric tractor. The results shown that the engine operation is well adapted to the tillage operation also for the conventional diesel tractor. The parallel hybrid takes advantage of the electric motor and can adjust the engine operation point more optimal way being close to the best efficiency area most of the time. The electric tractor does not to need change gears during tillage operation, which makes the speed control easier due to the wide speed range of the electric motor.

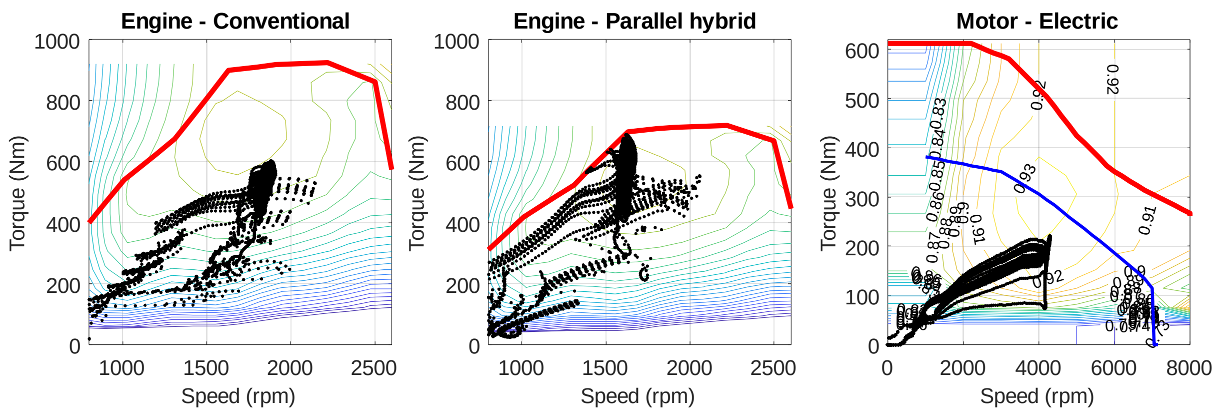

Figure 7: Engine and motor operation.

4.2 Energy consumption

The energy losses of the powertrain components were calculated for both the tillage and road cycles. The total energy consumption was calculated for one-hour period of work to be able to compare the cycle results to each other. The powertrain losses were divided into five separate groups of components as follows:

- Power sources (PS): engine, battery and traction motor
- Auxiliary components (AUX): engine fan, air conditioning, and power steering, etc.
- Transmission (TX): clutch, gearbox, transfer case, final drive
- Tires (TR): wheels and tire losses
- Work (WK): energy required by the work e.g. load force of an implement

Figures 8 and 9 shows the breakdown of energy losses in the tillage and road cycle respectively. According to the results, the energy savings of powertrain hybridization is from 8% to 20% being higher on the road cycle. The hybrid system can benefit more from the higher speed variation in the road cycle. The battery electric tractor illustrates a significant energy saving potential in both cycles being around 60% when compared to the conventional tractor.

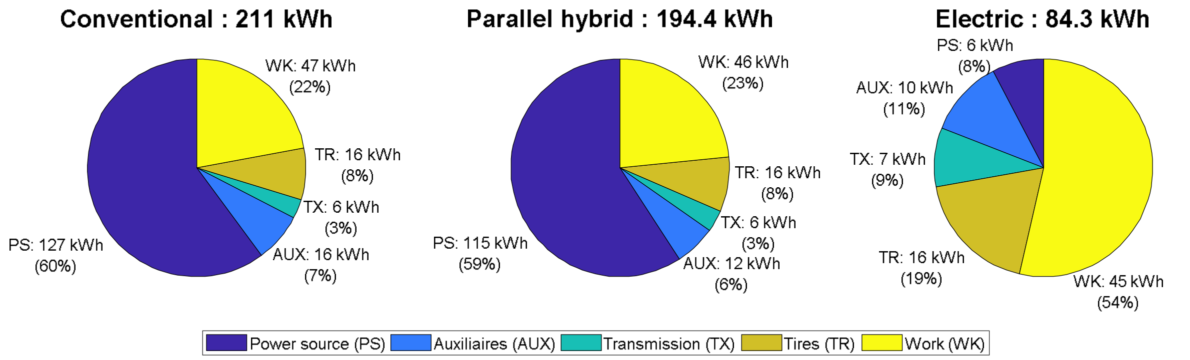

Figure 8: Energy losses in the tillage cycle.

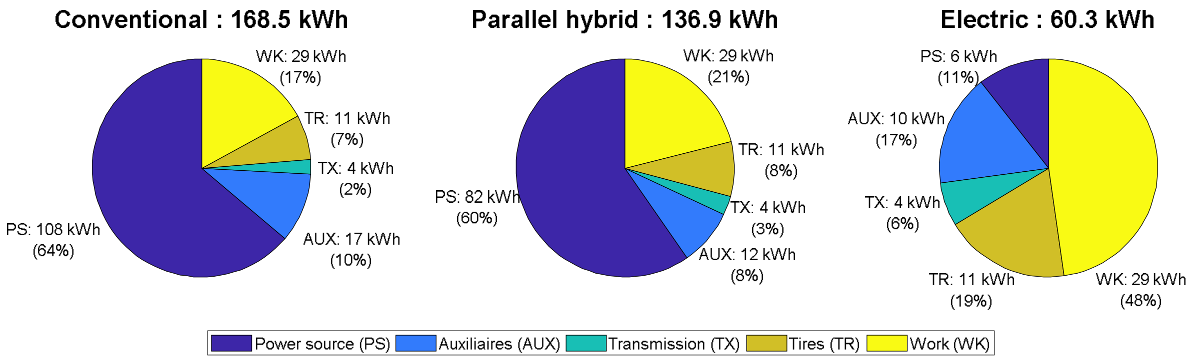

Figure 9: Energy losses in the road cycle.

The driving on the road provides more potential for energy savings for the hybrid system due to the speed variations and changes in road load. Figure 10 shows the cumulative energy consumption of the modelled tractors on the road cycle. It can be noticed that the energy savings for parallel hybrid and electric tractor cumulate steadily during the cycle.

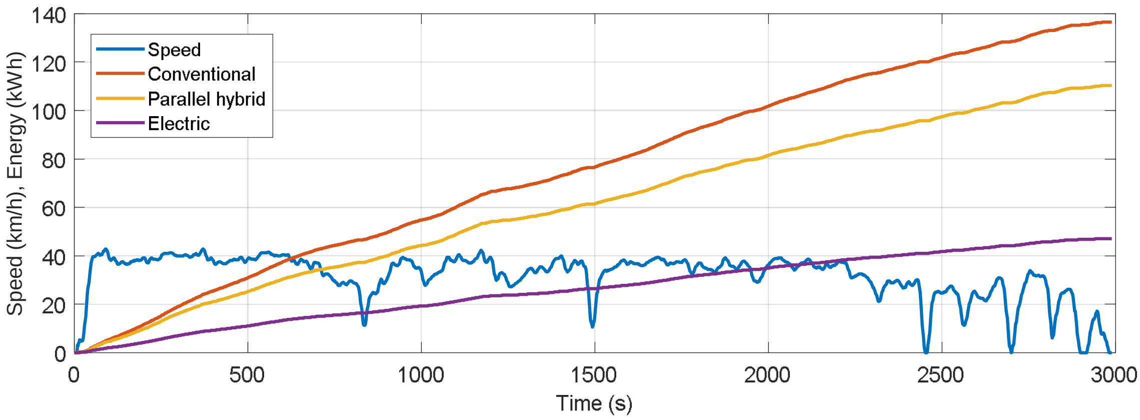

Figure 10: Cumulative energy consumption on the road cycle.

5 Discussion and conclusions

This paper presents an overview of powertrain electrification in agricultural tractors. The key elements, benefits and challenges of electrification technologies were analysed. The benefits of electric powertrains are well known for passenger vehicles and heavy vehicles. Agricultural tractors and vehicles have often dedicated transmissions that nowadays offer continuously variable speed control from the engine to wheels. Replacing the advanced CVTs with electrified systems requires more research and development work. Electric power is still rarely used for traction in agricultural vehicles but recent technological development provides affordable solutions even for tractors. Many power functions in agricultural tractors and implements are based on using hydraulic systems, which usually have good power to weight ratio with reasonable costs. Some of these hydraulic systems could be replaced by electric system for better control and higher energy efficiency. Agricultural tractors have been under tremendous technological development during the last decades. The modern CVTs in tractors are advanced and expensive technology. Electricity have not yet been widely implemented in tractors but there are important development paths in which electric powertrains and electric power are offering competitive solutions.

This research also presented a numerical modelling approach for the assessment of different powertrain technologies in terms of energy efficiency and performance. Modelling and virtual simulation are important tools especially when designing complex systems having different technologies. Especially when comparing new technologies, optimizing powertrain designs, and developing control systems, the virtual engineering tools are indispensable. This research will be continued by developing a dedicated virtual simulation approach for agricultural vehicles. The focus will be in the tire-soil interaction modelling which is important in order to understand the traction requirements in different tillage operations.

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