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Simulation of Alternative Powertrains in Agricultural Tractors

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Executive Summary

Simulation models were developed for evaluating alternative powertrains in agricultural tractors by using Autonomie vehicle simulation software. Conventional, parallel hybrid, fuel cell electric, and battery electric powertrains were modeled and simulated in a tillage operation and in a road cycle with a trailer. The alternative powertrains were configured to have at least the same tractive performance than the conventional, diesel powered tractor model. The simulation results show that the potential of the parallel hybrid powertrain to improve energy efficiency depends heavily on the operating cycle and conditions. The fuel cell hybrid and battery electric powertrains have higher potential to reduce energy consumption and emissions but still have inherent technical challenges for practical operation. The battery powered electric tractor would require much higher energy density from the energy storage to have a comparable operational performance in comparison to other powertrains. The fuel cell hybrid tractor could already provide quite adequate operating performance but the availability of hydrogen and refueling infrastructure would be challenging to resolve in the farming context.

Keywords: energy consumption, modeling, off-road, powertrain, simulation.

1 Introduction

Agricultural tractors have not been the most interesting application for powertrain electrification. The uncertainties about the future developments regarding to fossil fuels, environmental legislation, and emission standards, have increased the interest for the development of full electric and fuel cell hybrid powertrain solutions [1]. Therefore, it is reasonable to believe that the powertrain electrification will be one of the major technology trends also for agricultural tractors in the near future [2-4]. Recently, some of the tractor manufacturers have introduced new concepts for alternative powertrains. Some of the manufacturers are starting to offer even production versions of partly electrified powertrains but large-scale electrification has still quite many challenges to overcome. Powertrain electrification has been spread increasingly from passenger cars to utility vehicles and today even to heavy on-road vehicles [5]. There are also increasing activity for off-road machinery, especially now when the energy costs have increased in an exceptionally high level and there are many uncertainties in energy production worldwide. The high technology costs have been one of the major barriers in the past especially with heavy vehicles [6, 7].

Electrification of farm vehicles has started from the small-sized machines, for example, telehandlers and small loaders are having electrified version already for purchase [8, 9]. Over the years, research studies have been carried out for estimating the benefits and feasibility of hybrid electric powertrains in tractors [10-12]. Considering the off-road vehicles and machinery in general, agricultural tractors differ from the other machinery because they are often used for various purposes and many different types of field operations. Therefore, it is important to develop methods that provide the tools for evaluating the benefits of powertrain electrification of agricultural tractors. Vehicle modeling and simulation methods are practical and rather fast way of analyzing and comparing different powertrain solutions. In difference to many other vehicles, agricultural tractors are used in different types of field surfaces and in different conditions which creates specific challenges for modeling. Simulating reliably and accurately tire soil interaction would need high-fidelity models by using e.g FEM (Finite Element Method) or DEM (Discrete Element Method) based models that would need labourious development work and require significant amount of computational capacity [13]. In addition, acquiring reliable validation data for high-fidelity tire soil interaction models from field operations could be rather challenging. For effectively compare and evaluate the performance of alternative powertrains, less computationally intensive models are typically used such as numerical simulation.

This research will present a numerical modeling and simulation approach for evaluating alternative powertrains in agricultural tractors by using Autonomie vehicle simulation software. Off-road vehicles and machinery are typically simulated different way than on-road vehicles because they usually do repetitive tasks and do not have a traditional speed profile to follow. Instead, agricultural tractors are simulated distance-based by giving a target speed based on the distance travelled. Also, as these types of machines often do heavy work, a resistance force from implements has to be integrated in the model for example for simulating agricultural field work such as ploughing or harrowing. Naturally, a typical work is field cultivation which can be passive draft force or active by using the power take-off (PTO) or hydraulic power in an implement. For evaluating alternative powertrains in agricultural tractors, numerical modeling and simulation provides an effective approach to generate different simulation cases, compare component sizing and then evaluate the benefits in several use cases.

In this research, conventional, hybrid electric, fuel cell hybrid, and battery electric powertrains were modeled and simulated in dedicated operating cycles. The powertrain models are parametrized based on the performance of a conventional tractor having a diesel engine and dual clutch transmission. The operating cycles were generated based on field measurements (Figure 1) carried out in the Viikki Research Farm of the University of Helsinki, Finland. According to the simulation results, the benefits of hybridization and electrification are evaluated as well as the operating performance.

Figure 1: Field measurement with a tractor and chisel plow.

2 Material and methods

2.1 Simulation model development

Autonomie software was used for the model development and running the simulations in multiple cycles. The software has been developed by the Argonne National Laboratory (ANL) to be used as a vehicle system simulation tool for assessing the energy consumption, performance, and cost of advanced vehicle powertrain technologies in various types of vehicles [14]. Autonomie was originally designed for on-road vehicle simulations therefore implementing off-road simulation models with distance-based cycles required some modifications of the vehicle control systems and parameters. Otherwise, the software is well suitable for off-road vehicle simulation as long as a representative operating cycle can be generated. The first versions of the tractor models with time-based simulation approach were developed in the previous research, which focused on the electrification of agricultural tractors [4]. The previously developed simulation models were updated by changing them to suitable for distance-based cycle simulations. The modeled powertrain options include diesel powered conventional, diesel parallel hybrid electric, fuel cell hybrid, and battery electric powertrains. The conventional tractor and parallel hybrid electric tractor model have a diesel engine as a power source and a dual-clutch transmission. The parallel hybrid transmission has a mechanical gearbox with electric power path, and it uses a battery pack as an electrical energy storage. The fuel cell hybrid and electric tractors have a full electric powertrain consisting of a battery, electric drive motor and three-speed gearbox. The fuel cell hybrid model has a fuel cell stack as a primary power source and small battery pack for power load levelling. The electric tractor has a large energy type battery pack as an energy storage. A lithium-ion battery model was used as the energy storage in all electrified simulation models. Figure 2 presents the powertrain layouts of the different powertrains in the Autonomie software. The vehicle dynamics block is illustrated in Figure 3 and includes a transfer case, front and rear final drives, wheels, and chassis model. The transfer case splits the driving power between the front and rear axle.

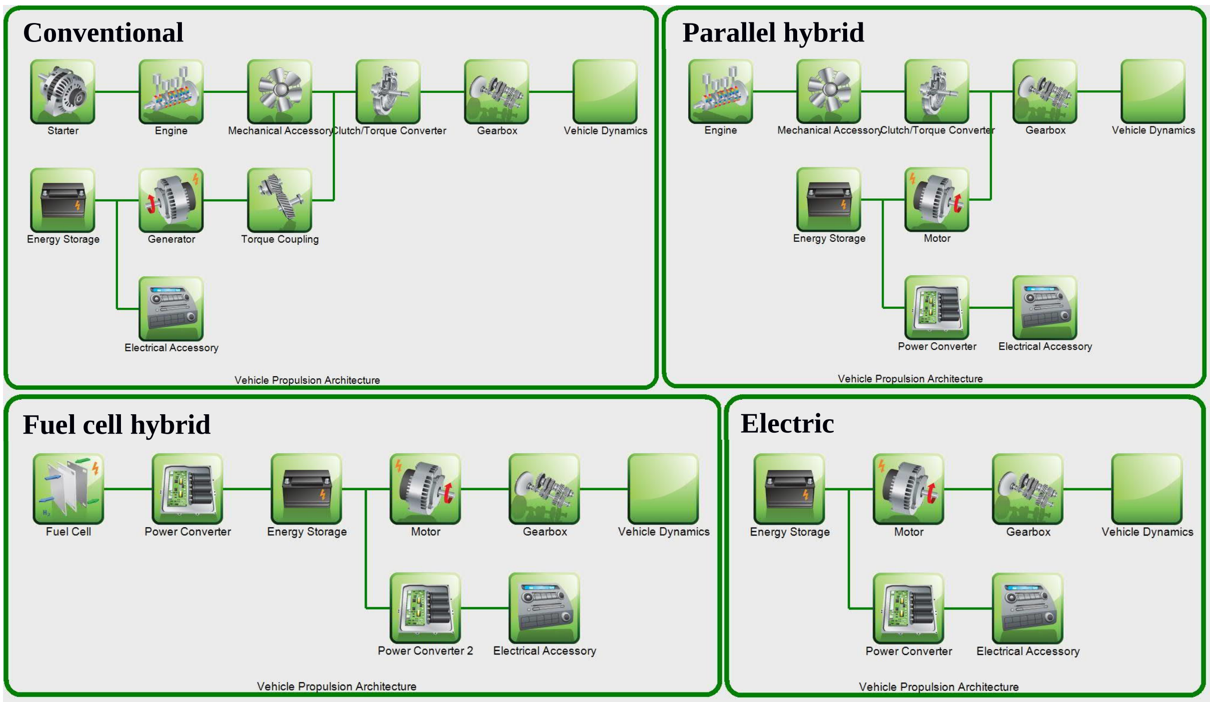

Figure 2: Powertrain layouts of the modelled tractors in the Autonomie.

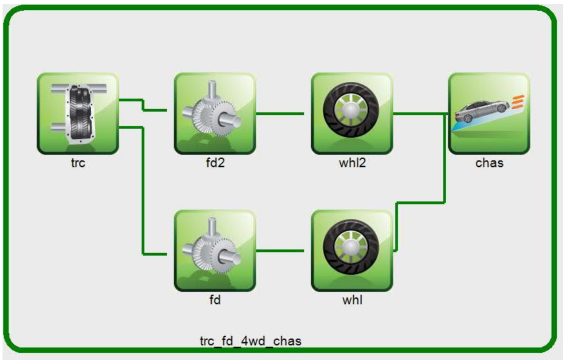

Figure 3: Vehicle dynamics block layout for tractors.

2.2 Model parameters

The baseline conventional simulation model corresponds to a large-size agricultural tractor with the rated power of 225 kW. The tractor models were configured by using the Autonomie libraries that provide component initialization data for a wide range of components used in light and heavy-duty vehicles. The powertrain component sizing was determined in a way that the alternative powertrains have at least the same tractive performance in comparison to the conventional, diesel engine powered tractor. The total weights of each powertrain was estimated and the results indicated that no major differences in weight could be considered therefore all the models were simulated with the weight of 10000 kg. The size and weight of the battery in the electric tractor was limited to be a less than 200 kWh for not to exceed the total tractor weight. Tables 1 presents the general technical specifications of the conventional tractor model thus the engine and transmission parameters. The front and rear axle, tires, weight have the same parameterization for all tractor models. Table 2 shows the powertrain specifications for the parallel hybrid, fuel cell hybrid, and battery electric tractor models.

Table 1. Conventional tractor powertrain and general technical specifications.

Component	**Description**
Diesel engine	maximum power 225 kW, maximum torque 1154 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
Weight	kerb weight: 10000 kg

Table 2. Specifications of the hybrid and electric transmissions.

Component	**Parallel hybrid**	**Fuel cell hybrid**	**Electric**
Diesel engine / Fuel cell stack	Diesel engine: power 175 kW, torque 898 Nm	Fuel cell stack: max power 160 kW	---
Transmission	8-speed (DCT) with 2 ranges	3-speed gearbox	3-speed gearbox
Battery configuration	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh	33 Ah cell, eight packs in parallel, 192 cells in series in a pack, 720 V, 190 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	max power 225 kW, max torque 611 Nm, max speed 8000 rpm

2.3 Operating cycles

Measurements were carried out in the Viikki Research Farm with a tractor (Valtra N141) and a chisel plow (Figure 1) to define different levels of load resistance for the operating cycles. The measurements were done in October 2022 in a stubbled field. Two tillage cycles were generated with target speeds of 8 and 12 km/h. For both cycles, three level of load resistance were defined them being light, medium, and high load. The resistance load was applied only when the implement was in use during operation. The tillage cycles are illustrated in Figure 4 with the target speed and force as load resistance.

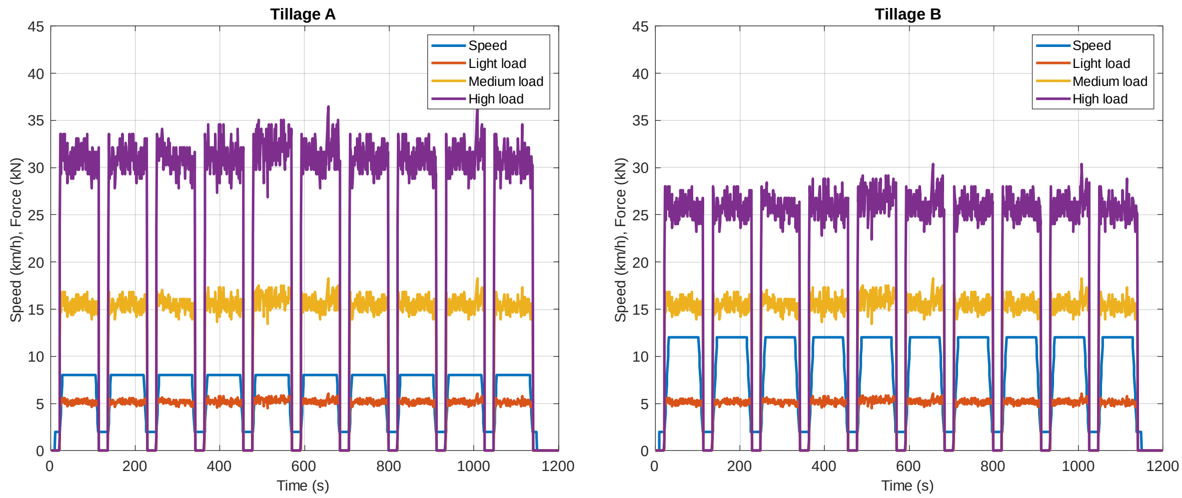

Figure 4: Generated tillage cycles with three defined load resistasnce profiles.

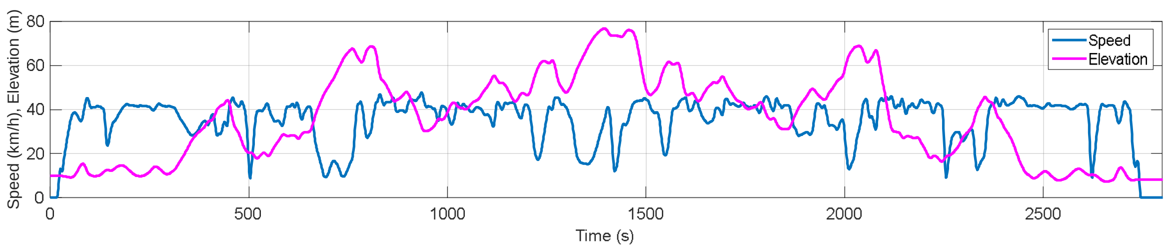

Figure 5: Measured road cycle for tractor trailer simulations.

Figure 5 shows the measured road cycle with the elevation profile. The road cycle corresponds to a typical road transport operation done with agricultural tractors with a trailer between fields and a farm. The 27 km roundtrip cycle was measured from the route that has been used for tractor comparison tests by a Finnish magazine. Simulations were carried out with a trailer having total weights of 10000 kg and 15500 kg. These loads correspond to payloads of 30% and 60%.

3 Results

3.1 Operating in cycles

All the simulations were done by using AMBER, which is model-based systems engineering (MBSE) platform that allows to run workflows with different software developed by ANL. Thus, the model development was done in Autonomie and the configuration and parametrization in AMBER. MATLAB software was used for analysing the simulation results. Overall, all the simulations were successfully carried out and it was concluded that all the models were operating correctly. It was observed that the target speed was followed quite well without any major deviations in all cycles, although the electrified powertrains did have more precise control for following the target speed especially in low speed driving. The speed trace in Tillage A cycle for all tractor models is illustrated in Figure 6. The conventional tractor does not follow the target speed very closely but in higher speeds the speed control works fine. Also, the load resistance in the tillage cycles had some influence on the driver dynamics and that will be a focus point in the future research when developing advanced driver models for agricultural tractors.

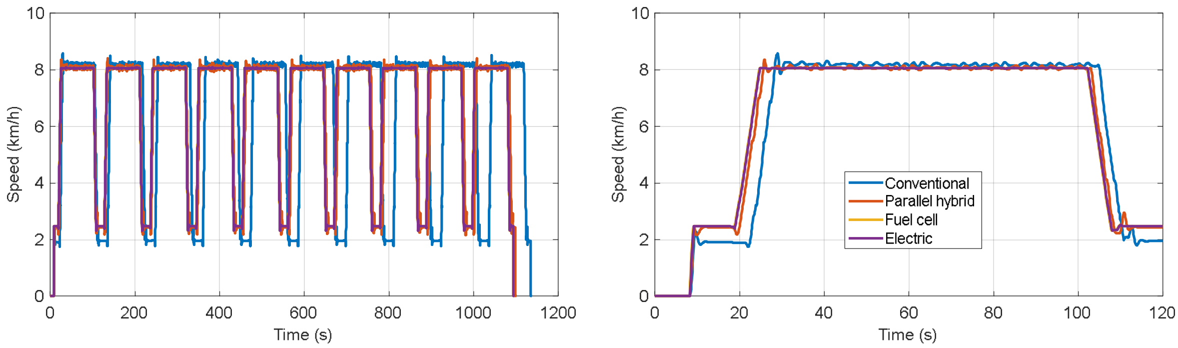

Figure 6: Tractor speed traces in Tillage A cycle.

3.2 Energy consumption

The energy consumption was calculated as on-board energy use therefore no charging losses were taken into account. Figure 7 presents the cumulative energy consumption for the simulated tractor models in the tillage A and road cycle. The reduction potential of energy consumption for the alternative powertrains are shown in Figure 8. These results clearly show that there is a significant potential for reducing energy consumption with the electric powertrain. The average reduction potential is around 60% in the tillage and road cycle. The potential to reduce energy consumption with the fuel cell hybrid varies from 20% to 30% and with the parallel hybrid from 0% to 20%. The variation in the potential is due to the operating conditions thus less reduction can be achieved with higher load workcycles with the hybrid powertrains. There were no major differences in simulation results between the two tillage cycles.

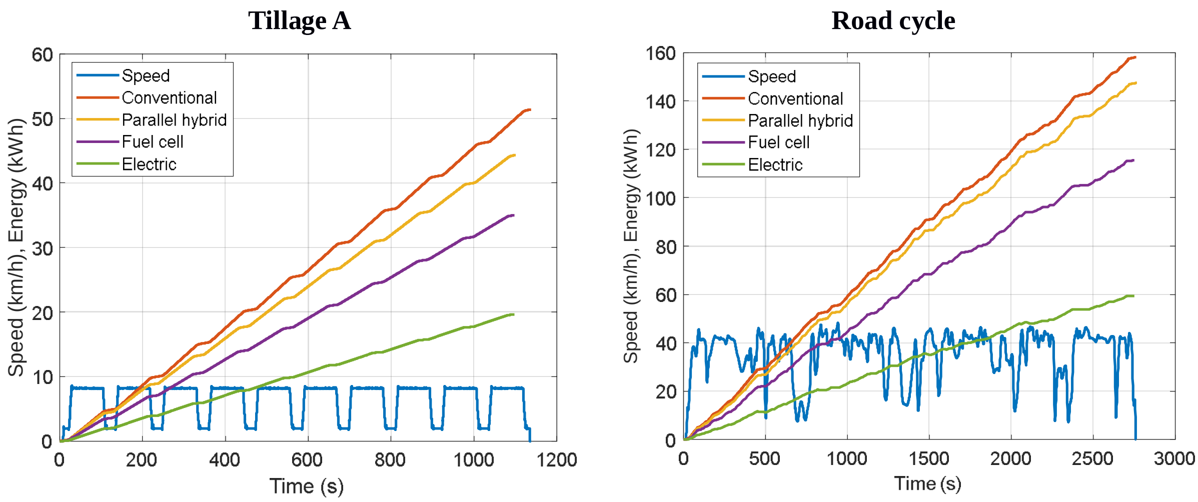

Figure 7: Cumulative energy consumption in the tillage A and road cycle.

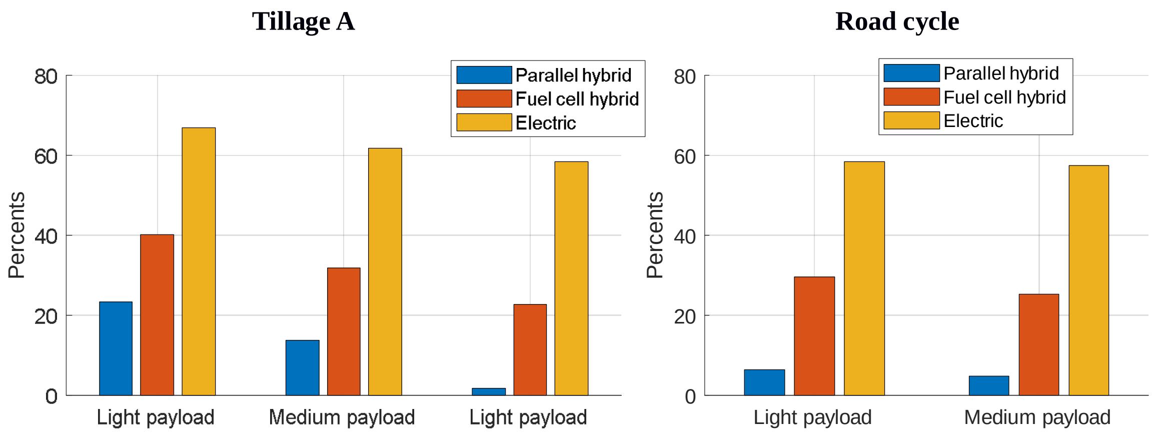

Figure 8: Potential for reducing energy consumption in the tillage A and road cycle.

3.3 Distribution of losses

From the simulation results, the energy consumption and breakdown of powertrain losses were calculated for all simulations. Figures 9-11 present the distribution of the powertrain losses in three simulated cycles with two load resistances. The presented pie diagrams illustrate the total energy consumption with units of kWh/h for all the cycles. The area of the pie diagrams also corresponds to the amount of energy consumed in relation to the energy consumption of the conventional tractor. For the conventional and parallel hybrid tractors, the major energy losses are generated by heat losses of the power source (PS) thus the diesel engine. Depending on the cycle and workload, the energy loss portion of the power source is 58-68% for the conventional and parallel hybrid tractor, 44-48% for the fuel cell hybrid, and 7-10% for the electric tractor. It is important to notice that the portion of the auxiliary loads in energy losses is quite significant especially when comparing it to transmission losses. The presented distribution losses also clarify the influence of the workload on the tractor operation. For the conventional tractor the energy consumption increase is about 80% between light and high workload and 120% for the alternative powertrains.

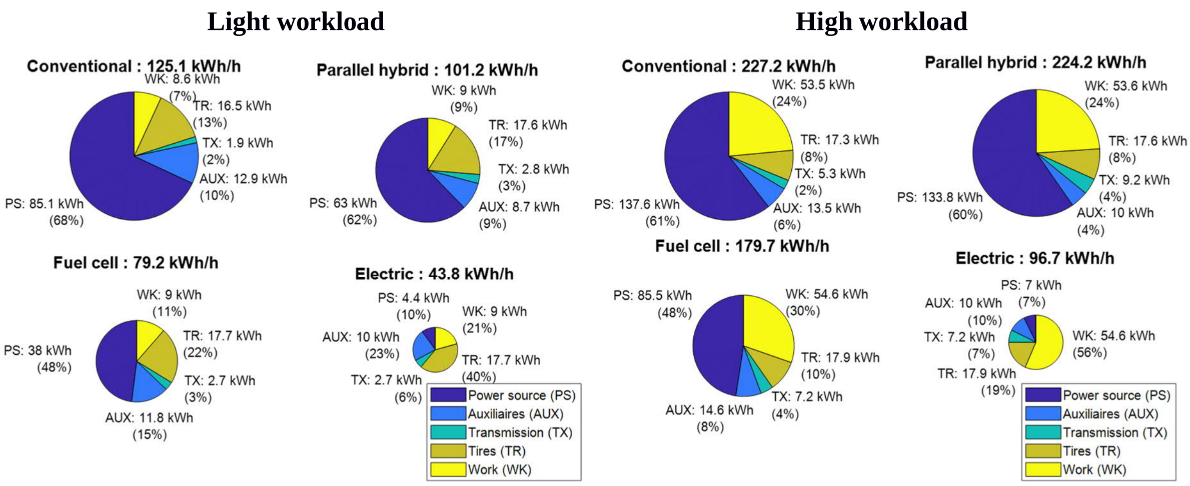

Figure 9: Distribution of losses of the different tractor models in Tillage A cycle with two workloads.

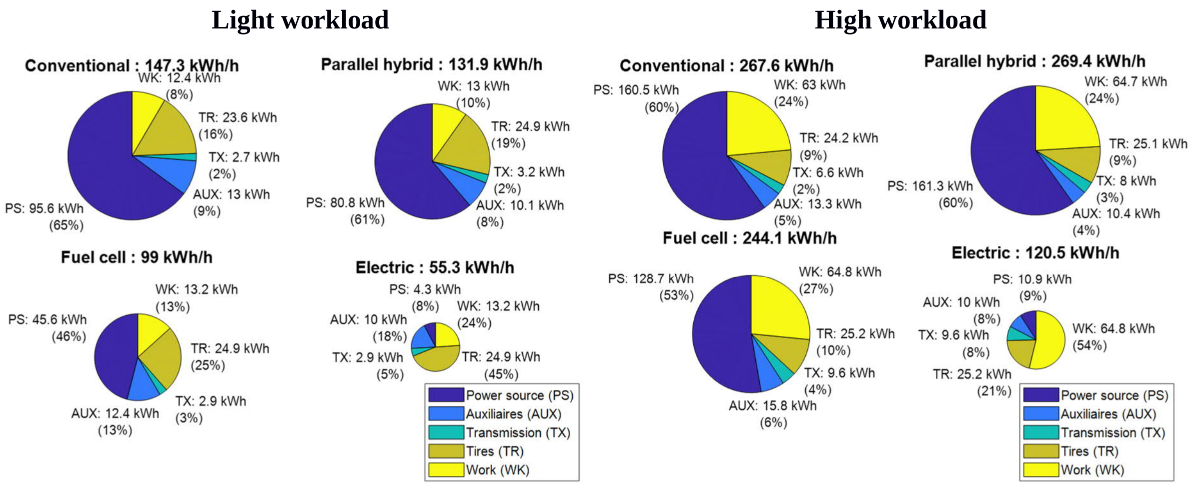

Figure 10: Distribution of losses of the different tractor models in Tillage B cycle with two workloads.

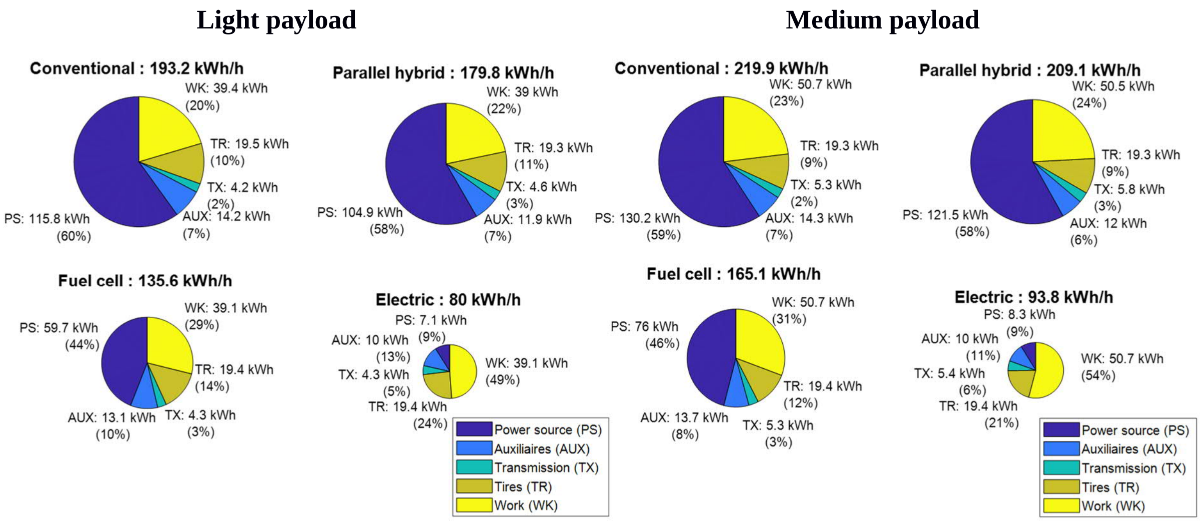

Figure 11: Distribution of losses of the different tractor models in the road cycle with two payloads.

3.4 Operating time

The operating performance was evaluated based on the calculated operation times in the simulated cycles. The fuel tank size for the conventional tractor was 500 liters and for the parallel hybrid 350 liters. The hydrogen storage was assumed to be 36 kg of compressed hydrogen in 700 bar. This is comparable to the amount of hydrogen storage capacity in the fuel cell hybrid city buses. The operating time variations in the simulated cycles are presented in the Figure 12. It can be observed that there are no major differences between the cycles but very significant differences between the tractor models. The conventional and parallel hybrid tractors have very long operation time without refueling which is typical nowadays for agricultural tractors. The fuel cell hybrid offers already a quite reasonable operating time without refueling from 5 hours up to 15 hours. The major challenge for the battery electric tractor is the low energy density of the energy storage therefore the operating time remains very low in comparison to the other tractor models. The operating time could be increased by adding battery capacity, but it is challenging in terms of weight and available volume. Another solution is the fast charging but there are usually no access to high power charging in the farming context.

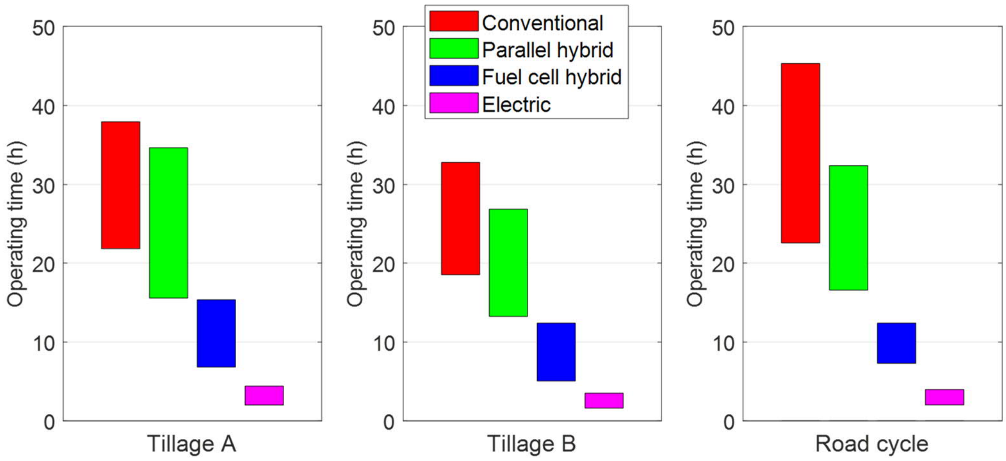

Figure 12: Calculated variation in operating time in different cycles.

4 Conclusions

Simulation models for conventional, parallel hybrid electric, fuel cell electric, and battery electric agricultural tractors were developed in the Autonomie software. Simulations in three different work cycles were carried out with different workloads for evaluating the energy consumption and operating performance. The results show that the battery electric powertrain provides the most efficient powertrain option for the agricultural tractors. However, the operating performance is quite poor because the energy intensity of the lithium-ion batteries does not provide a long enough operating time without fast charging. Furthermore, the fast charging could be challenging to provide in agricultural context. The simulation results indicate that the fuel cell hybrid tractor could provide substantial energy savings in comparison to the diesel powered, conventional powertrain. The major advantage is the much higher efficiency of the fuel cell system than a diesel engine. A reasonable amount of hydrogen storage would provide an adequate operating performance thus more than 10 hours of operation without refueling. The parallel hybrid powertrain does not provide significant energy savings with high workloads, but it has a quite good performance in terms of road transport and operating time.

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Presenter Biography

Antti Lajunen received the M.Sc. degree in Mechanical Engineering from Helsinki University of Technology, Finland, in 2005 and Master of Advanced Studies degree in Industrial Engineering from Ecole Centrale Paris (ECP), France, in 2007. He received his D.Sc. degree in 2014 from Aalto University, Finland. He is currently working as an Assistant Professor in Agricultural Engineering at the University of Helsinki, Finland. His main research interests are electrification of agricultural vehicles and machinery, automation in agriculture, and high fidelity modelling of off-road vehicles.

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Vincent Freyermuth is a research engineer at Argonne National Laboratory. He started at General Motors running fuel economy and performance simulations, then focused on hybrid technology at Ford Motor Company where he developed full vehicle models, vehicle control strategies to maximize fuel consumption and ran chassis dyno testing in preparation for EPA fuel economy certification. Vincent also worked at Cummins on hybrid powertrain for commercial vehicles. He currently focuses on the benefits of electrification and connected vehicles to reduce fuel consumption

Ram Vijayagopal is the group manager for Vehicle Technology Assessment at Argonne National Laboratory. He is responsible for quantifying the energy saving potential of technologies using modelling and simulation. After working at Mahindra & Mahindra and Hitachi Automotive Systems, he joined Argonne in 2008. He received his bachelor's degree in engineering from University of Kerala and a master's degree in engineering from University of Michigan. He has authored over 20 papers in the area of advanced vehicle technologies.

Namdoo Kim is a research engineer at Argonne National Laboratory. He graduated from the University of Sungkyunkwan, South Korea, with a Master's Degree in Mechanical Engineering in 2007. He focuses his research on the vehicle system modeling and simulation to assess the energy consumption, performance, and cost of advanced vehicle technologies across multiple classes, powertrains, components, and control strategies.