The effects of split direct injection on the operation of a tractor diesel engine fueled by biodiesel B20

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Abstract. The use of biodiesel-diesel blends is a current solution to some important problems, such as the depletion of oil resources, global warming, and the pollutant emissions of smoke, carbon monoxide, and hydrocarbons of diesel engines. However, the use of this alternative fuel is characterized by a reduction in engine effective power and an increase in brake-specific fuel consumption and nitrogen oxide pollutant emissions. Using the AVL MCC zero-dimensional combustion model of the AVL BOOST simulation program, it was evaluated to what extent split injection strategies can improve the performance and fuel economy of a tractor diesel engine fuelled with biodiesel B20 at maximum brake torque condition considering noise and pollutant emissions limitation. Various pilot – main – post split injection strategies have been studied to establish the optimal injection characteristics in terms of performance and fuel economy. Subsequently, they have been adapted in terms of compliance with current emission standards. In this way, it has been emphasized that the split injection solution is a viable way to improve performance, economy, and pollutant emissions of a tractor diesel engine.

1 Introduction

The depletion of oil resources, global warming, and the harmful effects caused by pollutant emissions as nitrogen oxides (NO_x) and soot on the environment have led researchers to find solutions to overcome these problems.

Biodiesel is a fuel obtained by transesterification processes of animal or vegetable oils. The use of biodiesel – diesel blends allows slowing down the depletion of oil resources. A slight increase of biodiesel fraction in fuel will offer enough time to car manufacturers for adapting the internal combustion engines to the operation with higher percentages of biodiesel, this way the oil resources depletion phenomenon being less and less overwhelming. The use of vegetable oils in the process of biodiesel production and its subsequent use in blend with diesel as fuel for the compression ignition engines is an effective solution to combat the global warming phenomenon. This is because plants

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consume carbon dioxide (CO_2) through the process of photosynthesis during their lifetime, and CO_2 is the main gas in the atmosphere responsible for producing this phenomenon.

The reduction of NO_x and soot emissions can be achieved by adopting split injection strategies associated with the presence of an electronically controlled injection system. These injection strategies involve the existence of pilot, main, and possibly post-injections coupled in different ways as number and timings.

By combustion of the amount of pilot injected fuel, there is a slight increase in pressure and temperature in the cylinder before the main injection. This reduces the ignition delay of the fuel amount delivered in the main injection, the combustion process developing more during the third stage, that of diffusive combustion with a lower peak temperature which causes a decrease in the formation of NO_x emissions [1].

A very effective and widely used solution for reducing soot emissions is the use of post-injections. A post-injection is a short injection that occurs after the main fuel injection [2]. The dwell time represents the duration between two consecutive injections. The amount of fuel injected during the pilot injection, as well as the dwell time, strongly influences the values of pollutant emissions, noise, and specific fuel consumption of a diesel engine [3].

D'Ambrosio and Ferrari [4] conducted an experimental study that aimed to evaluate the potential of triple injection (pilot – pilot – main) compared to the double injection (pilot - main). For medium loads and speeds of the Diesel engine, the use of triple injection reduces NO_x emissions, but the engine noise does not improve, and soot emissions increase.

Poorghasemi et al [5] have numerically studied the possibility of simultaneously reducing NO_x and soot emissions in a diesel engine by using split injection strategies. The results showed that the adoption of a post-injection with an adequate dwell time allows a significant and simultaneous reduction of these emissions.

Hiren et al [6] conducted a numerical and experimental study for the investigation of the influence of pilot injection on the combustion process and the formation of the pollutant emissions, keeping constant dwell time and main injection timing. A large amount of fuel introduced during the pilot injection reduces smoke and increases NO, HC emissions, and brake-specific fuel consumption. The injection strategy with only 15% pilot quantity is the optimal among all the considered pilot injection strategies (15%, 30%, and 45% pilot quantity) because it causes a reduction in brake-specific fuel consumption, NO, and HC emissions, while smoke emissions acceptably increase.

The authors of the paper [7] developed a single-zone phenomenological combustion simulation model for a diesel engine that uses conventional single injection or split injection strategies. Subsequently, they assessed the extent to which NO_x emissions can be reduced by using EGR or by adopting split injection strategies. They conclude that both methods can significantly reduce NO_x emissions, but with penalties in terms of engine performance when using EGR.

The researchers from reference [8] numerically and experimentally studied the effects of using various split injection strategies with different dwell times on the combustion characteristics and pollutant emissions. An increase of the dwell time determines the decrease of peak heat release rate, thus amplifying the diffusive combustion which leads to NO_x reductions and soot, HC, and CO increases.

The authors of work [9] investigated numerically and experimentally the effects of pilot injection on flame temperature and soot distribution for an optically internal combustion engine fuelled by pure diesel and biodiesel. The pilot injection improves combustion performance and increases fuel economy if it is positioned near the main injection. The combustion initiated by the pilot injection contributes to the development of the main fuel jet, resulting in a reduction of inhomogeneities in the combustion chamber. Thus, the fuel-rich local zones are reduced and the general temperature of the flame decreases, this having

an improved distribution along the combustion chamber. These changes affect the formation of NO_x and soot emissions.

In paper [10] was highlighted the impact of injection rate shape on the performance, efficiency, and pollutant emissions of a tractor diesel engine using the AVL MCC zero-dimensional combustion model of the AVL BOOST software. The actual paper represents a numerical study performed with the AVL MCC zero-dimensional combustion model of the AVL BOOST software on the possibilities of improving performance and reducing NO_x and soot pollutant emissions of a tractor diesel engine fuelled with B20 (20% rapeseed biodiesel and 80% diesel) at full load and maximum torque speed condition by using split injection strategies. The model was calibrated against experimental data obtained for pure diesel and B20 fuelling with a single injection strategy.

2 Materials and Methods

The test bench is equipped with UTB 2404055 tractor Diesel engine. Its main specifications are presented in Table 1.

Table 1. Engine specifications

Description	Specification
Engine Type	UTB 2404055
Bore x Stroke	102 mm x 115 mm
Compression Ratio	17.5
Number of Cylinders	4
Displacement (L)	3.76
Piston Type	Omega
Rated Power	48 kW / 2400 rpm
Rated Torque	224 Nm / 1400 rpm
Air System	Naturally-aspired
Injection System	Delphi
Number of Nozzle Holes	5
Nozzle Hole Diameter	0.24 mm

Figure 1 shows the configuration of the test bench and the AVL BOOST symbolic model of the engine. The instant torque and speed are measured and controlled using the AVL Alpha 160 eddy current dynamometer. The fuel consumption is recorded using the AVL Dynamic Fuel Meter 733 S coupled with AVL Fuel Temperature Controller 753 C. The volumetric air consumption is measured using the airflow meter SCHLUMBERGER Fluxi 2000/TZ. The carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), and total hydrocarbons (THC) pollutant emissions are evaluated using HORIBA Mexa 7170 D gas analyzer, while the smoke level in the exhaust gases is determined by the AVL Smoke Meter 415 S. The pressure traces are recorded for two engine cylinders (1 and 3) with a data acquisition system consisting of AVL GM 12 D quartz pressure transducers, AVL 3066A02 charge amplifiers and AVL 365 C crank angle encoder. All the equipment is connected to the data acquisition module AVL Indiset 620 provided with the AVL Indicom 1.6 software.

Numerous parameters were recorded, including engine brake power, fuel consumption, pressure trace, and pollutant emissions values when fuelling the engine with pure diesel (D100) and B20 for maximum brake torque test condition (full load, 1400 rpm).
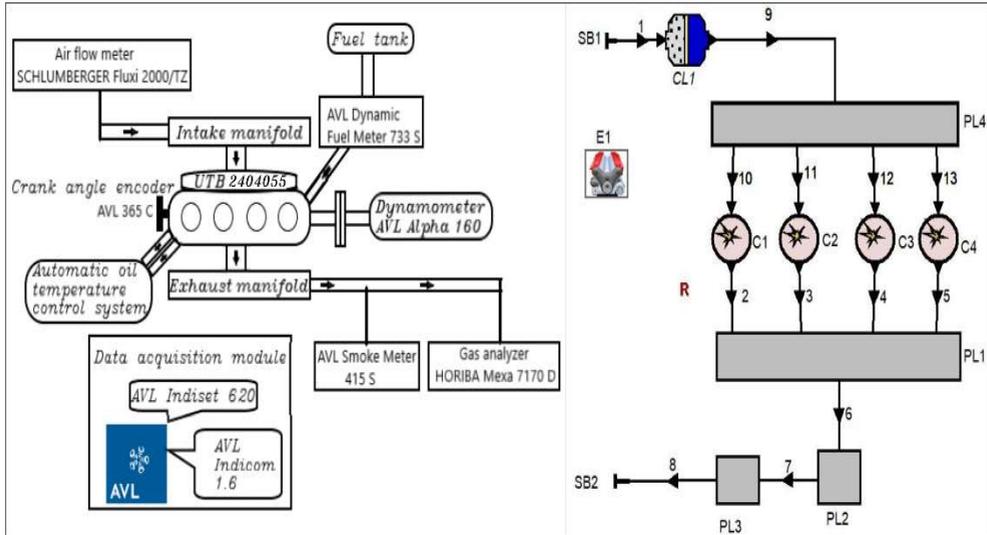
Fig. 1. Schematic diagram of the experimental set-up and the AVL BOOST symbolic model of the engine

Fig. 2 shows the values of the normalized rate of fuel injection (relative to peak velocity) depending on the crank angle for various injection strategies. Based on experimental data, the calibration of the simulation model was performed considering the single injection strategy with 16 °CA total duration. This injection starts at -5 °CA and ends at 11 °CA. Subsequently, to improve the engine performance without increasing the pollutant emissions level for B20 fuel, split injection strategies with 16 °CA and 10 °CA total duration were adopted. These strategies consist of: the pilot injection that delivers 10% of the total mass fuel, the main injection that delivers 80%, and the post injection that delivers 10%. The same value for dwell was considered between the pilot and main injections or between main and post. For split injection strategy with the same total duration like single injection (16 °CA), the start of injection (SOI) and dwell time were considered -11 °CA and 2 °CA (relative to Top Dead Center – TDC), while for the other one were set to -2 °CA and 4 °CA. These values have been chosen considering maximum engine effective power and pollutant emissions level closer to the experimental values obtained for B20 fuelling.
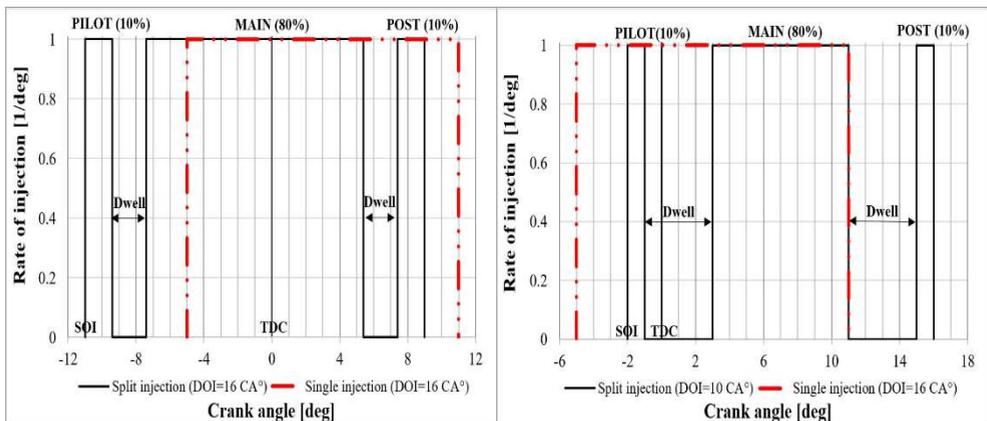
Fig. 2. The normalized split and single rate of injections studied with AVL BOOST software

3 Simulation Results

Table 2 shows the values obtained by experimental testing and by numerical simulation for brake power (BP), brake-specific fuel consumption (BSFC), peak pressure (p_{max}), peak pressure rise ($\dot{p}_{max}$), nitrogen oxides (NO_x), and soot when the engine was operated at maximum brake torque conditions (full load, 1400 rpm).

Table 2. The values of parameters considered for maximum brake torque test condition

	BP [kW]		BSFC [g/kWh]		p_{max} [bar]		$\dot{p}_{max}$ [bar/deg]		NO_X [ppm]		Soot [g/kWh]	
	D100	B20	D100	B20	D100	B20	D100	B20	D100	B20	D100	B20
Experimental	32.87	31.73	236.4	255.0	66.53	66.07	8.18	7.88	1082	1017	2.166	2.051
Single injection (16 CA°)	32.22	32.21	241.2	251.2	66.15	65.48	4.98	5.10	1083	1018	2.166	1.994
Split injection (16 CA°)	32.32	32.32	240.4	250.4	74.76	73.66	4.70	4.70	1422	1257	1.841	1.939
Split injection (10 CA°)	32.84	32.84	236.6	246.4	62.21	61.70	3.26	3.13	1094	1008	0.823	1.507

Table 3 displays the percentage differences of the AVL MCC combustion model results for the above-mentioned parameters when using single or split injection strategies relative to experimentally obtained values. Regarding the calibration step of the single injection strategy, it may be emphasised that the relative deviations of engine performance (ε_{BP} and ε_{BSFC}), pollutant emissions (ε_{NOx} and ε_{Soot}), and peak pressure ($\varepsilon_{p_{max}}$) considered relevant for simulation rest under 3% for both fuels. For peak pressure rise there are considerable errors ($\varepsilon_{\dot{p}_{max}}$), the calibration of this parameter requiring future improvements.

Table 3. Percentage differences relative to experimental data

	ε_{BP} [%]		ε_{BSFC} [%]		$\varepsilon_{p_{max}}$ [%]		$\varepsilon_{\dot{p}_{max}}$ [%]		ε_{NOx} [%]		ε_{Soot} [%]	
	D100	B20	D100	B20	D100	B20	D100	B20	D100	B20	D100	B20
Single injection (16 CA°)	-1.98	1.51	2.03	-1.49	-0.57	-0.89	-39.12	-35.28	0.09	0.10	0.00	-2.78
Split injection (16 CA°)	-1.67	1.86	1.69	-1.80	12.37	11.49	-42.54	-40.36	31.42	23.60	-15.00	-5.46
Split injection (10 CA°)	-0.09	3.50	0.08	-3.37	-6.49	-6.61	-60.15	-60.28	1.11	-0.88	-62.00	-26.52

Figure 3 illustrates the values of brake power (BP) and brake-specific fuel consumption (BSFC) obtained experimentally and by simulations considering different injection strategies. By adopting a split injection with 16 °CA total duration, the engine BP increased slightly from 32.21 kW (single injection) to 32.32 kW for both fuels. This increase is insufficient, so a split injection with a shorter total duration was adopted (10 °CA) because it allows obtaining a BP closer to that experimentally determined for pure diesel - D100 (32.84 kW for both fuels compared to 32.87 kW). In terms of BSFC, this injection strategy

offers minimum values for both fuels (236.6 g/kWh for D100 and 246.4 g/kWh for B20 compared to 241.2 g/kWh for D100 and 251.2 g/kWh for B20 when using the single injection strategy).
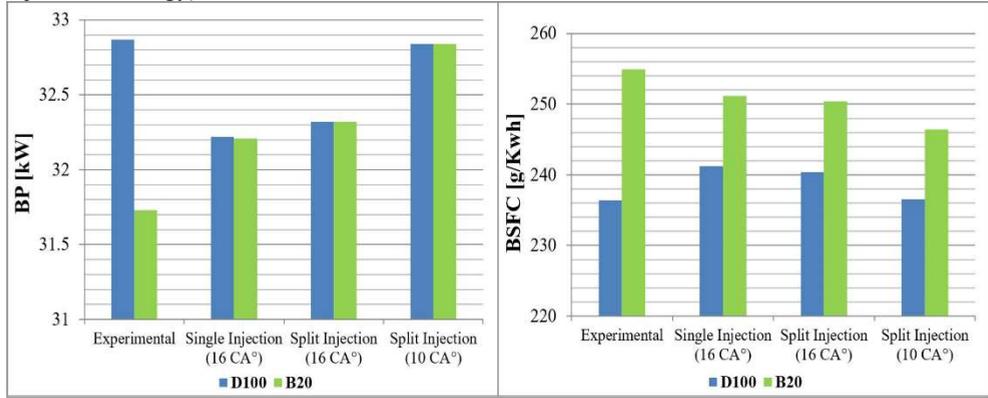
Fig. 3. Brake power (BP) and brake-specific fuel consumption (BSFC) variations by different injection strategies

Figure 4 displays the values of peak pressure (p_{max}) and peak pressure rise ($\dot{p}_{max}$) obtained experimentally and by simulations considering different injection strategies. The use of the split injection with a duration of 16 °CA determines a peak pressure increase of 12.4% for D100 and 11.5% for B20 and a peak pressure rise decrease of 42.5% for D100 and 40.4% for B20 compared to the experimental values. The split injection with 10 °CA total duration determines a simultaneous reduction of the peak pressure (6.5% for D100 and 6.6% for B20) and peak pressure rise (60.2% for D100 and 60.3% for B20), which determines lower stresses on the engine components and lesser operation noise.
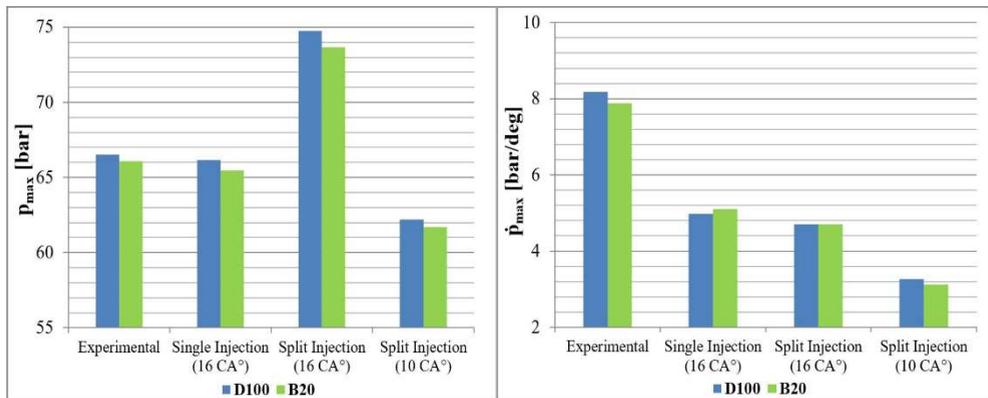
Fig. 4. Peak pressure (p_{max}) and peak pressure rise ($\dot{p}_{max}$) variations by different injection strategies

Figure 5 presents the values of nitrogen oxides (NO_x) and soot pollutant emissions obtained experimentally and by simulations considering different injection strategies. Using the split injection with a longer duration, NO_x emissions significantly increase by 31.4% for D100 and 23.6% for B20, while soot emissions decrease by 15% for D100 and 5.5% for B20 compared to the experimental values. The split injection with shorter duration allows obtaining a simultaneous reduction of these emissions for B20 (0.9% less NO_x and 26.5%

less soot) and slight growth in NO_x with a sharp decrease in soot for D100 (1.1 % more NO_x and 62% less soot).
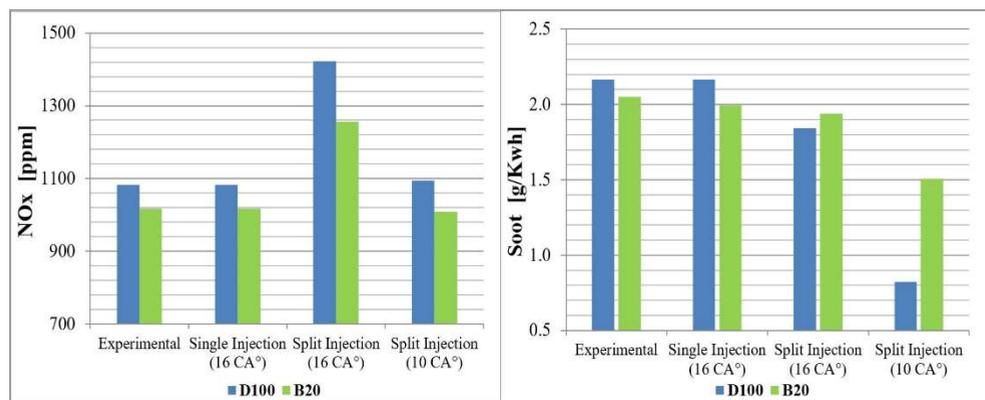
Fig. 5. Nitrogen oxides (NO_x) and soot emissions variations by different injection strategies

4 Conclusions

The main conclusions of this work can be summarized as follow:

• The use of a one-dimensional simulation model developed under AVL BOOST software allows the evaluation of the performance, efficiency, and pollutant emissions of a diesel engine when using various injection strategies with minimal computation resource consumption;

• The substitution of the original diesel fuel used in a compression ignition engine by biodiesel containing elevated fractions of biofuel is generally associated with a derating of the original engine power when no additional adjustment is performed; higher biofuel fractions are associated with lower engine performances and a similar effect was registered also in this case when for B20 use the decrease in brake power was 3.5%;

• A method to recover the engine power is to change the injection characteristic passing from the single injection to the split injection with multiple pulses (in this work with three pulses: pilot – main - post);

• The simulations performed showed that it is possible to find a suitable split injection characteristic for B20 and engine operating condition (full load and 1400 rpm speed) where power is entirely recovered but with lower peak pressure (61.7 bar relative to 66.53 bar), lower peak pressure rise (3.13 bar/deg relative to 8.18 bar/deg), lower NO_x (1008 ppm relative to 1082 ppm) and lower soot emission (1.507 g/kWh relative to 2.166 g/kWh);

• A slight penalty of engine economy in terms of BSFC outcomes, which increases by 4% from 236.4 to 246.4 g/kWh.

The model needs future refinements in the calibration stage but it emphasized the effectiveness of multiple pulses split injection technology to control the combustion process in diesel engines for lowering emissions while maintaining performances.

Acknowledgments

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