

Agricultural tractor engines from the perspective of Agriculture 4.0

Motores de tratores agrícolas na perspectiva da Agricultura 4.0

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ABSTRACT - Agricultural tractors have undergone significant changes in the last two decades promoted by precision agriculture and Agriculture 4.0. This review article collects data on the current status and future prospects of the use of artificial intelligence and advanced electronics in agricultural tractor engines. A literature search showed that tractor engines follow the technological trends of Agriculture 4.0. There are significant technological advances in engines regarding the incorporation of electronic control units, in which algorithms and programs are stored, allowing self-diagnosis, the control of air and fuel feeding systems based on pollutant emissions under different operating conditions, and data transfer. Therefore, such advances improved combustion, performance, and thermodynamic efficiency, and reduced pollutant emissions.

Key words: Technologies. Agricultural Mechanization. Embedded Electronics. Automation.

RESUMO - Os tratores agrícolas passaram por profundas transformações nas últimas duas décadas, impulsionadas pelo surgimento da Agricultura de Precisão e, recentemente, seguindo uma nova concepção, denominada de Agricultura 4.0. Neste sentido, este artigo de revisão tem por objetivo reunir informações sobre o estado atual e a perspectiva do uso de inteligência artificial e eletrônica avançada na avaliação de motores de tratores agrícolas. A partir de extensa busca na literatura científica tornou-se possível inferir que, os motores dos tratores agrícolas acompanham as tendências tecnológicas dentro das premissas da Agricultura 4.0. Foram constatados avanços tecnológicos significativos nos motores em relação às suas concepções originais decorrentes, principalmente da incorporação das unidades eletrônicas, nas quais são armazenados algoritmos e programações predefinidas, permitindo o autodiagnóstico, o gerenciamento dos sistemas de alimentação de ar e combustível, em consonância com as emissões de poluentes em diferentes condições de funcionamento e a transmissão de informações. Portanto, tais avanços permitiram otimizar o processo de combustão, refletindo positivamente nos parâmetros de desempenho e eficiência termodinâmica dos motores, além da redução das emissões.

Palavras-chave: Tecnologias. Mecanização Agrícola. Eletrônica Embarcada. Automação.

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INTRODUCTION

The term Agriculture 4.0 refers to the current state of the art in modern agriculture, which increasingly uses electronics, computing, and connectivity in production processes. Following the precepts of precision agriculture, these new technologies will cause changes in paradigms and insert new players into the agricultural sector.

The agricultural sector is adopting digital technologies, robotics, and automation, known as Industry 4.0, representing the fourth industrial revolution. Mazzetto, Gallo, and Sacco (2020) have shown that smart agriculture is an improvement of precision agriculture and is based on the framework of Industry 4.0.

If this technology stems from the need to feed nine billion people in 2050, enabling an increase in production and productivity, the environment will be more sustainable, and the amount of waste material will be reduced significantly. However, we will have fallen into a trap if this strategy seeks to create jobs, new useless technologies, and force drastic migrations in rural populations, driving the urbanization of producers.

The use of electronics in agricultural and forestry tractors has increased in the past few years. Since the development of fuel gauge systems with coils and sensors, embedded devices contain mechanical and electronic components.

In tractor engines, electronic components are used to control pollutant emissions and fuel injection. From mechanical and analogical systems, tractor engines started to use sensors and electronic control units (ECUs) for controlling and storing functions and detecting faults.

The challenges and difficulties inherent to electronic systems in agricultural need to be overcome. One of the main challenges is manufacturer data protection and restrictions to workers without licenses to use and change software. Manufacturers need to develop durable and intelligent systems to keep machines running.

In light of the difficulties of connectivity in the field, manufacturers have to provide functional redundancy, remote diagnostics, improved customer service, and online assistance, overcoming difficulties and providing responsive, fast, and secure communication. Interrupting engine operation because of failure of low-cost electronic components is unacceptable.

Other strategies include the adoption of the Internet of Things, communication between machines and management systems, and Big Data. However, it should be noted that nothing replaces knowledge and that regardless of the extent to which machines are endowed with technologically advanced systems, user information

is essential, and transferring the power of decision to third parties is disadvantageous.

This review article collects data on the current status and future perspectives of the use of artificial intelligence and advanced electronics in tractor engines.

Agriculture 4.0

Mazzetto, Gallo and Sacco (2020) discuss the concept of smart agriculture and the theoretical basis of Industry 4.0, which is based on Knowledge Management 4.0, in which integrated information systems are used to manage the production system, and raw data useful in one of the processes adopted in a production system are generated. Therefore, these technologies follow the framework of lean manufacturing, characterized by minimizing waste and reducing variability at the level of suppliers and customers (SHAH; WARD, 2007).

Zambon *et al.* (2019), analyzed aspects related to the industrial and agricultural revolution and the prospect of applying the concepts of Industry 4.0 to the agricultural sector to create Agriculture 4.0. The theoretical framework of Industry 5.0 is being developed, although the applications of Revolution 4.0 have not yet become widespread in the agricultural sector.

Digital technologies and artificial intelligence increase farming efficiency and productivity. Machines are becoming increasingly intelligent with information technology and connectivity, enabling analyzing and monitoring the power of tractors, harvesters, and other machinery. This strategy increases the quality of farming operations and controls their impact on the environment (MAGÓ; CVETANOVSKI, 2019).

Characteristics of modern engines

Tractors developed in the past 20 years have technological innovations of motor vehicles and are highly sophisticated. Tractor engines use the Common Rail injection system, multiple valves per cylinder, and variable geometry turbocharger to comply with pollution regulations (FILIPOVIĆ *et al.*, 2008).

Identifying the factors related to fuel consumption and pollutant emission is crucial for assessing environmental sustainability in agriculture. Lovarelli, Fiala and Larsson (2018) performed field tests to obtain reliable data on agricultural operations, such as soil preparation and sowing. During operations, fuel consumption and emissions were recorded by the tractor's controller area network (CAN)-Bus. These authors examined the paths, maneuvers, stops, and displacements using GPS data and correlated these data with operating parameters, including angular engine speed, torque, operational speed, and working depth.

These data improved the reliability of the analysis of the life cycle of agricultural machinery and the recommendations on environmental sustainability.

Materials used in engines

The improvement in the performance of Diesel engines and emission reductions are partly due to technological advancements in design materials. The most efficient engines require higher combustion pressure, which usually increases temperature (TURNER; PEARSON, 2010). Therefore, high pressure and temperature impose greater mechanical and thermal loads on engine components, including block, cylinder head, pistons, valves, and exhaust components, and these loads may exceed the limits of materials (PIERCE *et al.*, 2019).

The performance of Diesel engines has increased substantially in recent years with the use of a Common Rail fuel injection system with electronic control (HORROCKS, 2010), improvements in turbocharger efficiency and variable geometry supercharging, and the incorporation of sophisticated electronic controls (sensors), which improves the flexibility and refinement of engine systems and ultimately provide superior power and response.

Therefore, engine materials should be chosen based on functional characteristics, including the overall function of different components, including bearings, seals, structures, and heat conductors. Structural materials withstand high torque and power. Fatigue failure should be analyzed in this type of application. This type of failure is determined by several factors, including frequency, temperature, stress cycle, compounded stress, geometry, stress concentration, and creep failure (PIERCE *et al.*, 2019). Other properties such as material and manufacturing cost, availability, density, heat conductivity, hardness, thermal expansion, and corrosion resistance should also be considered.

A wide range of materials is currently used in components of Diesel engines, including gray cast iron, ductile cast iron, ferritic steel, austenitic steel, and nickel-based superalloys (PIERCE *et al.*, 2019). Palaci and Gonca (2020) assessed the effects of different materials, including palladium, titanium, thorium, zirconium, vanadium, alumina, aluminum bronze, copper, iron (gray cast), manganese, nickel, cobalt, and carbon steel, on equivalence ratio variations and found that the power and maximum efficiency of the engine increased as the melting point of the materials increased.

Therefore, the continuous improvement of materials and engine design, overcoming the limitations of maximum cylinder pressure and thermal load, and

reducing fuel consumption, increases the efficiency of Diesel engines (STANTON, 2013).

Connectivity and external control

One of the main concerns is the impact of tractors on the environmental pollution caused by fuel and lubricants. Bulgakov *et al.* (2020), created an environmental safety management system for Diesel engines. Therefore, the assessment of pollutant emission levels could be used to determine the operating regime of engines and adherence to existing standards. In addition, it is possible to reduce pollutant emissions by limiting the engine's angular speed regime.

Electronic Control Unit (ECU)

Tractor engines need to meet technological requirements, including tests for pollutant emissions, noise and vibration, and fuel consumption, and the latter is the only factor amenable to cost reduction (TUNKA; POLCAR, 2016). Farias *et al.* (2019b), highlight that fuel consumption should be considered by the user when purchasing an agricultural tractor because of fuel's non-renewable origin and high price.

Combustion engine control depends on the ECU, which has two main components: a chipset (hardware) and an embedded system (software). The chipset is connected to different engine monitoring sensors, and the embedded system uses the data received from the sensors, controlling the actuators (HAM; KO; PARK, 2017).

The programming of ECUs is predefined by the manufacturer, enabling the electronic control of the engine and providing information through error codes resulting from possible abnormalities. It is difficult to resolve failures without adequate technical knowledge for detection and repair. In addition, this technology enables configuring a specific engine for different tractor models and operating conditions (WANG *et al.*, 2009).

The incorporation of ECUs allowed developing new research to optimize the use of agricultural machinery. Engine load, fuel consumption, and pollutant emissions can be monitored during the operation depending on tractor characteristics and the data collected in a ECU histogram (JANULEVIČIUS; JUOSTAS; PUPINIS, 2013a). In addition, the use of new electronic devices increases the need for developing dynamic engine models that meet regulations, especially for pollutant emissions and fuel economy (LEE *et al.*, 2019).

Changes in classic engine configurations, such as injection angle and control inputs (variable geometry of turbochargers, exhaust gas recirculation (EGR), and Common Rail injection) can also help improve engine

performance (HAFNER *et al.*, 2000). However, modern combustion engines are complex and non-linear systems with multiple inputs and outputs and require appropriate algorithms.

Fuel consumption and pollutant emissions depend on the angular speed of the engine and load (JANULEVIČIUS; JUOSTAS; PUPINIS, 2013a), and ECUs are calibrated to provide the best relationship between performance and emissions (SENATORE *et al.*, 2008). However, parameters and the ECU of engines powered with alternative fuels such as fatty acid methyl ester fuels (biodiesel), whose characteristics are different from those of mineral Diesel, including calorific power, stoichiometric air to fuel ratio, density, and viscosity, need to be adjusted to reduce emissions (SENATORE *et al.*, 2008).

Knowledge of the combustion of alternative fuels helps increase engine performance and reduce emissions, improving the calibration of engine parameters by the ECU (ARMAS; GARCÍA-CONTRERAS; RAMOS, 2016). The optimization of the ECU can help reduce emissions from biodiesel combustion (CÁRDENAS *et al.*, 2016).

Reprogramming involves changing the fuel injection map to increase performance by increasing power and decreasing fuel consumption. However, this practice is not recommended because the ECU controls general systems, and failures can damage these systems and compromise safety (HAM; KO; PARK, 2017). Many users of agricultural machinery opt for reprogramming. However, this procedure should be performed by specialized companies because electronically-controlled Diesel engines are complex, requiring specialized knowledge in mechanics, hydrodynamics, electronics, control theory, and combustion (WANG *et al.*, 2009).

Electronic injection system

The operation of Diesel engines involves the contact of the fuel in the combustion chamber with atmospheric air superheated by compression, resulting in spontaneous combustion (GOMES *et al.*, 2016). Engine performance is directly related to engine volume, air quality, and the amount of fuel in the mixture (FARIAS *et al.*, 2017a).

Some Diesel engines used in tractors have a mechanical injection system composed of individual pumps, a rotary pump, a complete injection system, and a high-pressure electronically-controlled injection system (FARIAS *et al.*, 2017a). Most of the tractors sold in Brazil have a mechanical injection system. Nonetheless, with technological advancements and environmental concerns, high-pressure electronically-controlled systems are being increasingly used.

The difference between traditional and high-pressure injection systems is the amount of pressure. The injection pump transfers the fuel to a high-pressure line known as Common Rail, reaching a pressure of approximately 1 500 bar, and the injection unit is opened by pressure, i.e., the fuel is injected after reaching a certain pressure (BRIJESH; SREEDHARA, 2016).

The use of high-pressure injection systems allows changes in the injection time, opening pressure of the injection unit, and injection point (HORROCKS, 2010), improving adaptation and emission control (BASAVARAJAPPA *et al.*, 2015). In addition, it accepts the use of alternative fuels, and engine performance can be maintained using different fuel compositions.

The mechanical injection system is limited to a pressure of 240 bars, with limitations on injection time and pressure (BRIJESH; SREEDHARA, 2016). Electronically-controlled injection systems enabled developing several injection strategies based on engine sensors.

The main electronically-controlled sensors regulate the angular speed of the crankshaft and the position of the accelerator. These sensors transmit information on these parameters to the ECU, which changes the amount of injected fuel. In addition, sensors at air and fuel inlets monitor possible obstructions and engine temperature.

Current emission standards include TIER (North America), EURO (Europe), and Agricultural and Road Machinery-Phase 1 (*Máquinas Agrícolas e Rodoviárias-Fase 1 [MAR-I]*) (Brazil). The limits imposed by legislation can be met by changing fuel composition and using new technologies. Manufacturers can meet these standards by adjusting the electronically-controlled high-pressure injection system (JUNGLER; DIOTTO, 2018).

Emission targets can also be met by adjusting fuel injection (ÖZKAN, 2015). Golimowski, Pasyniuk, and Berger (2013) evaluated the performance of a Diesel engine equipped with a Common Rail injection system using raw rapeseed oil and found that this system minimized problems related to the use of raw fuels. This is due to the precision of the volume of injected fuel and constant pressure in the combustion chamber. In addition, performing multiple fuel injections in each duty cycle and heating the fuel improves the quality of the fuel mixture in the combustion chamber.

Alternative fuels and additives

Most agricultural machines are equipped with Diesel engines because of their high thermal efficiency and reliability (PERIN *et al.*, 2015; ZHAO *et al.*, 2017). However, these engines produce higher emissions than

those based on the Otto cycle, especially nitrogen oxide and particulate matter (BRJESH; SREEDHARA, 2013), because they use fossil fuels, which have been the main source of energy for Diesel engines since the beginning of oil exploration (PERIN *et al.*, 2015).

The use of fossil fuels causes environmental pollution (FRANTZ *et al.*, 2014). Less polluting fuels have been developed and used without affecting engine performance (AL-HASSAN *et al.*, 2012; BALLESTEROS; GUILLÉN-FLORES; MARTÍNEZ, 2014; CHAUHAN *et al.*, 2013; DWIVEDI *et al.*, 2011; ESTRADA *et al.*, 2016; FARIAS *et al.*, 2019a; PERIN *et al.*, 2015).

In this respect, the use of up to 12% of hydrated ethanol combined with mineral Diesel reduces exhaust gas emissions considerably without significantly affecting engine performance (ESTRADA *et al.*, 2016). The use of 10% ethanol mixed with mineral Diesel decreased carbon dioxide emissions by up to 6% when compared to pure Diesel (GUARIEIRO *et al.*, 2009).

Although only 1% of the exhaust gases emitted by Diesel engines are pollutants, 50% of this amount corresponds to nitrogen oxide (HOSEINI *et al.*, 2017). Given the higher heat of evaporation of ethanol mixed with Diesel oil, ethanol can significantly reduce the emission of nitrogen oxide (REN *et al.*, 2008), and 15% ethanol combined with Diesel oil can markedly reduce the emission of nitrogen oxide (ESTRADA *et al.*, 2016; GNANAMOORTHIA; DEVARADJANE, 2013; SONG *et al.*, 2010).

Several studies evaluated the benefits of using biodiesel alone or mixed with mineral Diesel. Biodiesel reduces the emissions of carbon oxide, hydrocarbons, and particulate matter (ALDHAIHAWI; CHIRIAC; BADESCU, 2017; DUDA *et al.*, 2018; JIAQIANG *et al.*, 2017; PERIN *et al.*, 2015).

However, the inclusion of biodiesel to Diesel oil tends to increase the emissions of nitrogen oxide (DUDA *et al.*, 2018; KUMAR *et al.*, 2018; SAHOO *et al.*, 2009; UYUMAZ, 2018), and the increase in the percentage of biodiesel in Diesel oil reduces the thermal efficiency of the engine (ALDHAIHAWI; CHIRIAC; BADESCU, 2017; DUDA *et al.*, 2018). Diesel oil mixed with 20% biodiesel is more efficient and less polluting (ASOKAN *et al.*, 2018; PERIN *et al.*, 2015).

The use of biodiesel is easily adapted to Diesel engines (HUANG *et al.*, 2019). However, biodiesel is not suitable for lubricating engine parts and evaporating the fuel because of its higher viscosity and may cause incomplete combustion (RAMESH *et al.*, 2019). In summary, the emission of pollutants from Diesel engines can be minimized by replacing conventional Diesel with

small amounts of renewable fuels or biodiesel (AZAM *et al.*, 2019).

The use of metallic combustion catalysts as additives in diesel can reduce emissions (AZAM *et al.*, 2019). Furthermore, nanometric metal oxides act as catalysts and provide additional oxygen during combustion because of their high effective surface area, improving combustion. Small amounts of nanoadditives are added to diesel and have negligible effects on the physicochemical properties of the fuel (KHALIFE *et al.*, 2017).

Nanoparticles used as additives include titanium dioxide, calcium carbonate, graphite oxide, ferric chloride, black coal, manganese oxide, copper oxide, ferrous oxide, zinc oxide, alumina, silicon oxide, magnesium, cerium oxide, palladium, platinum, and water emulsions (CHEN *et al.*, 2018; JEYAKUMAR *et al.*, 2018; NAJAFI, 2018; PATNAIK *et al.*, 2017; YASHNIK *et al.*, 2016).

One of the challenges is reducing emissions of particulate matter, hydrocarbons, nitrogen oxides, and carbon monoxide to avoid damage to the environment and health. Several solutions are proposed at the current stage of technology. Azam *et al.* (2019), designed a hybrid ECU composed of a counterflow heat exchanger, oil bath cleaning unit, and an EGR system, and this unit was installed in the exhaust manifold of a tractor engine. The results of dynamometric tests showed a decrease in most emissions, with the exception of carbon monoxide. Decreasing carbon monoxide emissions requires increasing the amount of free oxygen during combustion, which could be achieved using a turbocharger.

In addition to the use of alternative fuels and additives to minimize pollutant emission without reducing performance, other technologies are used in Diesel engines of on-road and off-road vehicles, including EGR and selective catalytic reduction (SCR). However, their efficiency and cost-effectiveness regarding smoke reduction and nitrogen oxide emission are unknown (KUMAR *et al.*, 2020).

Use of EGR and SCR for emission control

Given the concern with the emission of nitrogen oxide, a highly toxic pollutant (NARESH *et al.*, 2015), environmental protection agencies worldwide have defined acceptable thresholds (KUMAR *et al.*, 2020), and stringent emission regulations pose challenges for developing Diesel engines (DHANASEKARAN *et al.*, 2017).

These challenges are being overcome using new technologies (KUMAR *et al.*, 2020), including changes in engine design and EGR and SCR systems

(KONSTANDOPOULOS *et al.*, 2015; SHUKLA *et al.*, 2018). Furthermore, corporate social and environmental responsibility stimulates industries and researchers to focus on reducing emissions (GUNASEKARAN; GOBALAKICHENIN, 2016).

The EGR technology consists of a valve in the combustion chamber, which allows the mixing of intake air with exhaust gases, corresponding to 5–15% of the intake air volume (LOVARELLI; BACENETTI, 2019). This system limits the emission of NO_x (NO and NO_2) by preventing temperature spikes during combustion. One of the disadvantages is that the decrease in the amount of intake air during combustion decreases fuel efficiency, i.e., higher fuel expenditure is necessary to reach the same performance (LOVARELLI; BACENETTI, 2019).

Since 2010, most medium and heavy Diesel vehicles in international markets, including the United States, Europe, and Japan, incorporated the SCR technology (GUAN *et al.*, 2014). Regulations for SCR technology are becoming more stringent and have reached the off-road market.

In the catalyst, ammonia (NH_3), used as a reducing agent, causes the conversion of NO_x into molecular nitrogen (N_2) and water vapor (LOVARELLI; BACENETTI, 2019). Ammonia in the form of 32% urea in water catalyzes NO_x by thermolysis and hydrolysis. Urea is the preferred reducing agent for SCR applications because of its safety and low toxicity (GUAN *et al.*, 2014).

SCR is more effective than EGR and increases fuel efficiency by 4–5% (MAIBOOM *et al.*, 2009). SCR increases engine life by working with clean air, requiring less maintenance. In the SCR system, only one valve controls gas recirculation. However, this system is more complex, requiring specific parts, such as a urea solution tank, a distribution nozzle, and a reaction chamber (LOVARELLI; BACENETTI, 2019). Moreover, although SCR increases fuel efficiency, urea consumption needs to be considered when analyzing the environmental benefits of its production, use, maintenance, and disposal, as well as the conservation and use of urea by farmers (BACENETTI *et al.*, 2018).

Thermodynamic efficiency

The thermodynamic efficiency (TE) is a measure of the performance of a thermal machine, i.e., the efficiency of converting combustion into work (KIM *et al.*, 2013a). Information on combustion efficiency is useful for engine operation and development of electronic controls (TAGLIALATELA *et al.*, 2013).

TE is calculated using data on specific fuel consumption and calorific value (FARIAS *et al.*, 2017a).

TE depends on the engine configuration that provides the lowest specific fuel consumption at a constant calorific value (RAKOPOULOS *et al.*, 2008). TE can reach a combustion efficiency of 39.5% using a supercharger (FARIAS *et al.*, 2017a).

The most important aspects of engine performance and efficiency are related to thermodynamics and are determined by the first and second laws of thermodynamics (CATON, 2018). The first law-energy conservation-states that energy cannot be created or destroyed. The second law has implications for engineering projects and is related to available energy, which is a measure of the maximum useful work produced in a system.

The conditions for maximum engine efficiency include the absence of heat loss and mechanical friction, lean operation, and short duration of combustion (CATON, 2017). One of the most important parameters used to assess the quality of combustion is cylinder pressure (TAGLIALATELA *et al.*, 2013). Thermodynamic diagnosis, which allows determining combustion characteristics, has been used since the 1990s (ARMAS; GARCÍA-CONTRERAS; RAMOS, 2016).

In addition to the potential to implement a thermodynamic diagnosis system in commercial engines to change combustion parameters throughout the engine life cycle (ARMAS; GARCÍA-CONTRERAS; RAMOS, 2016), simulation models that assess performance parameters, such as thermal and volumetric efficiency, torque, power, and specific consumption for different fuels and engine geometries, are useful for designing thermal machines (PARIOTIS *et al.*, 2012).

Strategies for reducing fuel consumption

The agricultural sector is undergoing improvements in efficiency and technological advancements (LANG *et al.*, 2018). The focus on mechanized agricultural operations has a negative environmental impact, especially because of high fuel consumption (LOVARELLI; BACENETTI, 2017). For this reason, the greatest challenge is the need to increase energy efficiency (LOVARELLI; BACENETTI, 2019).

The factors that directly affect fuel consumption are the suitability and use/maintenance of mechanized sets, depth of operation, type and condition of the soil, total number of operations used in soil preparation (MONTANHA *et al.*, 2011); gear selection (FARIAS *et al.*, 2019b; GABRIEL FILHO *et al.*, 2010; KIM *et al.*, 2013b); angular speed and engine load (JANULEVIČIUS; JUOSTAS; PUPINIS, 2013b); and working speed (JASPER; SILVA, 2013).

The search for tractor operation strategies can reduce production costs (FARIAS *et al.*, 2018). These strategies include the control of the engine and transmission to reduce fuel consumption and improve fuel efficiency (FARIAS *et al.*, 2019b; HOWARD *et al.*, 2013;). This control is described as “Gear Up and Throttle Down” (GRISSE *et al.*, 2014a). Savings can be estimated using this technique by multiplying the hours worked annually by the difference consumed (GRISSE *et al.*, 2014b).

The “long gears and reduced acceleration” technique should be used as a rational strategy for operating tractors, with fuel savings of up to 22.43% (FARIAS *et al.*, 2018) and up to 29.39% (FARIAS *et al.*, 2019b) when compared to the maximum acceleration mode commonly used by farmers. Increasing the working speed from 6.5 to 7.5 km h⁻¹ and changing the gear from B2 to B3 improved energy efficiency and decreased specific fuel consumption by 9.5% (MONTEIRO *et al.*, 2011).

However, this fuel-saving strategy can be optimized when the load demands on the drawbar are less than 75% of the nominal power (GRISSE *et al.*, 2014a). When the actual engine power is less than 80% of nominal power, rotation should not exceed 80% of nominal rotation (JANULEVIČIUS; JUOSTAS; PUPINIS, 2013b). For drawbar power between 35% and 50% of maximum power, the strategic use of powershift transmission is more efficient than tractors with continuously variable transmission (CVT) (HOWARD *et al.*, 2013).

In addition to improving driving, new technologies have been developed to reduce production costs and increase energy efficiency (FARIAS *et al.*, 2017b). CVT is currently used in Brazil and paved the way for comprehensive engine and transmission control, improving productivity and user comfort (LINARES *et al.*, 2010).

Given the joint control of the engine and transmission by CVT, the possibility of working with lower revolutions and adequate working speeds increases fuel efficiency, as long as there is no overload to the extent of reducing torque reserve (FARIAS *et al.*, 2017b). There was a significant decrease in fuel consumption using CVT in automatic mode because the load imposed on the tractor was higher.

However, further studies are necessary to evaluate energy efficiency in CVT systems, according to the operating demand and operator training (FARIAS *et al.*, 2017b).

Assessment of engines in the context of Agriculture 4.0

Agriculture 4.0 promoted changes in strategies to evaluate engines. Data can be collected for the same

parameters during tractor tests, and the efficiency of the engine power transmission system can be measured under varying operating conditions, enabling producers to select the most suitable tractor for the intended use (HOY; KOCHER, 2020).

Electronic devices allow access to a large amount of measurable data simultaneously during fieldwork using GPS technologies (PITLA *et al.*, 2016). These data include engine operation, type of fuel, pollutants emitted, and work characteristics and interactions (JANULEVIČIUS; JUOSTAS; ČIPLIENE, 2016).

Collecting data and monitoring tractor activity enable improving efficiency and environmental management (LOVARELLI; BACENETTI; FIALA., 2016). These technologies can avoid underestimating or overestimating bench tests, quantifying the difference between the most sustainable operation relative to other strategies, determining where improvements can be made during fieldwork, and increasing the awareness of users of their role in the sustainability of farming practices (LOVARELLI; FIALA; LARSSON, 2018).

Dynamometry

Digitization can move agricultural management to a data-driven approach (CAROLAN, 2017). Collecting data and monitoring tractor activity allow improving efficiency, dimensioning fleets, and optimizing their use (LOVARELLI; FIALA; LARSSON, 2018). Technological advances enabled combining machines to use engine power effectively (ROEBER *et al.*, 2017). Data on engine torque at each angular speed, power, and hourly and specific fuel consumption are fundamental for customers who purchase an agricultural machine or adjust mechanized sets.

Hoy and Kocher (2020) argue that users better understand what functions and characteristics are most important for their applications and compare results from different reports, giving more weight to the most relevant data.

There are doubts about the accuracy of manufacturer data, especially regarding motorization (FARIAS; SCHLOSSER, 2018). Farias *et al.* (2016) found that data on actual maximum power agreed with manufacturers' specifications in 67.5% of cases.

In this respect, the use of dynamometers is an essential part of engine performance tests (RUAN *et al.*, 2018). The operation of commonly used dynamometers, such as Foucault currents, is based on the production of electric currents inside a metallic rotor surrounded by a variable magnetic field. The variation in electric current produces torque on the dynamometer and is measured by

the load cell coupled to a lever of known length (GALLO *et al.*, 2017).

To obtain actual torque data, effective power, and specific fuel consumption, free of commercial interference or design errors, the tests are carried out by independent agencies and promote competition between manufacturers, allowing improvements in tractor design (FARIAS; SCHLOSSER, 2018).

In Brazil, the evaluation of torque and power using dynamometric tests is not mandatory, and data on actual performance are limited. The lower torque and maximum power in some tractors can adversely affect field performance, interfering in the size of machines and implements, and causing economic losses to users by reducing power (FARIAS *et al.*, 2016).

Farmers have doubts about the operation of new generations of engines in the context of Agriculture 4.0, and dynamometric tests can assist in decision-making. Working with extremely low or extremely high engine loads increases fuel consumption and pollutant emissions and decreases efficiency (LOVARELLI; BACENETTI, 2019). Working in the average torque range and angular speed providing good performance in the field and satisfactory results regarding fuel and lubricant consumption and emissions.

Official testing standards

Agricultural tractors can perform a wide range of tasks, including the use of implements to carry out multiple activities. The tractor test follows technical development and several methodologies, standards, and protocols from manufacturers with the view to meet all performance standards (CUTINI; BISAGLIA, 2016).

Official tests follow standards and depend on accreditation of the executing agency, availability of facilities and equipment, trained and qualified technical staff, and other requirements, including comparability, reproducibility, and reliability (FARIAS; SCHLOSSER, 2018). Since 1959, the norms of the Organization for Economic Cooperation and Development (OECD) have facilitated international trade as well as simplifying and integrating documentation, inspection, and testing procedures (CUTINI; BISAGLIA, 2016).

Auxiliary systems made a significant contribution to the assessment of engine power; some components, such as fans or water pumps, were driven by the crankshaft and decreased the steering wheel's output power, whereas other components, such as silencers and filters, increased air and fluid resistance (SANDU, 2018).

The nominal power of internal combustion is defined as the power obtained in a bench test at the end

of the crankshaft at the angular speed of the engine, under atmospheric conditions, and is calculated as the difference between the gross and net power of the accessories defined by different norms (SANDU, 2018).

In Brazil, the Brazilian Association of Technical Standards (Associação Brasileira de Normas Técnicas–ABNT), through NBR ISO 789-1:2020 (ABNT, 2020), specifies the test procedures to measure power take-off (PTO) in wheeled tractors and loading conveyors.

Testing using PTO and power losses

The characteristics and performance of Diesel engines are determined by dynamometric tests and are represented by graphs, which show data on torque, power, and fuel consumption (FARIAS; SCHLOSSER, 2018).

The most efficient transmission—approximately 90% of the net engine power of a tractor—is indicated by the PTO axis (ROEBER *et al.*, 2017). Tests are performed using PTO to preclude the need to remove the engine during the evaluation. However, it is necessary to correct data on torque and power, considering the losses in the transmission system due to empty operation of the hydraulic system, hydraulic oil heating in hydrostatic transmissions, and the friction and heat generated in the gearbox (FARIAS; SCHLOSSER, 2018).

Atmospheric pressure, temperature, and relative air humidity influence torque, power, and specific fuel consumption (SANDU, 2018). This set of atmospheric parameters depends on the climate and geographical region. To assess and compare engine performance, certification procedures are performed under standard atmospheric conditions. However, correction factors are adopted because laboratories are located in regions with different altitudes and climates (SANDU; UNGUREANU, 2019).

CONCLUSIONS

1. Modern internal combustion engines of agricultural tractors follow the technological trend of Agriculture 4.0, regarding the development of electronic systems and use of algorithms, combining artificial intelligence for different operating conditions, improving combustion, performance, and TE;
2. Engine technologies improve the use of non-renewable fuels by adjusting the programming of the ECU, which controls the high-pressure injection system, and reduce pollutant emissions according to legislation.

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