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Performance of a diesel engine using different biodiesel blends and injection configurations[1]

Desempenho de um motor diesel utilizando diferentes misturas de biodiesel e configurações de injeção

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HIGHLIGHTS:
Mechanical fuel injection systems with an injection pump can be replaced by electronic control systems.
Use of blends with biodiesel leads to a shorter ignition delay.
Advancing the injection point increases the power and decreases the specific fuel consumption.

ABSTRACT: Diesel cycle engines are widely used in a wide range of agricultural activities. Recently, with the increasing use of biodiesel mixed with petroleum diesel and the introduction of pollutant emission regulations for agricultural and road machinery, there has been a growing migration from mechanical to electronic fuel injection systems. In this experiment, the primary aim was to verify the behavior of a diesel engine, electronically managed, with controlled variation of the fuel feeding system parameters (injection time and volume injected). A four-cylinder agricultural tractor with a turbocharged engine and a common rail electronic fuel injection system was used. Tests with diesel B10 and blends of 20 and 30% biodiesel were carried out, all with 10 ppm of sulfur and the injection system electronically reprogrammed. The tests were performed under full engine load from 1,300 to 2,000 rpm. The torque, power and fuel consumption were evaluated. Advancing the injection point increased the power and decreased the specific fuel consumption for all fuels. The greater amount of injected fuel provided average power gain of up to 14.96% and average torque gain of 15.50%.

Key words: electronic injection, reprogramming, common rail

RESUMO: Os motores ciclo diesel são amplamente empregados para a execução das mais diversas atividades agrícolas. Recentemente, com o incremento da utilização do biodiesel em mistura ao diesel de petróleo e o início da vigência da regulamentação de emissões de poluentes em máquinas agrícolas e rodoviárias, ocorreu uma crescente migração do sistema mecânico de injeção para o sistema de injeção eletrônica de combustível. Neste experimento, o objetivo principal foi verificar o comportamento de um motor diesel, gerenciado eletronicamente, com variação controlada dos parâmetros, momento de injeção e volume injetado, do sistema de alimentação de combustível. Foi utilizado um trator agrícola com motor de quatro cilindros, sobrealimentado e com injeção eletrônica de combustível common rail. Foram realizados ensaios com diesel B10 e misturas de 20 e 30% de biodiesel, todos com 10 ppm de enxofre, e realizada a reprogramação eletrônica do sistema de injeção. Os ensaios foram realizados em regime de carga plena do motor de 1.300 a 2.000 rpm. Foram avaliados o torque, a potência e o consumo de combustível. O avanço do ponto de injeção aumentou a potência e diminuiu o consumo específico de combustível em todos os combustíveis. A maior quantidade de combustível injetado proporcionou ganho de potência médio de até 14,96% e de torque médio de 15,50%.

Palavras-chave: injeção eletrônica, reprogramação, common rail

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Introduction

Internal combustion engines are widely used in agriculture and most are compression-ignition endothermic engines (diesel cycle), which are currently assembled with an electronic fuel injection system (Schlosser et al., 2020), allowing more precise adjustment of the injection time and pressure (Kumar et al., 2020).

In the electronic injection system, an electronic control unit (ECU) is responsible for monitoring all the sensors available in the engine and, after processing the data, controlling the fuel injection parameters (Gabdrafikov et al., 2019). Consequently, the accelerator pedal position sensor (APPS) plays an important role in the engine operation, as it informs the ECU of the power required (Ramesha et al., 2016), reducing the fuel consumption as the engine throttle speed is decreased (Farias et al., 2019).

In addition, the fuel volume to be injected at each stroke is dependent on the common rail pressure and injection nozzle opening time, which are also controlled by the ECU (Sala et al., 2022). It also varies according to the rotation, and fuel characteristics (Gutierrez & Sala, 2015). The use of blends with biodiesel tend to lead to a shorter ignition delay and, consequently, a higher pressure rise rate, which indicates the need for a lower injection point advance (Das et al., 2018).

In this context, the aim of this study was to verify the behavior of an electronically managed diesel engine by measuring the torque, power and fuel consumption with the use of different biodiesel blends and varying the injection parameters of the fuel feeding system.

Material and Methods

The study was carried out in the Laboratório de Agrotecnologia at the Universidade Federal de Santa Maria, in Santa Maria-RS, Brazil (29°43' 21.2" S and 53°43' 08.5" W, with average altitude of 113 m).

A Massey Ferguson 6713R tractor, with a four-cylinder engine, was used. Its features include the following: displaced volume of 4,397 cm^3, Bosch common rail direct-injection, supercharged with a turbocharger, intercooler, managed by an electronic fuel injection system, maximum power of 96 kW at 2,000 rpm and maximum torque of 540 N m at 1,500 rpm.

The base fuel used was diesel S10 with 10 ppm of sulfur and 10% of biodiesel in its composition, according to the current Brazilian legislation. The fuel blends were mixed at the experiment site using the volumetric blending method. To formulate the B20 and B30 blends, soybean oil-based B100 biodiesel was used, in accordance with ANP Resolution No. 45 of 2014. Furthermore, 125 mL of B100 biodiesel was added to the B20 fuel per liter of B10 Diesel and 285.7 mL of B100 biodiesel was added to the B30 fuel per liter of B10 diesel. The volumetric density of the fuels ranged from 0.8440 kg m^{-3} for B10 to 0.8820 kg m^{-3} for B100.

The fuel samples were stored in external 20 L polyethylene containers, which were connected to the MF 6713R tractor through the fuel suction and return hoses. Thus, the fuel changeover procedure between tests was controlled, neutralizing possible interference between the different types of fuel used in the different experiments.

The experimental design was completely randomized with four repetitions in a factorial arrangement (3 × 2 × 2 × 8). The factors evaluated were: the proportion of biodiesel in the blend with S10 diesel (using fuel samples B10, B20 and B30, with 10, 20 and 30% biodiesel, respectively); the fuel injection time, applying the original time set by the tractor manufacturer and another (called "+F") with an increase in the amount of fuel injected; and the fuel injection point, applying the original condition established by the manufacturer and another with an advanced injection point (called "+P"). The engine rotation range used was 2,000 to 1,300 rpm.

To impose the partial loads on the engine, an air-cooled electromagnetic brake-type (Foucault currents) portable dynamometer with an electronic system for load control was used (model PT 301 MES, EGGERS) with coupling through the tractor power take-off (PTO). The applied loads and the acquisition of torque and engine angular speed data were controlled using the EGGERS Power Control software, which is included with the equipment. The atmospheric pressure, temperature and relative humidity data used in the atmospheric correction factor were provided by the meteorological station present in the equipment.

A data acquisition rate of 1 Hz was adopted for all parameters and test times at each rotation. For the statistical analysis of the results, data from extreme points were disregarded and only the last 30 data points of each angular speed used during the tests were considered.

The power generated by the engine was calculated as a function of the torque available at the flywheel and the angular speed at which it occurred using Eq. 1.

$$P = T \times N \times \pi \times 30,000^{-1} \tag{1}$$

where:
P - power produced (kW);
T - torque generated (N m); and,
N - engine angular speed (rpm).

The atmospheric factors must be considered when calculating the corrected power, because this allows the comparison of tests performed in different locations and with various atmospheric conditions. Thus, the correction factor (ABNT, 1996) is given by Eq. 2.

$$Fa = \left(\frac{99}{Pd}\right)^{0.7} + \left(\frac{T}{298}\right)^{1.2} \tag{2}$$

where:
Fa - atmospheric correction factor (dimensionless);
Pd - dry atmospheric pressure (kPa); and,
T - temperature at the engine inlet (K).

Therefore, after calculating the correction factor, the corrected engine power was obtained using Eq. 3.

$$Pc = P \times Fa \tag{3}$$

where:

Pc - corrected power (kW);

P - measured power (kW); and,

Fa - reduction factor due to atmospheric conditions.

The fuel consumption was measured using an EGGERS flow meter (model FM3-100), with a measurement range of up to 100 L h^{-1}, which enables its use for engines of up to approximately 300 kW. In addition, the flow meter used provides a volumetric measurement of consumption, but with the data on the temperature and fuel density the value in mass was directly calculated. Therefore, the amount of hourly fuel consumed by the engine was calculated by measuring the flow available to the engine and subtracting the flow back to the fuel tank.

To calculate the specific fuel consumption, Eq. 4 was used.

$$Cs = Ch \times P^{-1} \tag{4}$$

where:

Cs - specific fuel consumption (g kW h^{-1});

Ch - hourly fuel consumption (g h^{-1}); and,

P - engine power (kW).

The specific fuel consumption of the engine is represented by the ratio between the mass of fuel used by the engine and the power produced in a one-hour period. The fuel mass is the product of the volume consumed and its specific mass. Its magnitude is directly related to the thermal efficiency of the engine and serves as an indication of the amount of fuel needed to perform any given work.

Since the amount of fuel injected in each engine cycle is dependent on the pressure in the fuel distribution pipe and the nozzle opening time, both commanded by the ECU, a fuel pressure sensor signal emulator was used, as the original ECU is blocked from being changed by the manufacturer.

The emulator acts on the reading of the signal coming from the fuel pressure sensor in the common rail, applying an offset of -7% to its voltage and sending the new reading to the ECU. With the new voltage value, the fuel pressure reported to the ECU was lower than the real value. In this way, the injector opening time was automatically recalculated, resulting in a longer opening time and consequently an increase in the amount of fuel injected.

The emulator works by controlling a signal through free hardware (an electronic prototyping platform), where the analog signal coming from the sensor is read as its analog input and converted into a pulse width modulated (PWM) output according to the logic programmed in its code. The PWM output signal is filtered by resistors and capacitors to give a value as close as possible to an analog signal.

The location where the crankshaft position sensor is fixed was modified to change the fuel injection point. This change caused the phonic wheel reading to be advanced by 2.5 degrees and consequently all injection parameters were advanced by the same number of degrees when compared to the original condition. To change the crankshaft sensor position, eccentric bushings were designed and manufactured using 3D printing.

The injected fuel volume and injection start time were modified after the tests with the control treatment and verification of the thermal efficiency of the engine under the manufacturer's original conditions with B10, B20, and B30 fuels.

The data collected were submitted to analysis of variance, the Tukey test (considering $p \leq 0.05$) and linear regression analysis.

Results and Discussion

A significant interaction between the fuel and the rotations was observed for all variables analyzed (Table 1).

With the engine in its original condition, the B10 fuel did not statistically differ from the B20 fuel in terms of the torque and power produced over the entire rotation range observed (Table 2). The B30 fuel, on the other hand, with 30% biodiesel in the blend, presented an average decrease in the power curve of 4.48% and in the torque curve of 3.60%, with more accentuated differences at higher rotations, as shown in Figures 1 and 2. Aldhaidhawi et al. (2017) and Duda et al. (2018) found variations similar to those reported herein.

Guimarães et al. (2018) reported decreased performance for blends with biodiesel contents above 25%. Part of this variation is due to the lower calorific value of the biodiesel, which consequently provides a smaller amount of heat for the engine to transform into mechanical energy. The different combustion dynamics of biodiesel also makes the rate of heat release slower when compared to conventional diesel. As a result, the difference in performance is greater at higher rotations, with less time available for the combustion heat to be used.

In the tests performed with the B10 fuel, the best results for both for torque and power were obtained with added fuel (B10+F). In this situation, the 16.96% increase in the injected fuel volume provided average increases of 14.96% for power 15.50% for torque. These results show that this engine can be used in other applications with higher power demand because it does not use all the admitted air in the combustion. This result was expected due to this excess air, since greater fuel injection results in greater heat release and consequently a greater production of mechanical energy.

Table 1. F calculated from the analysis of variance for torque, power, hourly consumption, and specific fuel consumption

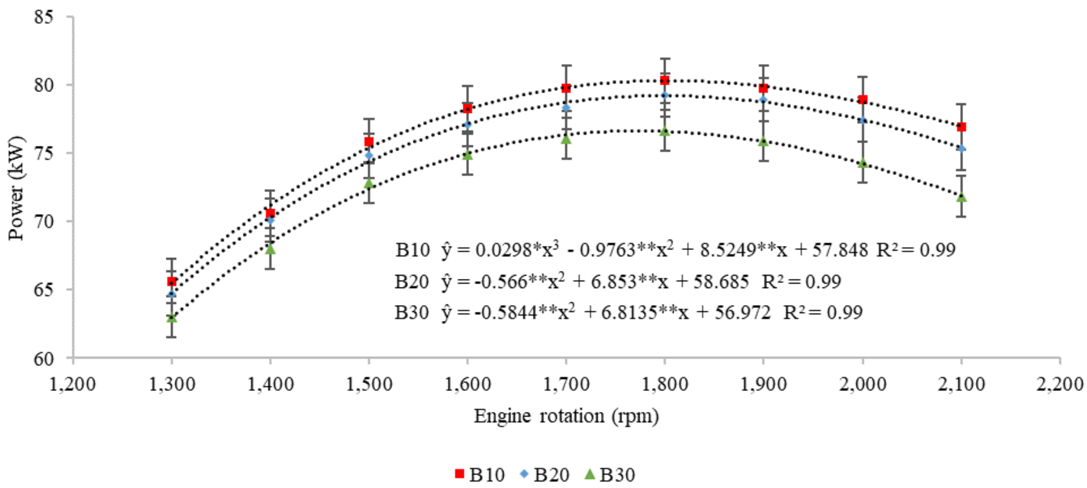
Sources of variation	DF	Torque	Power	Hourly consumption	Specific consumption
		F calculated			
Fuel (F)	2	285.4*	273.5*	179.8*	245.9*
Debit (D)	1	21,904.8*	16,084.6*	18,239.0*	438.7*
Point (P)	1	1223.9*	481.5*	2,741.1*	663.3*
Rotation (R)	7	9,175.8*	2,558.2*	4,106.7*	421.0*
F × D	2	14.9*	11.9*	63.8*	61.3*
F × P	2	47.9*	85.1*	4.4*	45.3*
F × R	14	1.5*	1.5	49.1*	33.2*
D × P	1	3,424.3*	2,634.4*	774.5*	204.2*
D × R	7	280.9*	56.7*	209.9*	62.1*
P × R	7	45.2*	21.0*	51.1*	17.1*
F × D × P	2	0.02	1.6	78.7*	55.9*
D × P × R	7	10.9*	0.9	41.8*	24.0*
F × D × P × R	14	0.8	1.1	36.8*	22.2*
CV (%)		1.98	2.26	2.64	3.58

* - Significant at $p \leq 0.05$, by F test; CV - Coefficient of variation; DF - Degrees of freedom

Table 2. Mean values for engine power and torque in the tests at each engine rotation

	Engine rotations (rpm)							
	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000
				Power (kW)				
B10	66 de	71 80	76 de	78 de	80 de	80 de	80 de	79 de
B10F	79 a	83 ab	89 a	90 a	90 a	90 a	90 a	88 a
B10P	66 d	71 d	77 d	79 d	81 d	82 d	81 c	80 d
B10PF	72 c	77 c	82 c	84 c	86 c	86 c	85 c	83 c
B20	65 de	70 d	75 e	77 e	78 e	79 e	79 e	77 e
B20F	80 a	84 a	88 ab	90 a	90 a	90 a	89 a	88 a
B20P	66 de	71 d	76 de	79 80	81 d	81 80	80 cd	79 d
B20PF	73 c	77 c	82 c	84 c	86 c	86 c	84 c	83 c
B30	63 f	68 e	73 f	75 f	76 f	77 f	76 f	74 f
B30F	77 b	82 b	86 b	87 b	88 b	88 b	87 b	86 b
B30P	64 ef	69 de	76 de	79 de	80 d	81 80	80 cde	79 d
B30PF	72 c	77 c	81 c	85 c	85 c	85 c	84 c	82 c
				Torque (N m)				
B10	498 d	497 d	499 de	482 def	463 de	440 e	414 e	389 de
B10F	602 a	587 ab	583 a	555 a	525 a	496 a	469 a	435 a
B10P	497 d	499 d	504 d	489 d	469 d	449 d	422 d	397 d
B10PF	549 c	541 c	538 c	517 c	495 c	468 c	441 c	410 c
B20	491 de	494 de	492 e	476 f	455 e	435 e	411 e	383 e
B20F	603 a	589 a	574 b	552 a	523 a	492 a	465 a	433 ab
B20P	494 d	497 d	499 de	484 de	465 d	443 de	416 de	391 d
B20PF	549 c	544 c	534 c	518 c	495 c	467 c	435 c	407 c
B30	482 f	482 f	482 f	466 g	445 f	424 f	398 f	371 f
B30F	588 b	579 b	570 b	541 b	514 b	484 b	454 b	426 b
B30P	486 ef	488 ef	494 e	481 ef	463 de	440 e	415 de	389 de
B30PF	546 c	538 c	532 c	520 c	490 c	464 c	434 c	406 c

F - Increase in the amount of fuel injected; P - Advance of the injection point; PF - Advance of the injection point plus an increase in the amount of fuel injected; MSD - Minimum significant difference; Means followed by the same letter in the column for each variable do not differ according to the Tukey test (considering significance at p ≤ 0.05)



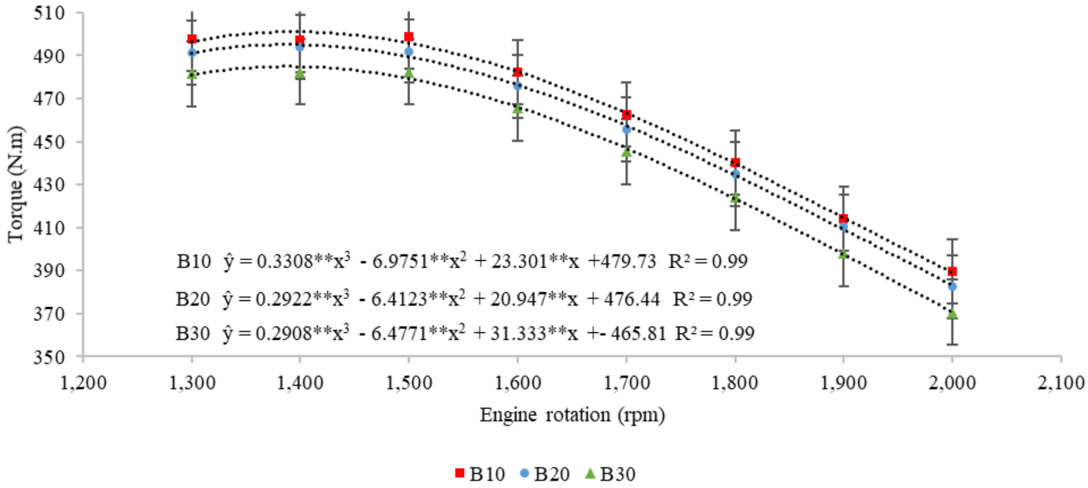
Vertical bar - Standard error; *, ** - Significant at p ≤ 0.05 and p ≤ 0.01, respectively, by F test

Figure 1. The power as a function of engine rotation for the fuel with 10% of biodiesel (B10), 20% of biodiesel (B20) and 30% of biodiesel (B30), with the original engine condition

Advancing the ignition point by 2.5° along with an 8.60% increase in the injected fuel volume (B10+F+P) resulted in increases of 7.62% for power and 7.54% for torque. Only the advance of the injection point (B10+P) did not show a statistical difference compared to the original condition, although this did show a trend toward a better yield. Agarwal et al. (2015) found an increase in power output for B10 as the injection point was advanced and when working with an injection pressure greater than 500 bar. Figure 3 shows the different power curves for the B10 fuel.

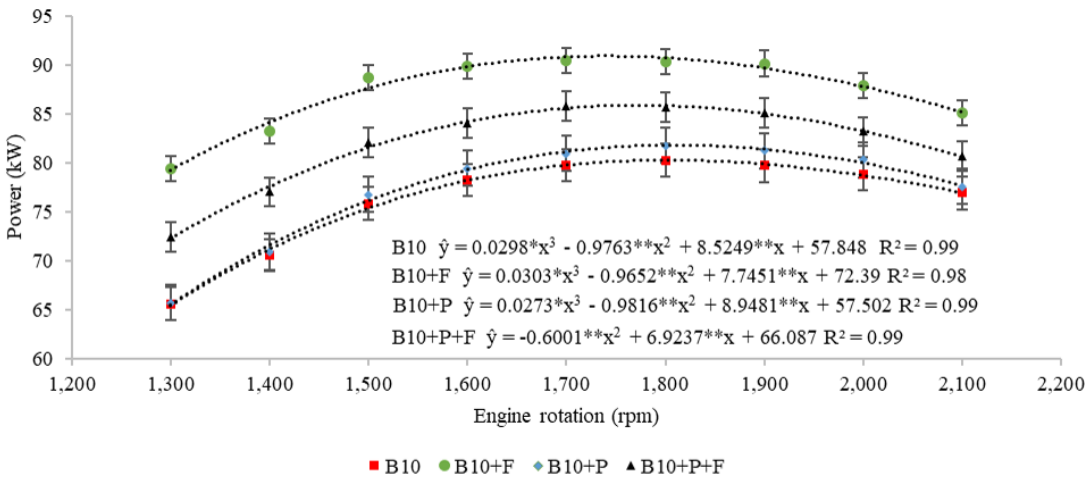
The tests carried out with B20 fuel presented similar results to those conducted with B10, as also observed by Deep et al. (2017) in studies conducted with biodiesel produced from castor beans. Figure 4 shows the result, but the B20+P condition presented a statistically significant power increase of 2.40% at rotations greater than 1,600 rpm.

For the B30 fuel (Figure 5), the gain with only an advance in the injection point was greater, with increases of around 5.38% for power and 3.71% for torque, starting at 1,500 rpm, when compared to the original configuration. This change in the mapping made the power produced with the B30 very similar to that of B10 in its original condition. The injection point advance is shown to be more effective with higher percentages of biodiesel, since the rate of heat release during combustion is lower as the amount of biodiesel blended increases (Ramlan et al., 2015).



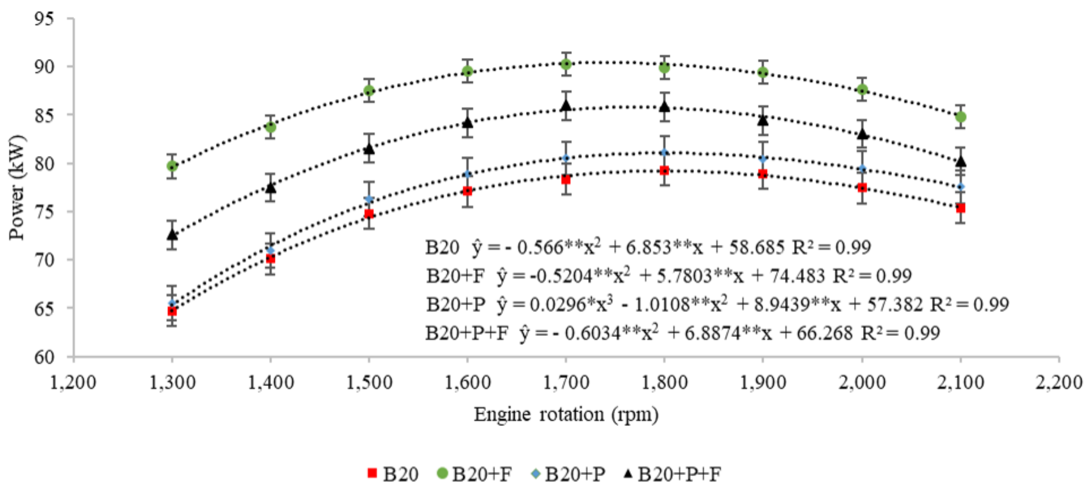
Vertical bar - Standard error; ** - Significant at p ≤ 0.01 by F test

Figure 2. Torque as a function of engine rotation for the fuel with 10% of biodiesel (B10), 20% of biodiesel (B20) and 30% of biodiesel (B30), with the original engine condition



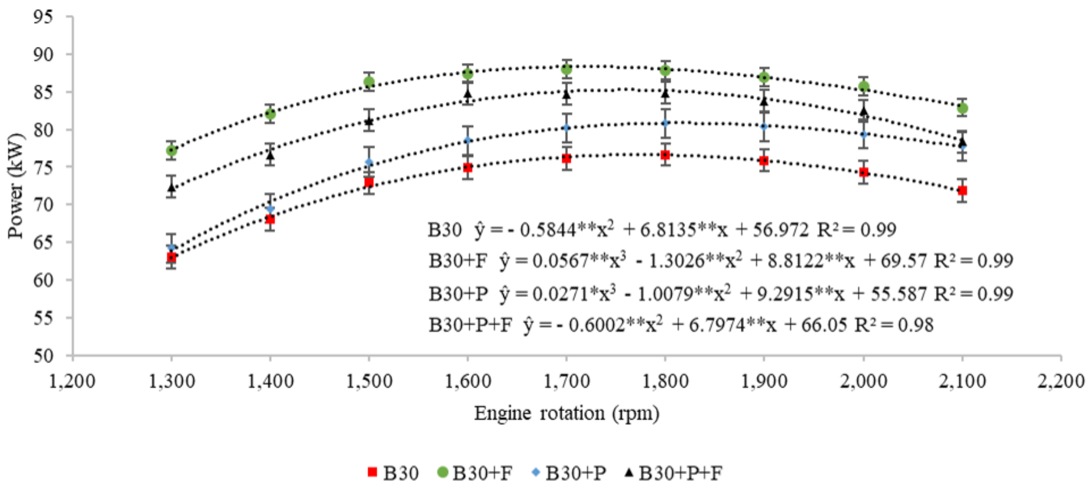
Vertical bar - Standard error; *, ** - Significant at p ≤ 0.05 and p ≤ 0.01, respectively, by F test

Figure 3. Power as a function of engine rotation for the fuel with 10% of biodiesel, with the original condition (B10), increase in the amount of fuel injected (B10+F), advance of the injection point (B10+P), and advance of the injection point plus an increase in the amount of fuel injected (B10+P+F)



Vertical bar - Standard error; *, ** - Significant at p ≤ 0.05 and p ≤ 0.01, respectively, by F test

Figure 4. Power as a function of engine rotation for the fuel with 20% of biodiesel, with the original condition (B20), increase in the amount of fuel injected (B20+F), advance of the injection point (B20+P), and advance of the injection point plus an increase in the amount of fuel injected (B20+P+F)



Vertical bar - Standard error; *, ** - Significant at $p \leq 0.05$ and $p \leq 0.01$, respectively, by F test

Figure 5. Power as a function of engine rotation for the fuel with 30% of biodiesel, with the original condition (B30), increase in the amount of fuel injected (B30+F), advance of the injection point (B30+P), and advance of the injection point plus an increase in the amount of fuel injected (B30+P+F)

The hourly fuel consumption presented very similar values for the condition with original injection mapping and the advance injection point (+P) condition because there is no variation in the total nozzle opening time, only an advance of the opening and closing (Table 3). The condition of more fuel injected (+F), on the other hand, showed an average increase of 16.9% in fuel volume over the original condition, and the condition of more fuel and injection advance (+P+F) provided an increase of 8.6% (Table 4).

Initially, all conditions with more fuel were expected to present similar values and the variation from 16.9% to 8.6% can be explained by the higher pressure in the fuel chamber with the advance of the injection, which decreases the pressure differential between the internal and external parts of the nozzle, thus causing a lower volumetric fuel flow. Another factor that may have contributed to the electronic system not maintaining the fuel gain around 16.9% is that some other variable measured by the ECU, such as intake air temperature or supercharging pressure, caused some negative correction factor to be applied to the injection timing.

Table 4. Hourly fuel consumption for the original engine condition, increase in the amount of fuel injected (+F), advance of the injection point (+P) and advance of the injection point plus an increase in the amount of fuel injected (+P+F)

Fuel	Original engine condition	+P	+F	+P+F
	Consumption (L h^{-1})			
B10	25.44	25.36	29.89	27.81
B20	25.87	25.79	30.24	27.76
B30	25.46	25.55	29.65	27.81
Mean	25.59	25.57	29.93	27.79
Total	100%	99.92%	116.96%	108.60%

With the engine in its original electronic mapping condition, B10 showed the lowest specific fuel consumption. The data presented consider the net power available at the PTO. It was found that the higher the biodiesel concentration in the blend the higher the consumption will be. Compared to B10, the consumption values obtained with the use of B20 and B30 were 3.6% and 5.9% higher (Table 5 and Figure 6).

The lower calorific value and the change in the behavior of the heat release during the combustion process are factors that

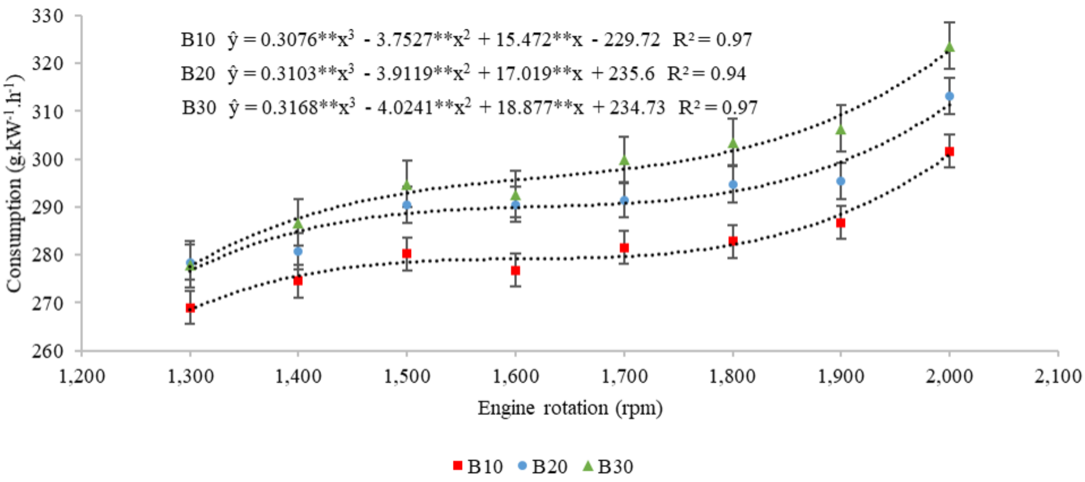
Table 3. Mean values for the hourly consumption of the engine at the rotations evaluated with the original engine condition, increase in the amount of fuel injected (+F), advance of the injection point (+P) and advance of the injection point plus an increase in the amount of fuel injected (+P+F)

	Engine rotations (rpm)							
	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000
	Hourly consumption (L h^{-1})							
B10	20.9 fg	23.0 d	25.2 e	25.7 g	26.6 fg	26.9 g	27.1 fg	28.2 e
B10F	25.8 b	28.3 a	30.5 a	30.5 b	30.4 b	31.0 ab	30.8 ab	31.7 a
B10P	16.3 h	20.5 e	25.6 e	25.9 fg	26.4 gh	26.9 g	27.1 g	28.3 e
B10PF	23.1 e	25.7 c	28.8 b	29.3 f	29.9 c	28.4 80	27.9 e	29.4 c
B20	21.2 f	23.2 d	25.6 e	26.4 e	26.9 ef	27.5 ef	27.5 efg	28.6 de
B20F	26.4 a	28.4 a	30.6 a	31.1 a	31.2 a	31.3 a	31.2 a	31.9 a
B20P	21.2 f	23.3 d	25.5 e	26.1 ef	27.1 e	27.5 ef	27.3 fg	28.3 e
B20PF	23.6 d	25.8 c	27.4 d	28.1 d	28.9 d	29.0 c	29.0 c	30.1 b
B30	20.5 g	22.9 d	25.2 e	25.7 fg	26.7 efg	27.3 fg	27.2 fg	28.2 e
B30F	25.4 c	27.8 b	30.5 a	30.5 b	30.5 b	30.6 b	30.4 b	31.6 a
B30P	20.5 g	19.1 f	25.3 e	20.4 h	26.0 h	27.7 e	27.5 ef	28.9 d
B30PF	23.9 d	26.0 c	28.0 c	28.4 d	28.8 d	29.4 c	28.6 d	29.5 c

F - Increase in the amount of fuel injected; P - Advance of the injection point; PF - Advance of the injection point and increase in the amount of fuel injected; MSD - Minimum significant difference; Means followed by the same letter in the column for each variable do not differ according to the Tukey test (considering significance at $p \leq 0.05$)

Table 5. Average specific consumption for the original engine condition, increase in the amount of fuel injected (+F), advance of the injection point (+P), advance of the injection point plus an increase in the amount of fuel injected (+P+F), and percentage in comparison to the original engine condition and B10 fuel

Fuel	Original engine condition		+P		+F		+P+F	
	Average consumption (g kW^{-1} h^{-1})							
B10	281.65	100.0%	276.85	98.3%	288.00	102.2%	286.50	101.6%
B20	291.89	103.6%	285.07	101.2%	293.96	104.0%	287.46	102.1%
B30	298.20	105.9%	286.18	101.6%	296.80	105.4%	291.64	103.5%



Vertical bar - Standard error; ** - Significant at p ≤ 0.01 by F test

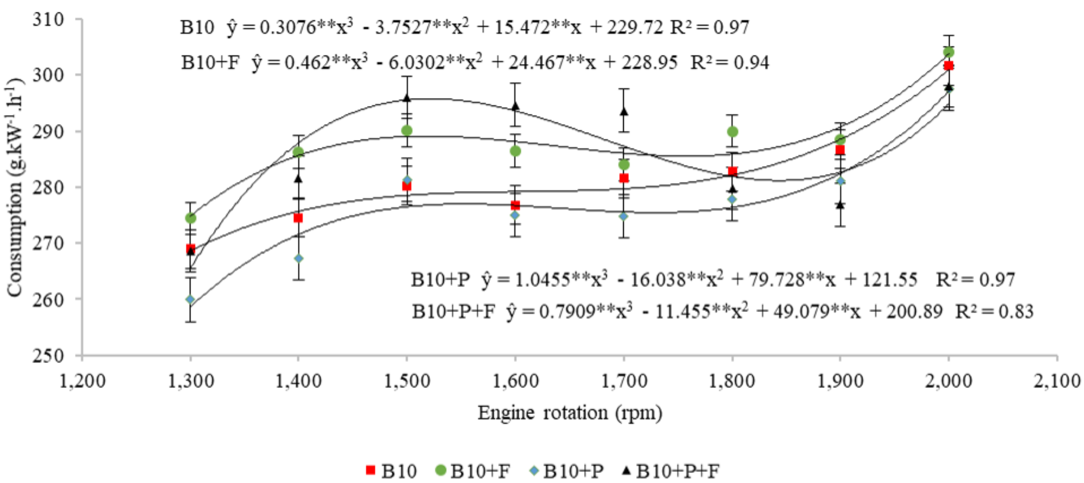
Figure 6. Specific fuel consumption as a function of engine rotation for the fuel with 10% of biodiesel (B10), 20% of biodiesel (B20) and 30% of biodiesel (B30), with the original engine condition

highlight the need for engine adjustments to obtain a better performance and lower specific consumption with these fuels. The results follow the same trend as that reported by Perin et al. (2017), who found that the specific consumption increased by 7.10% and 9.33% for B20 and B50, respectively, compared to B10. Godeša et al. (2010), on the other hand, observed corresponding increases in the specific consumption of 1.25% and 2.5% for B20 and B30, respectively.

For the B10 fuel, the +P condition presented the lowest average specific consumption among all tests performed, with a decrease of 1.7% compared to the control test, but the result was statistically different only for the speeds of 1,300 and 1,400 rpm (Figure 7). The +F and +P+F maps, on the other hand, had a higher specific consumption presenting a lower thermal efficiency than the original condition.

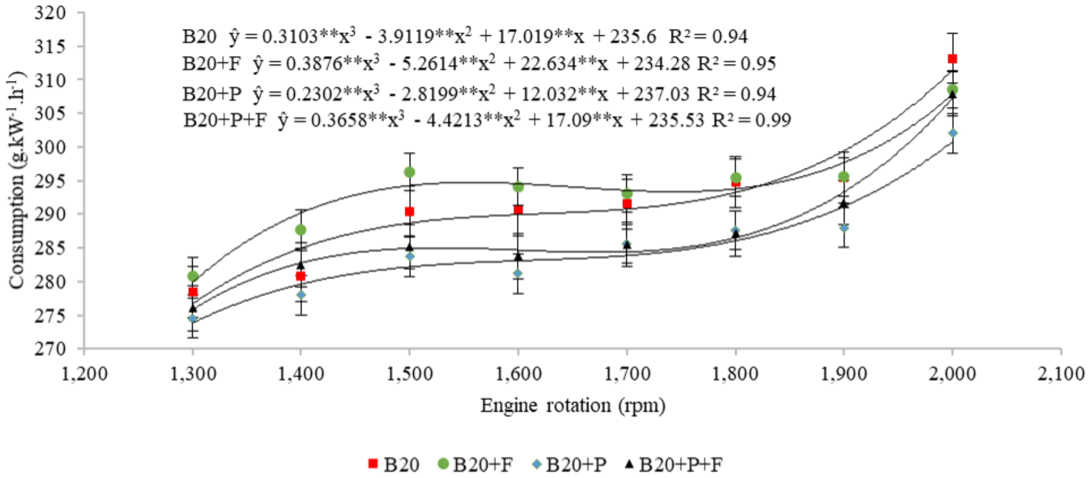
The tests with the B20 fuel showed a tendency for the specific fuel consumption to decrease with an advance in the injection point (+P and +P+F), although for most rotations the differences in the results are not statistically significant. This trend can be easily observed in Figure 8.

For the B30 fuel, the +P test condition presented an average decrease in the specific consumption of 4.0%, this being statistically significant for all rotations evaluated (Figure 9 and Table 6). The +P+F condition also showed a tendency to improve, but with statistically different results only at rotations above 1,700 rpm. This can be explained by the fact that at high



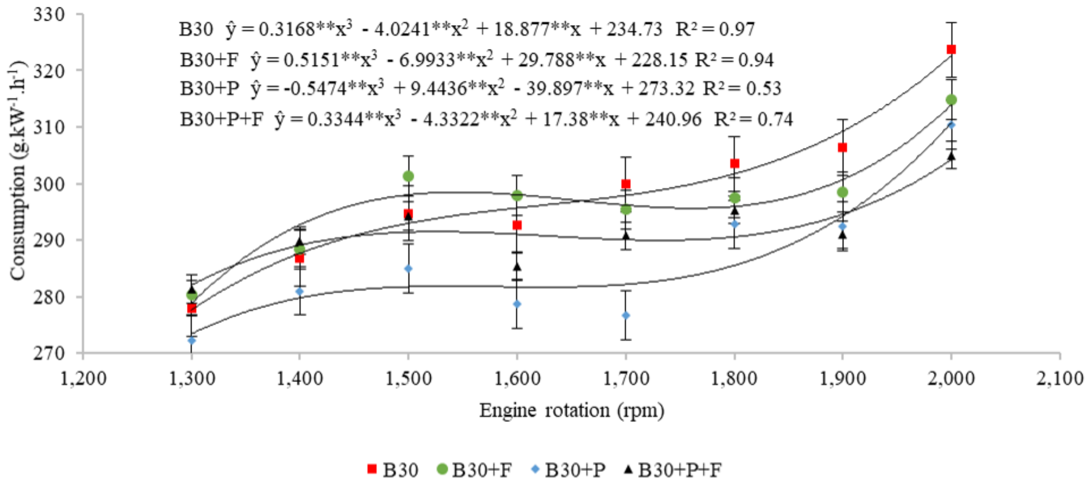
Vertical bar - Standard error; ** - Significant at p ≤ 0.01 by F test

Figure 7. Specific fuel consumption as a function of engine rotation for the fuel with 10% of biodiesel with the original condition (B10), increase in the amount of fuel injected (B10+F), advance of the injection point (B10+P), and advance of the injection point plus an increase in the amount of fuel injected (B10+P+F)



Vertical bar - Standard error; ** - Significant at $p \leq 0.01$ by F test

Figure 8. Specific fuel consumption as a function of engine rotation for the fuel with 20% of biodiesel with the original condition (B20), increase in the amount of fuel injected (B20+F), advance of the injection point (B20+P), and advance of the injection point plus an increase in the amount of fuel injected (B20+P+F)



Vertical bar - Standard error; ** - Significant at $p \leq 0.01$ by F test

Figure 9. Specific fuel consumption as a function of engine rotation for the fuel with 30% of biodiesel with the original condition (B30), increase in the amount of fuel injected (B30+F), advance of the injection point (B30+P), and advance of the injection point plus an increase in the amount of fuel injected (B30+P+F)

Table 6. Mean values for the specific consumption of the engine at the rotations evaluated with the original engine condition, increase in the amount of fuel injected (+F), advance of the injection point (+P) and advance of the injection point plus an increase in the amount of fuel injected (+P+F)

	Engine rotations (rpm)							
	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000
	Specific consumption (g kW⁻¹ h⁻¹)							
B10	242 d	247 e	252 d	249 f	253 ef	255 fg	258 de	271 def
B10F	247 abcd	258 abc	261 bc	258 cde	256 de	261 cdef	260 cd	274 cdef
B10P	188 e	219 f	253 d	247 f	247 f	250 g	253 ef	268 f
B10PF	242 d	254 bcd	267 ab	266 ab	265 ab	252 g	249 f	268 ef
B20	251 abc	253 cde	261 bc	262 bcd	262 bc	265 bcd	266 bc	282 b
B20F	253 ab	259 ab	267 ab	265 ab	264 ab	266 bc	266 bc	278 bcd
B20P	247 bcd	250 de	255 cd	253 ef	257 cde	259 def	259 de	272 def
B20PF	249 abc	255 bcd	257 cd	256 de	257 cde	259 ef	263 bcd	277 bcd
B30	250 abc	258 abc	265 ab	263 abc	270 a	273 a	276 a	291 a
B30F	253 ab	260 ab	271 a	268 a	266 ab	268 ab	269 b	283 b
B30P	245 cd	212 g	257 cd	199 g	249 f	263 bcde	263 bcd	279 bc
B30PF	254 a	262 a	266 ab	257 cde	262 bcd	266 bc	262 cd	275 cde

F - Increase in the amount of fuel injected; P - Advance of the injection point; PF - Advance of the injection point plus an increase in the amount of fuel injected; MSD - Minimum significant difference; Means followed by the same letter in the column for each variable do not differ according to the Tukey test (considering significance at $p \leq 0.05$)

RPMs the time available for combustion is shorter and the effect of advancing the injection point is more pronounced. The results for the +F condition were similar, with a small gain at rotations above 1,800 rpm.

Conclusions

1. With the use of 20% of biodiesel (B20) there is no change in the performance or specific consumption compared to the fuel containing 10% of biodiesel (B10).

2. On using the fuel with 30% of biodiesel (B30) there is lower thermal efficiency and the power generated is lower compared with the fuel containing 10% of biodiesel (B10).

3. The change in the injection system to increase the fuel volume injected results in higher power compared to the original engine condition, providing a power gain of up to 14.9% and torque gain of up to 15.5%.

4. The advance of the injection point results in a power gain and the lowest specific fuel consumption for all fuels analyzed and was more effective in the case of fuels with higher biodiesel concentrations.

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