PREDICTION OF ENVIRONMENTAL IMPACT OF HYBRID-ELECTRIC TRACTOR USING ITS DIGITAL MODEL

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Abstract. The use of agricultural machines to perform field operations impacts heavily on the environment, as fossil fuel consumption and generated carbon footprint. Nowadays, alternative powertrain technologies are being developed and tested; among them, powertrain hybridization is one of the most promising approaches. Hybrid-electric tractors combine a traditional diesel internal combustion engine (ICE) with one or more electric motors. Usually, time-consuming and expensive field tests are performed to assess the environmental impact of a tractor. The development of digital models of tractors in simulation tools allows to test rapidly the machine and predict accurately its environmental impact in simulated working cycles. This paper reports the modelling and simulation, in the "Autonomie" software, of the digital model of a 260 kW 4-wheel-drive agricultural tractor with a connected stone burier machine in two different architectures: the conventional one and the parallel hybrid-electric configuration. The digital model replicates the main technical specifications of the considered agricultural tractor and the connected operating machine. The propulsion architecture and its configuration parameters were modified, and a new block, to model the stone burier machine, was added. The power required by the operating machine was measured by a power transducer and inserted as a parameter in the developed digital model. The imposed custom-defined working cycle simulates the stone burying operation, defining a target speed profile. The aim of this paper is to predict the performance of the modelled architectures, in terms of followed working cycle, fuel consumption and CO_2 emissions using a simulation approach. The results of simulations highlight that the parallel hybrid-electric tractor can perform correctly the simulated field operation, revealing that its fuel consumption and CO_2 emissions are respectively two and three times lower compared to those of a conventional tractor.

Keywords: hybrid-electric agricultural tractor; digital model, simulation approach.

Introduction

The execution of typical field operations performed by agricultural tractors with diesel Internal Combustion Engines (ICEs) generates a considerable amount of Green House Gases (GHGs) emissions, that impact drastically on the environment [1; 2]. In addition, field operations related to soil preparation are characterized by low speed and high torque, forcing ICE to work in an inefficient region, where exhaust emissions are particularly critical. To reduce the dispersion of harmful GHGs, agricultural machine manufacturers have equipped tractors with specific exhaust gas treatment devices [3; 4], but a change of the paradigm is needed. It is time to exploit new approaches and technologies to convert conventional diesel-powered tractors into vehicles with reduced pollutant emissions and fuel consumption, prioritizing sustainability and efficiency. Int this context, nowadays there is an always increasing interest in agricultural tractors' powertrain hybridization. This process is in its early stage, but academic researchers and industrial manufacturers have started to analyse and design new concepts of tractors, equipped with hybrid-electric powertrains [5-8]. Hybrid-electric tractors combine the conventional diesel ICE with one or more electric machines and an energy storage system (ESS), able to store a large amount of energy, is mandatory. The most employed architecture to make hybrid an existing tractor is the parallel hybrid-electric architecture, thanks to its low-cost and simple implementation [9]. In this architecture an electric motor, which provides the starting torque and boost ICE, is added. The electric motor is mechanically connected to the ICE shaft, which is linked to the final drive through a gear transmission. Moreover, large Li-ion based ESS are usually chosen thanks to their high-power density. The most important drawback of this architecture is the mechanical connection between ICE and the load, which cannot guarantee the lowest fuel consumption [9].

Generally, nowadays for the evaluation of the environmental impact of an agricultural tractor, several expensive and time-consuming field tests are required, thus the use of simulation tools, to create digital models of agricultural tractors and simulate the execution of the agricultural operation, can be a viable solution [10-12]. This approach offers several advantages, ensuring a more efficient and performance-oriented design of the powertrain.

The novelty of this paper lies into the employed methodologic approach. In this paper the digital models of two different architectures of a 260 kW 4-wheel-drive agricultural tractor, with a connected stone burier machine, have been developed in a simulation tool. The first architecture is the conventional one, a diesel-powered tractor; the second is the parallel hybrid-electric configuration. In the same simulation tool, a working cycle that simulates the execution of the stone burying operation was defined. The performance of the two architectures, in terms of followed working cycle and environmental impact, has been predicted and compared.

Materials and methods

Employed Software. The software employed for the modelling and simulation is "Autonomie" (https://www.anl.gov/taps/autonomie-vehicle-system-simulation-tool, accessed on 10 December 2024). It is developed by the Argonne National Laboratory Vehicle & Systems Mobility Group (VMS) [13]. "Autonomie" software allows the modelling of conventional powertrains and also hybrid-electric, full electric, and fuel cell architectures [13]. It is a Simulink®-based software, which automatically interconnects the subsystems to create the entire model. The software is designed for on-road vehicles' simulation but, modifying the propulsion architecture and adding a new block to model the connected operating machine, it becomes suitable for modelling agricultural tractors. In "Autonomie" it is possible to simulate vehicles' performance in terms of tracking of imposed working cycles, fuel consumption and CO_2 emissions.

Developed Digital Models. In agricultural tractors, the power generated by ICE is used for traction effort and for the power demand coming from the operating machine connected to PTO. Typical field operations, such as ploughing and digging, require high torque at low speed to correctly perform the operation [14]. In "Autonomie", the digital models are composed of some fundamental blocks: i) the driver; ii) the environment; iii) the propulsion architecture; iv) the powertrain controller, which is a supervisory controller. The digital model of the conventional diesel-powered tractor has the same main technical specifications of the Fendt 936 Vario tractor. The main technical characteristics are reported in Table 1.

Table 1

Design parameters of the digital model of the conventional diesel-powered agricultural tractor

Parameter	Fendt 936 Vario
ICE Maximum power	261 kW @2200 rpm
Maximum torque	1970 Nm @1600 rpm
Mass	11200 kg
Anterior and posterior wheel radius	872 mm and 1084 mm

The connected stone burier machine was modelled in a block directly connected to ICE. The parameters of this block are its mass (11400 kg) and the power required at PTO, which was experimentally measured using the contactless 420 PTO Shaft Torque and Power Monitoring System transducer (Datum Electronics, Isle of Wight, United Kingdom) [15]. The modelled parallel hybrid-electric architecture is schematized in Fig. 1. In this configuration the electric motor is directly connected to the Li-ion battery pack and to the gearbox.

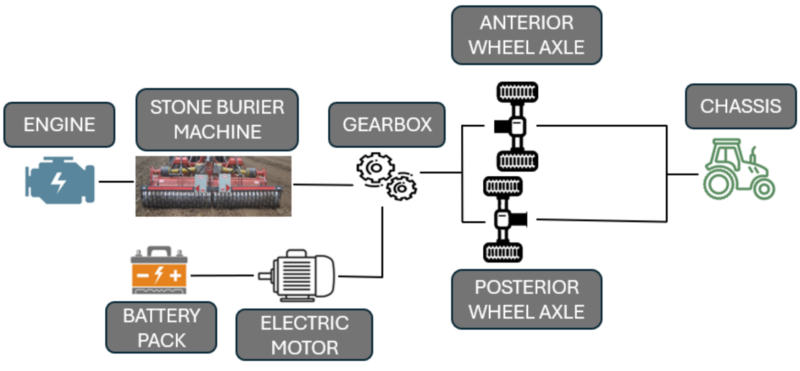

Fig. 1. **Schematic of the modelled parallel hybrid-electric powertrain architecture**

The Simulink® models employed by **"**Autonomie**"** software to model the discharge of the battery pack and the fuel consumption are detailed described in [16]. In this configuration, to evaluate the hybridization, the ICE has been downsized of 10% compared to the conventional diesel-powered architecture, according to [17]. The electric motor and the battery pack have been sized to guarantee a sufficient autonomy, without increasing so much the weight of the tractor. The ICE and the electric motor efficiency has been set to 42% and 90%, respectively [16]. Table 2 reports the main parameters of the modelled parallel hybrid-electric powertrain.

Table 2

Design parameters of the digital model of the parallel hybrid-electric tractor

Component	Parallel Hybrid-Electric Tractor
ICE maximum power, kW	234
Electric motor, kW	80
Battery pack, kWh	40

Custom-defined Working Cycle. The custom-defined working cycle (Fig. 2), which simulates the stone burying operation, begins with the tractor stopped; after 3 s it accelerates with a constant acceleration (for 45 s), thus its speed increases linearly up to 2 km·h^{-1}. The developed working cycle is composed of nine repetitions of four fundamental sections. The first section (red arrow in Fig. 2), in which the speed of the tractor remains constant to 2 km·h^{-1} for 20 s; this section simulates the headland turns. In the second section (orange arrow in Fig. 2), which lasts 20 s, the tractor accelerates with a constant acceleration up to 4 km·h^{-1}. In the third section (green arrow in Fig. 2) the tractor maintains fixed its speed for 60 s and simulates the burying operation. The fourth section (black arrow in Fig. 2), in which the tractor decelerates again to 2 km·h^{-1} lasts 20 s. At the end of the working cycle, the tractor decreases linearly its speed up to the stop of the vehicle. The entire working cycle lasts 1200 s (20 min) and the mean speed of the tractor during the cycle is 3.1 km·h^{-1}.

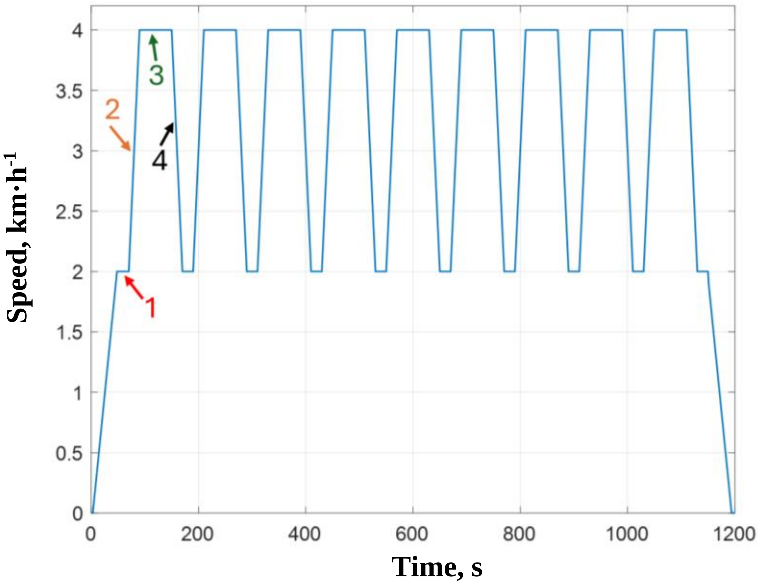

Fig. 2. **Custom-defined working cycle which simulates the stone burying operation**

Results and discussion

The power required at PTO (P_{PTO}) by the stone burier during the execution of the field operation has been experimentally measured using the contactless 420 PTO Shaft Torque and Power Monitoring System transducer. The power required at PTO, as is known, is given by (1):

$$P_{PTO} = \omega * \tau, \tag{1}$$

where ω – PTO angular speed, rad·s^{-1} and τ is the torque, Nm.

The PTO angular speed ω and the torque τ measured by the transducer during the execution of the stone burying operation are reported in Fig. 3.

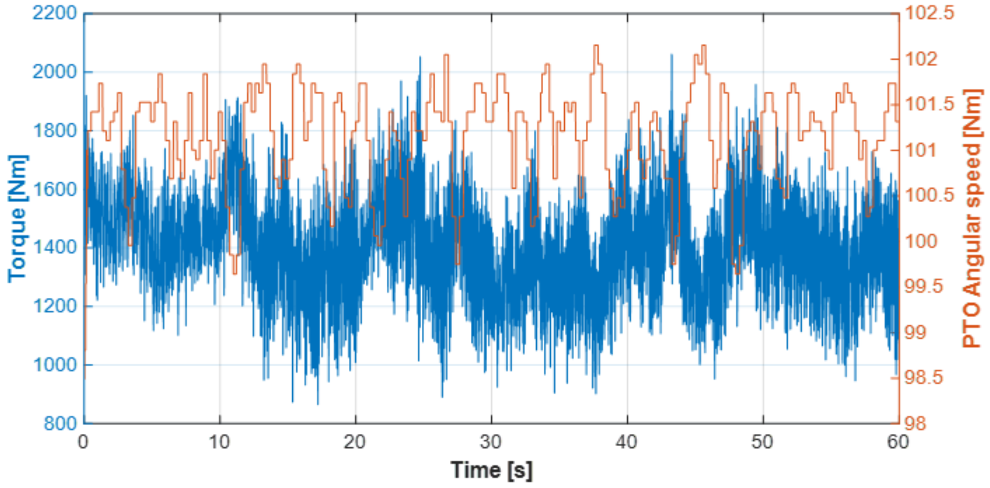

Fig. 3. **PTO angular speed ω and the torque τ measured by the transducer during the execution of the store burying operation**

Table 3

Basic statistics of the measured parameters

Parameter	Min	Max	Average	Standard Deviation
PTO Angular speed, rad·s^{-1}	98.5	102.2	101.1	0.6
Torque, Nm)	865.1	2062	1403	183
Power, kW)	85.2	210.8	141.7	25.2

The measured power required by the stone burier at PTO is on average 141.7 kW. This value, together with the mass of the burying machine, have been inserted as a parameter in the block that models the operating machine. Figure 4 shows the comparison of the execution of the imposed working cycle (blue line) between the two defined architectures, the conventional diesel-powered one (red line) and the parallel hybrid-electric (yellow line).

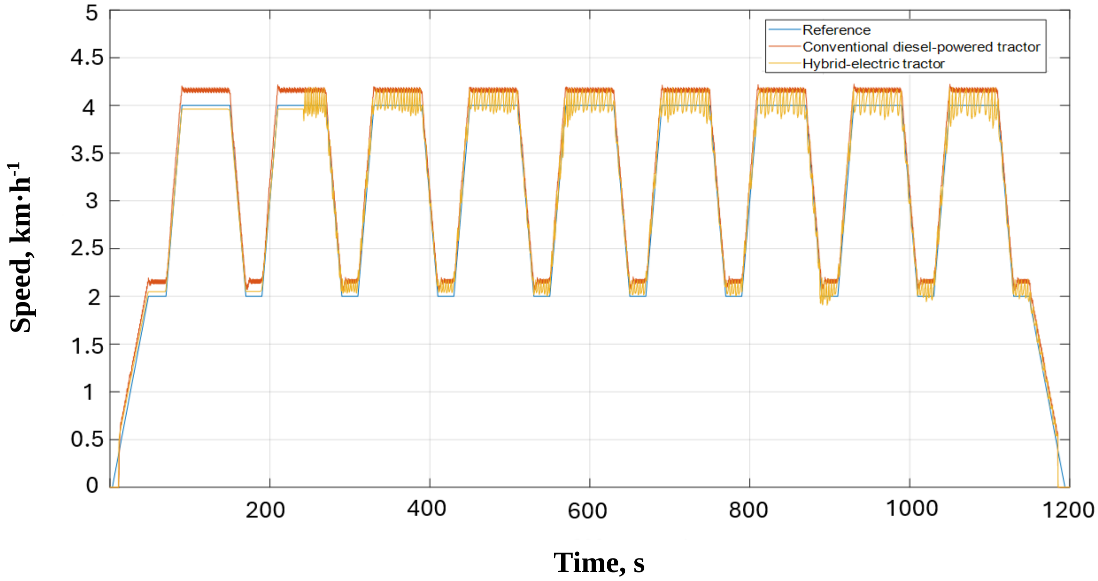

Fig. 4. **Comparison of the working cycle followed by the two defined architectures, the conventional one and the parallel hybrid-electric tractor**

Figure 4 highlights that up to 300 s the parallel hybrid-electric tractor follows perfectly the speed profile imposed by the working cycle. When the battery pack autonomy starts to run out and the ICE starts to work, the speed profile presents some controlled fluctuations (~ 5% around the target speed).

Moreover, the software gives as output also the environmental impact of the simulated working cycle in terms of fuel consumption and CO_2 emission (Table 4).

Table 4

Environmental impact of the simulated stone burying operation

Parameter	Conventional Diesel Tractor	Parallel Hybrid-Electric Tractor
CO_2 emission, kg·h^{-1}	62	35
Fuel consumption, L·h^{-1}	30.1	10.3

Table 4 highlights that CO_2 emissions and fuel consumption of the parallel hybrid-electric tractor are relevantly lower compared to those of the conventional tractor; in particular, CO_2 emissions and fuel consumption are 43% and 66% lower compared to the conventional tractor.

Conclusions

The aim of this paper was to develop, in the software "Autonomie", the digital model of a 260 kW 4-wheel-drive agricultural tractor in two different architectures, the conventional one and the parallel hybrid-electric configuration, with a connected stone burier machine. To evaluate the performance of the two architectures, a working cycle, which simulates the execution of the stone burying operation, was defined, and their environmental impact was predicted. For the modelling, the propulsion architecture and its configuration parameters were modified and a new block to model the stone burier machine was defined. The power required by the operating machine at PTO was measured and inserted as a parameter in the developed digital models. The environmental impact was assessed in terms of fuel consumption and CO_2 emissions. The performed simulations highlight that the parallel hybrid-electric tractor can perform correctly the simulated field operation, indeed, the working cycle is adequately followed. Moreover, it was pointed out that the fuel consumption and CO_2 emissions of the hybrid-electric architecture are respectively 43% and 66% lower compared to the conventional tractor. This study highlights that hybridization cuts down the environmental impact of an agricultural tractor, showing also enhanced performance compared to the conventional diesel-powered tractor. Thanks to these advantages, hybrid-electric agricultural machinery aims to revolutionize agriculture in the next future, providing a productive and sustainable solution for farmers.

Author contributions

Conceptualization, F.P., methodology, F.P. and S.P., software, F.P., validation, F.P., formal analysis, F.P and A.F., investigation, A.F. and G.P., data curation, F.P. and A.F., writing – original draft preparation, F.P., writing – review and editing, F.P., A.F., G.P. and S.P., visualization, F.P. and A.F., project administration, S.P., funding acquisition, S.P. All authors have read and agreed to the published version of the manuscript.

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