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Evaluation of Alternative Powertrains in Wheel Loaders by Modeling and Simulation

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Executive Summary

Numerical simulation models were developed for different types of alternative powertrains for heavy wheel loaders by using Autonomie vehicle simulation software. The modelled powertrains included conventional, parallel hybrid electric, series hybrid electric, fuel cell hybrid electric, and battery electric powertrains. A specific duty cycle was generated for simulating the operating performance and energy efficiency of the wheel loader models. The simulation results indicated that the fuel cell hybrid and battery electric powertrains have high potential to reduce energy consumption and emissions. The series hybrid powertrain can reduce substantially energy consumption in the low-speed loading cycle whereas parallel hybrid can provide only little savings in energy consumption. The detailed breakdown of the powertrain component losses clearly shows that the major advantage of fuel cell hybrid and battery electric powertrains is the significantly reduced losses in the primary power source thus fuel cell stack and battery pack.

Keywords: alternative powertrain, wheel loader, modeling, simulation, energy consumption

1 Introduction

Wheel loaders are essential heavy machinery in industries such as construction, mining, agriculture, and waste management, where they are widely used for material handling, earthmoving, and loading operations. With the help of advanced technology, wheel loaders have become increasingly efficient, versatile, and sophisticated, incorporating digital controls, telematics, and automation to optimize performance and reduce operational costs. These machines operate through varied duty cycles that involve repetitive, high-intensity work, typically characterized by alternating heavy lifting, transporting, and loading tasks [1]. The demand for increased productivity and fuel efficiency, together with stricter emissions regulations, has driven innovations in the powertrain technologies of wheel loaders, including hybridization and electrification [2].

Powertrain hybridization and electrification have introduced significant benefits to wheel loaders, such as reduced fuel consumption, lower greenhouse gas emissions, and quieter operation, making them more suitable for urban and sensitive environments [3, 4]. Hybrid wheel loaders, which often use a combination of an internal combustion engine as the main power source and an electric system to make the powertrain more energy efficient [5, 6]. Hydraulic hybrid powertrains have also been proposed for increasing the efficiency of the hydraulic system to capitalize on better energy management and energy recovery during braking [7, 8]. Recently, more interest has been focused to fully electric wheel loaders, which would offer near-zero emissions and minimal noise, benefiting indoor and emission-sensitive areas [9, 10]. However, these advancements also bring certain challenges, such as high initial costs, the need for charging infrastructure, and limitations in battery capacity, which may not support extended operations in remote or high-demand applications.

Numerical simulation of off-road machinery is an effective approach for evaluating performance, energy efficiency, and design feasibility across a range of operating conditions. By replicating real-world tasks, these simulations allow for the modeling of complex interactions, such as resistance forces during heavy-duty operations like loading, lifting, and discharging. One key benefit of numerical simulation is its ability to test and compare alternative powertrain technologies, component sizing, and system configurations without the need for physical prototypes, which can be costly and time-consuming to produce [11]. Additionally, simulations support rapid iteration, enabling engineers to explore various scenarios, optimize performance, and reduce fuel consumption [12]. Overall, numerical simulation serves as a valuable tool for advancing sustainable and efficient machinery design, enhancing productivity, and reducing costs in the development of off-road machinery.

Evaluating the operating performance of alternative powertrains, hybrid and electric wheel loaders generally demonstrate higher efficiency and emission performance in light and medium duty cycles, where energy recovery and shorter operating periods suit their capabilities. Nevertheless, for more intensive tasks requiring prolonged operation or in rugged terrains, traditional diesel-powered models still maintain an edge due to their power density and extended range. However, the present literature is rather limited in research studies that would provide an extensive insight to the energy efficiency and operational performance of alternative powertrains in wheel loaders.

This research presents a comparison of wheel loaders with alternative powertrains by using Autonomie vehicle simulation software [13]. To better evaluate performance through simulation, off-road machinery is often modeled based on its typical operations. These machines generally perform repetitive tasks and lack a predefined speed profile to follow. Instead, they are more accurately simulated using distance-based, task-specific cycles with target speeds set according to distance traveled. Given the heavy-duty nature of these machines, it is essential to incorporate a resistance force into the model to reflect work requirements, such as loading and discharging materials with a bucket. When assessing alternative powertrains in wheel loaders, numerical modeling and simulation offer an effective method to generate various simulation scenarios, compare component sizing, and evaluate benefits across multiple use cases.

2 Materials and methods

2.1 Simulation model development

The wheel loader models were developed in the Autonomie simulation software environment. Autonomie is a sophisticated vehicle system simulation software developed by Argonne National Laboratory (ANL) and serves as a versatile tool for evaluating the energy consumption, performance, and cost implications of advanced vehicle powertrain technologies across a wide spectrum of vehicle types. Originally designed for on-road vehicle simulations, Autonomie has been adapted to accommodate off-road vehicle models by implementing modifications to vehicle control systems and parameters, particularly for distance-based cycles. This adaptability ensures that Autonomie remains a reliable and effective simulation platform, provided that a representative operating cycle can be generated. Conventional, parallel hybrid, series hybrid, fuel-cell hybrid, and battery electric wheel loader simulation models were developed in this research.

2.1.1 Conventional Diesel Powertrain

The conventional diesel powertrain model within Autonomie is characterized by its reliance on a diesel engine as the primary power source. This setup includes a five-speed gear box, which facilitates a smooth working and driving performance. The conventional diesel powertrain is a well-established technology, offering robust performance and reliability, particularly suited for applications where traditional fuel sources are preferred. The powertrain layout with main components is presented in Figure 1.

2.1.2 Parallel Hybrid Electric Powertrain

The diesel engine powered parallel hybrid electric powertrain represents an innovative approach to reducing fuel consumption and emissions while maintaining the power and versatility of diesel engines. This topology integrates also a five-speed mechanical gearbox with an electric power path, utilizing a battery pack as an electrical energy storage system as presented in Figure 1. The hybrid nature of this powertrain allows for the seamless integration of electric and mechanical energy sources and benefits from optimization of efficiency and performance. The energy management system (EMS) has an important role, at the same time, provide peak power demand from the battery and sustain the battery state-of-charge (SOC). The developed parallel hybrid wheel loader model has a power following EMS strategy thus it prioritizes the electrical power delivery for better operational performance over energy efficiency.

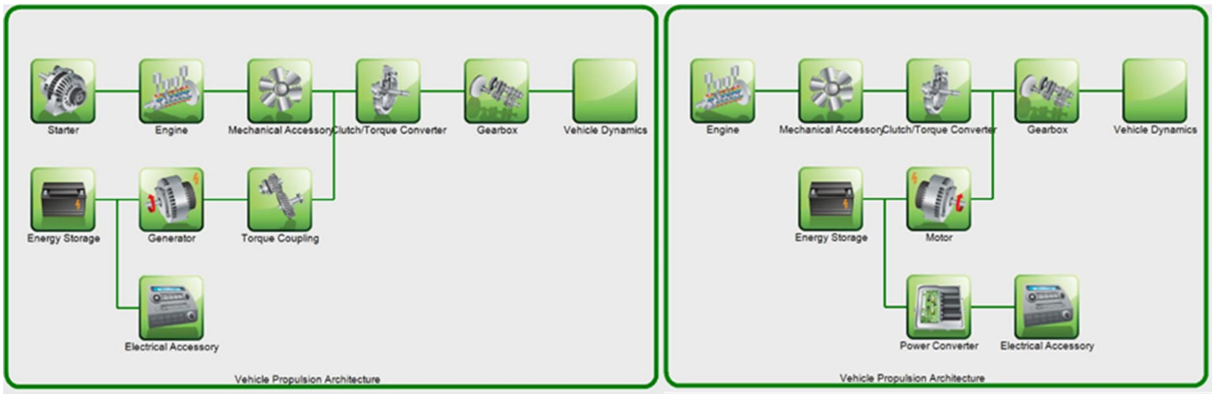

Figure 1: The conventional diesel (left) and parallel hybrid (right) powertrain layouts in Autonomie.

2.1.3 Series Hybrid Electric Powertrain

The series hybrid powertrain layout is presented in Figure 2. It has also a diesel engine as the primary power source and a small battery pack as the electrical energy storage. In the series hybrid topology, there is no mechanical connection from the engine to the drivetrain instead the engine powers a generator that delivers electrical energy to the electric drive motor, to the electric motor running the hydraulic pump, to auxiliary devices, and also to charge the battery. The powertrain includes a three-speed gearbox to satisfy the lower speed operation and 40 km/h top speed requirement. The series hybrid powertrain is also controlled with a power-following and charge-sustaining EMS strategy. The topology allows for better optimization in the use of the engine since its operation speed is not dependent on the driving speed.

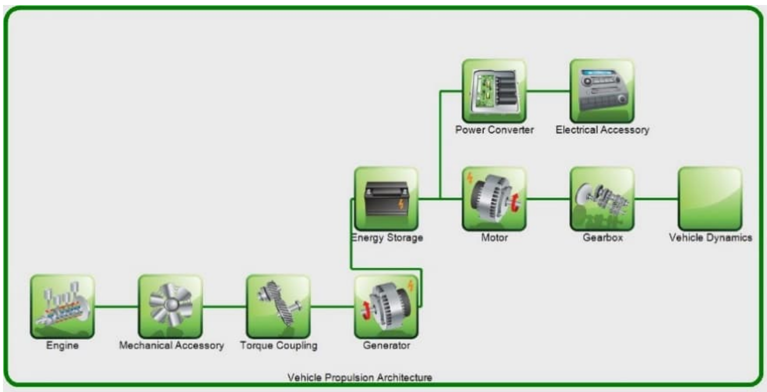

Figure 2: The series hybrid powertrain layout in Autonomie

2.1.4 Fuel Cell Hybrid Powertrain

The fuel cell hybrid powertrain model consists of a full electric system with a fuel cell stack as the primary power source, complemented by a small battery pack for power load leveling. The electric drive motor, paired with a three-speed gearbox, ensures efficient power delivery and management. The fuel cell hybrid powertrain offers significant advantages in terms of reduced emissions and enhanced energy efficiency, making it an attractive option for future vehicle technologies. The fuel cell hybrid also uses power-following and charge sustaining EMS strategy. Figure 3 presents the powertrain layout of the fuel cell hybrid powertrain.

2.1.5 Battery Electric Powertrain

The battery electric powertrain model showcases the potential of fully electrified vehicles. This topology includes a large lithium-ion battery pack as the primary energy storage system, powering an electric drive motor connected to a three-speed gearbox. The battery electric powertrain is designed to deliver optimal energy efficiency and zero emissions, presenting a sustainable solution for off-road machinery in general. The energy storage capacity is a bit limited by the volume that can be easily fitted into a wheel loader. The battery electric powertrain layout is presented in Figure 3.

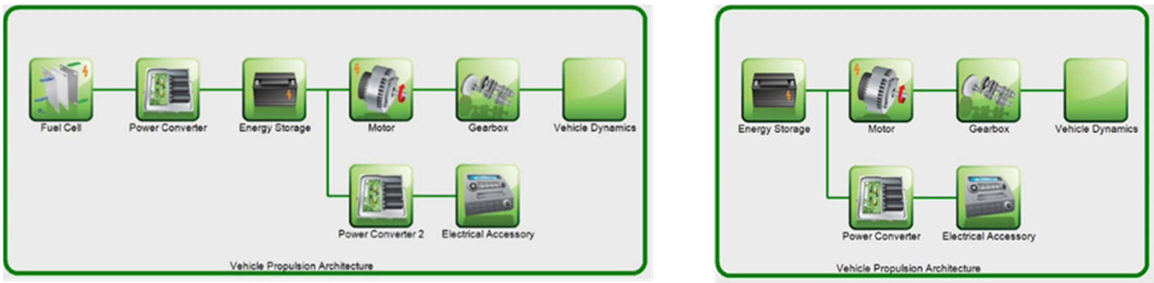

Figure 3: The fuel cell hybrid (left) and battery electric (right) powertrain layouts in Autonomie.

2.1.6 Vehicle Dynamics

In Autonomie, the vehicle dynamics block plays a crucial role in simulating realistic vehicle behavior. This block includes components such as a transfer case (trc), front and rear final drives (fd1 and fd2), axles and wheels (whl1 and whl2), and a chassis (chas) model. The layout of the vehicle dynamics block is presented in Figure 4. The transfer case is responsible for distributing driving power between the front and rear axles, ensuring balanced traction and stability. This comprehensive integration of vehicle dynamics into the simulation models allows for accurate and detailed analysis of each powertrain topology, providing valuable insights into their performance and efficiency under various operating conditions. The chassis model also includes the integration of loading resistance thus a specific resistive force impacted on the loader corresponding to the resistance when filling in the bucket during loading.

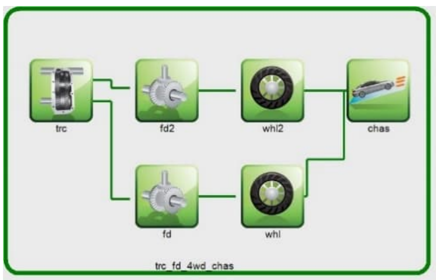

Figure 4: Vehicle dynamics block layout in Autonomie.

2.1.7 Hydraulic System

By default, Autonomie does not have work hydraulic components in the component library. In collaboration with ANL, hydraulic component models were developed for a hydraulic cylinder and hydraulic pump. The hydraulic cylinder model includes a double-acting cylinder and a directional control valve. The wheel loader model has two lift cylinders and one tilt cylinder. The load force form bucket to cylinders was calculated based on the defined bucket payload in respect to the boom position. The work hydraulics are powered by a hydraulic pump, which is powered directly from the engine shaft with a gear reduction in diesel and parallel hybrid powertrains and by the electric motor in series hybrid, fuel cell hybrid and battery electric loader models. Hydraulic cylinders receive control inputs from the driver model and the hydraulic pump control is based on the required hydraulic fluid flow.

2.1.8 Driver Model

The driver model used in the wheel loader simulation models was modified from the original distance-based driver model included in the Autonomie library. Basically, the driver model interprets the predefined driving cycle by calculating the target driving speed and then calculates acceleration and braking commands. A specific hydraulic control block was developed in the driver model. It takes the vehicle driven distance as an input and based on a determined loading and discharging control sequence, it sends the control signals to the cylinders. The loading and discharging sequences are presented in the chapter 2.3.

2.2 Model Parameters

The reference simulation model of the conventional diesel wheel loader corresponds to a 20 tons wheel loader with 194 kW of engine power. The wheel loader models were configured by using the Autonomie component libraries that provide initialization data for numerous components typically used in light and heavy-duty vehicles. The sizing of the alternative powertrain models was done by matching their performance to the performance of the conventional wheel loader. It was estimated that only minor increases on weight would occurred by the alternative powertrain components therefore all the models were simulated with the weight of 19000 kg. The size of the battery storage system in the electric wheel loader was chosen to be 200 kWh to keep the loader total weight under the defined weight. The simulations were done with the bucket load of 3000 kg. The general technical specifications of the conventional and parallel hybrid powertrains are presented in Table 1. The specifications of the front and rear axle and tires have the same parameterization for all tractor models. Table 2 shows the powertrain specifications for the series hybrid, fuel cell hybrid, and battery electric wheel loader models. The specifications for rear and front axle and tires are the same for all loader models.

Table 1: The specifications of the conventional and parallel hybrid powertrains.

Component	Conventional	Parallel hybrid
Diesel engine	maximum power 194 kW, maximum torque 995 Nm	maximum power 194 kW, maximum torque 913 Nm
Energy storage		6 Ah cell, 180 cells in series in a pack, 648 V, 3.9 kWh
Transmission	hydraulic torque converter and 5-speed gearbox	
Rear axle	bevel set ratio of 3.2:1 and planetary gear ratio of 5:1	
Front axle	bevel set ratio of 3.2:1 and planetary gear ratio of 5:1	
Tires	Front and rear: 23.5 R25	
Weight	19000 kg	

Table 2: The specifications of the series hybrid, fuel cell hybrid and battery electric powertrains.

Component	Series hybrid	Fuel cell hybrid	Electric
Diesel engine / Fuel cell stack	Diesel engine: power 185 kW, torque 949 Nm	Fuel cell stack: max power 160 kW	---
Transmission	3-speed gearbox	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, 190kWh
Electric motor	max power 194 kW, max torque 527 Nm, max speed 8000 rpm		

2.3 Operating Cycle

Wheel loaders are used in various types of work tasks in different environments. The most typical duty cycle is the short loading cycle which usually has either V or Y-pattern [14]. In this research, a dedicated test cycle was generated to evaluate the model operation and assess the energy efficiency. The test cycle, presented in Figure 5, includes two loading and two discharge phases. The first phase is operated in low driving speed (from t = 0 s to t = 55 s) and the second with higher speed corresponding to a typical load and carry cycle. The predetermined controls of the lift and tilt cylinders are also shown in Figure 5. The simulation included five consecutive test cycles for ensuring robust model operation and charge-sustaining operation for the hybrid powertrains.

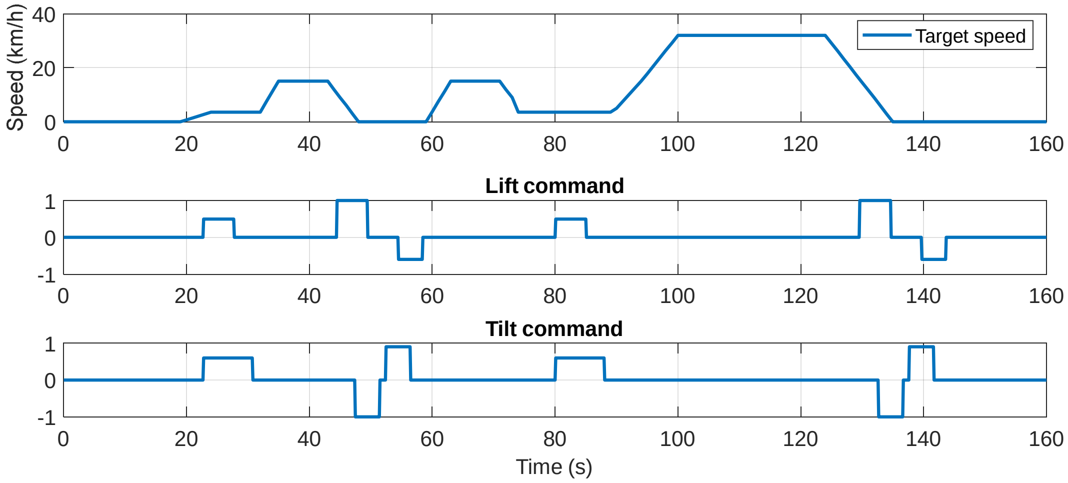

Figure 5. Test cycle and cylinder commands.

3 Research Results

3.1 Model Operation

Each model operation was evaluated based on the simulation results. The component signals and energy flows were carefully investigated to ensure correct operation in relation to the duty cycle and energy consumption. Especially, the operation of the hydraulic system was evaluated, and the different models' results were compared to each other. Figure 6 presents the power signals of the hydraulic pump and engine for the conventional diesel and hydraulic pump and battery power for the battery electric wheel loader.

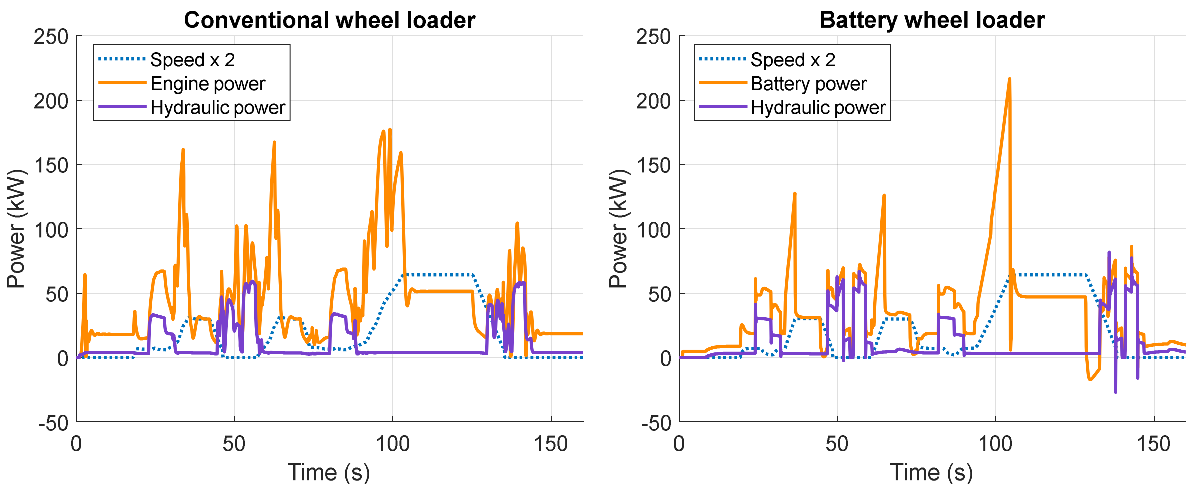

Figure 6. Hydraulic system operation signals.

3.2 Energy Consumption

The energy consumption was analyzed for each loader model on the test cycle. The cumulative energy consumption and battery SOC are presented in Figure 7. The parallel and series hybrid powertrains have slightly lower energy consumption than the conventional wheel loader. Instead, fuel cell hybrid and battery electric loaders have much lower energy consumption due to the higher energy efficiency of the primary power source. It can be observed in the Figure 7 that the battery SOC of the hybrid models stays quite constant during multiple cycles.

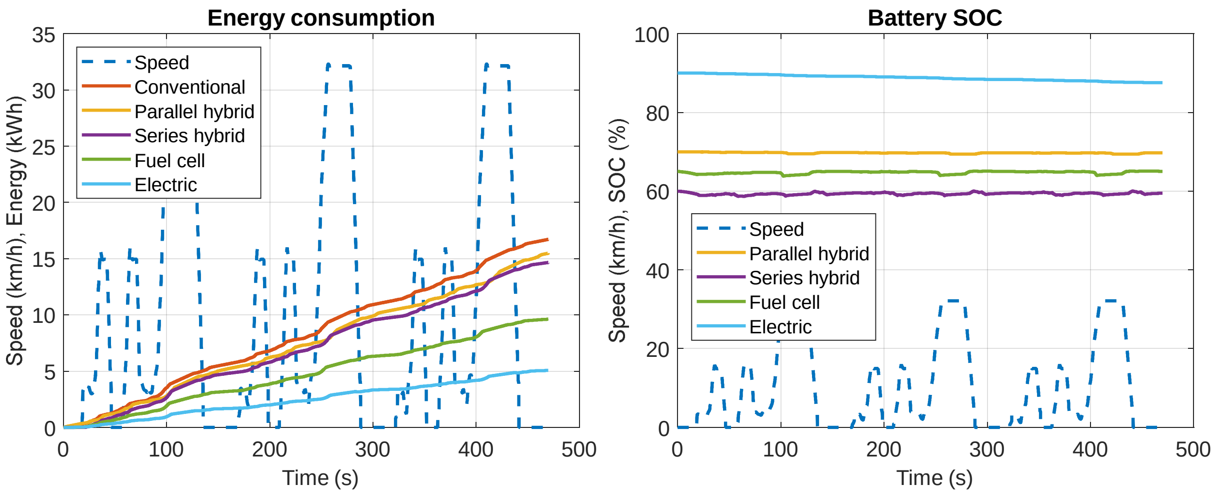

Figure 7. Cumulative energy consumption and battery SOC in the test cycle.

The simulation results in the test cycle were processed to analyze the energy consumption in the loading cycle (low speed part of the cycle) and in the load and carry cycle (higher speed part of the cycle). Figure 8 presents the energy consumption results for each wheel loader model in these two different operations. It is clear that in the low-speed operation the parallel hybrid powertrain provides only a minimal savings for the energy consumption. Instead, the series hybrid powertrain offers quite substantial energy consumption reduction about 25% in the low-speed operation but much less in the load and carry cycle (7%) when there is more driving in operation. Fuel cell hybrid and battery electric powertrains can provide significant reductions on both type of operations. The reduction can be more than 70% for the battery electric powertrain and between 40-50% for the fuel cell hybrid powertrain. The fuel consumption of the conventional diesel wheel loader is between 10 and 14 l/h which corresponds to a typical operation of diesel wheel loaders.

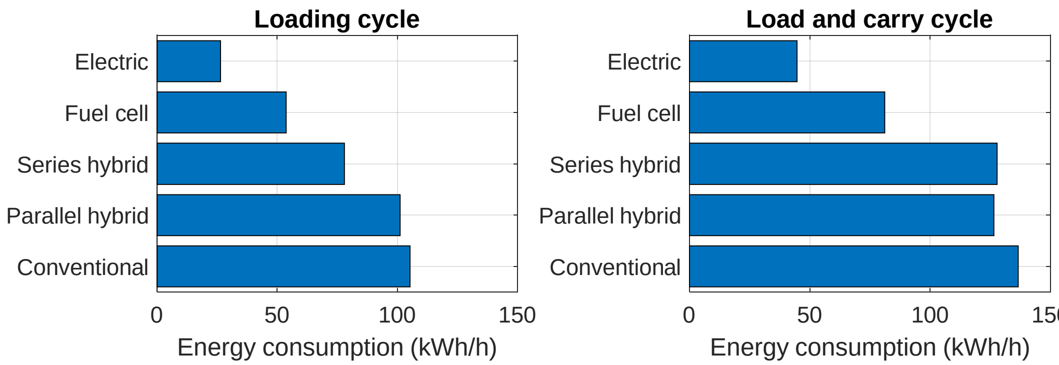

Figure 8. Energy consumption on the loading and load & carry cycles.

The energy losses were calculated for each component and groups of components were created as follows:

- **Main power source**: This includes the engine for all the diesel-powered models, also the generator for series hybrid, and a battery is included in this for the all the hybrid models. Fuel cell stack, battery and converter for the fuel cell hybrid, and naturally battery for the battery electric model.
- **Auxiliaries**: This group includes mechanical and electric auxiliary devices.
- **Hydraulics**: Work hydraulic system including hydraulic pump, valves, cylinders, and possible gear reductions and electric motors.
- **Transmission**: Electric drive motor, gearbox, final drives and wheel gear reductions. Hydraulic torque converter for conventional and parallel hybrid.
- **Tires**: Front and rear tires.
- **Brakes**: Energy losses in mechanical brakes.

Figure 9 shows the distribution of energy losses for all the wheel loader models in the test cycle. The major differences can be observed in the losses of the main power source group. The battery losses are quite minimal, and the energy losses of the diesel engine covers about 65% of the total losses. There are no major differences in the losses of auxiliaries, hydraulics, transmission and tires between the different models. These are the type of losses that would be hard to reduce even with a full electric powertrain. The alternative powertrain models can profit from the regenerative braking, and it is visible in the braking losses.

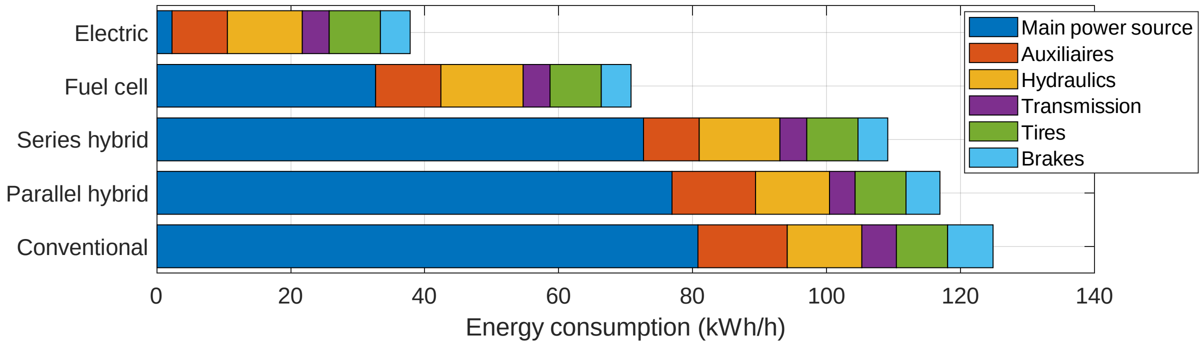

Figure 9. Distribution of energy losses in the test cycle for each powertrain.

4 Conclusions

In this research, conventional, parallel hybrid electric, series hybrid electric, fuel cell hybrid, and battery electric powertrains were modeled for a wheel loader. All the models were simulated in a specific test cycle that was generated from the typical operational context of wheel loader. The components models of the powertrains were parametrized based on the performance of the conventional wheel loader. According to the simulation results, the energy efficiencies of the alternative powertrains were compared to the conventional loader and the benefits of hybridization and electrification were evaluated.

Autonomie's flexible architecture and advanced modeling capabilities make it a practical tool for researchers and engineers seeking to explore the full spectrum of vehicle powertrain technologies. By offering detailed simulations of conventional, hybrid, and electric powertrains, Autonomie facilitates the development of innovative solutions aimed at improving energy efficiency, reducing emissions, and advancing the future of vehicle technologies.

The simulation results indicated that the fuel cell hybrid and battery electric powertrains have significant potential to reduce energy consumption of wheel loaders. In practical operations, depending on the working site, there could be inherent technical challenges for practical operation in terms of refueling hydrogen and recharging batteries. The parallel and series hybrid powertrains seem to have limited potential to increase energy efficiency, and it is dependent on the operating cycle. The energy efficiency of the hybrid powertrains could be further improved by advanced energy management strategies.

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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, agricultural robots, 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.

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.