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Typical performance behavior of a Diesel cycle agricultural tractor engine with electronic injection management and turbocharger

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ABSTRACT: *Over the past few years, changes have been observed in the behavior of typical performance curves, after higher technology has been incorporated into the agricultural tractor engines, either to satisfy the ceiling of the new pollutant gas emission limits or to achieve better efficiency. The aim of this study was to assess the typical performance behavior of an agricultural tractor engine, possessing electronic injection management, turbocharger, aftercooler and EGR (Exhaust Gas Recirculation) treatment system. An analysis was done of the information the manufacturers provided, in terms of nominal power, maximum power and maximum power with Booster, maximum torque and maximum torque with Booster. From the results, the percentage difference between the nominal power and maximum power were found to hover anywhere from 1.49 to 11.97%, for the same manufacturer, 0% in another manufacturer and 9% in a third manufacturer, for all the models. Similar results were noted for the data reported on the maximum torque and maximum torque with Booster, giving 0.62% as the minimum value, 7.44% as the average value and 12.65% as the maximum value for the entire series.*
Key words: *dynamometric test, torque, power, constant range.*

Comportamento típico de desempenho de um motor de trator agrícola ciclo Diesel com gerenciamento eletrônico da injeção e turbocompressor

RESUMO: *O comportamento das curvas típicas de desempenho passou por alterações nos últimos anos, com a adoção de maior tecnologia pelos motores de tratores agrícolas, seja para atender aos novos limites de emissões de gases poluentes ou na busca por maior eficiência. Este trabalho teve como objetivo avaliar o comportamento típico de desempenho de um motor de trator agrícola, equipado com gerenciamento eletrônico da injeção, turbocompressor, aftercooler e sistema de tratamento de gases EGR (Exhaust Gas Recirculation). Também foram analisadas as informações disponibilizadas pelos fabricantes para os dados de potência nominal, potência máxima e potência máxima com Booster, torque máximo e torque máximo com Booster. Os resultados demonstraram que a diferença percentual entre a potência nominal e a potência máxima pode variar de 1,49% a 11,97% para um mesmo fabricante, 0% em outro e em um terceiro fabricante os valores situam-se em aproximadamente 9% para todos os seus modelos. Resultados similares foram encontrados para os dados informados de torque máximo e torque máximo com Booster, com valor mínimo encontrado de 0,62%, valor médio de 7,44% e o valor máximo de 12,65% para toda a série.*
Palavras-chave: *ensaio dinamométrico, torque, potência, faixa constante.*

Besides the transmission, the agricultural tractor engine is one of the distinguishing components that sets it apart. A farmer purchases a tractor, making his selection, for the features of its power, comfort, operational ease, maintenance and price. However, SILVEIRA & GIL SIERRA (2010) indicate that besides these features, the energy efficiency of the tractor could be one more factor to consider during tractor selection, as it is most pertinent while fixing the price; it is also a criterion employed in the harmonic sizing between the tractor and implement (SIMONE et al., 2006).

After dynamometric tests are done, without commercial interference, data on the torque, power and specific fuel consumption can be acquired (FARIAS & SCHLOSSER, 2018). The agricultural tractor engines can be subjected to dynamometric tests directly on the flywheel or via the tractor's power take-off (PTO).

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When the PTO is used during the test, the results will be lower in comparison to the findings obtained directly on the flywheel, because of the transmission losses. The technical instructions of ASAE 496.3 and ASAE D497.7 reveal around a 10% loss between the engine and PTO (ASABE, 2006; ASABE, 2015). However, MÁRQUEZ (2012) stated that because of the complexity of the transmission and its association with the PTO, a 4 to 12% variation in the losses can be observed.

According to VSÓROV (1986) the graphical representation of the data acquired through experimentation, is the engine performance curve, which can be distinguished into two categories, namely typical and special. According to LILJEDAHL et al., (1996) the representation of a typical curve reveals that the 'load capacity' of the engine is the performance criterion or, more accurately, the torque curve. This representation, according to the authors, can be expressed as a percentage of the maximum torque in relation to the engine speed (rpm), as well as via the ratio of the engine torque in N.m versus rpm.

In accordance with the convention used in technical standards, the performance characteristics of the engine, acquired through dynamometric tests, and the variable responses are given in tables and through figures (curves), based strictly on the respective test standard employed. This is because the operating characteristics for the same specimen can show considerable variations in accordance with the conditions prevailing during the measurement procedure (MÁRQUEZ, 2012; MIALHE, 1996).

Therefore, each test standard sets up procedures that, for the same engine, give different performance values. According to MÁRQUEZ (2012), the main protocols are the OECD Code, the ISO TR 14396, SAE J1995, SAE J1349, DIN 70020 standards, the European directives 80/1269/EEC and 2000/25/EC and the Geneva regulation ECE R24.

These assessment procedures vary with regard to the correction standards for the atmospheric state, temperature reference and kind of fuel, apart from the expression of the elements or their suppression (accessories crucial for engine operation). A less limiting standard ignores the power demands of the air filter, exhaust, water pump, radiator and fan, which may reveal differences in the torque and power to a maximum of 12.1% compared to those observed when another standard or protocol is adopted.

Over the recent few years, while seeking means of raising the engine efficiency, plus achieving the standard emission regulations for pollutant gases, the supply of supercharged engines has escalated, as they are specially fitted with aftercooler and managed with electronic fuel injection. In reality, new technologies were incorporated, like the sizing of intake manifolds with more efficient utilization of the pressure waves (resonance) (MAZZARO et al., 2020), besides others. Such progress gave rise to the production of different performance curves, unique from those resulting from the use of classic or old engines, which employed the mechanical injection management system and natural air aspiration.

Simply expressed, power (kW) is the product of the engine speed (rpm) and torque (Nm), implying that for the same torque, a higher engine speed will release higher power. The action of the mechanical injection system gets transferred to the engine power curve, which is achieved from the dynamometric test and shown in the Cartesian plane, as a peak (maximum point); this represents the maximum power point, after which, with the imposition of a greater load the engine begins to decelerate, reducing both, the power and engine speed. For these engines, the maximum power point is otherwise termed the 'rated power point'. Thus, according to SIMONE et al., (2006) the interval between the maximum power engine speed (or rated speed) and the maximum engine speed, is called the zone of action of the governor, or the 'governor of rotation'.

At present, it is evident that the employment of engines having different settings in the injection system permits a rise in the elasticity, thereby establishing a 'constant power' range, because of the nearly flat shape of the power curve and achieving of the maximum power before the rated power (MÁRQUEZ, 2012). Generally, the manufacturer declares the rated power, which concurs with the regimen employed, at which the engine continuously reaches its maximum power (SIMONE et al., 2006). The modern agricultural tractors reveal the achievement of maximum power before the rated power, which on average, ranges from 100 to 500 rpm.

The constant power range in the direct-injection and turbocharged engines occurs via a two-stage injection pump. In the first stage, the injection acts in a manner similar to the engines that use the conventional injection pump. In the second stage, a continuous injection of fuel happens in such a way as to compensate for the decrease in the engine speed with an increase in the cylinder's average combustion pressure, thus either maintaining the power as it is or raising it, rather than causing it to drop (MÁRQUEZ, 2012). Thus, engines having a constant power range facilitate the operations to occur even at lower engine speeds, establishing the best energy efficiency range and, thereby, utilizing the lowest amount of fuel. However, this necessitates an oversized engine with a more advanced injection system, which places a restriction on the maximum producible power.

This notion of constant power is also evident in the engine families adopted by the manufacturers, in which the same engine design provides a wide range of power via technologies like utilizing four valves per cylinder, a variable camshaft at the intake and/or exhaust, supercharging, aftercooler and electronic engine management systems.

By employing electronic units in the engine for fuel injection control, manufacturers are able to produce injection maps by assigning the constant and desired power range for each tractor. This design is also applicable to the range of the torque in the engine, thus providing a constant torque range. It is noteworthy that in the engine families, there are normally two conditions for engine usage: one is the use of an oversized engine for the lower power tractors; the other is the use of an undersized engine in the higher power tractors. Such a design influences the engine performance, efficiency and durability.

Booster and Eco modes are examples of torque and power curves additionally programmed into the mapping of the electronic engine. The Booster mode can be activated automatically when the tractor identifies an overload in the hydraulic system, or also when transporting at high speed, or even when high power is required with the activated PTO, for example. However, it is worth noting that the Booster increases the torque and power for a short time span, just enough to overcome the overload of the systems and return, in sequence, to the original condition. In this sense, the power value with Booster must not be considered during the sizing of mechanized sets.

The Eco mode, however, normally involves manual activation, either using a particular button or through a variety of gear shifts, in an engine and transmission integration, which alters the injection maps. This system enables the engine mapping strategies to be changed by the operator, when an activity that needs minimum effort is being attempted, thus ensuring maximum engine efficiency as the priority and, thereby, economizing on the fuel. The programming of such additional curves in the engine result in other nominal and maximum points, because of its layout, which differs completely from the standard engine curve.

In the current study, the objective is to use the typical performance curves to investigate the behavior of a modern agricultural tractor engine. The engine under analysis has four cylinders, four valves per cylinder, 4400 cm³ displaced volume, turbocharger with aftercooler, gas treatment system provided with EGR valve and a fuel injection with electronic management of the Common Rail type system. Using a dynamometer coupled to the PTO of the tractor, a performance test was conducted.

The bibliography available on this subject is very limited; however, the facts mentioned earlier, concurred with and are included in the works of VSÓROV (1986), GOERING (1992), LILJEDAHL et al., (1996), MIALHE (1996), SRIVASTAVA et al. (1996), SIMONE et al., (2006) and MÁRQUEZ (2012). As well as the findings of the tests performed on several engines in the Laboratório de Agrotecnologia - Agrotec (UFSM) from 2010 to 2020, and all the data drawn from the main global test stations.

Thereby, the figure 1 represent the typical performance curves and the principal points, characteristic of an agricultural tractor engine operating at full load. Curve 1 shows the way the power behaves, curve 2 reveals that of the torque, curve 3 depicts the fuel consumed per hour and curve 4 denotes the specific fuel consumed, the results are indicated at the momentary engine speed, at full load. There are nine main points, as explained below:

A - Maximum power point - in the engine test this is the maximum value achieved by the product of torque versus engine speed;

B - Point of nominal power - normally, the manufacturer declares it, and this corresponds to the regime employed, at which the engine continuously achieves its maximum power;

C - Maximum torque point – this is the operational state at which the highest value is observed for the average effective pressure that can be built up in the engine cylinders. This point is indicative of the lower limit of the engine utilization range (UR_{mp}) and the utilization range, in light of the constant range of power or nominal power (UR_{np});

D – The site of the upper limit of the range of constant torque – observed on the curve where the range of the torque values remains constant from their maximum point;

E - Maximum power torque point - the torque produced at the engine speed that facilitates achieving the maximum power, at this point, which indicates the upper UR_{mp} limit;

F - Rated power torque point or rated torque - the torque produced at the engine speed, which enables the engine to reach the rated power; this point indicates the upper UR_{np} limit;

G - Optimal hourly fuel consumption point – this relates to the fuel consumption per hour

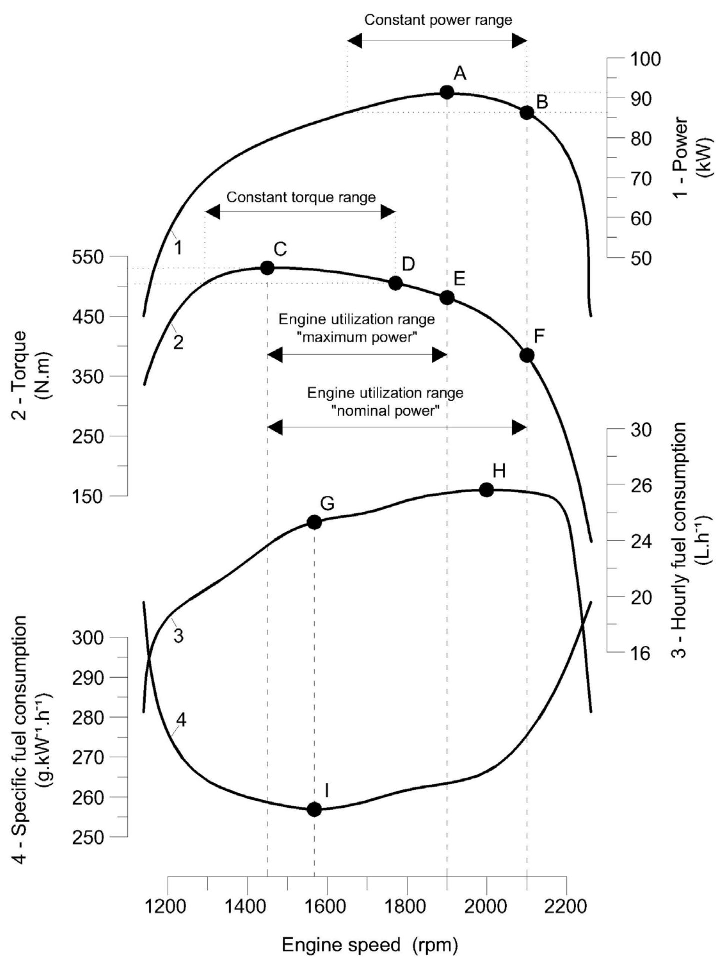

Figure 1 - Typical performance curves of a Diesel cycle engine, with a turbocharger and an electronic fuel injection management system, and the principal parameters characteristic of the operation at full load.

at the engine speed when the minimum specific consumption is observed to take place;

H - Maximum hourly fuel consumption point – this indicates the point at which the engine reaches the maximum fuel consumption;

I - Point of minimum specific fuel consumption – this is the point at which the thermodynamic efficiency reaches the maximum, which is the ideal operational condition with respect to the engine speed and torque for the engine (MIALHE, 1996).

In fact, MIALHE (1996) determined that the maximum torque and maximum power speeds, restrict the alleged utilization range (UR_{mp}) of the engine. The engine, within this range, exhibits stable operation, and is capable of self-regulation when slight variations occur in the resistant torque. Self-regulation, according to GARCIA & BRUNETTI (1992), is specified by what they termed the 'elasticity index'(EI). This index will be higher and the engine will be more elastic, as the torque increases and the UR_{mp} rises. SIMONE et al., (2006) interpreted the elasticity of the engine as its capacity to absorb a specific overload, and continue working (neither stopping nor going off), by accommodating the overlap and running without interruption despite the overload, until the overload ends, enabling it to resume the initial working regime.

MIALHE (1996) identified another parameter that distinguishes the UR_{mp} at full load, which is termed the 'torque holding capacity' or torque reserve. This is estimated by the torque range between Point E and Point C, with the results being expressed in percentage. Over the recent years, tractor manufacturers have begun to regard, possibly as a marketing method, the rated power to assess the torque reserve of the engine, rather than the maximum power. Therefore, the torque range was considered from Point F to Point C. As the manufacturer determines the rated power, it is possible to boost these values, by moving the rated power further ahead on the power curve of the engine. This enables a greater torque reserve to be the set up, which in turn justifies values of 50% or more, as revealed by some manufacturers.

Thus, the UR_{np} begins to appear because the manufacturers starts to utilize the nominal power value for their calculations, and/or adopted the constant power engines (including engines possessing the electronic injection management). As the engine manufacturers adopted the fuel injection methods, the constant torque range could be observed, restricting the fuel injection at certain points and adding it in other points, thus producing a range of the same torque. This is a very common characteristic of the engines belonging to engine families or underutilization, or even due to the marketing strategies of some companies. An identical feature occurs with the methodology adopted by each company to assess the torque reserve, dependent of which torque points are used or not, the torque at the maximum power or the torque at nominal power.

It is also noteworthy that with the arrival of modern engines, the maximum power engine speed regime decreased. For the classic engines, the maximum power routinely hovered between 2200 to 2400 rpm. As pollutant gas emissions were required to be reduced, which caused the downsizing of the engines, furthermore the quest for engines with low fuel consumption and high durability, the modern engines today can provide maximum power in the 1600 to 1900 rpm regimes.

To represent this manufacturer-generated data, the information was compiled listing the features of the tractors marketed in Brazil in 2020, related to nominal power, maximum power, maximum power with Booster, maximum torque and maximum torque with Booster. This information is listed in their catalogs.

The percentage difference between the nominal power and maximum power (Figure 2A)

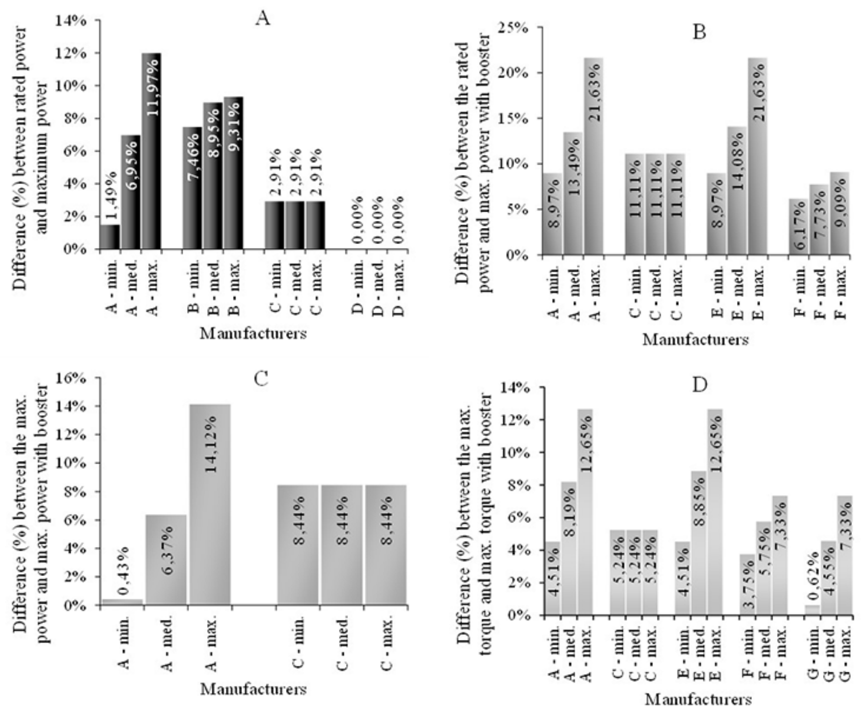

Figure 2 - The differences in percentage among the minimum, average and maximum values, as declared by each manufacturer, between the rated power and maximum power (A); between the rated power and maximum power with Booster (B); between the maximum power and maximum power with Booster (C); and between the maximum torque and maximum torque with Booster (D).

of each tractor model was verifiable for the same manufacturer (manufacturer A) and variations were from 1.49 to 11.97% were noted. In the case of manufacturer B, a reference value of about 9% difference was evident between the maximum and nominal powers in almost all its models. For manufacturer C, data was presented only for one model, showing the minimum, average and maximum values of 2.91%. In the case of manufacturer D, no differences were reported between the nominal and maximum powers. For this relationship, the minimum value was 0%, while the general average and maximum were 7% and 11.97%, respectively.

With reference to the nominal power and the maximum power with Booster (Figure 2B), both manufacturers A and E revealed similar behaviors, registering variations from 8.97 to 21.63%. The minimum value for this relationship was around 6.17%, with the general average standing at 12.96% and the maximum at 21.63%.

From the findings of the maximum power related to the maximum power with Booster (Figure 2C), the same manufacturer (manufacturer A) showed variations from 0.43 to 14.12% in all the tractors, which indicate the minimum and maximum values for the whole series. The 6.47% average suggests an escalation in the values between the maximum power and maximum power in Booster mode, for the entire series.

With respect to the data reported for the maximum torque and maximum torque with Booster (Figure 2D), two manufacturers, who share an engine family, reveal 4.51 to 12.65% augmentations for the various tractor models. For the entire series, the least rise in the maximum torque on activation of the Booster mode was evident in a model showing 0.62%, with an average of 7.44% and maximum value of 12.65%.

In this regard, irrespective of the reason, either for the purchase of a machine, or to more clearly comprehend the behavior of the machine, or to find ways to enable it to achieve higher efficiency, some basic knowledge about the performance curves of the engine and the distinguishing features of each characterizing point is fundamental. This will enable correction of the tractor and ensure the highest yield possible, as well as minimize the expenditure costs and protract the service life.

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DECLARATION OF CONFLICT OF INTEREST

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

AUTHORS' CONTRIBUTIONS

All authors contributed equally for the conception and writing of the manuscript.

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